CENTURY Model Simulation of Soil C and N on a Thin Black Chernozem.

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Abstract

CENTURY is a process oriented soil organic matter (SOM) model, based on the conceptual division of SOM into active, slow and passive phases. Carbon (C) and nitrogen (N) flow, from plant residue through the SOM compartments, is driven by monthly precipitation and temperature and moderated by the nutrient content of the residue. CENTURY simulations of cultivated soils in the American Great Plains have agreed well with the changes in C and N observed over the last 100 yrs. However, use of this model to predict SOM in Saskatchewan soils, is limited by incomplete validation under our conditions.

The Thin Black Chernozemic soils of the Indian Head Experimental farm provide a unique opportunity to validate the CENTURY model, since both cropping history and soil C and N have been recorded for over 100 years. CENTURY predicted C and N levels (mass per unit area basis) within 4 to 21% of those observed, after 26 years under fallow-wheat, fallow-wheat-wheat, continuous wheat and fallow-wheat-wheat-hay-hay-hay. Where soil erosion was not considered as a mechanism of SOM loss, CENTURY overpredicted C and N by 30 to 45% of the observed. CENTURY prediction of mean annual C production as grain was 25 to 41% lower than the observed levels. Such yield functions, which consider the loss of available nutrients in the SOM as well as less residue returned to the system may be useful in estimating the long term direct costs of soil erosion on grain production

Introduction:

In 1941, Hans Jenny first described soil as a function of five state variables: climate, parent material, time, topography, and the action of organisms. Since this time, soil scientist have been attempting to use Jenny's relationship to predict the response of a soil to some change in these variables. The CENTURY model is an attempt to quantify some of the relationships between soil forming factors using both the mechanistic and regression model approach.

CENTURY stems from a simple carbon (C) and nitrogen (N) model which divides soil organic matter (SOM) into three different pools based on the relative decomposability of the substrateParton et al., 1983). Active substrates are considered to be a relatively small (1 to 8%) but quickly decomposable part of the total SOM. Moderate or slow SOM comprises from 30 to 50% of the total SOM and provides a slow but steady source of C for microbial oxidation. Passive SOM is highly polymerized and/or physically entrapped, rendering it very resistant to microbial attack. Approximately 40 to 70% of the SOM can be in this form.

Plant residues added to the soil also moderate the C and N flow through SOM. Plant production, predicted using meteorological variables and available N, phosphorus (P), and sulfur (S) (Parton et al., 1987; 1988), contributes C to the soil as surface litter or incorporated belowground litter. The lignin to N ratio (L/N) of the litter determines the allocation of C into structural (slowly decomposing, high L/N) or metabolic (rapidly decomposing, low L/N) fractions. The net change in C depends on the additions of litter to, and the microbial oxidation from, these four plant litter and three SOM pools.

Organic transformation, mediated by microorganisms, is fundamental in driving the flow C and N through the soil. Each substrate is decomposed as a function of the moisture, temperature, and maximum decomposition rate (K). K values are fixed for all substrates except: a). structural plant litter, where K decreases as lignin content increases, and b). active SOM, where K decreases as texture (clay + silt) increases. Texture also controls the stabilization of active SOM into the slow SOM pool. This 'clay protection' of SOM has been considered as an important mechanism in maintaining a pool of fairly labile SOM in extensively cultivated soils (Anderson and Paul, 1984).

The basic structure of C and N flows through plant and soil organic compartments (illustrated in Parton et al., 1987), has recently been modified to accommodate the inorganic reactions of P and S (Parton et al., 1988). Another important modification was the quantification of C lost with soil erosion. Carbon removed by erosion is simply calculated by multiplying the mean monthly soil loss (known value) by the C concentration of the soil layer during that month. Earlier CENTURY simulations were based on the intrinsic assumption that erosion was not a factor (Parton et al., 1983). This may, in part, explain the variable agreement between predicted and observed SOM C and N after long term cultivation (Cole et al.,1989).

Despite the gross assumptions required to emulate the complex soil-plant system, CENTURY has been able to predict reasonable changes in SOM C and N in simple cereal crop rotations. This initial success has heightened the interest in using CENTURY as a soil management and/or extension tool throughout the Great Plains of North America. The objective of this study was to test the ability of the CENTURY model to predict the change in SOM C and N after 26 years of crop rotation on well documented soils at the Agriculture Canada Experimental farm, Indian Head, Sk.

