Surface soil organic carbon sequestration under post agricultural grasslands offset by net loss at depth

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Abstract Post agricultural grasslands are thought 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, changes in SOC stock in CRP lands have mostly been evaluated at local scales and focused on the surface 20–30 cm of the soil profile. Thus, we lack knowledge of SOC dynamics in CRP lands on a continental scale, especially 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 profile across the conterminous US. Here we analyzed data from RaCA to evaluate the SOC stocks of both surface and subsurface soil of the CRP on a continental scale. 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 CRP lands have higher SOC stocks in the surface soil (0–5 cm). However, such higher SOC levels 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 CRP lands in humid and warm regions may have net soil C sequestration because they have much more SOC in the surface as compared with croplands in the same regions. Whether the lower SOC in the subsurface of CRP lands 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.

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Introduction

The conversion of row crop agricultural lands to perennial vegetation is regarded as an important approach for soil organic carbon (SOC) sequestration and as a climate change mitigation strategy (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, and economic benefits, such as reducing cropping area to elevate commodity prices (Morefield et al. 2016), CRP is considered a legitimate large-scale (~8.9 Mha) effort to sequester C from the atmosphere and control the greenhouse effect (Bronson et al. 2004; Kucharik 2007; USDA 2020). Agricultural practices disturb soil and deplete SOC (Knops and Tilman 2000; Conant et al. 2001). Once agricultural lands are converted to perennial vegetation SOC losses can be reversed due to increased belowground primary production and physical protection of organic matter in soil aggregates (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 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 variation 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.

Like most of the research in post agricultural lands, C sequestration research in CRP lands has primarily been focused on the top 10 to 30 cm soil (Gebhart et al. 1994; Bronson et al. 2004; Kucharik 2007; Baer et al. 2010; Li et al. 2017). Hence, we have limited knowledge of SOC stocks 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 organic matter (SOM) also has slow decomposition 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 are as important as surface SOC to understand and predict soil C sequestration potential in CRP lands (Rumpel and Kögel-Knabner 2011).

The Rapid Carbon Assessment (RaCA) program, 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. In RaCA, a multi-level hierarchical sampling scheme was used to collect soil samples from wetlands, forestlands, rangelands, pasturelands, croplands, and CRP lands down to 100 cm or the depth of the restrictive layer (Wills et al. 2014). It was the first time that CRP lands were included in a CONUS soil survey. Before sample collection, Wills et al. (2013) developed a statistical algorithm to group soil pedons in each region with similar taxonomy, moisture and temperature regimes, texture, drainage, and depth to the restrictive layer. This grouping method ensures the SOC stocks are more similar within soil groups than among soil groups in each sampling region (Wills et al. 2013). Furthermore, current estimates of SOC stock (Kern 1994; Guo et al. 2006) of CONUS are based on samples (STATSGO, USDA) collected over several decades (Wills et al. 2014). Whereas RaCA represents a static inventory of SOC collected over a short period (2011 to 2012) that can serve as a baseline for changes in SOC stocks in the future.

In this study, we analyzed the RaCA dataset to directly compare the total SOC stocks in croplands and CRP lands in the 0–100 cm soil profile at a continental scale and examined the relationship of climate and edaphic factors with the SOC stocks in surface and subsurface soil. We hypothesized that 1) the CRP lands have higher SOC stocks than croplands, 2) surface soil SOC stocks contribute most to the

differences between CRP and croplands, and 3) climate and edaphic factors modulate SOC stocks differently between CRP and croplands.

