Soil Carbon Sequestration Potential in Semi-Arid Grasslands in the Conservation Reserve Program

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Abbreviations: CRP, Conservation Reserve Program; SOM, soil organic matter; SOC; soil organic carbon; POM, particulate organic matter; SHP, Southern High Plains

Abstract

The Conservation Reserve Program (CRP) in the USA plays a major role in carbon (C) sequestration to help mitigate rising CO₂ levels and climate change. The Southern High Plains (SHP) region contains more than 900,000 ha enrolled in CRP, but a regionally specific C sequestration rate has not been studied, and identification of the C pools and processes important in controlling C sequestration rates remain unresolved. We aimed to address these gaps by utilizing a CRP chronosequence with historical rangeland as a reference ecosystem. Soil samples (0-10 and 10-30 cm) were collected in 2012 and 2014 from a total of 26 fields across seven counties within the SHP and included seven croplands (0 y in CRP), 16 CRP fields of varying ages (6, 8, 11, 12, 13, 14, 15, 16, 17, 20, 22, 23, 24, 25, 26, and 28 y), plus three rangelands. Multiple regression analysis was conducted to gauge the rate of C sequestration under CRP within C pools: soil organic C (SOC), particulate organic matter C (POM-C), and microbial biomass C (MBC), with two additional predictors (soil clay+silt content and precipitation). Despite attempts to control for soil texture by targeting a dominant soil series (Amarillo fine sandy loam), the percent of clay+silt (15.2-48.7 %) significantly influenced C accrual. The C sources (C₃ from previous cropping systems or C₄ from CRP grasses) in SOC and POM-C were assessed using stable C isotope signatures. Additionally, the role of soil microbes in C sequestration was evaluated by investigating the relationship between MBC and CO₂ flux and C

sequestration. SOC increased at a rate of 69.82 and 132.87 kg C ha⁻¹ y⁻¹ and would take approximately 74 and 77 y to reach the rangeland C stocks at 0-10 and 0-30 cm, respectively. The C₄-C primarily from the introduced grasses was the main source of C sequestration. SOC gains were essentially due to increases in POM-C and MBC, accounting for 50.04 and 15.64 % of SOC sequestration at 0-30 cm, respectively. The highest semi-partial correlation coefficients between the increasing years under CRP restoration and MBC indicated CRP had the strongest effect on MBC compared to other C pools. In addition, increasing soil CO₂ flux and MBC:SOC ratio with years of CRP restoration indicated MBC played a critical role in the C sequestration process. Conservation of CRP lands and efforts to sustain perennial systems in this highly erodible landscape should be a high priority of conservation programs. In doing so, significant offsets to increasing atmospheric CO₂ levels may be achieved in addition to erosion control and improved wildlife habitat.

Keywords

C sequestration, Conservation Reserve Program, soil texture, soil microbes

1. Introduction

In 1985, the United States Department of Agriculture's (USDA) initiated the Conservation Reserve Program (CRP), which is a cost-share and rental program that pays landowners to convert environmentally sensitive land from agricultural production and planting species that reduces soil erosion and improve wildlife habitat and water quality. Through the establishment of grasslands, forests, or wetlands on marginal lands, CRP enrollment increased surface cover and by 2009 reduced soil erosion nationwide by 215 and 230 teragrams due to water and wind erosion, respectively (USDA-FSA, 2009). In May 2016, Texas led the USA in hectares (ha)

enrolled in CRP (1.21 million or 12.5 % of total ha), with the majority of this land (0.92 million ha) located on sandy, highly erodible soils within the semi-arid Southern High Plains (SHP) (USDA-FSA, 2016). Additionally, these perennial grasses also play a critical role in sequestering atmospheric CO₂ linked to global climate change (Piñeiro et al., 2009) and because of the vast areas enrolled in CRP, these lands may sequester large amounts of C (Gebhart et al., 1994). Programs that have set aside agricultural lands such as CRP have shown a quick increase in soil labile C and total long-term C sequestration over an average time span of 10 y (Piñeiro et al., 2009). Following conversion of cropland to grassland or pastures, C sequestration rates have been shown to vary from 0 to 1224 kg C ha⁻¹ y⁻¹ at 0-10 cm and 100 to 2220 kg C ha⁻¹ y⁻¹ at 0-30 cm soil depth in cool temperate steppe ecosystems (Follett et al., 2001; Gebhart et al., 1994; Post and Know, 2000) to 4731 kg C ha⁻¹ y⁻¹ at 0-20 cm in frigid temperature and udic/aquic moisture regime in Minnesota (Follett et al., 2001). In addition, negative C sequestration rates also have been found in mesic temperature regimes with arid/ustic or udic/aquic moisture regimes (Follett et al., 2001), or tropical yet dry regions (Trumbore et al., 1995). The potential of soils to sequester C varies depending on regional differences due to climate and plant species composition, age of ecosystem, and inherent soil properties such as texture, (Conant et al., 2001; Kucharik, 2007; Lal and Kimble, 1997; Post and Kwon, 2000; Six et al., 2002), and is determined by a balance of plant C inputs and C outputs through decomposition (Jenny, 1994; Schlesinger, 1977). In general, total SOC increased with more precipitation (Lal and Kimble, 1997) and decreased with increasing temperature (Jobbágy and Jackson, 2000). Under similar climate conditions, soil texture was the dominant factor controlling SOC decomposition (Schimel et al., 1994). SOC mineralization rate decreased with soil clay+silt content (Bai et al., 2012; Bosatta and Agren, 1997) and SOC increased with clay+silt content (Bai et al., 2012).

Despite numerous conservation successes provided by CRP lands and the increasing public demand to participate, the CRP program is threatened by a decline in acreage allowed to enroll as well as market demands on land that is scheduled for contract expiration (Stubbs, 2014). Recognizing the specific contribution of CRP on additional ecosystem services, such as C sequestration to offset rising CO₂ levels and mitigate climate change may provide policy makers with enhanced justification to continue support and increase allowable acreage and cost-shares. A key step in this process is to develop accurate estimates for C sequestration that are regionally specific and can account or adjust for key factors that influence rates (e.g., soil texture, site age, etc.). Numerous studies have attempted to calculate C sequestration rates across diverse soil types and spatial regions (local areas to states) (Derner and Schuman, 2007; Kucharik, 2007; Paustian et al., 1997; Post and Kwon, 2000) but these estimates are subjected to over- or under-estimating rates when scaling to larger regional or national levels if key properties, such as particle-size distribution, are not accounted for. For instance, Gebhart et al. (1994) reported a C sequestration rate of 800 kg C ha⁻¹ y⁻¹ for a depth of 0-40 cm during the first five y of CRP management (significance at $p < 0.1$), which was an average across three soil types (Patricia fine sandy loam, Ulysses silt loam, and Valentine fine sand) and three states (Texas, Kansas, and Nebraska). The soils varied greatly in their C sequestration rate and was mainly associated with textural differences: silt loam soil sequestered an average of 1,590 kg C ha⁻¹ y⁻¹ (2,380 and 800 kg C ha⁻¹ y⁻¹ in Colby and Atwood, Kansas, respectively) in the top 40 cm; whereas the sandy loam soil sequestered an average of 240 kg C ha⁻¹ y⁻¹ (420 and 60 kg C ha⁻¹ y⁻¹ in Big Spring and Seminole, Texas, respectively). Moreover, C sequestration rates differed widely within the same soil textural class, indicating a need to adjust for specific soil particle distribution (i.e. clay %, silt %, and sand %) in the C sequestration rate estimations. To address this variability and

improve the accuracy and robustness of these estimates, a significant number of local-scale (e.g. county level) studies that normalize C sequestration based on soil texture and environment factors are needed (Lal and Kimble, 1997; Post and Kwon, 2000).

