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COMPARISON OF METHODS TO EVALUATE SOIL AND CROP MANAGEMENT-INDUCED SOIL CARBON CHANGES

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ABSTRACT

The majority of previous research evaluated soil organic carbon (SOC) mass using SOC concentration and soil bulk density (ρ_b) associated with a fixed-depth (FD) without considering the soil thickness or soil mass. The objectives of this study are (i) to compare between the changes in SOC calculated on an equivalent soil mass (ESM_{org}) of the original condition with the SOC calculated on a FD basis; (ii) to compare the application of this calculation methods on the recommended residue-C amount necessary to sustain SOC levels. The experimental design is a split-plot with no-tillage (NT) and chisel plow (CP); the cropping rotations were multiple crops and continuous corn; and the irrigation system was (full and delayed). In 2001 a study was initiated on Weld silt loam soil. After seven years, the SOC at 0-30 cm calculated on ESM_{org} gained on an average of 6.2 Mg C ha^{-1} compared with 2001. This approach suggests that the SOC levels could be sustained even by removing the entire crop residue. Apparently, the amount of crop residue-C required to sustain SOC levels depended on the calculation approaches. Calculation approach needs to be carefully addressed due to its influence on SOC levels and residue removal/retention.

INTRODUCTION

The majority of previous research (Mikha and Rice, 2004; Mikha et al., 2006; Benjamin et al., 2010) had assessed management practice-induced changes in SOC using SOC concentration and soil bulk density (ρ_b) associated with a specific soil depth. However, management practices that influence SOC concentration may also affect soil ρ_b (Halvorson et al., 1999; Mikha et al. 2006; Benjamin et al, 2007). Recently, researchers are arguing the fact that changes in soil ρ_b and its effect on unequal soil mass associated with the fixed depth has a confounding effect on estimation of SOC (Mg ha^{-1}) mass (Ellert and Bettany, 1995; Wuest, 2009). Recognizing the influence of soil mass and soil ρ_b on SOC storage, current research is estimating SOC based on their concentration, soil thickness, and soil ρ_b (Ellert and Bettany, 1995; Gál et al., 2007).

One of the alternative approaches, to the fixed-depth method, is to evaluate SOC and other soil nutrients on an equivalent soil mass (ESM) basis (Ellert and Bettany, 1995; Gál et al., 2007; Wuest, 2009). With the ESM calculation method, soil masses associated with different management practices are standardized to a specific soil mass per unit area of a certain layer and the equivalent soil C mass is the soil C mass associated with ESM (Ellert and Bettany, 1995). The ESM calculation method and its associated equivalent C mass is projected to reduce the SOC calculation error in soil profile because of soil ρ_b changes under different management practices (Ellert and Bettany, 1995; Lee et al., 2009).

Although calculating SOC on an equivalent mass basis has been proposed by researchers for more than a decade, the ESM has not been readily applied to different management practices and different applications (Ellert and Bettany, 1995; Lee et al., 2009). Limited research are available on the influence of normalizing soil mass and its associated SOC in relation to the amount of crop residue-C returned with SOC and soil bulk density measured data. Recently, there is a great interest for using crop residues, remain after harvest, for biofuel production, therefore; this type of research is vital. The objectives of this study were to compare changes in SOC reported on a fixed-depth basis (Benjamin et al., 2010) to (1) the equivalent soil mass (ESM_{org}) of the original/initial measured condition and (2) to compare how application of this calculation method would alter the recommended amount of crop residue necessary to prevent SOC losses over time.

