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Sensitivity of the Century Model to Scale-Related Soil Texture Variability

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Sequestering C in agricultural soils presents an immediate viable option to reduce atmospheric CO_2 to help mitigate global warming. Agricultural land managers who adopt practices that sequester C might market the sequestered (i.e., stored) C as a C credit to industrial CO_2 emitters who wish to reduce their net CO_2 emissions. Land managers or landowners will need to verify changes in soil organic carbon (SOC) related to a change in management practice to facilitate C credit trading. The objective of this study was to assess the accuracy of Century model predictions of SOC change due to the adoption of no-tillage using site-specific data and data from existing soil databases. We hypothesized that (i) using site-specific soil data would result in the most accurate Century estimates and (ii) Century estimates are sensitive to soil clay percentage. Five paired tillage/no-tillage farm sites in north-central Montana were used to test model predictions. Sites were chosen such that soil, landscape, climatic conditions, and historical cropping systems were similar within each tillage/no-tillage pair. The Century model overestimated SOC content using site-specific soils data by an average of 10%. Century was sensitive to the effects of clay content when predicting the total amount of SOC in a particular field. There was insufficient evidence to suggest that a linear association exists between clay content and Century-estimated C change due to no-tillage. Results suggest that (i) the effect of clay percentage on the rate of C change is not well understood and (ii) the Century model is an acceptable predictor of soil C for C trading. Further examination of the relationship between soil clay content and the rate of C storage in agricultural systems is needed to determine if adjustments to the Century model are required.

Abbreviations: SOC, soil organic carbon; SOM, soil organic matter.

Implementation of agricultural best management practices, most notably the adoption of no-tillage systems, has become a potential technique to sequester (i.e., store) C in soils and help mitigate the effects of global warming. Carbon sequestered in soils will probably have an economic value to land managers in the form of C credits. Currently, large industrial CO_2 emitters who wish to lower net CO2 emissions can either reduce production or purchase C credits (i.e., emission offsets). It will be necessary for both buyers (i.e., government or private entities paying for C) and sellers (i.e., farmers) of C to estimate the amount of C that has been stored on a given land unit. The use of process-based SOC dynamics models is a potential method of predicting, monitoring, and verifying soil C change. Estimated rates of SOC accumulation will probably be determined from experimental data and from application of simulation models such as the Century model (Parton et al., 1987). Thus, it is important to determine the accuracy of a model like Century for predicting soil C rates in various agroecosystems.

Previous studies have used the Century model for estimating SOC dynamics under various soil, climatic, and agricultural practices (Parton et al., 1987; Paustian et al., 1992; Monreal et al., 1997). Parton et al. (1987) found that the model adequately estimated soil C values representing various soil textures and climates in the Great Plains (R^2 = 0.88, 0.92, and 0.92 for coarse-, medium-, and fine-textured soils, respectively). Century tended to overestimate SOC for fine-textured soils and underestimate SOC for coarse soils (Parton et al., 1987). In Sweden, the model predicted SOC values within 5 to 15% of measured values for treatments varying in the amount and type of organic matter added in long-term plots (Paustian et al.,

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1992). Century has also been validated in eastern Canada where the model estimated SOC to within 10% of measured values for four crop rotations in three soil climosequences (Monreal et al., 1997). There is growing interest in this model as a market support tool for estimating soil C change in situations where little site-specific information is known for specific fields or farms (e.g., Brenner et al., 2002; Paustian et al., 2002; Zimmerman et al., 2003).

Soil organic C change due to cultivation and agricultural management has been modeled using the Century model in the Argentine Pampa (Alvarez, 2001), Canadian prairies (Smith et al., 2001; Monreal et al., 1997; Campbell et al., 2001; Smith et al., 1997), U.S. agroecosystems (Parton et al., 1994; Parton and Rasmussen, 1994; Paustian et al., 2002), Swedish agroecosystems (Paustian et al., 1992), and European systems (Falloon and Smith, 2002), among others. The sensitivity (i.e., how much SOC estimates change when certain input values are changed) of Century to some of the major input variables was found to be dependent on site-specific model run conditions. Considering the main input variables, Century output values appeared to be most sensitive to temperature and native (pre-agricultural) soil C content, where a 20% change in temperature and native C values changed predicted soil C content by 50 kg C ha^{-1} yr^{-1} in three major agricultural soil groups of Canada (Smith et al., 1997). Selecting soil input data from alternative sources and scales could have a similar effect.

The State Soil Geographic (STATSGO) database and the Soil Survey Geographic (SSURGO) database, although found to be highly correlated ($r^2 = 0.98$), have the potential for differences in soil attributes (Juracek and Wolock, 2002). The degree of discrepancy among soil attributes at the 1:250 000 scale (STATSGO), 1:24 000 scale (SSURGO), and site specific can be substantial. For example, general soil attributes including clay percentage, soil permeability, and hydrologic group were spatially and statistically analyzed for differences (Juracek and Wolock, 2002). For small areas (<0.01 km^2) in Kansas, differences in reported clay content ranged from −45 to 58%. As the area increased from 25 to 400 km^2, the range in difference was reduced (−11 to 4%). The correlation between the databases also varied with landscape position, with the most variability falling within stream networks. Mean clay content stabilized with distance from stream networks, with mean differences in the ±1% range. Although agreement in the databases increased with area and distance away from stream bottoms, site-specific ranges can be large and could result in substantial differences in model-predicted SOC values for a specific farm field.

Compared with estimates of soil attributes derived from soil survey maps, site-specific measurements should provide the most reliable data inputs for modeling purposes. Even at field scales, however, the variability in measured soil characteristics can be considerable and well-designed sampling procedures are critical for making sound inferences about site and management effects on soil C changes. Therefore, the objectives of this study were to compare estimates of soil C change using simulation- vs. measurement-based approaches and to evaluate the sensitivity of Century model predictions to clay content.