Evaluation of the relative proportions of the different C pools (Bell and Lawrence, 2009) as well as tracking of C using stable C isotopes holds great promise in enhancing our understanding of how soil will respond to management shifts or a changing climate. Labile fractions of SOC including particulate organic matter C (POM-C) (Cambardella and Elliott, 1992; Cambardella and Elliott, 1993) and microbial biomass C (MBC), reflect the active C fractions of SOC and serve as early indicators of SOC changes (Mao et al., 2012). During CRP establishment, agricultural fields are converted from the dominant crop species (typically cotton in the SHP, a C₃ plant species), to C₄ grasses. Therefore, sources of C in CRP lands include the C₃-C from the previous crop as well as natural C₃ species including forbs and perennial shrubs such as yucca (*Yucca glauca*) and fresh C₄-C from C₄ grasses seeded during CRP establishment as well as volunteer species. By tracking the fate of different C sources (previous C₃ and current C₄ inputs) into SOC and POM-C using specific $\delta^{13}\text{C}$ values for C₄ vegetation (range from -10 to -15 ‰ with an average of -14 ‰) and C₃ vegetation (range from -21 to -30 ‰ with an average of -27 ‰), we can better understand the rate, magnitude and processes of C sequestration in CRP lands (Bernoux et al., 1998; Boutton, 1991; Ehleringer et al., 2000; Henderson et al., 2004; O'Leary, 1988).

The understanding of SOM formation and C sequestration continues to evolve. Organic matter exists as an on-site continuum of organic fragments which are continuously processed by the decomposer community (mainly microbes) towards smaller molecular size (Grandy and Neff, 2008; Lehmann and Kleber, 2015). C sequestration is mediated by soil microbes as they are

involved in the majority of processes in C storage and decomposition (Agnelli et al., 2014; Trivedi et al., 2013). Most studies that investigate soil microbes in CRP restoration have focused on using MBC as an indicator of soil health restoration (Acosta-Martinez et al., 2003; Bach et al., 2012; Karlen et al., 1999) and less on the role they play in C sequestration and SOM formation. Recent studies by Kallenbach et al. (2016) challenge traditional views of SOM dynamics by providing direct evidence that soil microbes are responsible for the formation of chemically diverse, stable SOM. It is critical to understand how microbes influence C sequestration in long-term CRP restoration, ultimately to help predict how soil will respond to management practices and shifts in climate.

Hence, the goals of this study were to: 1) utilize the cumulative temporal effect of lands under CRP to develop more accurate soil C sequestration estimates in different C pools (SOC, POM-C, and MBC); 2) investigate processes of C sequestration by assessing sources of sequestered C using natural abundance ^{13}C isotope tracking; and 3) explore influences of CRP restoration on soil microbes and the role of microbial biomass in C sequestration. We hypothesized that: 1) C stocks in the SHP under semi-arid climate with fine sandy loam soil would increase with increasing years under CRP attributed to the continued organic inputs and no disturbance but will remain lower than undisturbed rangeland soils; 2) C sequestration rate estimates would be improved by adjusting for soil particle size distribution (soil clay+silt %); and, 3) that MBC and POM-C would be sensitive indicators for C sequestration potential in SHP CRP lands. By exploring the rate and magnitude of C sequestration, we aim to gain increased knowledge regarding how long CRP restoration (i.e. 10, 20, 50, or 100 y) was needed to reach concentrations/content of C stock similar to that found in undisturbed rangeland soils. Identification of the dominant processes (e.g., CRP C inputs and environmental constraints) and

the relationships between C sequestration and soil microbes will provide critical insights for establishing regional C sequestration estimates in these and similar semi-arid ecosystems.

2. Materials and methods

2.1. Site locations and description

Soil samples were collected from CRP, croplands and rangelands located within the SHP of West Texas, USA. This region belongs to Major Land Resource Area (MLRA) 77C and has an average annual precipitation of 405-560 mm, fluctuating widely from year to year (USDA-NRCS, 2006). With the assistance of Natural Resources Conservation Service (NRCS) staff, we identified a total of 26 fields within a seven-county area on the SHP, which met the following criteria: (1) cooperation by the landowner to allow access to the land and collect soil samples; (2) dominant soil classification is Amarillo fine sandy loam (Fine-loamy, mixed superactive, thermic Aridic Paleustalf), with minimal to no slope (0-1 %) or a similar, competing soil series; (3) CRP enrollment should vary from as recent as possible to fields established at the beginning of CRP in 1986; and, (4) cropland fields should be located as near as possible to one of the CRP fields and should span the entire geographical boundary selected (i.e., the seven counties identified). The Amarillo soil series was identified as a benchmark soil for the region (Soil Survey Staff, 1999). These soils are characterized by high sand (>45 %), low clay (<20 %) content, and secondary calcium carbonate (>5 %) features forming at ~70 cm. For two of the selected fields, the dominant soil type was a Patricia loamy fine sand (Fine-loamy, mixed superactive, thermic Aridic Paleustalf), which is considered a competing soil series with similar physicochemical properties to the Amarillo series. Patricia soils feature high sand (>75 %) content and low clay (<15 %) content, and secondary calcium carbonate (>40 %) features forming at ~200 cm (Soil Survey Staff, 1999). Amarillo and Patricia soil series are related to Chromic Luvisols soil in

World Reference Base system (personal communication with Dr. Laura Paulette, University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Romania; FAO, 2015). Under the third criterion of CRP restoration years, a total of 16 CRP fields were identified that ranged from 6 to 26 y (as of 2012) (Fig. 1). As of 2014, a total of 259,148 ha were enrolled in CRP in seven counties (Bailey, Cochran, Hockley, Lamb, Lubbock, Lynn, and Terry), which represented 28 % of the CRP on the SHP (918,731 ha) (USDA-FSA, 2014). Due to the change of seeding strategy from monoculture to mixed species seeding from the beginning to more recent enrollments in CRP, it was not possible to identify all the CRP fields with the same seeding management. Seeding information for each CRP field is provided in Supplementary Table 1, and species present during a vegetation survey conducted in November 2012 are provided in Table 1 (modified from Bugge, 2013). Seven croplands, one in each county, were identified that have been in production for >50 y with the dominant cash crop of dryland cotton and represented 0 y under CRP restoration (Fig. 1). Despite our efforts to identify cotton fields, two of seven croplands were planted with sorghum (*Sorghum bicolor* L.) during the sampling years. Three rangelands with similar soil characteristics as the CRP fields and croplands were identified and evaluated to represent non-ploughed land under historical and natural conditions that more closely represent maximal C sequestration potential. These three rangelands included an area in the Muleshoe National Wildlife Refuge, a rangeland within the city limits of Lubbock, Texas managed by the Department of Natural Resource Management, Texas Tech University, and a privately owned ranch located 30 km west of Lubbock, TX. Rangelands had never been cultivated but were used for grazing cattle (Muleshoe) or horses (private ranch), while the Texas Tech University rangeland serves as ranch, wildlife, and fisheries teaching and research facility (Fig. 1).