MATERIALS AND METHODS

Site Description and Soil Sampling

In 2001, an irrigation-tillage-crop rotation study was established at the Central Great Plains Research Station (USDA-ARS) near Akron, CO (Benjamin et al., 2010). The mean annual precipitation at the study location is around 400 mm. Soil type is a Weld silt loam (fine, smectitic, mesic Aridic Argiustolls). The irrigation was the main plot and the subplot was the tillage and crop rotation that were randomized within the main irrigation plots. Treatments were arranged in a split-plot design with three replications. Details of previous and current cropping history and site management were reported in detail by Benjamin et al. (2010). Soil samples were collected before planting, using a hydraulic soil sampler, were collected from each treatment replicate using a 5 cm diam from the 0-15 and 15-30 cm depths in the spring of 2001 and 2008. Soil bulk density (ρ_b), for each individual plot, was evaluated.

Soil Total C, Soil Inorganic C, Soil Organic C, and Grain and Residue Carbon Content

Soil total C contents from the 0-15 and 15-30 cm depth were evaluated at a commercial lab (Ward Laboratories, Kearney, NE) using dry combustion method with a Carlo Erba C-N analyzer (Haake Buchler Instruments, Inc., Saddle Brook, NJ). Soil inorganic C content was evaluated using a modified pressure-calcimeter method (Sherrod et al. 2002). Soil organic C (SOC) content was calculated by subtracting the inorganic C from the total C. Grain yield and crop residues biomass remaining after harvest was evaluated every year. Detailed descriptions were reported by Benjamin et al. (2010) for crop residue, grain yield, and root and rizodeposition carbon estimation for various crops.

Calculation of Soil Mass and Soil Organic C Content on a Soil Fixed-Depth Basis

Soil mass on a soil fixed-depth at 0-15 and 15-30 cm depth were calculated using soil bulk density and soil depth. The mass of soil organic C for the fixed-depth measured (0-15 and 15-30 cm) was calculated from field measured SOC concentration using soil bulk density, soil depth, and soil C concentration.

Calculation of Soil Organic C Content on an Original Equivalent Soil Mass Basis

The SOC content (Mg ha^{-1}) was calculated on an original equivalent soil mass (ESM_{orig}) based as reported by Ellert and Bettany (1995) and Lee et al. (2009). For each soil increment, the ESM_{orig} assumed to be on an average of 2258 Mg ha^{-1} for 0-15 cm and at 2190 Mg ha^{-1} for 15-30

Table 1. Soil thickness and soil organic carbon (SOC) in 2001 and in 2008 and the change in soil organic C content (ΔSOC) between 2001 and 2008 (Mg ha^{-1}) calculated on the fixed-depth and on the original equivalent soil mass (ESM_{org}) of the 2001.

Irrigatio	Tillage†	Rotation	-- Fixed		ESM_{ori}	Fixed-	ESM_{orig}	T_{add} §§
			2001	2008	2008	2008	2008	ESM_{orig}
0-15 cm			-------------- SOC†† ----			--------- ΔSOC ‡‡ -----		-- mm -
			--------------------- Mg C ha^{-1} ----------------------					
Full	NT	CC	19.6	24.6	26.2	5.0	6.6	13.9
Full	CP	CC	23.7	20.2	23.9	-3.5	0.2	33.8
Delayed	NT	CC	18.8	22.1	24.1	3.3	5.3	20.0
Delayed	CP	CC	18.5	18.1	22.2	-0.4	3.7	42.9
Full	NT	Rot	21.1	20.5	22.5	-0.6	1.4	20.8
Full	CP	Rot	21.0	15.9	19.6	-5.0	-1.4	36.0
Delayed	NT	Rot	20.0	18.1	20.6	-1.9	0.5	25.6
Delayed	CP	Rot	20.1	18.2	22.0	-1.9	1.9	34.8
15-30 cm depth								
Full	NT	CC	18.7	16.8	18.2	-1.9	-0.5	26.1
Full	CP	CC	13.3	16.3	18.2	3.0	4.9	51.0
Delayed	NT	CC	12.3	15.2	17.9	2.9	5.6	46.6
Delayed	CP	CC	12.5	14.2	16.7	1.7	4.2	69.6
Full	NT	Rot	14.1	14.1	16.3	0.0	2.2	44.6
Full	CP	Rot	13.5	15.6	18.5	2.1	5.0	64.0
Delayed	NT	Rot	13.9	14.0	17.0	0.1	3.1	58.1
Delayed	CP	Rot	12.6	16.4	19.5	3.8	6.9	62.8
0-30 cm depth								
Full	NT	CC				3.2	6.1	
Full	CP	CC				-0.5	5.1	
Delayed	NT	CC				6.2	10.9	
Delayed	CP	CC				1.3	8.0	
Full	NT	Rot				-0.6	3.6	
Full	CP	Rot				-2.9	3.7	
Delayed	NT	Rot				-1.8	3.6	
Delayed	CP	Rot				1.9	8.8	