MATERIALS AND METHODS

Century Model Description

The process-based Century model estimates SOC changes based on macroenvironmental gradients, management, and soil and plant properties (Parton et al., 1987). The model is initiated with specific input variables describing the soils, climate, vegetation, and management of a site. Century simulates soil organic matter (SOM) formation and calculates decomposition rates based on first-order kinetics that vary as a function of soil temperature and moisture, soil texture, and other variables. Century segregates SOM into three fractions: (i) an active pool with short turnover time [1–5 yr]; (ii) a slow pool with moderate turnover time [20–40 yr]; and (iii) a recalcitrant or passive pool with long turnover time [200–1500 yr]. The model uses a monthly time step and includes both C and N flows.

In Century, soil texture influences the decomposition rate of the active SOM pool and the efficiency of SOM stabilization in the slow pool. Fine textures favor slow decomposition rates and greater stability of SOM. Each of the SOM pools, litter pools, and the surface microbial pools have decomposition rates that vary with respect to monthly soil temperature, precipitation, litter quality and location (i.e., surface vs. buried), soil texture, and tillage disturbance (Parton et al., 1987). The active SOM pool is comprised of soil microbes and microbial byproducts. The decomposition rate for the active pool ($K_5{}^d$) is calculated as the maximum decay rate (per week) for the active pool (K_{A5}) and is adjusted as a function of the silt and clay fraction (T), where

$$K^d{}_5 = K_{A5}(1 - 0.75T) \quad [1]$$

Stabilization efficiency of active SOM to slow SOM (E_s) is also a function of T, where

$$E_s = 0.85 - 0.68T \quad [2]$$

Soil texture effects on stabilization were developed by fitting a model to data from an incubation of cellulose in soils with differing textures (Sørensen, 1981). The slow SOM pool consists of resistant plant material from the structural pool, mainly plant residues with 2- to 5-yr turnover time, and stabilized microbial byproducts from the active and surface microbial pools. The surface microbial pool consists of decomposition products from plant residues and SOM. The lignin fraction of the structural pool influences the decomposition rate of the structural pool. The turnover rate for the surface microbial pool is independent of soil texture and is transferred directly into the slow SOM pool (Metherell et al., 1993). The passive SOM pool, which includes physically and chemically stabilized SOM, is highly resistant to decomposition. Sensitivity of the Century model SOC predictions to different soil texture input values might have significant implications for modeling SOC based on input data from site-specific fields and existing soil databases.

Soil Data and Databases

Soil properties can be obtained at various scales of spatial and soil-attribute resolutions ranging from site-specific to state or regional. Existing soil databases, such as STATSGO and SSURGO, are generalizations of soil patterns across the landscape. Soil mapping units in both the STATSGO and SSURGO databases often contain more than one defined soil series, each with its own soil attributes. The reported ranges in clay content for all soils within a soil mapping unit could span 50% or more. Relative proportions of each soil series are reported for each mapping unit; however, the spatial distribution of the soil series is not given within the unit. Therefore, it is not possible to determine in which soil series a particular site is located without visiting the site. Additionally, properties for each soil series are reported as a range in values, therefore choosing a representative value for use in the Century model could greatly influence predicted soil C values.

Table 1. Geologic, farm management, and climatic characteristics for five sites in Montana, 2001.

County, Site, Attribute	Chester, Liberty	Conrad W, Pondera	Ft. Benton, Liberty	Saint Johns, Hill	Simpson, Hill
Latitude	48°42′4″ N	48°10′32″ N	48°8′19″ N	48°56′9″ N	48°56′9″ N
Longitude	110°58′46″ W	111°41′13″ W	110°56′44″ W	110°4′57″ W	110°13′10″ W
Elevation, m	1038	1037	960	842	847
Years in no-till	9	10	6	8	7
2001 crop	spring wheat	spring wheat	winter wheat	spring wheat	spring wheat
Crop rotation†	CW(NT)/W–F(T)	W–F	W–F	W–F	W–F
Tillage implements‡	cult, rw	cult, rw, harrow	cp, sweeps, rw	cult, cp, rw	cult, rw
Slope steepness, %	0–3	0–2	0–4	0–1	0–2
Landform	Till plains	Till plains	Till plains	Till plains	Till plains
MAP, cm¶	27	31	36	26	26
MAAT, °C¶	5.4	6.0	7.5	5.0	5.0

† CW = continuous wheat, NT = no-tillage, W = wheat, F = fallow, T = tillage.

‡ cult = cultivator, rw = rod weeded, cp = chisel plow.

¶ 30-yr mean annual precipitation (MAP) and mean annual air temperature (MAAT) estimated from the weather station nearest the site (1961–1990) (National Climate Data Center, 2003).

Century Model Initialization

The Century model, version 4.0, was initialized for five paired no-tillage and tilled field comparisons using present and historical management information supplied by producers. Soil data from site-specific field sampling, existing soil databases, and climate data from the National Oceanic and Atmospheric Administration (2003) (Table 1) were used for modeling. Default cultivation effects and crop growth parameters developed for southwestern Saskatchewan, which is also in Agroecoregion 12 (Padbury et al., 2002) (Fig. 1), were used in this study. The values for cultivation effects on decomposition rates used in this study were either 1.3 or 1.6, depending on the site-specific farm equipment used. Data for site-specific modeling supplied by producers included the year the field was first cultivated, management operations (by month), equipment used, crops grown (by year), rotations (by year), fertilizer use (type, amount, and date applied), and average yields (by crop) for each field.