2.2. Soil sample collection

Soil samples (0-10 and 10-30 cm) were collected from cropland and CRP fields in June or July 2012 and June 2014. Rangelands, which were not identified until December 2012, were sampled at the same depths in June of 2013 and 2014. For all fields, samples were collected by digging a hole approximately 35 cm deep and extracting a 5 cm thick by 13 cm wide slice (approximately 1950 cm³ across both depths) from one side of the hole. The edges were trimmed to obtain a uniform amount of soil and the sample was divided into depths of 0-10 cm and 10-30 cm. Five to eight subsamples were collected per field, and soils were gently mixed to obtain homogenized samples. Soil samples were stored at 4°C and within 48 h, passed through 8 mm and 4.75 mm sieves with any visible plant material removed and stored as two sets of subsamples. A sub-set of 4.75 mm samples was analyzed for soil microbial properties at field-moisture conditions and the remaining samples (8 mm and 4.75 mm) were air-dried.

2.3. Environmental data collection

Precipitation, soil temperature, soil diurnal temperature range (DTR, daily maximum temperature - daily minimum temperature), and soil volumetric water content measured every 15 minutes from 2011 to 2014 were provided by the West Texas Mesonet Climate Center, Texas Tech University (West Texas Mesonet). The 5 cm and 20 cm depth data were selected to represent 0-10 cm and 10-30 cm. Data from each field were calculated as the weighted average of three nearby weather stations (<70 km) based on their distance to the fields. Weather stations recorded information for both bare soil and native soil with plant cover. Due to the limited amount of ground cover early in the growing season, the bare soil temperature, DTR, and volumetric water content were applied to cropland fields, and CRP fields were treated as natural soil with plants.

2.4. Physicochemical soil characterization

Bulk density was measured in the field using an Xplorer Model 3500 neutron density probe (InstroTech, NC, USA) at depths of 10 and 30 cm (InstroTech, 2011). A minimum of five measurements was taken per CRP and rangeland field with six measurements taken in continuously cultivated fields (three on ridges and three in furrows). Soil particle size analysis was conducted using the adapted pipette method (Gee and Bauder, 1986) on air-dried 4.75 mm samples. Soil pH was measured in a 1:1 mixture of soil:water (Thomas, 1996) using an Oakton pH 1000 Series model pH meter (Vernon Hills, IL, USA).

2.5. C properties analysis

2.5.1. Microbial biomass

Soil MBC was determined using the chloroform fumigation–extraction method in duplicate on 15 g oven-dry equivalent field-moist soil samples and one non-fumigation control (Vance et al., 1987). Soil samples were fumigated with ethanol-free chloroform for 24 h in the dark at ambient temperature. Following fumigation, both C and N were extracted by adding 75 ml of 0.5 M K₂SO₄ and shaking for one hour. Extractants were filtered and analyzed using a Shimadzu Model TOC/VCPH-TN C/N analyzer (Shimadzu, Kyoto, Japan). Values for non-fumigated samples were subtracted from fumigated samples, and a K_{EC} of 0.45 (Wu et al., 1990) was used as a constant. Results were expressed on a moisture-free basis by drying a subsample at 105°C for 48 h.

2.5.2. Soil CO₂ efflux

Soil CO₂ efflux *in situ* was measured using a LI-8100A Soil CO₂ Flux Survey System with a 20 cm chamber (LI-COR, NE, USA). Soil collars were installed 24 h ahead of the three

measurements and removed afterward for croplands but were maintained in CRP fields and rangelands for the two-year study. Soil CO₂ flux readings occurred one week prior to, the day of, and one week after soil samples were collected. Three replicates close to the soil sampling cores were taken, avoiding water drainage, roads, and plant bases.

2.5.3. Sample preparation for C stable isotope analysis

Subsamples of the 8 mm whole soil were hand ground to a fine powder and analyzed for calcium carbon equivalents (CCE), total C, and $\delta^{13}\text{C}$. Grinding equipment was rinsed with acetone between each sample to minimize residual C and isotopic carryover. The pressure calciminer method (Loeppert and Suarez, 1996) was used to measure CCE. Samples containing >0.7 % CCE were fumigated with 12M hydrogen chloride vapor for six h and analyzed for SOC concentration and $\delta^{13}\text{C}$. To determine the CCE cutoff and optimal fumigation time, a subset of samples were fumigated from 2 to 48 h and analyzed for organic C concentration and $\delta^{13}\text{C}$ until no decrease in C concentration or change in C isotope ratios ($\delta^{13}\text{C}$) was detected.

2.5.4. Particulate organic matter fractionation

POM subsamples (sieved through 8 mm sieve) were hand ground and the POM fraction was isolated using a size and density fractionation method adapted from Crow et al. (2009). A 30 g soil sample was placed in a 250 ml centrifuge bottle to which 200 ml of 0.5 % sodium hexametaphosphate (NaPO_3)₆ was added. The samples were shaken overnight (~15 h) to completely disperse soil particles and washed through a 53 μm sieve to separate POM and sand material from the silt and clay particles. The material remaining on the sieve was collected, dried at 50°C overnight, and weighed. Both isolated POM and sand samples were transferred to a glass

beaker and ~40 ml of 1.85 g ml⁻¹ sodium polytungstate (SPT, 3Na₂WO₄•9WO₃•H₂O) (SPT-0, GEOLIQUIDS, IL, USA), a low C chemical, was added to separate the POM material from the sand particles. The samples were mixed gently and allowed to sit overnight at which point the light-fraction POM (floating material) was aspirated from the surface. The process was repeated until no material remained floating (typically only one additional cycle was needed). The POM material was then washed onto a 20 µm mesh nylon sieve to remove any remaining SPT, collected, dried at 50°C, and weighed. Used SPT material was collected and recycled according to Six et al. (1999). Subsamples of used and recycled SPT were collected and analyzed for C concentration and natural abundance of δ¹³C to ensure reused SPT was free of any C contamination.

2.5.5 C stable isotope analysis

Ground whole soil and POM that contained ~20 µg C were analyzed for δ¹³C using a Costech Analytical Technologies (Valencia, CA, USA) Model 4010 elemental analyzer equipped with a zero-blank autosampler coupled to a Thermo-Finnigan (Bremen, Germany) Delta V Plus isotope ratio mass spectrometer (IRMS). Total C and nitrogen (N) concentrations, and δ¹³C values for both whole soil and POM were obtained from IRMS. δ¹³C values of whole SOC and POM-C were reported using the δ-notation (‰) and referenced to the universal ¹³C standard, Vienna-Pee Dee Belemnite (V-PDB) per Eq. 1:

$$\delta^{13}\text{C} = [(R_{\text{sample}}/R_{\text{V-PDB}})-1] \times 1000 \quad [1]$$

where R_{sample} is the ¹³C/¹²C ratio of the sample and $R_{\text{V-PDB}}$ is the ¹³C/¹²C ratio of the standard.

Two in-house glutamic acid isotopic standards (δ¹³C = -13.62 and +16.80 ‰) were used for C isotope ratio analysis, and the data were normalized to the standards using the two point-slope

method (Coplen, 2011; Paul et al., 2007). Duplicate samples were used to determine analysis precision.