† NT = No-tillage; CP = Chisel plow. ‡ CC = Continuous corn; Rot = mixed grass and broadleaf crops. § Fixed-depth data for SOC and ΔSOC were taken from Benjamin et al., 2010 at 0-15 cm, 15-30 cm, and 0-30 cm depth. †† SOC for the 2001 and 2008 calculated on an ESM_{org} for 0-15 cm, 15-30 cm, and 0-30 cm depth. ‡‡ Δ SOC from 2001 to 2008 calculated on a fixed-depth and on an ESM_{org} for 0-15 cm, 15-30 cm, and 0-30 cm depth. §§ Soil thickness (mm) required to attain the ESM_{orig} soil mass of 2001, the ESM_{max} of 2008, and the ESM_{min} of 2008 at both 0-15 cm and 15-30 cm depth.

cm depth (Table 1). The soil mass in 2008 at 0-15 cm depth on FD basis was about 1815 Mg ha^{-1}, which was less than the baseline in 2001. Therefore, a specific soil thickness was needed to adjust for the differences in equivalent soil mass of 2001. Consequently, the addition of 33.8 mm depth would be added. The soil mass of 443 Mg ha^{-1} associated with the additional depth and its associated SOC (3.7 Mg C ha^{-1}) was added to 0-15 cm depth. Therefore, the equivalent C mass ($M_{C\text{-}equiv}$) was calculated to be 23.9 Mg C ha^{-1} (Table 1).

For sublayer soil depth (15-30 cm depth), the ESM_{orig} in 2001, average across the treatments, was 2190 Mg ha^{-1} were in 2008 the soil mass on a fixed-depth was 1965 Mg ha^{-1} (Table 1). Since the 15-30 cm depth interval lost 443 Mg ha^{-1} to the surface depth, therefore added soil thickness was calculated to be 668 Mg soil ha^{-1} and the 5.5 Mg C ha^{-1}. Since the SOC content in 2008 at 15-30 cm depth was 16.3 Mg C ha^{-1} (Table 1), the sublayer (15-30 cm depth) equivalent C mass ($M_{C\text{-}equiv}$) increased to be around 18.2 Mg C ha^{-1} ((16.3-3.7) + 5.5)).

RESULTS AND DISCUSSIONS

Soil Thickness, SOC Mass (Mg ha^{-1}) on an Equivalent Soil Mass, and Changes in SOC