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 of depth 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 groups, and land use/land cover classes. The detailed sampling scheme is described in Wills et al. (2014) and shown in Supp. Fig. 1. Briefly, CONUS was divided into 17 major regions based on the USDA's major land resource areas (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. (2013). This approach used soil information from official soil series descriptions and the soil data access portal at NRCS to cluster soils with potentially similar levels of SOC and similar responses to land-use change. In the algorithm, soil information, such as taxonomy, moisture and temperature regimes, particle size class, drainage, and depth to the restrictive layer, was translated to ordinal scores. 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 potential RaCA site using the national land cover dataset (Fry et al. 2011). Five pedons were sampled at each site, one in the center and one 30 m away in each of the four cardinal directions. A small pit was first excavated to 50 cm or the bedrock depth at each pedon. The top 5 cm was collected regardless of the horizon from the pit and the soils were sampled from 5–50 cm by soil horizon. Samples below 50 to 100 cm were collected with probes or augers by the length of soil horizons. The lengths of each soil horizon were recorded. Samples were collected volumetrically from 0 to 50 cm to measure bulk density.
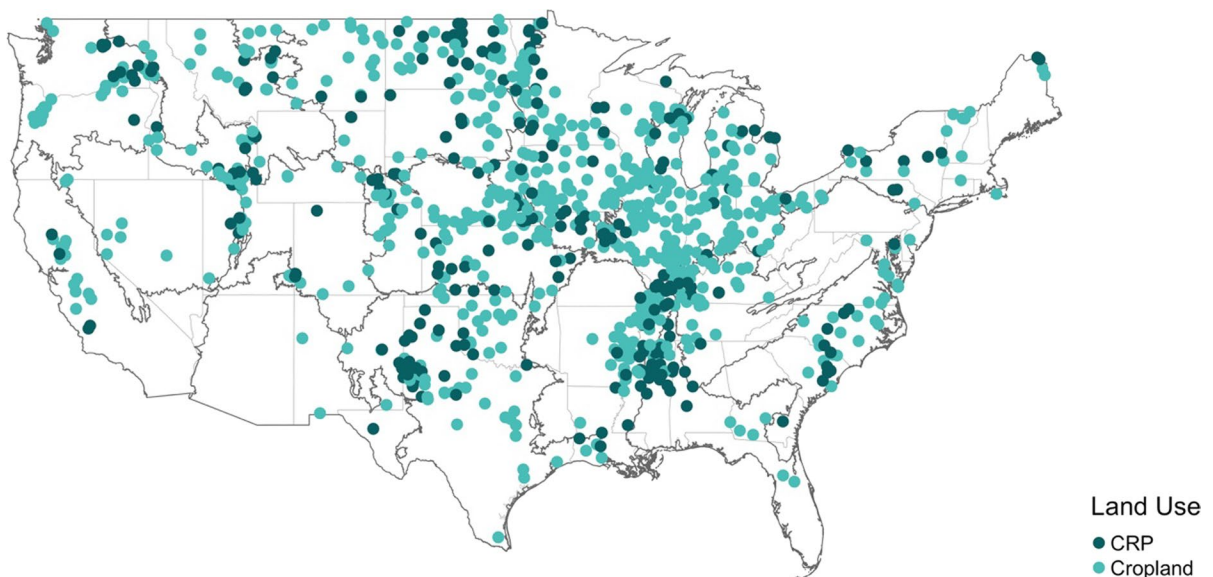

Fig. 1 Locations of croplands (teal) and CRP lands (dark green) pedons of RaCA data that were used in this study. There are 278 and 748 pedons for CRP lands and croplands that have SOC measurements that cover the 0–100 cm soil respectively

Soil sample processing and analysis

Soil samples for C analysis were dried and sifted with 2-mm-sieves. Soil samples from the central pedon of each site were analyzed for total C content with the dry combustion method at the Kellogg Soil Survey Laboratory in Lincoln Nebraska, US. The detailed methodology can be found in Wills et al. (2014). The volumetric samples were oven-dried to calculate bulk density. Bulk density for 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 was calculated as the difference between total carbon and inorganic C, which is measured as calcium carbonate calcimeter equivalence (Wills et al. 2013). SOC stocks were calculated from bulk density, coarse fragment volume, and the SOC concentrations. SOC stocks were then summarized to fixed depths of 0–5 cm, 5–30 cm, and 30–100 cm for each pedon with recorded lengths of soil horizon data.