Due to preferential uptake of $^{12}\text{CO}_2$ compared to $^{13}\text{CO}_2$, C_3 species have lower $\delta^{13}\text{C}$ than that of C_4 species, making it possible to calculate and trace the SOC back to the vegetation source. Two assumptions made in this study were that: (1) the SOM pool was stable, and a well-mixed reservoir of C; and, (2) cropland had been dominated by C_3 isotope signature after over a 50 y cultivation of cotton. During reestablishment of warm season grasses on CRP land, the $\delta^{13}\text{C}$ should become more positive resulting from the shift from C_3 dominance (from cotton plants) to C_4 dominance (C_4 grasses) as described in Eq. 2:

$$\delta_{Ct} = \delta_{C3} + (\delta_{C4} - \delta_{C3}) e^{-kt} \quad [2]$$

where δ_{Ct} is the $\delta^{13}\text{C}$ of the SOC or POM-C at the time of sample collection, δ_{C4} is the average $\delta^{13}\text{C}$ value of organic matter inputs from C_4 grasses, δ_{C3} is the average $\delta^{13}\text{C}$ value of cotton (dominate agricultural crop), and k is the fractional rate constant. The relative fraction of whole SOC and POM-C from C_4 grasses versus C_3 croplands was calculated per Eq. 3:

$$F_{C4} = (\delta_{Ct} - \delta_{C3}) / (\delta_{C4} - \delta_{C3}) = 1 - e^{-kt} \quad [3]$$

where the $\delta^{13}\text{C}$ value (-14 ‰) was estimated for δ_{C4} based on average published $\delta^{13}\text{C}$ data for the dominant plant species identified in the 2012 vegetative survey (Supplementary Table 3) and plant cover percent in each CRP field (Table 1). A $\delta^{13}\text{C}$ of -27 ‰ for cotton was based on previously reported data (Whelan et al., 1970; Saranga et al., 1999). Similarly, the fraction of whole SOC and POM-C from C_3 croplands was calculated from Eq. 4:

$$F_{C3} = 1 - F_{C4} \quad [4]$$

The SOC and POM-C from C₄ or C₃ resource (SOC-C₄, SOC-C₃, POM-C₄, and POM-C₃) were calculated by multiplying SOC and POM-C with the specific fractions.

2.6. Statistical analyses

All statistical analyses were conducted using R-project (R Core Team, 2015). C stock per ha (kg C ha⁻¹) of SOC, SOC-C₄, SOC-C₃, POM-C₄, POM-C₃, and MBC were calculated for each depth (0-10 and 10-30 cm) from Eq. 5:

$$C \text{ stock} = C \text{ concentration} \times \text{bulk density} \times \text{depth} \quad (5)$$

C stock in depth increments of 0-30 cm was the sum of the C stock for the 0-10 cm and 10-30 cm samples. The C sequestration rate was estimated based on C stocks of depth increment of 0-10 cm and 0-30 cm over the years under CRP (0-28 y) using multiple linear regressions.

Ideally, C sequestration rate estimates would be acquired by tracking the same CRP fields for several decades; yet in the interest of alacrity, we targeted time spans under CRP to represent a single CRP chronosequence. To reduce variability between sampling sites, we targeted the same or physiochemically similar soil types across fields. The textural classifications were very similar, but actual particle size varied among fields within each textural class (Supplementary Table 3). Besides CRP restoration years (0-28 y), soil clay+silt content and total precipitation of one year before sampling (i.e. August 2011 to July 2012 and August 2013 to July 2014) were added as predictors to control the potential variations between sites caused by the range of soil particle size distribution and precipitation variability prior to and during the sampling effort. When not all three predictors were statistically significant in the full model, then the model was repeated with non-significant predictor removed. The semi-partial correlation coefficient (r_{sp}) for each predictor in the multiple regressions were calculated using R package *ppcor* (Kim, 2015) as the unique effect size of CRP restoration years, soil clay+silt content, and precipitation on C

sequestration for different C pools. The total amount of C sequestered in the CRP per year was estimated via multiplying the calculated C sequestration rate by hectares of CRP.

3. Results and discussion

3.1. Soil physicochemical characterization data

Soil particle size distribution was not influenced by management or years under CRP. Most soil textures were sandy loams or sandy clay loams with average textural separates of 71.6 % sand, 18.0 % clay, and 10.4 % silt (Supplementary Table 3). Soil clay+silt concentration ranged from 15.2 % to 48.6 % ($\bar{x}$ 27 %). A total of six samples (one 0-10 cm and five 10-30 cm samples) were loamy sand with an average of 82.6 % sand, 9.6 % clay, and 7.8 % silt. Bulk density did not change with years under CRP. However, CRP ($\bar{x}$ 1.45 g cm⁻³, 1.27 to 1.64 g cm⁻³) had greater bulk density than cropland and rangeland ($\bar{x}$ 1.39, $p=0.0160$) and increased with depth from 1.33 g cm⁻³ at 0-10 cm to 1.45 g cm⁻³ at 10-30 cm ($p<0.0001$). All samples had an acceptable bulk density in terms of root penetration according to the limiting bulk density of 1.80, 1.79, and 1.75 g cm⁻³ for root growth in loamy sands, sandy loams, and sandy clay loams, respectively (Daddow and Warrington, 1983; USDA-NRCS, 2013). The lower bulk density in cropland was expected since samplings were conducted after cotton planting and tillage practices. Slightly increased bulk density has been shown in the early stages of conversion of conventional tillage to a no-till system (Stipesevic and Kladvko, 2002). With perennial organic matter inputs and no disturbance, CRP lands should reach similar bulk densities but may require more than the 28 y in this chronosequence. Soil pH ranged from 6.5 to 8.4 ($\bar{x}$ 7.6). Calcium carbonate equivalents ranged from 0 to 1.74 % CaCO₃ ($\bar{x}$ 0.62 %), except one site (6.72 %), and were not influenced by years under CRP or increased soil pH.

3.2. Modeling soil C sequestration potential

Soil C and N contents in cropland and CRP ($\bar{x}$ 3.8 C and 0.5 N g kg⁻¹) were significantly lower than rangeland (6.4 C and 1.1 N g kg⁻¹). In general, rangeland samples contained the greatest SOC and POM-C stocks for the 0-10 cm samples and the greatest POM-C stock for 0-30 cm. Cropland (0 y under CRP) had the lowest SOC and MBC at 0-10 cm (Table 2). Multiple regression with two predictors (CRP restoration year and soil clay+silt content) was the best model for SOC (Table 3). Soil texture (clay+silt content) had a larger r_{sp} (>0.6) than years under CRP, highlighting the importance of this inherent soil property on C sequestration potential. Fine particles such as clay and silt assist SOM formation and stabilization via two ways: 1) formation of mineral-OM at micro-aggregate or smaller scales, and 2) promotion of soil aggregation, creating spatial inaccessibility of SOM from soil microbes and enzymes (Cotrufo et al., 2013, 2015; Lehmann and Kleber, 2015; Lützow et al., 2006).

The multiple regression equations for SOC at 0-10 and 0-30 cm are as described below in Eqs. (6) and (7):

$$SOC_{(0-10 \text{ cm})} = -720.85 + 69.82 \times CRP \text{ restoration years} + 205.22 \times \text{soil clay+silt content}. \quad (6)$$

$$SOC_{(0-30 \text{ cm})} = 2031.69 + 132.87 \times CRP \text{ restoration years} + 453.57 \times \text{soil clay+silt content}. \quad (7),$$

where *SOC* and *soil clay+silt content* were reported in kg ha⁻¹ and percent (%), respectively.