Soil data required for Century initialization includes soil texture (sand, silt, and clay content), bulk density, and drainage class. Drainage class is the fraction of excess water lost to drainage, which indicates if the soil is sensitive to anaerobiosis (value of 0) or not (value of 1) (Metherell et al., 1993). Paired fields were first modeled using site-specific soil data (Table 2) and land management history. The STATSGO and SSURGO soil data were then used in place of the site-specific soil data (Table 2). Both STATSGO and SSURGO soils data are reported as a range of high and low values, and all reported ranges in SSURGO soil data were contained within the STATSGO range for clay percentage and bulk density in this study. Century assumes a depth of 0.2 m, thus soil inputs spanned the full range of STATSGO data for the top 0.2 m of soil. The SSURGO soil database is most commonly used at the farm level; however, results will be discussed for both STATSGO and SSURGO databases.

Equilibrium SOM pools were obtained by modeling each field for 7000 yr as a native, primarily cold-season C_3 grass species prairie with moderate grazing pressure and 10-yr fire frequency using 30-yr (1961–1990) average air temperatures (minimum and maximum) and annual precipitation data for each site (National Climate Data Center, 2003). Historical agricultural management practices from first cultivation to present were then modeled for both fields at each site. Modeled and measured SOC results for the tilled field were used as a proxy to represent SOC before the adoption of no-tillage. Carbon losses equilibrate after the first several decades of cultivation and SOC levels in agricultural fields have stabilized in areas such as western Canada (Janzen et al., 1997, 1998).

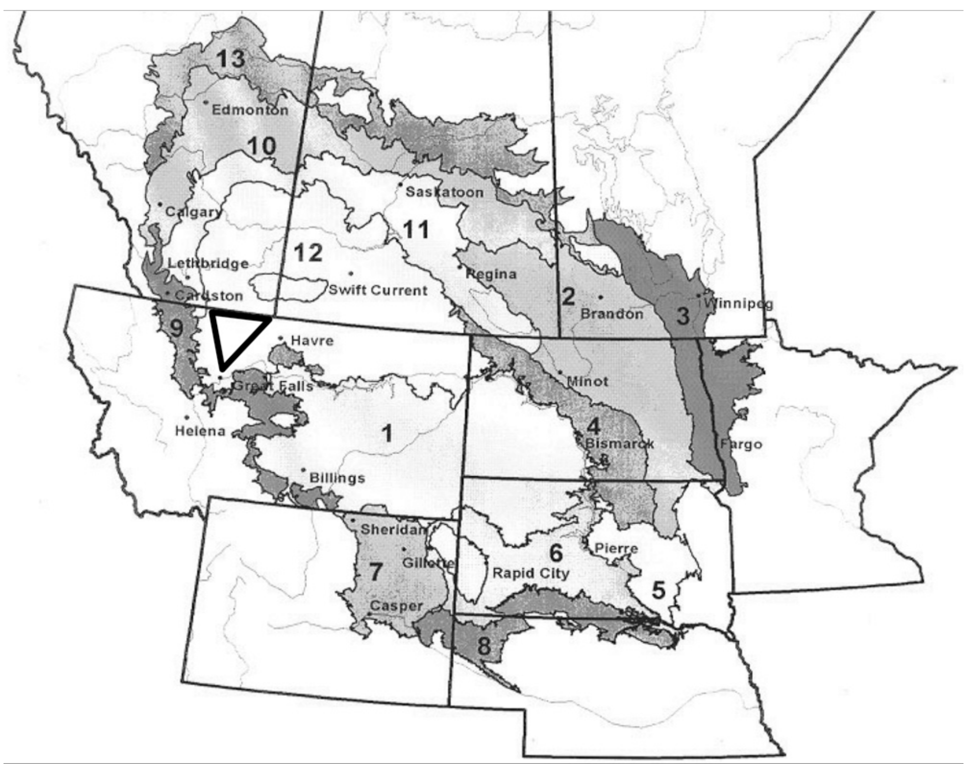

Fig. 1. Agroecozones of the northern Great Plains (Padbury et al., 2002) showing the study area in north central Montana (in triangle).

Sensitivity Analysis

Holding the site-specific land management history constant, the Century model was run using the complete range of clay percentages and soil bulk density values reported in STATSGO to determine how Century SOC estimates change due to changing soil texture and soil bulk density inputs. As previously mentioned, it is important to note that STATSGO reports the relative composition of soil series in mapping units (data not shown); however, the database does not delineate the distribution of soil series within the mapping unit. For this reason, the widest ranges in clay percentages and soil bulk density values were used to model the broadest spectrum of conditions for the sites. The model was reinitialized beginning with the lower limit of STATSGO data and proceeded by increasing clay content (in 5% increments) and decreasing soil bulk density proportionally, since clay content is generally inversely related to soil bulk density (Brady and Weil, 1996), to cover the complete STATSGO range in clay percentage and soil bulk density for each field. All fields were classified as "well drained" in the site-specific and the STATSGO databases. Since, soil water-holding capacity is strongly associated with soil texture, soil water status at wilting point (−1.5 MPa [−15 bar]) and field capacity (−0.03 MPa [−0.33 bar]) were estimated according to sand, silt, clay, and organic matter percentages, and soil bulk density in an equation developed by Rawls et al. (1982). Site-specific hydraulic parameters (i.e., wilting point and field capacity) were not measured in the field. Soil erosion effects on SOM can also be modeled using Century; however, erosion rates and erosion effects on SOM are difficult to estimate in the field and the study sites had minimal topographic variation, thus erosion was ignored.