Data analysis

In this study, we focused 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 CPR lands. Nested two-way analysis of variance (ANOVA) was used to compare SOC stocks at different depths and land use/land cover, with sampling sites nested in soil groups, then nested in regions as a random effect. The statistical significance (alpha of $P < 0.05$) of the ANOVA was tested with type II Wald chi-square tests (Mann and Wald 1942). Pairwise comparisons were performed at each depth with adjusted Tukey tests on the log scale (Tukey 1949). The reported means of SOC stock are estimated marginal means that were estimated by the above linear mixed effect model to account for variation between regions and soil groups. We also investigated the influence of environmental variables, such as temperature, precipitation, and soil texture, on SOC stocks in cropland and CRP land. The relationship between each environmental variable with SOC stocks and their interactions with land-use and soil depths were evaluated by linear mixed effect models with regions and soil groups as random effects. We used the WorldClim 2 dataset (Fick and Hijmans 2017) for the

mean annual temperature and mean annual precipitation data at each pedon. The soil texture data were from the RaCA data set. The sandy soils were defined as the pedons with at least one soil horizon with sandy texture (i.e., any texture description containing sand, e.g., loamy sand, sandy clay, etc.). All statistical analyses were performed using R version 3.5.2 (R Core Team 2019). The 'lme4' package (Douglas et al. 2015) was used to perform a nested ANOVA. The 'emmeans' package (Russell 2019) was used to perform pairwise comparison for the nested two-way ANOVA. Because we are only interested in comparing SOC within depths, instead of between depths, for the post hoc analysis, we made the comparison between the two land use/ land cover types for each depth when coding with 'emmeans'. The 'ggplot2' package (Wickham 2016) was used to make the figures. The 'tmap' package (Tennekes 2018) was used to create maps.

Results

There were 278 and 748 pedons of CRP lands and croplands with SOC measurements that covered the 0–100 cm soil depth, respectively. These pedons belonged to 102 of the RaCA soil groups and represent all 17 major regions (Fig. 1). After accounting for the geological variations among regions and soil groups with separate nested two-way ANOVAs, there was no significant difference in SOC stocks between CRP lands and croplands in the 0–100 cm soil depth (Fig. 2 and Supp. Table 2) on a continental scale.

Comparing SOC stocks at each depth, we found there was a significant interaction between land use and depth (Supp. Table 1). Specifically, on average, CRP lands had 38% higher SOC stock at 0–5 cm, yet 11% lower SOC stock at 30–100 cm than croplands, whereas there was no significant difference of SOC at 5–30 cm (Fig. 2 and Supp. Table 1). Such patterns occurred widely in almost every region (Fig. 3 and Fig. 4). Out of 102 soil groups, 63 soil groups showed CRP lands had higher SOC stock at 0–5 cm than croplands, and 62 soil groups showed CRP lands had lower SOC stock at 30–100 cm than croplands.

Climate factors and soil texture had different impacts on SOC stocks at different depths in croplands and CRP lands (Fig. 5 and Supp. Table 3,4
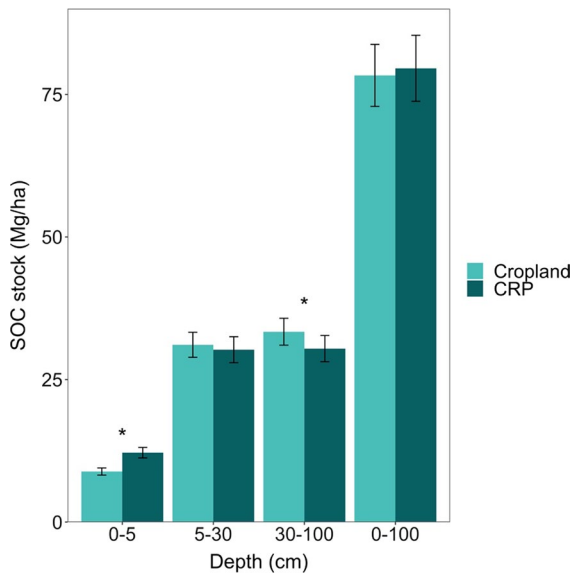
Fig. 2 Average SOC across the conterminous United States in croplands (teal) and CRP lands (dark green) at 0–5 cm, 5–30 cm, 30–100 cm, and 0–100 cm. The bars represent the modeled stocks with separate nested two-way ANOVAs, which account for the geological variation between regions and soil groups (see Results section and Supp. Table 1 for detailed statistics). Data shown are the estimated marginal means ± 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 the means within each depth