Assuming similar soil texture, SOC sequestration rate may be estimated by the coefficient for CRP restoration years (Table 3). Thus, SOC increased at rates of 69.82 and 132.87 kg C ha⁻¹ y⁻¹ at 0-10 cm and 0-30 cm, respectively. The total CRP land in the seven counties of this study was 259,148 ha and on the Texas SHP was 918,731 ha (USDA-FSA, 2014). Assuming seeding management of CRP and soil texture on the SHP is similar, there would be 34.43 and 122.07 gigagrams (Gg) C sequestered at 0-30 cm of total CRP lands in these seven counties and CRP

lands on the Texas SHP each year, respectively (Table 4). Using the average rangeland SOC value (Table 2) and the average soil clay+silt content across all fields (27 %), it would take approximately 74 y to reach the rangeland 0-10 cm C level ($9,961 \text{ kg ha}^{-1}$) and 77 y for 0-30 cm ($24,502 \text{ kg ha}^{-1}$). These results highlight the need for longer restoration periods and enhanced management efforts, especially in the SHP region with extreme weather (e.g. frequent drought) and fragile soils. Recognizing the important contributions to soil health from the integration of livestock into the land use system (Fultz et al., 2013; Zilverberg, 2012), increasing management efforts that include the reintroduction of animals to the landscape may facilitate increased rates of SOC accrual and associated ecosystem benefits (Banwart et al., 2014).

Constraining to similar climates, soil C sequestration rates reported in the present study were similar to some of the sites reported by Gebhart et al. (1994) and lower than those reported by Follett et al. (2001). In Gebhart et al. (1994), an average of $800 \text{ kg C ha}^{-1} \text{ y}^{-1}$ in the top 40 cm soil depth was sequestered across five locations in three states that have similar climate but substantially different soil texture. Two locations with Patricia fine sandy loam soil had similar C sequestration rates as ours (200 and $100 \text{ kg C ha}^{-1} \text{ y}^{-1}$ at 0-30 cm). However, the other two locations with silt loam soil had much higher C sequestration rates than ours (680 and $1,120 \text{ kg C ha}^{-1} \text{ y}^{-1}$ at 0-30 cm). The main factor differentiating these rates was soil particle size distribution. In CRP grassland, Follett et al. (2001) reported $910 \text{ kg C ha}^{-1} \text{ y}^{-1}$ was sequestered in the upper 20 cm soil across a 13-state region. These authors calculated a weighted average based on soil temperature and moisture regimes but did not adjust for differences in soil particle size distribution. Based on our results and those reported by Gebhart et al. (1994), it is likely that the C sequestration rate of the Pullman clay loam soil diverged significantly from the Dallam fine sandy loam soil (both assigned to the thermic/ arid ustic group) due to the significant difference

in clay+silt content between the two soils (55-80 % for clay loams vs. 15-55 % for sandy loams). However, the average C sequestration rate of these two soil types ($1,224 \text{ kg C ha}^{-1} \text{ y}^{-1}$ in 0-10 cm, respectively) was used in the 13-state regional calculation. Therefore, to more precisely predict C sequestration within a region, a large number of local-scale studies (e.g., within an MLRA and adjusted for soil particle size distribution in addition to temperature/moisture regimes) should be adopted.

3.3. Fate of C from CRP grasses and previous cropping systems

Roughly half of the POM-C in cropland and rangeland soils came from C_3 and half came from C_4 sources (Table 2). In contrast, 58.65--91.58 % of POM-C in CRP lands came from C_4 sources. The relatively high proportion of POM- C_4 in CRP compared with that in cropland or rangeland sites indicates that the ecosystem may still be in transition as C_4 sources are the dominant C inputs. Isotopic interpretation in cropland is confounded by the planting of sorghum or millet, both C_4 plants, if a cotton crop is not established early in the season. Rangeland POM- C_4 : POM-C ratio and $\delta^{13}\text{C}$ values were lower than some of the CRP fields, likely because the rangeland sites were characterized by a greater proportion of C_3 plants such as mesquite and forbs (qualitative observations), which likely contributed to the more even distribution of POM-C sources.

SOC- C_4 , as part of the SOC pool, increased at higher rates than SOC (79.27 and $163.94 \text{ kg C ha}^{-1} \text{ y}^{-1}$ at both depths, respectively). POM- C_4 pool increased at the higher rates of 36.45 and $77.22 \text{ kg C ha}^{-1} \text{ y}^{-1}$ than POM-C, which increased at 33.03 and $66.49 \text{ kg C ha}^{-1} \text{ y}^{-1}$ at the depths of 0-10 cm and 0-30 cm. The lower C accrual rate in SOC than SOC- C_4 and POM-C than POM- C_4 was possibly due to the declining SOC- C_3 and POM- C_3 , even, which was not statistically significant (data not shown). Limited C_3 -C inputs in CRP lands after CRP grassland

establishment is likely a major factor responsible for the lack of significant model fitting for SOC-C₃ and POM-C₃ stocks. In cropland, C₃-C stocks did not change with fresh C₃-C inputs, indicating rapid decomposition of fresh C₃-C inputs at 0-10 cm. At 0-30 cm, SOC-C₃ was negatively associated with precipitation; indicating increased decomposition of C₃ residues and overall loss of SOC-C₃ with increased precipitation.

3.4. The interaction between CRP and soil microbes: the strategy of C sequestration

As plant residues are decomposed, POM-C is released to the atmosphere as CO₂ respiration and incorporated into MBC. POM-C stock in 0-30 cm was best described by the model that included three predictors (CRP restoration years, soil clay+silt content, and precipitation). Additionally, the ratio of POM-C to SOC (POM-C:SOC) increased with CRP restoration years and was influenced by precipitation but not soil clay+silt content in both depths (Table 3). POM-C is more sensitive to changes in precipitation because it reflects organic inputs from vegetation residues especially plant root and root exudates, which response to abiotic environment conditions such as precipitation and temperature (Gosling and Parsons, 2013; Janzen et al., 1992). POM-C sequestration accounted for 47.31 % of SOC sequestration at the 0-10 cm depth and 50.04 % SOC sequestration at the 0-30 cm depth (Table 4).

Out of three C pools investigated (SOC, POM-C, and MBC), CRP restoration years had the greatest impact on MBC (i.e. the highest r_{sp} values) (Table 3). MBC comprised an average of 5.82 % of SOC and ranged from 2.73 to 10.97 % (Table 2), and accounted for 12.59 % and 15.64 % of SOC sequestration in 0-10 cm and 0-30 cm depths, respectively (Table 4). The MBC is influenced by environmental factors, management, and soil texture (Wardle, 1992). Oftentimes, environmental factors more strongly influence changes in MBC than management (Cotton et al.,

2013; Moore-Kucera and Dick, 2008), however, in this study, MBC was most influenced by CRP restoration years, followed by precipitation and lastly soil texture.