The 2008 SOC associated with soil fixed-depth was adjusted to the initial/original equivalent soil mass of the 2001 (ESM_{orig}). Since the 2001 soil sampling occurred before treatment initiation, the ESM_{orig} was averaged across the treatments for each depth studied (Table 1). The ESM_{orig} in 2001 was greater than the soil mass in 2008 (Table 1), at each depth studied. For each treatment, a specific soil thickness (T_{add}) was added to each depth to adjust to the ESM_{orig} of 2001 (Table 1). At the 0-15 cm depth, the soil T_{add} (mm) in 2008 was lower ($P = 0.006$) with NT, an average of 20 mm, compared with CP, 37 mm. The low T_{add} with NT was a result of greater soil ρ_b in 2008 and more soil mass per unit volume sampled with NT than CP. Previous research reported that greater soil mass per unit volume was associated with soil samples with high ρ_b than the samples with low ρ_b (Ellert and Bettany, 1995; Wuest, 2009). At 15-30 cm depth, the soil T_{add} was lower ($P = 0.02$) with NT by an average of 44 mm compared 62 mm with CP. Over all, the soil T_{add} from below 30 cm layer to 15-30 cm layer, to achieve the ESM_{orig} of 2001, was between 1.5 to 2.3 times greater than the 0-15 cm T_{add} (Table 1). The high amount of T_{add} to 15-30 cm compared with 0-15 cm was a consequence of losses some of the soil thickness associated with 15-30 cm to the surface 0-15 cm (Ellert and Bettany, 1995; Lee et al., 2009). In addition, the greater T_{add} to 15-30 cm with CP compared with NT for standardizing to the ESM_{orig} of 2001 was a consequence of less soil ρ_b associated with CP than NT practices.

The soil C mass added ($M_{C\text{-}add}$) associated with the soil T_{add} for each depth increment was added to the soil C mass of the fixed depth ($M_{C\text{-}FD}$) basis (Table 1). The percentage increase in SOC for 2008 between the $M_{C\text{-}equiv}$ calculated on an ESM_{orig} and the $M_{C\text{-}FD}$ was by an average of 6% to 19% for 0-15 cm and by 8% to 18% for 15-30 cm depth (Table 1). The increase in $M_{C\text{-}equiv}$ associated with ESM_{orig} calculation was attributed to increased soil masses per unit volume in 2008, ranging from 8% to 24% for 0-15 cm and 8% to 18% for 15-30 cm depth. Apparently, the SOC mass per unit volume is highly dependent on its associated soil mass (Ellert and Bettany, 1995; Ellert et al. 2002).

The estimate ΔSOC between 2001 and 2008 was influenced by the 2008 SOC calculation approach at 0-15 cm, 15-30 cm, and 0-30 cm depth (Table 1). On a fixed-depth basis, Benjamin et al. (2010) reported the variation in SOC for the 0-30 cm depth ranged between -0.4 Mg ha^{-1} y^{-1} to 0.9 Mg ha^{-1} y^{-1}. When the ΔSOC was estimated on an ESM_{orig} of 2001 (Table 1), the variation in SOC ranged between 0.5 Mg ha^{-1} y^{-1} to 1.6 Mg ha^{-1} y^{-1} for the 0-30 cm depth. A SOC gain on an $M_{C\text{-equiv}}$, across the cropping systems at 0-30 cm depth, was observed to be on average of 6.2 Mg ha^{-1} for both NT and CP practices (Table 1). The over estimation in SOC that we observed with ESM_{orig} approach could be a consequence of the similarity in ρ_b and SOC for 15-30 cm and below 30 cm depth assumption. Nevertheless, the total soil depth studied, with ESM_{orig} approach, was not 0-30 cm depth, as reported with the fixed-depth, but it was on an average of 0-34.4 cm for NT and 0-36.2 cm for CP (Table 1). The SOC gain associated with ESM_{orig} approach in relation with FD reported by Benjamin et al. (2010) was a result of the additional soil thickness added for soil mass standardization to the initial masses of 2001.

Relationship between Crop Residue-C Input and Changes in SOC on an Equivalent Soil Mass