and 5). First, we found SOC stocks in croplands decreased with mean annual temperature at all three depths. In contrast, SOC stocks in CRP lands decreased in the 5–30 cm and 30–100 cm depths while increased in the 0–5 cm depth with mean annual temperature. In the warmest regions, CRP lands had much higher SOC stocks than croplands. Second, SOC stocks in cropland and CRP lands increased with mean annual precipitation at all depths. However, in the 0–5 cm depth, CRP lands had much higher SOC stocks than croplands in humid regions. Finally, SOC stocks were generally lower in sandy soil in both cropland and CRP lands at all depths. However, there were significant interactions between soil texture and land-use at 0–5 cm and 30–100 cm depths, where croplands had much lower SOC in sandy soil at 0–5 cm, yet higher SOC in non-sandy soil at 30–100 cm as compared with CRP lands.

Discussion

In this study, we present a collective effort to directly quantify the SOC stocks in the top 100 cm of soil in croplands and CRP lands across CONUS and highlight the importance of deep soil C measurements when evaluating C dynamics in CRP lands. On average, there were no significant differences in SOC stocks between croplands and CRP lands in the 0–100 cm depth. We did find that the surface soil (0–5 cm) in CRP lands had higher SOC stocks than croplands, which is consistent with previous research quantifying CRP C sequestration rates (Baer et al. 2002; Kucharik 2007; O'Brien et al. 2010). However, CRP lands had lower SOC stocks in the subsurface (30–100 cm) than the croplands. Such SOC differences in the subsurface soil would not be revealed if RaCA had only collected samples in the surface soil.

The SOC differences in the surface and subsurface soil between CRP lands and croplands within the RaCA regional soil groups could result from the following three scenarios. First, the SOC levels in CRP lands and croplands were the same in all depths at the time of conversion. Thus, the greater SOC stocks in the surface soil and lower SOC stocks in the subsurface we reported would represent soil depth specific changes following the conversion from cropland to CRP. Second, the CRP lands had lower SOC stocks in both surface and subsurface soils upon conversion. This scenario is consistent with the notion that enrollment in CRP is biased towards less productive soils (Taylor et al. 1994) even within a soil group. In this case, the surface soil in the CRP lands would be accumulating SOC, whereas the subsurface soil of the CRP would have not sequestered SOC to the same quantity as the croplands within a soil group. Third, the CRP lands had higher SOC levels than the croplands in all depths and the pattern we observed was caused by losses of SOC in the subsurface soil in the CRP lands. This third scenario is unlikely given it is inconsistent with the incentives to enroll less productive soils into CRP (Taylor et al. 1994) and thus we will not discuss it further.