The MBC and fraction of MBC in SOC increased with years under CRP (Table 3). The MBC:SOC ratio has been considered as a sensitive indicator of changes in SOM (Sparling, 1992). In general, situations that promote the accumulation of organic matter increase both MBC and MBC:SOC (Jenkinson and Ladd, 1981). The range of MBC:SOC (%) has been studied since the late 1970s, and the range of 1-5 % has been widely accepted (Anderson and Domsch, 1989; Jenkinson and Ladd, 1981; Nie et al., 2013). A recent meta-analysis conducted by Xu et al. (2013), which consisted over 3,000 data points from 315 papers from the late 1970s to 2010, reported a global average MBC:SOC 1.2 % with the temperate coniferous forest having the lowest average (0.99 %) and deserts having the highest average (5.0 %). However, substantial variation existed in the MBC:SOC ratio across regions even within the same biomes (Xu et al., 2014). For instance, the average of MBC:SOC in the desert was 5.0 %, but the range was quite wide (0.6-70 %). Similarly, the average MBC:SOC ratio of grassland was 2.1 %, but values between 5 to 10 % were reported. Considering our study sites were located in semi-arid grasslands, our relatively high values aligned with the higher data points in the large meta-analysis by Xu et al. The increase in MBC and the relatively high ratio of MBC:SOC with the increasing years of CRP restoration supports the concept of the important role soil microbes play in C sequestration and soil restoration processes (Condon et al., 2010; Cotrufo et al., 2013). It is reasonable to assume that because these levels have not plateaued, that these ecosystems are still in a regenerative state and will require more time to approach a new equilibrium.

Soil CO₂ flux increased with years under CRP at a rate of 2.1 mg CO₂-C m⁻² h⁻¹ per year (Fig. 2). Rangelands had the highest CO₂ flux (254.8 mg CO₂-C m⁻² h⁻¹) compared to CRP (101.5 mg

CO₂-C m⁻² h⁻¹) and cropland (56.2 mg CO₂-C m⁻² h⁻¹) ($p < 0.0001$). Soil CO₂ flux was more than two-fold greater in 2014 (125.3 mg CO₂-C m⁻² h⁻¹) than in 2012 (50.2 mg CO₂-C m⁻² h⁻¹) ($p < 0.0001$), which was likely the result of rainfall that alleviated a previous extreme drought (Acosta-Martinez et al., 2014). The CO₂ flux primarily came from respiration of both root and microbes (Kuzyakov, 2006), which indicated a higher microbial-mitigated decomposition rate of organic residues which produce plant-available nutrients and a greater amount of microbial biomass nourished by increased plant-derived debris. This could benefit multiple aspects of soil C sequestration. Although plant residues contribute the majority of C to soil, a large proportion actually “filters” through microbial biomass before being transformed into SOM (Cotrufo et al., 2013; Grandy and Neff, 2008). Soil microorganisms exude enzymes to decompose plant-derived organic C to CO₂, microbial biomass, and extracellular substances (Hannachi et al., 2015; Trivedi et al., 2013). Microbial necromass and extracellular substance as precursors would be stabilized and ultimately become part of recalcitrant SOM via physical and physiochemical protection by soil aggregation and organo-mineral complexes (Gougoulas et al., 2014; Lehmann and Kleber, 2015; Prosser, 2007). Therefore, increasing soil microbial biomass is key to SOM accumulation and C sequestration.

With grass establishment on CRP, the soil was covered by perennial grasses with living roots. Besides more organic inputs from the perennial grassland, an improved soil micro-environment could be another factor that assisted soil microbial growth. Increased ground cover by grasses could have contributed to decreased soil DTR (~50 % decrease) (Fig. 3), although soil temperature and water content did not change in CRP lands (data not shown). The enzymatic C decomposition process is temperature sensitive (Dick, 2011). Wider DTRs have been associated with accelerated decomposition rates of organic residues (Li et al., 2014). Wide DTR has been

shown to adversely impact microbial biomass (Biederbeck and Campbell, 1973; van Gestel et al., 2011, 2016) and depress certain “temperature-sensitive” groups of microbes and functions (Biederbeck and Campbell, 1973). Under greater DTR, microbes may use more energy to maintain metabolic activity to overcome the stress, resulting in less microbial biomass assimilation. The long-term effects could be that the microbial community could shift to groups with a higher capacity to decompose C for survival. In contrast, a reduction in soil DTR generated a twofold increase in soil microbial biomass C on average (van Gestel et al., 2011). The amplified soil MBC and MBC:SOC ratio with years under CRP and lower DTR in CRP and rangeland supported the positive effects of reduced DTR on soil MBC. Therefore, establishing ground cover to increase organic inputs, improve soil microenvironments consequentially ameliorating soil microbial growth, and eventually increasing C sequestration is a promising and important management strategy for C sequestration.

4. Conclusions

This study investigated the C sequestration rate and the potential for future C sequestration of CRP lands on the SHP. SOC was sequestered at a rate of 69.82 and 132.87 kg ha⁻¹ y⁻¹ at 0-10 cm and 0-30 cm, respectively, which translates to 64.15 and 122.07 Gg C sequestration each year on CRP lands within the Texas SHP at 0-10 cm and 0-30 cm, respectively. Years under CRP was an important predictor of seven out of nine soil C stocks and properties that were evaluated, however, soil clay+silt content was a significant predictor of six out of nine, emphasizing the importance of including a textural component for C sequestration models and landscape-scale estimates. The continued groundcover reduced soil DTR and provided plant organic residues, which stimulated the microbial community that ultimately transformed these residues into POM-C, MBC, and SOC and increased soil C sequestration potential in CRP lands in the Texas SHP

region. Specifically, labile pools of soil C (POM-C and MBC) were important contributors to C sequestration rates in these semi-arid coarse soils and accounted for 50.0 and 15.6 % of C sequestration at 0-30 cm, respectively, and also should be considered in modeling efforts. By coupling isotopic analysis with soil C fractionation techniques, this study provided mechanistic information outlining the important contribution of the microbial biomass in transforming C from introduced grasses and provided a more precise estimate of C sequestration potential in the SHP region. These results add to the growing body of literature that supports soil health practices that aim to increase aboveground diversity, minimize soil disturbance, and support year-round plant cover to enhance ecosystem services including C sequestration potential and microbial habitat.

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Fig. 3. Monthly average diurnal temperature ranges (DTR) of Conservation Reserve Program (CRP), cropland, and rangeland at the 0-10 cm and 10-30 cm soil profiles from 2011 to 2014.

Table1

Table 1. Location information and cover percent (% of mixture) for Conservation Reserve Program (CRP) fields in the Southern High Plains.