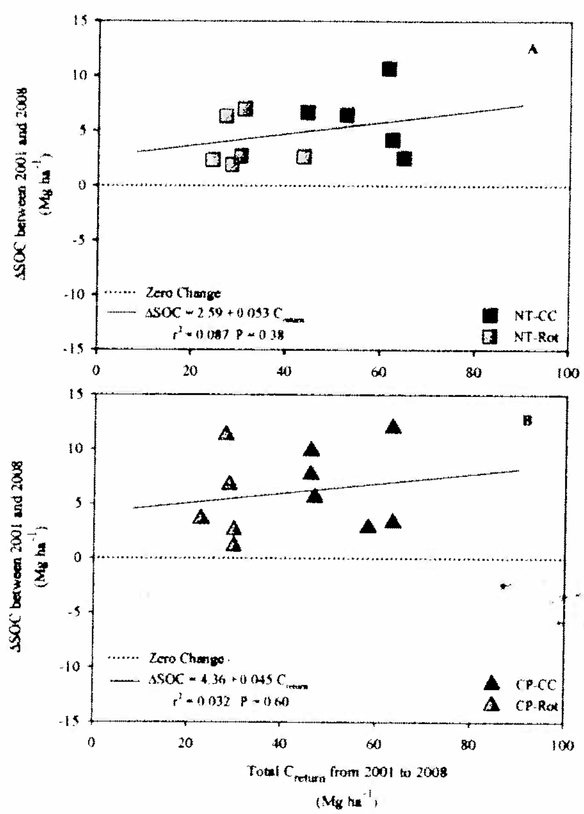

Figure 1: Changes in soil organic C (ΔSOC) from 2001 to 2008 calculated on the ESM_{orig} basis of the 2001 original/initial condition measured in Mg ha^{-1}, at 0-30 cm depth, in relation with estimated crop residue and root plus rhizodeposition carbon added (C_{return}) measured in Mg ha^{-1} for no-tillage (A) and chisel plow (B). NT represents no-tillage, CP represents chisel plow, CC represents continuous corn, and Rot represents mixed grass and broadleaf rotation.

The relationship between ΔSOC estimated on an ESM_{orig} of 2001 at 0-30 cm depth and C_{return} was evaluated (Fig. 1). A positive linear relationship between C_{return} and ΔSOC with both tillage practices, NT and CP was observed. A weak and insignificant correlation between C_{return} and ΔSOC was observed with low coefficient of determination of 8.7% for NT and 3.2% for CP. The regression slope was 0.053 Mg C ha^{-1} for NT and 0.045 Mg C ha^{-1} for CP practice. At both tillage practices, the regression line did not cross the zero SOC change line suggesting that the crop residue could be entirely removed with no changes in SOC level under current management practices. These results are contrary to what Benjamin et al. (2010) reported, where SOC was calculated on a soil FD, for the same set of data. Benjamin et al. (2010) reported, with NT system, an average of 4.6 Mg C ha^{-1} y^{-1} of C_{return} is required to maintain SOC level. Apparently, standardizing the soil mass in 2008 to the ESM_{orig} of 2001 increased the calculated soil depth for 2008 and consequently an increase of SOC on an $M_{C\text{-equiv}}$, suggesting that the SOC level could be maintained even by removing the entire crop residue under this set of study management conditions. Previous research documented that to sustain SOC levels a specific amounts of crop residue are required (Johnson et al., 2006; Blanco-Canqui et al., 2009), removing these residue may have a negative effect on soil quality and sustainability (Blanco-Canqui et al., 2009). Apparently, calculating SOC using the ESM_{orig} approach is an ineffective method, under these study conditions, to evaluate the amount of crop residue required to maintain SOC levels.

Over all, evaluations of SOC storage and crop residue removal potential were influenced by SOC calculation methods. The estimated SOC mass depended on the method used to calculate the changes in soil mass associated with different management practices. The amount of residue-C required to sustain a specific amount of SOC level was influenced by the estimated changes in soil mass associated with each method. Using an equivalent soil mass for SOC calculation could be an accurate approach; however, different assumptions associated with the calculation could present some errors or biases. Standardizing soil mass to a specific mass influenced soil depth studied and consequently, unequal soil depth comparison among the treatments. Care needs to be taken in selecting the calculation approaches due to their influence on SOC levels and residue retention/removal to preserve soil quality and prevent soil degradation.

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