If CRP lands are indeed losing C in the deeper soil as suggested in the first scenario, several mechanisms could be involved. First, the losses of SOC in the subsurface can be a result of tilling cessation. Tilling increases residue incorporation and moves organic matter-rich surface soil to the subsurface (Alcantara
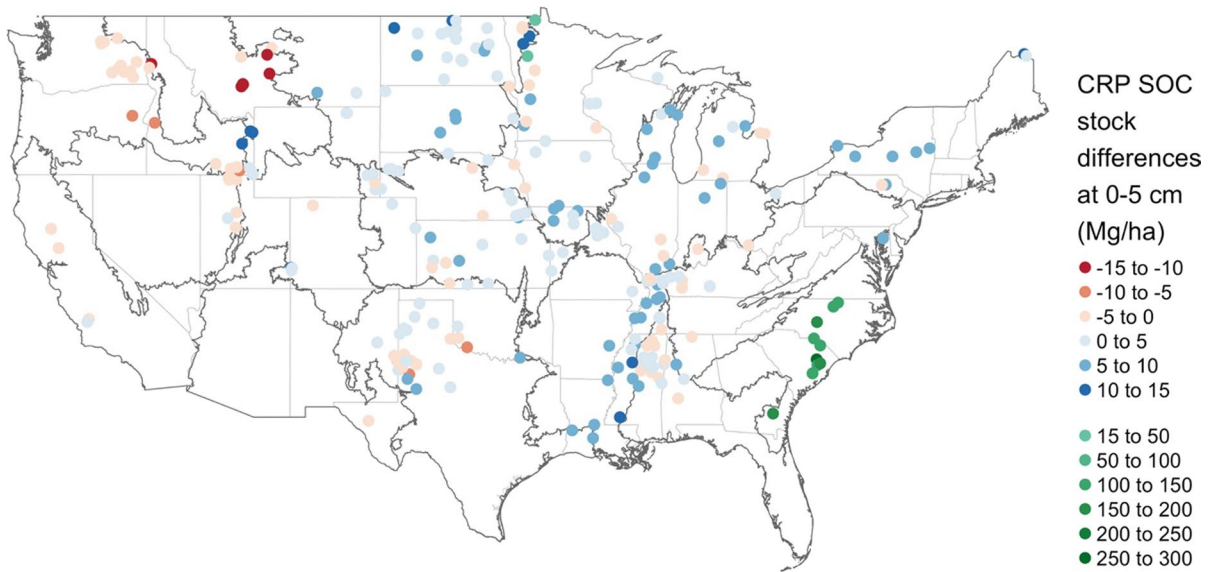
Fig. 3 CRP SOC stock change relative to the croplands in the same soil group lands at 0–5 cm. The circles are the locations of the pedons of the CRP lands. The differences were calculated as the mean SOC stock of CRP lands minus the mean SOC stock of croplands within each soil group. The blue shades 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 in the surface. We use two color schemes SOC differences between croplands and CRP within soil groups, one to indicate subtle stock differences (red to blue) and the other to indicate larger stock differences (green)
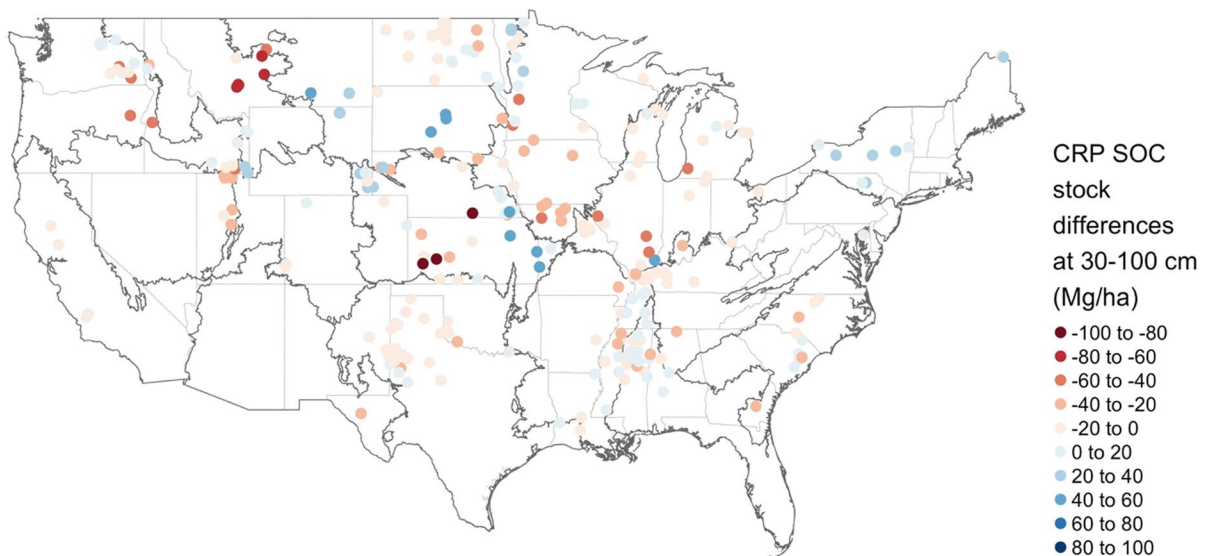