Century model predictions were compared with measured SOC values and measured implied SOC change (Bricklemyer, 2003). A soil–landscape stratification approach was used to select paired cultivated and no-tillage fields to measure and compare the effects of tillage systems and soil characteristics on soil organic C (Bricklemyer, 2003; Bricklemyer et al., 2005). Implied SOC change due to the adoption of no-tillage management for the field sites was calculated as the amount of SOC in the tilled field subtracted from the corresponding paired no-tillage field. Soil organic C content was determined at five paired no-tillage and conventionally tilled agricultural fields for inferential comparisons of SOC related to field management. Distance between the five paired locations ranged from 15 to 137 km. Six sampling locations (i.e., microsites) in each tillage system at each site randomly positioned within a defined soil–landscape association were chosen for SOC sampling in August 2001. The soil sampling scheme was adapted from the Canadian Prairie Soil Carbon Balance Project (Ellert et al., 2001), where six 50-cm soil cores were taken around a 2- by 5-m frame centered on a randomly selected sampling location. Soil cores were divided into 0- to 10-, 10- to 20-, and 20- to 50-cm samples for analyses. Sample preparation and C analysis procedures were adapted from Conant and Paustian (2002). Samples were oven dried at 40°C for 4 d, weighed for bulk density determination, and passed through a 2-mm sieve to remove rock fragments, surface plant litter, and coarse root material. Visible litter and root material that passed through the 2-mm sieve were removed by hand. Soil texture and bulk density were measured on each soil sample from site-specific field sampling. Soil texture was measured using the modified hydrometer method (Gee and Bauder, 1986) and bulk density was measured using dry soil weight and a known volume from core samples. Approximately 50 g of each core sample (i.e., 360 total cores) was composited by depth for each frame (i.e., six frames per tillage treatment, 12 frames per site). Approximately 30 g of the composite sample was milled to fine powder (<200 μm) in a ball mill (Pica Blender Mill Model 2601, Cianflone Scientific Instruments Corp., Pittsburgh, PA) for C analysis. Samples were analyzed for total C and inorganic C. Total C content was measured by dry combustion using a LECO C/N/S 2000 analyzer (LECO Corp., St. Joseph, MI). Inorganic C was determined using a modified pressure calcimeter method (Sherrod et al., 2002). Using the measured bulk density of field samples, all SOC values

Table 2. Soil characteristics for five sites in Montana, 2001. Values are for the 0- to 0.2-m depth.

Site and tillage treatment	Soil series	Soil classification†	Texture class‡			Clay			Bulk density		
			Site-specific	SSURGO	STATSGO	Site-specific	SSURGO	STATSGO	Site-specific	SSURGO	STATSGO
						%			g cm^{-3}		
Chester	Hillon	Fine-loamy, mixed (calcareous), frigid Aridic Ustorthent	cl	fsl, l, sil, cl	l		18–35	5–35		1.20–1.40	1.10–1.45
No-tillage						38			1.27		
Tillage						39			1.28		
Conrad W	Etheridge	Fine-loamy, mixed, frigid Aridic Argiustoll	cl	fsl, l, sicl, cl	sicl		27–35	5–40		1.15–1.35	1.15–1.40
No-tillage						39			1.40		
Tillage						42			1.36		
Ft. Benton	Kobase	Fine, smectitic, frigid Torrertic Haplustept	c, cl	fsl, l, cl	sicl		30–35	5–35		1.20–1.40	1.15–1.45
No-tillage						47			1.29		
Tillage						45			1.29		
Saint Johns	Telstad	Fine-loamy, mixed, frigid Aridic Argiustoll	l	fsl, l, cl	l		18–27	5–40		1.20–1.40	1.15–1.45
No-tillage						23			1.46		
Tillage						26			1.47		
Simpson	Telstad	Fine-loamy, mixed, frigid Aridic Argiustoll	sl,l	fsl, l, cl	l		18–27	5–40		1.20–1.40	1.15–1.45
No-tillage						16			1.45		
Tillage						19			1.51		

† Reported by SSURGO.

‡ c = clay, cl = clay loam, fsl = fine sandy loam, l = loam, sic = silty clay, sicl = silty clay loam, sil = silt loam, sl = sandy loam.