Site ID ¹	Year enrolled in CRP	Years restored ²	Foliar cover (%) ^{3,4}	Plant $\delta^{13}\text{C}$ (‰) ⁵
LU06a	2006	6	<i>Bo. ischaemum</i> (59), <i>B. curtipendula</i> (8)	-14.7
LU06b	2006	6	<i>Bo. ischaemum</i> (25), <i>B. curtipendula</i> (25), <i>He. stenophylla</i> (19), <i>Ar. purpurea</i> (11), <i>L. dubia</i> (10)	-16.8
LY01	2001	11	<i>B. curtipendula</i> (48), <i>Sp. crytandrus</i> (11), <i>Ar. purpurea</i> (6)	-13.1
LA99	1999	13	<i>B. curtipendula</i> (41), <i>Bo. ischaemum</i> (22), <i>B. dactyloides</i> (12), <i>B. gracilis</i> (7)	-13.9
LY98	1998	14	<i>B. curtipendula</i> (59), <i>B. gracilis</i> (20)	-13.2
HO98	1998	14	<i>B. curtipendula</i> (79), <i>B. gracilis</i> (23)	-13.1
BA98	1998	14	<i>B. curtipendula</i> (67), <i>Bo. ischaemum</i> (37)	-13.6
LA97	1997	15	<i>B. curtipendula</i> (60), <i>Bo. laguroides</i> (17), <i>B. gracilis</i> (8), <i>P. virgatum</i> (5)	-12.9
LY92	1992	20	<i>B. curtipendula</i> (57), <i>P. coloratum</i> (7)	-12.9
HO90	1990	22	<i>Ar. purpurea</i> (38), <i>Bo. laguroides</i> (14), <i>He. stenophylla</i> (10), <i>Sa. iberica</i> (6)	-15.2
LY89	1989	23	<i>B. curtipendula</i> (65), <i>S. scoparium</i> (16), <i>Bo. laguroides</i> (11)	-12.9
TE89a	1989	23	<i>B. curtipendula</i> (31), <i>B. gracilis</i> (19), <i>He. stenophylla</i> (15), <i>Ar. purpurea</i> (6), <i>Bo. laguroides</i> (5), <i>Y. glauca</i> (5)	-16.4
TE89b	1989	23	<i>P. coloratum</i> (48), <i>Ar. purpurea</i> (7), <i>P. virgatum</i> (7), <i>Sp. crytandrus</i> (5)	-13.2
CO86a	1986	26	<i>E. curvula</i> (94), <i>Ar. purpurea</i> (5)	-13.6
CO86b	1986	26	<i>E. curvula</i> (65), <i>He. stenophylla</i> (10)	-15.5
CO86c	1986	26	<i>E. curvula</i> (72), <i>Bo. laguroides</i> (12), <i>Ar. purpurea</i> (5)	-13.5
Average				-14.0

¹LU – Lubbock county; LY – Lynn county; LA – Lamb county; BA – Bailey county; HO – Hockley county; TE – Terry county; CO – Cochran county. The numbers following county abbreviations indicate years of enrollment to CRP.

²As of 2012

³Ar.: *Aristida*, B: *Bouteloua*, Bo.: *Bothriochloa*, E.: *Eragrostris*, He.: *Hetherotheca*, L.: *Leptochloa*, P.: *Panicum*, Sa.: *Salsola*, S.: *Schizachyrum*, Sp.: *Sporobolus*, Y.: *Yucca*

⁴Species listed when % foliar cover >5 %

⁵For each site, the average $\delta^{13}\text{C}$ value was calculated based on the foliar cover percentage in this table and $\delta^{13}\text{C}$ value of each grass shown in the Supplementary Table 2. The Average (-14.0 ‰) was the mean $\delta^{13}\text{C}$ value of all CRP sites listed above.

Table2

Table 2. Summary of soil carbon (C) stocks in different pools: soil organic C (SOC), SOC-C₄, particulate organic matter C (POM-C), POM-C₄, microbial biomass C (MBC), and the ratio of POM-C to SOC (POM-C:SOC) and MBC to SOC (MBC:SOC) within the surface 10 and 30 cm soil profiles with 28 restoration years (as of 2014) under Conservation Reserve Program (CRP) and rangelands.

Years under CRP	SOC	SOC-C ₄	POM-C	POM-C ₄	MBC	POM-C:SOC	MBC:SOC
0-10 cm	10 ³ kg C ha ⁻¹					%	
0	4.92 (0.65) [†]	3.41 (0.46)	0.96 (0.23)	0.44 (0.14)	0.18 (0.03)	19.02 (3.05)	3.90 (0.45)
6	5.78 (2.22)	4.42 (2.22)	1.45 (0.97)	1.28 (1.08)	0.18 (0.03)	21.90 (8.35)	4.01 (2.13)
8	6.07 (1.28)	4.70 (1.80)	1.82 (0.76)	1.49 (0.95)	0.60 (0.08)	28.63 (6.42)	10.01 (0.72)
11	3.30 (na)	2.54 (na)	0.31 (na)	0.21 (na)	0.25 (na)	9.36 (na)	7.55 (na)
13	5.37 (0.87)	4.19 (1.20)	1.15 (0.17)	0.89 (0.24)	0.26 (0.03)	21.50 (0.32)	5.02 (1.42)
14	5.33 (0.83)	3.98 (0.82)	1.34 (0.14)	0.89 (0.02)	0.28 (0.06)	25.84 (2.70)	5.16 (0.39)
15	8.74 (0.36)	7.49 (0.66)	1.99 (0.09)	1.72 (0.10)	0.32 (0.03)	22.79 (0.07)	3.64 (0.45)
16	6.53 (0.64)	5.44 (0.51)	2.07 (0.63)	1.52 (0.25)	0.51 (0.03)	30.55 (6.15)	7.93 (0.78)
17	5.59 (na)	5.33 (na)	1.58 (na)	1.44 (na)	0.40 (na)	28.28 (na)	7.09 (na)
20	9.25 (na)	5.46 (na)	1.04 (na)	0.61 (na)	0.25 (na)	11.22 (na)	2.73 (na)
22	6.39 (0.32)	4.83 (0.48)	2.50 (0.10)	1.85 (0.08)	0.26 (0.06)	39.12 (0.39)	4.11 (1.08)
23	6.75 (0.71)	5.15 (0.71)	1.62 (0.23)	1.28 (0.31)	0.37 (0.02)	24.20 (2.64)	5.47 (0.27)
24	5.21 (na)	4.08 (na)	1.38 (na)	1.04 (na)	0.34 (na)	26.57 (na)	6.63 (na)
25	6.05 (1.70)	5.51 (1.98)	1.85 (0.44)	1.48 (0.36)	0.42 (0.07)	31.47 (5.26)	7.84 (2.35)
26	6.20 (1.36)	4.67 (1.10)	1.26 (0.44)	0.95 (0.34)	0.33 (0.02)	19.15 (3.25)	5.93 (1.33)
28	5.07 (1.45)	4.17 (1.23)	1.69 (0.43)	1.29 (0.38)	0.48 (0.10)	33.67 (1.97)	10.97 (3.6)
Rangeland	9.96 (1.52)	6.66 (0.90)	2.80 (0.56)	1.49 (0.30)	0.44 (0.09)	27.37 (3.18)	5.17 (1.35)
0-30 cm							
0	14.77 (1.38)	11.01 (1.02)	1.81 (0.30)	0.80 (0.18)	0.46 (0.07)	12.47 (1.73)	3.33 (0.36)
6	14.42 (3.55)	11.48 (3.60)	2.34 (1.75)	2.06 (1.81)	0.42 (0.08)	14.11 (8.68)	3.48 (1.56)
8	16.23 (5.71)	13.80 (6.28)	4.20 (2.26)	3.65 (2.56)	1.30 (0.40)	23.97 (5.50)	8.81 (0.57)
11	10.52 (na)	7.75 (na)	0.64 (na)	0.44 (na)	0.71 (na)	6.12 (na)	7.00 (na)
13	13.07 (3.65)	10.90 (3.87)	1.82 (0.36)	1.44 (0.42)	0.53 (0.04)	14.26 (1.24)	4.61 (1.56)
14	16.58 (2.39)	13.65 (1.78)	2.79 (0.07)	2.07 (0.13)	0.67 (0.14)	17.53 (2.45)	4.30 (0.48)
15	24.83 (1.45)	21.99 (0.28)	3.72 (0.40)	3.27 (0.40)	0.78 (0.04)	15.13 (2.49)	3.33 (0.15)
16	18.97 (1.63)	16.93 (1.34)	3.58 (0.58)	2.81 (0.20)	1.35 (0.11)	18.70 (1.67)	7.48 (1.01)
17	15.38 (na)	14.79 (na)	2.97 (na)	2.72 (na)	0.82 (na)	19.32 (na)	5.84 (na)
20	20.96 (na)	14.85 (na)	2.73 (na)	2.10 (na)	0.67 (na)	13.02 (na)	3.06 (na)
22	14.68 (1.17)	11.84 (1.30)	3.64 (0.49)	2.78 (0.45)	0.67 (0.16)	25.22 (5.35)	4.49 (1.33)
23	18.14 (2.21)	14.32 (2.23)	3.08 (0.75)	2.56 (0.87)	0.90 (0.18)	16.76 (2.58)	5.12 (0.61)
24	13.74 (na)	12.16 (na)	2.80 (na)	1.95 (na)	1.04 (na)	20.40 (na)	7.27 (na)
25	14.72 (3.39)	13.21 (3.67)	3.30 (0.87)	2.73 (0.85)	0.87 (0.11)	22.16 (2.83)	6.83 (1.66)
26	18.08 (2.89)	13.07 (1.75)	2.76 (0.67)	2.18 (0.58)	0.88 (0.01)	14.90 (1.91)	5.48 (1.13)
28	11.72 (1.88)	10.40 (1.68)	2.73 (0.58)	2.17 (0.48)	0.98 (0.10)	22.86 (2.05)	9.43 (2.08)
Rangeland	24.50 (3.01)	19.98 (2.92)	5.03 (0.98)	3.13 (0.76)	1.07 (0.21)	20.48 (3.30)	5.03 (1.38)