Fig. 4 CRP SOC stock change relative to the croplands in the same soil group lands at 30–100 cm. The circles are the locations of the pedons of the CRP lands. The differences were calculated as the mean SOC stock of CRP lands minus the mean SOC stock of croplands within each soil group. Blue shades indicate CRP lands that have higher SOC stock than the croplands in each soil group, whereas red shades indicate CRP lands that have lower SOC stock than the croplands

Fig. 5 Soil organic C stocks in cropland and CRP land at different depths and relationships with mean annual temperature (**a**) and mean annual precipitation (**b**), and contrasts in soil texture (**c**). Data shown in the figures are estimated marginal means and modeled standard error by linear mix effect models. SOC stocks were log-transformed for the modeling and back-transformed to show in the figures. In (**c**), "s" denotes sandy soils and "ns" denotes non-sandy soils
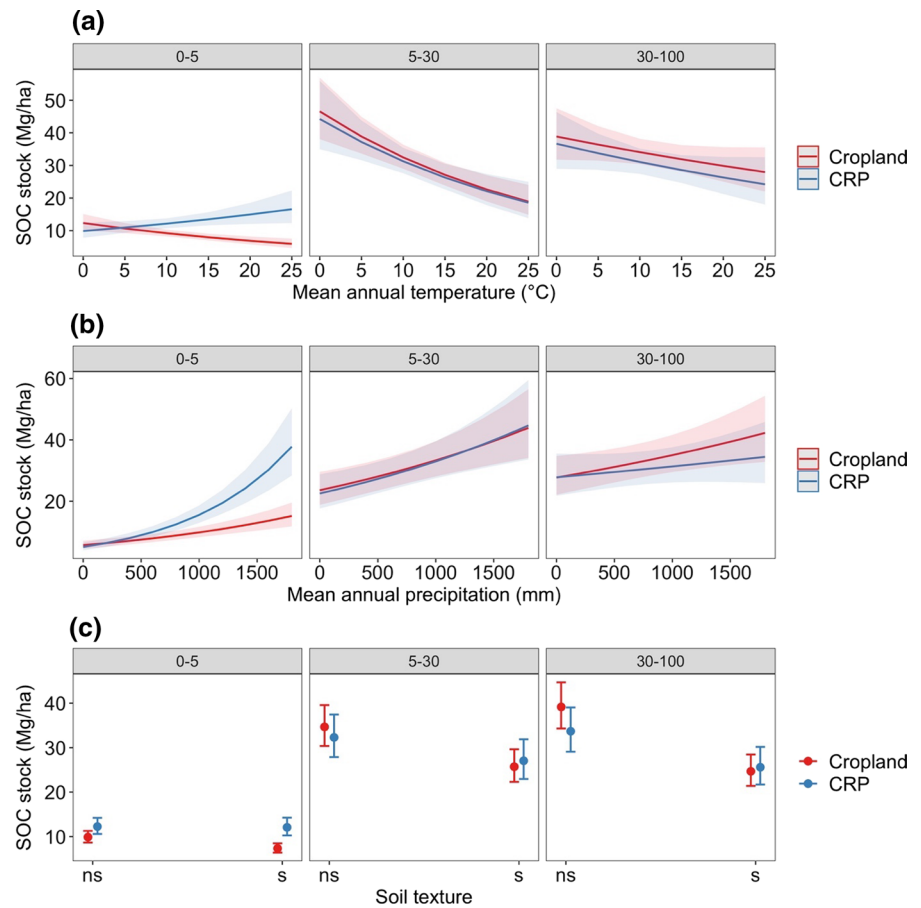
et al. 2016). Transitioning from conventionally tilled croplands to non-disturbed systems can reduce such SOC redistribution, thus decreasing the C input in the subsurface soil. This mechanism was found to explain the decline of SOC in the subsurface in numerous "no-till" cropping systems (Angers and Eriksen-Hamel 2008; Luo et al. 2010). Second, the vegetation cover shift in CRP lands could destabilize deep SOC. Compared to crop species, grassland perennial plants have much higher root biomass (DuPont et al. 2014; Von Haden and Dornbush 2019). The increased root biomass can have opposite effects on soil C. For example, increasing C input from increased dead roots can stimulate SOC decomposition (Dijkstra et al. 2021). This priming effect hypothesis suggests that increased root biomass can activate a dormant subsoil microbial community through deposition of labile organic matter (e.g., rhizodeposition) and accelerate SOC turnover (Blagodatskaya et al. 2014; Bernal et al. 2016). Increased rooting in subsoils can