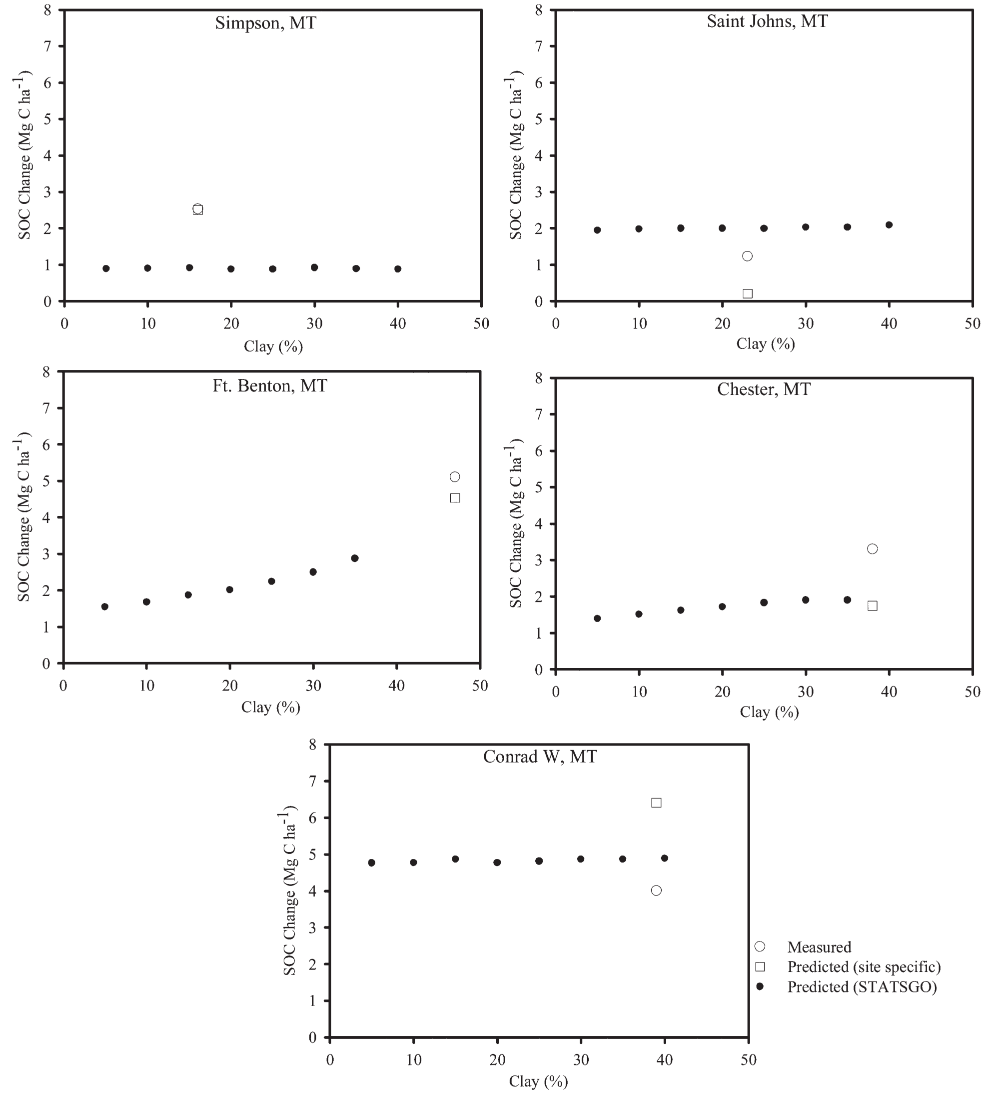

Fig. 2. Implied C change (no-till C minus tilled C) for measured and modeled soil organic C (SOC) values using STATSGO reported clay content for Century model input at Chester, Conrad W, Ft. Benton, Simpson, and Saint Johns, MT, 2001.

were converted to and are reported on an equivalent-mass basis according to methods described by Ellert and Bettany (1995). Soil organic C was calculated by difference given by the equation

$$\mathrm{TotC} - \mathrm{IC} = \mathrm{SOC} \qquad [3]$$

where TotC = total soil C and IC = inorganic soil C. The comparison of C change between tilled and no-tillage management systems required careful site selection in terms of soil, landscape position, and number of years under each management system. Additional details of the soil–landscape association approach for SOC measurement is described in detail in Bricklemyer et al. (2005).

Statistical Analysis

Simple linear regression modeling tested the linear association of Century-estimated C change and mean observed C change. In addition, an index of response or bias value was calculated for each field at each site to determine how well Century predicted present SOC. This bias value was calculated as

$$Y_{ijk} - X_{ijk}$$

where Y_{ijk} = observed SOC and X_{ijk} = Century-estimated SOC. The data were analyzed using a mixed model for a randomized complete block design with subsampling (Littell et al., 1996; Kutner et al., 2005). Specifically, the model incorporated random effects for the sites, replicates, and subsamples along with fixed tillage effects. There was no true replication in this observational study and thus no site × tillage interaction term was used in the model. The site × tillage interaction was not permissible; otherwise there is no term for experimental error. If sites and tillage interact, then the design would have been biased. Tukey's Test for Additivity, however, along with an interaction plot, showed no significant evidence of a site × tillage interaction, thus the assumption of no site × tillage interaction was reasonable. The data were then analyzed using ANOVA to determine if significant differences existed between sites and treatments.

Century-estimated data were analyzed using a mixed analysis of covariance (ANCOVA) model in a randomized complete block design with a one-way treatment structure for tillage, random block (site) effects, and a covariate present where the covariate (i.e., clay content) was measured on the experimental unit or field. The design was unreplicated, with only a single datum per experimental unit and no subsampling. The analysis required three parts. First, a model was fit to test if Century estimates were linearly associated with soil clay content. This determines if a model without the covariate can be used to describe the data. Second, it was necessary to determine if the slopes of two simple linear regression models, one for each tillage treatment, were equal to see if a common slope model would be adequate to describe the data. This test would determine if changes in clay content input into Century result in similar changes in SOC within each tillage treatment. Last, a common slope model was fit to the data to describe the relationship between clay percentage and Century-estimated SOC. Residual diagnostics were used to verify the efficacy of the models used in this analysis.

RESULTS

Century model estimates showed inconsistent results when predicting the implied C change in the no-tillage fields due to the adoption of no-tillage (i.e., no-tillage SOC minus tilled SOC). Century estimates did not accurately predict the measured implied change in SOC associated with the adoption of no-tillage at any of the five sites using STATSGO or SSURGO data. Century underestimated implied C change in the no-tillage field at Chester, Saint Johns, and Ft. Benton;

however, implied C change was overestimated at Simpson and Conrad W (Fig. 2). From simple linear regression of observed C change on Century C change (Fig. 3), a two-sided 95% confidence interval for the slope was calculated to be −0.17 to 1.14. Although the confidence interval contains 0, the sample sizes in this study were insufficient to make a reliable conclusion about the linear relationship.

The accuracy of Century model SOC estimates using STATSGO and SSURGO database information were largely dependant on whether the reported ranges in clay content included the measured site-specific values. The range of STATSGO reported clay contents fell short of measured clay values at Chester, Ft. Benton, and the tilled field at Conrad W, but contained the measured clay values at Saint Johns, Simpson, and the no-tillage field at Conrad W (Table 2). The SSURGO ranges in clay content did not include measured values at Chester, Conrad W, Ft. Benton and the tilled field at Simpson, but included measured values at Saint Johns and the no-tillage field at Simpson (Table 2). Modeled estimates of SOC in the 0- to 0.2-m soil depth at each site deviated from measured values by an average of 10%, with a range of −1 to 28% (Table 3). A point estimate of the mean bias was −2.3 Mg C ha^{-1} (Fig. 4) and was different from zero as shown by an approximate 90% confidence interval (df = 4) that did not include 0 (−4.54 to −0.09 Mg C ha^{-1}). This estimated negative mean bias represents an average overestimation of SOC by the Century model. Average modeled SOC estimates for the two tillage systems deviated from measured values by 9% (−1 to 28%) and 11% (1–18%) for no-tillage and tilled, respectively, indicating that the Century model is not biased toward a particular tillage system (Table 3). This was also seen from the results of modeling bias, where there was insufficient evidence to suggest a pairwise difference between tillage effects. An approximate 95% confidence interval (df = 4) for this difference was −1.70 to 1.96 Mg C ha^{-1}.