[†] mean (standard error)

Table3

Table 3. Multiple regression results for carbon (C) stocks in different C pools within the surface 10 and 30cm soil profiles with 28 restoration years (as of 2014) under Conservation Reserve Program (CRP). The model evaluation used three predictors: CRP restoration years, soil clay+silt content, and precipitation. Predictors marked “na” indicate they were not significant in the full model and model was repeated with this predictor removed.

		SOC ¹	POM-C	MBC	SOC-C ₄	POM-C ₄	POM-C: SOC	MBC:SOC
		kg C ha ⁻¹					%	
0-10cm	P-value							
	Model	<0.0001*** ²	0.0001***	<0.0001***	<0.0001***	<0.0001***	0.0005***	<0.0001***
	Intercept	0.3678	0.4247	0.0297*	0.0025 **	0.0578	0.9163	0.417
	CRP restoration years	0.0007***	0.0016 **	<0.0001***	<0.0001***	<0.0001***	0.0031**	0.0016**
	Soil clay+silt content	<0.0001***	0.0006***	0.0416*	<0.0001***	0.0002***	na	0.0211*
	Precipitation	na	na	<0.0001***	na	na	0.0035**	0.0028**
	adjusted R ²	0.6058	0.3073	0.4802	0.7316	0.4218	0.2639	0.3585
	Semi-partial correlation coefficient (r _{sp})							
	CRP restoration years	0.4810	0.4524	0.6359	0.6454	0.6182	0.2758	0.4558
	Soil clay+silt content	0.7672	0.4875	0.3051	0.8357	0.6834	na	-0.3429
Coefficient	Precipitation	na	na	0.5145	na	na	0.3349	0.4396
	Intercept	-720.85	-326.81	-229.14	-1864.33	-617.6	4.54	1.83
	CRP restoration years	69.82	33.03	8.79	79.27	36.45	0.22	0.12
	Soil clay+silt content	205.22	48.42	4.50	193.56	42.26	na	-0.11
	Precipitation	na	na	0.92	na	na	0.04	0.02
0-30cm	P-value							
	Model	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***	<0.0001***
	Intercept	0.2964	0.0158 *	0.0495*	0.8150	0.0239 *	0.9423	0.8371
	CRP Restoration years	0.0088**	<0.0001***	<0.0001***	<0.0001***	<0.0001***	0.0003***	0.0001***
	Soil clay+silt content	<0.0001***	<0.0001***	0.0074**	<0.0001***	<0.0001***	na	0.0711
	Precipitation	na	0.0286 *	0.0022***	na	na	0.0011 **	0.0005***
	adjusted R ²	0.5525	0.4813	0.4639	0.6502	0.4718	0.3460	0.436
	Semi-partial correlation coefficient (r _{sp})							
	CRP Restoration years	0.3743	0.5698	0.6252	0.5360	0.6196	0.5118	0.5259
	Soil clay+silt content	0.7310	0.6038	0.3856	0.7877	0.5698	na	na
Coefficient	Precipitation	na	0.3290	0.4486	na	na	0.4688	0.5027
	Intercept	2031.69	-2153.04	-465.48	-750.37	-1317.39	-0.29	0.35
	CRP Restoration years	132.87	66.49	20.78	163.94	77.22	0.30	0.11
	Soil clay+silt content	453.57	90.64	13.26	428.59	83.99	na	-0.06
	Precipitation	na	4.57	1.77	na	na	0.04	0.02

¹SOC: Soil organic C, POM-C: particulate organic matter C, MBC: microbial biomass C, SOC-C₄: C₄ in SOC, POM-C₄: C₄ in POM-C, POM-C:SOC: ratio of POM-C to SOC, and MBC:SOC: ratio of MBC to SOC.

²Significant codes: ‘***’ for α=0.001 ‘**’ for α=0.01 ‘*’ for α=0.05

Table 4. Total amounts of soil organic carbon (SOC) sequestered per year in the Conservation Reserve Program (CRP) lands within the study area (seven counties) and scaling to the Southern High Plains (SHP) region, and the contributions of labile C pools (POM-C: particulate organic matter C and MBC: microbial biomass C) in the total SOC sequestration at both soil depths.

		SOC sequestered Gg C y ⁻¹	Contribution of C pools (%) ¹	
			POM-C	MBC
0-10 cm	CRP in seven counties ²	18.09	47.31	12.59
	CRP on the SHP ³	64.15		
0-30 cm	CRP in seven counties	34.43	50.04	15.64
	CRP on the SHP	122.07		

¹Percentages calculated using the regression coefficients for C sequestration rates reported in Table 3.

²Total area of CRP lands within the seven SHP counties (Bailey, Cochran, Hockley, Lamb, Lubbock, Lynn, and Terry) was 259,148 ha as of September 2014 (USDA-FSA, 2014)

³Total area under CRP across the SHP was 918,731 ha as of September 2014 (USDA-FSA, 2014)

Figure1

Fig. 1. Twenty-six sampling sites located in the Southern High Plains, with seven dryland croplands laid out in seven counties, 16 Conservation Reserve Program (CRP) fields close to croplands, and three rangelands that had never been plowed or cropped.

Figure2

Fig. 2. Linear regression of soil CO₂ flux (mg CO₂-C m⁻² h⁻¹) on restoration years under Conservation Reserve Program (CRP). Rangeland was plotted but not included in the regression.

Figure3

Fig. 3. Monthly average diurnal temperature ranges (DTR) of Conservation Reserve Program (CRP), cropland, and rangeland at the 0-10 cm and 10-30 cm soil profiles from 2011 to 2014.