disrupt chemical bonds between organic matter and polyvalent metals through rhizodeposition (Clarholm et al. 2015). Root exploration can also break existing soil aggregates by intensifying drying-rewetting cycles in soils thereby releasing intra-aggregate labile C from chemical or physical protection (Wang et al. 2016; Lu et al. 2019). The increase of C input and destabilization effect from the roots can occur in both surface and subsurface soil. The direction of SOC stock change, thus depends on which effect is dominant. As the majority increase in roots after agriculture cessation is located in the surface soil (DuPont et al. 2014), the destabilization effect may be dominant in the subsurface soil and lead to SOC stock losses. Finally, increasing atmospheric CO_2 concentration and cessation of fertilizer application could lead to nitrogen limitation in CRP lands and lead to C loss in the subsurface soil. Recent studies showed that elevated CO_2 could enhance nitrogen demand of vegetation, thus increasing nitrogen competition between

plants and the soil microbial community (Billings and Ziegler 2008). Such nitrogen limitation can further intensify the decomposition of recalcitrant SOM to make more inorganic nitrogen available (Dijkstra et al. 2009; Drake et al. 2011).

In the second scenario, the lower SOC in the subsurface in CRP lands could be a legacy effect. In the early years of the CRP enrollment, there were erodibility criteria (USDA 2020) favoring enrollment of highly erodible soils. However, since 1989 soil erodibility criteria were no longer required for CRP enrollment, and since 1990 non-marginal lands that provide environmental benefits, such as maintaining water quality and wildlife habitat, were encouraged to enroll. Therefore, CRP lands enrolled in recent years are not necessarily more eroded than croplands in the same soil group. An analysis of the RaCA soil horizon thickness showed that CRP sites had similar Ap horizon depths, but shallower A horizons as compared with croplands within soil groups (Supp. Fig. 2). This result supports the notion that CRP lands were more eroded prior to CRP enrollment. Whereas the similarity of the Ap horizons between croplands and CRP among soil groups suggests that CRP effectively suppressed further erosion. The implication for SOC stocks of an eroded shallower A horizon of CRP versus cropland is that the 30–100 cm depth increment would be deeper relative to the pre-cropland soil surface than ones that were not eroded. Because SOC content tends to decrease with soil depth, the apparent low SOC stocks in the subsurface in CRP lands could be simply caused by the mismatch of the soil depth sampled between CRP lands and croplands.

Soil erosion also tends to selectively remove soil particles based on particle size, resulting in less silt in surface soils (Renard et al. 1991). If soil erosion accounts for the land use differences in the depth of the A horizons, then we would also expect to see differences in soil particle size classes in the surface soils. For RaCA cropland and CRP lands, we found no difference between land uses within regional soil groups for the portion of silt, sand, or clay of the surface 5 cm (Supp. Fig. 3). Less productive soils may also have a greater volume of coarse fragments (i.e., gravel greater than 2 mm in diameter). RaCA CRP lands are only slightly less likely to be free of coarse fragments than croplands (73% versus 77%, respectively, Supp. Fig. 4). Thus, the notion of a CRP selection bias within soil groups is supported by shallower

A horizons, but the bias does not appear to be due to pre-CRP enrollment surface soil erosion or due to soils containing more coarse fragments larger than 2 mm in diameter (e.g., gravel).