Ranges in Century model SOC estimates using STATSGO and SSURGO soil data included the measured SOC values for the tilled fields at Chester (SSURGO data), Conrad W, Saint Johns, and Simpson (with the exception of the tilled field using SSURGO data). Model estimates of SOC using STATSGO data were lower than measured values at Chester and Ft. Benton (Table 3, Fig. 5), largely because the STATSGO and SSURGO databases underrepresented soil clay content for these sites. Using site-specific soil data, Century overestimated SOC compared with measured values with the exception of the no-tillage fields at Saint Johns (Table 3, Fig. 5).

Estimates of SOC from Century for the no-tillage and tilled systems were sensitive to the effect of clay content. The three-part mixed ANCOVA analysis showed that (i) Century estimates appear to be linearly associated with clay values (P = 0.06), (ii) the slopes of the linear association between clay content and Century appear to be the same for tilled and no-tillage fields (P = 0.71), (iii) the common slope was estimated as 0.56 Mg C ha^{-1} (% clay)$^{-1}$ with an approximate 95% confidence interval of (0.24–0.88 Mg C ha^{-1} [% clay]$^{-1}$), and (iv) mean Century SOC estimates for no-tillage fields were 3.9 Mg C ha^{-1} greater than for tilled fields, with an approximate 95% confidence interval of 0.48 to 7.47 Mg C ha^{-1} regardless of clay value (Fig. 6). Estimated SOC for the upper limit of reported clay contents was 2.3 to 2.7 times greater than SOC estimates for the lower clay limit at the five sites modeled using STATSGO database ranges in clay content (Table 3, Fig. 6).

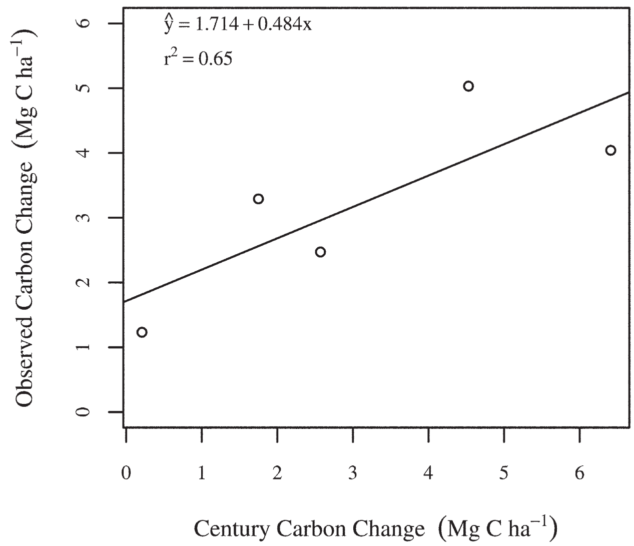

Fig. 3. Regression of Century model estimates of soil organic C (SOC) change (no-till SOC minus tilled SOC) on observed SOC in north-central Montana, 2001.

DISCUSSION

Century estimates did not show a direct clay content effect on soil C change in response to the adoption of no-tillage. This was revealed in the ANCOVA model, where mean Century estimates for no-tillage fields were 3.9 Mg C ha^{-1}

Table 3. Soil organic carbon (SOC) measured and predicted using site-specific and soil databases for soils inputs values for the 0 to 0.2-m soil depth in no-till and tilled fields at five sites in Montana, 2001.

Site and tillage treatment	Mean measured SOC	Century-estimated SOC			Difference†	
		Site-specific	SSURGO	STATSGO		
	Mg C ha^{-1}					%
Chester						
No-tillage	24.7	25.3	16–24	10–23	0.6	2
Tillage	21.4	23.6	15–22	9–21	2.2	10
Conrad W						
No-tillage	24.1	30.7	23–27	13–29	6.6	28
Tillage	20.1	24.4	19–22	9–24	4.3	21
Ft. Benton						
No-tillage	32.9	36.7	26–30	13–29	3.8	12
Tillage	27.8	32.2	24–27	11–26	4.4	16
Saint Johns						
No-tillage	19.8	19.7	18–22	12–28	−0.1	−1
Tillage	18.5	19.4	16–20	10–26	0.9	5
Simpson						
No-tillage	17.1	17.4	17–22	10–27	−0.3	−3
Tillage	14.6	14.8	15–19	10–26	0.2	1

† (Site-specific Century SOC estimate) – (mean measured SOC).

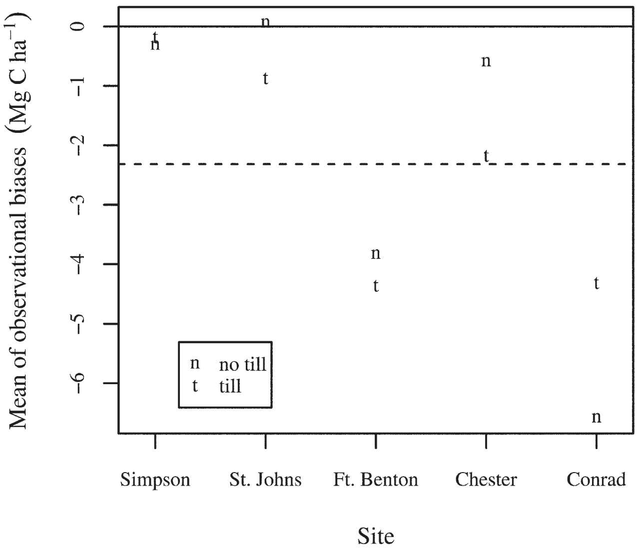

Fig. 4. Mean of observational biases (measured soil organic C [SOC] minus Century estimated SOC) for no-till and tilled fields at Chester, Conrad W, Ft. Benton, Simpson, and St. Johns, MT, 2001. Solid line at zero represents no bias or perfect agreement. Dashed line at −2.3 is the mean bias.