RaCA is a one-time soil survey and lacks data on the duration of lands under CRP management due to landowner privacy concerns, thus no inference can be drawn on the rates of SOC dynamics in CRP lands versus croplands. However, evidence of deep soil C loss after agricultural cessation is accumulating. For example, a recent study (Yang 2019) found SOC accumulated in the surface (0–20 cm) yet decreased in the subsurface (20–100) in repeated sampling, separated by 13 years, of 21 old fields dominated by perennial herbaceous vegetation on sandy soils located in central Minnesota, USA. Mobley et al. (2015) found subsoil SOM loss over the first 50 years of agricultural abandonment 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 (Baer et al. 2002; Kucharik 2007; O'Brien et al. 2010), such as 10–20 cm. To confirm if the CRP lands are losing SOC in the subsurface, long-term repeated soil surveys across CONUS and records of CRP lands abandonment timelines are needed.

Evaluating the impact of climate factors and soil texture on SOC stocks, we found CRP lands had higher surface (0-5 cm) SOC than croplands in warmer and more humid regions, whereas the impacts of climate factors on SOC have no significant interaction with land-use in the subsurface horizons (5–30 cm and 30–100 cm). These results manifested in regional land use variation in the surface soil but not in the subsurface soil (Fig. 3 and Fig. 4). Again, these regional patterns may arise from changes in SOC stocks or variation in the initial soil conditions (i.e., a legacy effect) at the onset of CRP enrollment as described above. In general, our results also provide evidence that the recovery of perennial vegetation stabilizes soil C storage in the surface soil. In the croplands, the SOC stocks decrease with mean annual temperature and are lower in sandy soils because higher temperature promotes soil organic matter decomposition and sandy soils form fewer aggregates that physically protect soil organic matter from microbial activities (Wiesmeier et al. 2019). In contrast, the surface SOC stocks in CRP lands increase with mean annual temperature and are higher than that in

croplands with sandy soils at the 0–5 cm depth. The perennial root systems in restored grasslands have higher productivity as compared with croplands, thus increasing soil C inputs (Munson et al. 2012; DuPont et al. 2014; Von Haden and Dornbush 2019). The increased organic C inputs and reduced soil disturbance under perennial vegetation can also promote the formation of soil aggregates which further stabilize SOC (Dijkstra et al. 2021), even in warmer regions and sandy soil. However, these environmental and edaphic factors are not differentiating CRP and croplands in the subsurface soils. This finding may be due to most CRP lands are planted to perennial grasslands (Gelfand et al. 2011) and the majority of the roots in temperate grasslands and restored grasslands are located in the surface soil (Jackson et al. 1996; Von Haden and Dornbush 2019), and therefore planting perennial grasslands have less effect on C dynamics in the subsurface than the surface soils (DuPont et al. 2014).

Conclusions

This analysis of RaCA data provides important insights into the SOC stocks of CRP lands. We found no difference in SOC stock between CRP lands and croplands in the 100 cm depth across the CONUS. It is well established that rehabilitation of agricultural land with grassland vegetation can enhance soil C accumulation in the surface soil (Gebhart et al. 1994; Post and Kwon 2000; Munson et al. 2012; Li et al. 2017), due to the improved belowground productivity, the cessation of tillage and a reduction in erosion (Kucharik 2007). However, we currently lack a clear understanding of the lower SOC in subsurface soil in CRP lands as compared to croplands. Whether this difference is caused by a land-use change/land cover shift or by a legacy effect of bias in CRP site selection 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.

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

Declarations

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

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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