greater than for tilled fields (Fig. 6). Had a direct effect of soil texture on C change been present in Century, it is conjectured that an increase in the rate of C change with higher clay content soils would have been seen across all sites, similar to that seen for Ft. Benton and somewhat at Chester (Fig. 2). Century estimates lower than measured values could be a function of both a misrepresentation of soil clay content in STATSGO and SSURGO soils data, such as at Chester and Ft. Benton, or a potential insensitivity of the Century model to a tillage effect on SOC as a function of soil clay content such as at Ft. Benton. What was seen at Ft. Benton and Chester was probably due to indirect effects of soil texture on SOC in Century's water balance, plant production, and SOM decomposition submodels, as opposed to a significant site × clay interaction. Even considering the wide range in STATSGO clay percentages reported for the five sites in this study, Century did not accurately predict the amount of implied C change due to the adoption of no-tillage. Model results for the five sites in Montana showed little difference in the amount of C stored in coarse-textured soils (e.g., 5% clay) compared with fine-textured soils (e.g., 35–40% clay), with the exception of the Ft. Benton and Chester sites, which showed a slight increase in SOC with clay percentage.

The lack of a soil texture effect on C sequestration under no-tillage management is consistent with the Century model's assumed direct influence of tillage disturbance on C dynamics. The Century model treats the influence of tillage as a relative increase in the potential rate of decomposition independent of soil texture. Texture sensitivity in Century occurs as indirect secondary effects through the water balance, productivity, and SOM decomposition submodels. Thus, soil texture may not have a strong influence on the tillage effect on C sequestration in these types of systems. There is no clear consensus regarding the relationship between C sequestration rates and soil clay content in the literature. Results from this study did not show higher C sequestration rates in no-tillage soils with higher clay content. Similarly, Smith et al. (2001) showed no influence of soil texture on C change in response to changes in tillage management when modeling C dynamics across Canada. Using Century, Smith et al. (2001) determined soil C sequestration coefficients for a wheat (*Triticum aestivum* L.)–fallow system in sandy loam (0.052 t C ha^{-1} yr^{-1}), loam (0.052 t C ha^{-1} yr^{-1}), and clay loam (0.049 t C ha^{-1} yr^{-1}) soils in the Brown Chernozem soil group, which are similar to the soils in the Montana study area. Conversely, Campbell et al. (1996) observed increased C gains of nearly 0.12 t C ha^{-1} per 1% increase in clay content, and McConkey et al. (2003) found a positive linear relation-

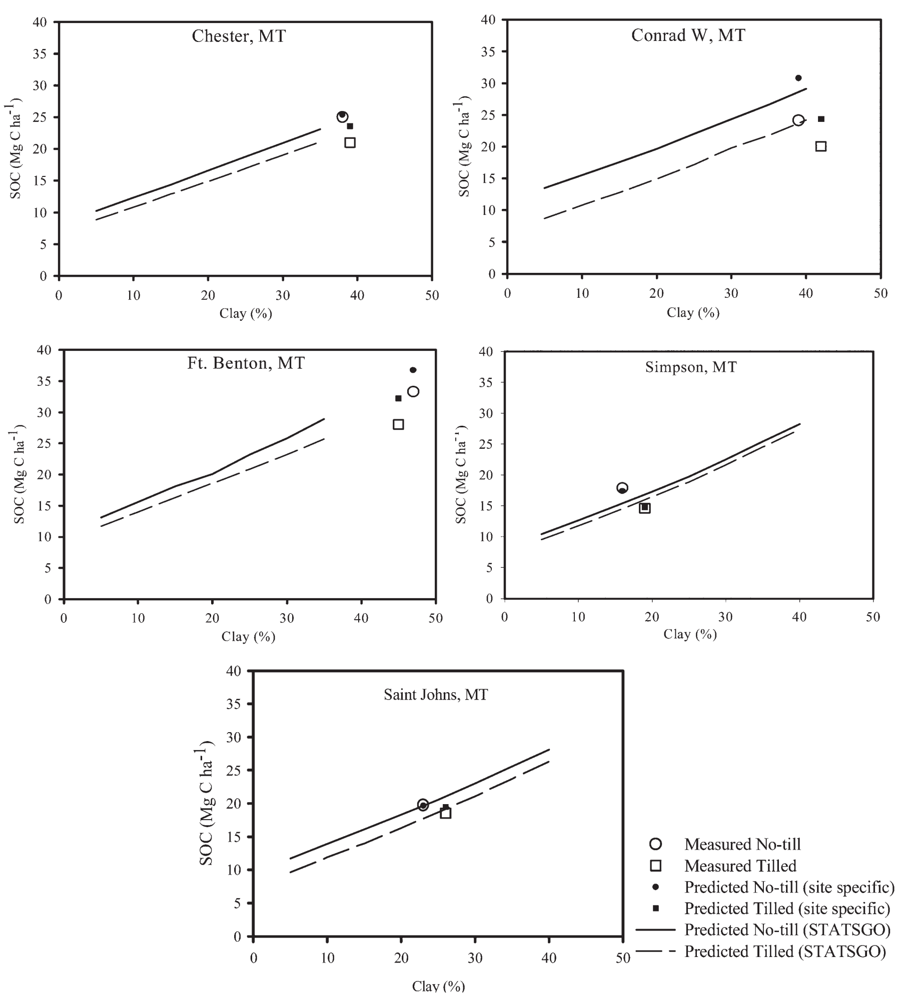

Fig. 5. Measured and predicted soil organic C (SOC) values using the Century model for no-till and tilled fields using site-specific clay content and STATSGO reported clay content in 5% increments at Chester, Conrad W, Ft. Benton, Simpson, and Saint Johns, MT, 2001.

ship between the relative annual increase in SOC with the adoption of no-tillage and clay percentage.

As clay content increased, SOC estimates from Century also increased for each site and tillage system. Carbon predictions increased nearly 2.5-fold from low clay values to high clay values. The significance and characterization of this linear association is given by the first three results of the ANCOVA mixed model, where (i) a linear association exists between Century estimates and clay content, (ii) the slopes of the linear association between clay content and Century estimates appear to be the same regardless of tillage practices, and (iii) the common slope was estimated as 0.56 Mg C ha^{-1} (% clay)$^{-1}$.This supports the claim that Century is sensitive to the effects of soil texture when predicting SOC. Century calculates a decomposition rate of the active soil organic matter pool and the stabilization efficiency of the active SOM pool to the slow pool as functions of soil silt and clay fractions (Eq. [2]; Parton et al., 1994).

The accuracy of Century SOC estimates was influenced by the type of soil input data. The overall average deviation of Century model SOC estimates from measured values was 10% when using site-specific soils data and was shown to be statistically significant according to the ANOVA mixed model results. The lack of site-specific hydraulic parameters is a potential source of error for site-specific simulations. The STATSGO and SSURGO database ranges of clay content did not encompass all of the measured clay values at all sites, which, due to extrapolation, had a profound effect on the accuracy of model estimates. Despite the large range in predicted SOC values estimated when using STATSGO and SSURGO soils data, in only 6 of 10 cases did the range in model SOC estimates include measured values. Although the range of SOC estimates was less than the measured values, the slope of the prediction line suggests that, had the range of clay values been extrapolated to include the measured clay value, then the model would have potentially predicted SOC accurately (Fig. 5).

Also noteworthy is an examination of the variance component estimates from the two statistical models used in the analysis that reveals large site-to-site variation. The variability between sites was substantially greater than the tillage effect. A failure to have accounted for this source of variation using random block effects in this analysis, where sites were the blocks, would have eroded the usefulness of the statistical models with respect to hypothesis testing and estimation using confidence intervals and the subsequent reliability of results. Blocking by site may be an important consideration in the analysis of future similar studies.

Additional research is needed on both the effect of soil texture on C sequestration with the adoption of no-tillage and the Century model's sensitivity to soil texture on estimated tillage effects to determine if adjustments to the model would be necessary. Changes to the Century model would be necessary only if a significant effect of soil texture can be demonstrated to influence C storage under various agricultural management scenarios. The results presented here are for a relatively homogenous agroecoregion in north-central Montana

In general, it was misrepresentation of clay percentage in the STATSGO and SSURGO soils databases that limited the effectiveness of Century in this study. There was no advantage to using the finer scale SSURGO data over the coarse-scale

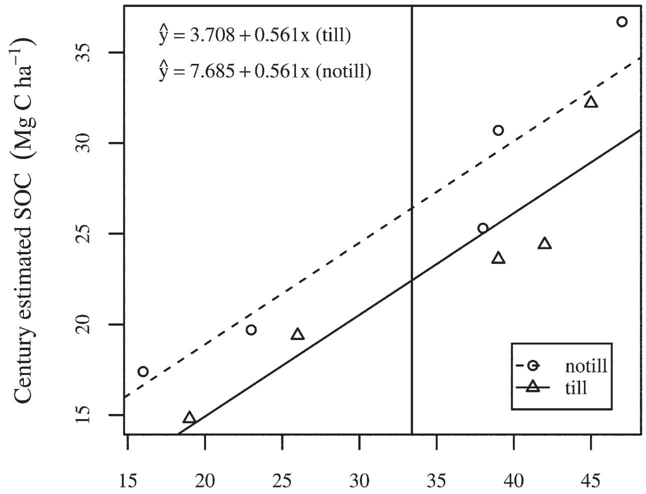

Fig. 6. Regression of clay content on Century model estimates of soil organic C (SOC) in no-till and tilled fields at Chester, Conrad W, Ft. Benton, Simpson, and Saint Johns, MT, 2001.

STATSGO data. Results of using either the 1:250 000 scale STATSGO or the 1:24 000 scale SSURGO data for Century soil texture and soil bulk density inputs were equally poor for predicting C change due to the adoption of no-tillage in north-central Montana (data not shown).

In an effort to market C credits, the Century model is being considered as a method of measuring and verifying C change associated with changes in agricultural management. Modeling SOC change with the Century model using STATSGO and SSURGO soil databases could present issues for accurately estimating C sequestered in agricultural settings. The misrepresentation of clay content was a major influence on the accuracy of Century model C change estimates. These discrepancies could cause some farmers who choose to market their C to underestimate their credits and not receive proper compensation. Conversely, if C estimates are overinflated, purchasers of C credits could risk not receiving all the C they purchased. If tradable C units were to coincide with field-scale SOC estimations, the reliability of SOC estimates using Century with either soils database might not meet uncertainty standards of C buyers. Field-scale sources of soil data and optimized methods of soil sample collection would be needed to reduce costs and increase statistical efficacy of monitoring and verifying C change. If C contract units encompassed relatively homogenous argoecozones, a "representative soil" may be defined for that particular region. This representative soil may be initially delineated using SSURGO soil mapping units; however, additional soil sampling for accurate determination of soil attributes for the agroecozone would be needed to increase the reliability of soil C estimates.

CONCLUSIONS

The Century model was sensitive to the effects of soil texture when predicting the amount of SOC in fields managed with and without tillage; however, the model failed to exhibit a soil texture influence on the rate of SOC accumulated in response to a change in tillage management duirng a 6- to 10-yr period. From a modeling standpoint, neither the STATSGO nor the SSURGO databases provided adequate field-scale soil texture information for use in the Century model, thus site-specific soil information is recommended for use with the Century model for modeling C dynamics at the farm and field level.

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