Methods and Model Parameters

Organic nitrogen (ON), organic carbon (OC), and ^{137}Cesium (^{137}Cs) concentrations were measured on soils from selected rotation treatments, started in 1958 at the Indian Head Experimental farm. The rotations under study included:

FW

- Fallow-Wheat (unfertilized).

FWW (N+P;+straw)

- Fallow-Wheat-Wheat (4.5 gN m^{-2} and 2.1 gP m^{-2} added every 3 years; straw retained)

FWW (N+P;-straw)

- Fallow-Wheat-Wheat (4.5 gN m^{-2} and 2.1 gP m^{-2} added every 3 years; straw removed)

FWWHHH

- Fallow-Wheat-Wheat-Hay-Hay-Hay (unfertilized; Brome-alfalfa Hay)

cont.W

- Continuous Wheat (3.9 gN m^{-2} and 1 gP m^{-2} added every year)

A detailed account of equipment used and yields observed from 1960 to 1984 is given by Zentner et al. (1986). Replicates sampled, analytical techniques used, and observed levels of OC, ON, and soil erosion are reported by Greer (1989).

A current version of the CENTURY model for IBM PC was used to generate simulated OC, ON and C production as grain (Cgrain). Input parameters controlling initial OC levels, soil erosion, cultural practices, meteorological conditions, soil properties, and length of simulated management were initialized at levels known for this site at Indian Head. A complete listing of input values and sources of data are given in Appendix A. The model was run from the spring of 1961 to the spring of 1987, with input variables which best approximated the actual management conditions.

Extensive alterations to the grass submodel input parameters were required to approximate the hay years in the FWWHHH rotation. Such forage rotations had not been attempted previously, therefore, extra caution is required when comparing the predicted and observed variables. A complete list of the altered input parameters and assumptions required to simulate this rotation are given in Appendix B and C.

Bulk density values were needed to convert C and N concentrations to a mass/unit area, over a given soil depth. Soil bulk densities were not taken on this site prior to 1987. Therefore bulk density was assumed to be 0.88 Mg m^{-3} for native sod in 1885, and 0.99 Mg m^{-3} for the field in 1961.

Output variables describing the total soil OC, ON and Cgrain were recorded each year the model was run. Agreement among observed levels in 1987 and model predicted levels in 1987 are expressed as the percent difference from the observed.

Results and Discussion

Initializing the SOM pools in 1961

Zentner et al. (1986) reported a mean ON concentration of 0.2% for the top 15 cm of a cultivated Indian Head heavy clay soil. However unpublished data taken by Dr. E.D. Spratt in the spring of 1961, indicate that the mean total N concentration of this particular site was 0.36% in the 0 to 15 cm layer. Given the cultivation history of this field (approximately 76 years in FW) and a total N concentration of 0.371% for native sod reported by Shutt (1923), such a concentration of total N in 1961 is considered highly unusual.

An earlier, more detailed study of the Indian Head Experimental farm recognized the large variability in OC and total N concentrations not only among the lighter textured till and the heavy lacustral clay soils, but also within the heavy clay soils (Alway and Vail, 1909; Alway and Trumbull, 1910). Total N concentrations of native sites varied from 0.385%, to as high as 0.822% in the lacustral clay soils. The highest total N and OC concentrations were found in the slight depressions or rifts, while the soils having less total N and OC were located on slight hummocks. Such large differences in native fertility, as well as the relative obscurity of these microtopograhic features, prompted Alway and Vail (1909) to conclude that:

> "it will be extremely difficult to estimate the original content of humus and of nitrogen in a field of lacustral clay that has long been under cultivation. The portion of the surface originally occupied by hummocks and rifts, which offer no serious obstacle to the plow, would need to be known, as well as the relation between the distribution of hummocks and the average composition of soil."

In an attempt to validate the total N measured in 1961, simulated cultivation histories were run using the initial OC levels reported by Alway and Vail (1909). Running two scenarios, starting at the maximal and minimal OC levels, the range of OC content most likely to exist in 1961 can be generated.

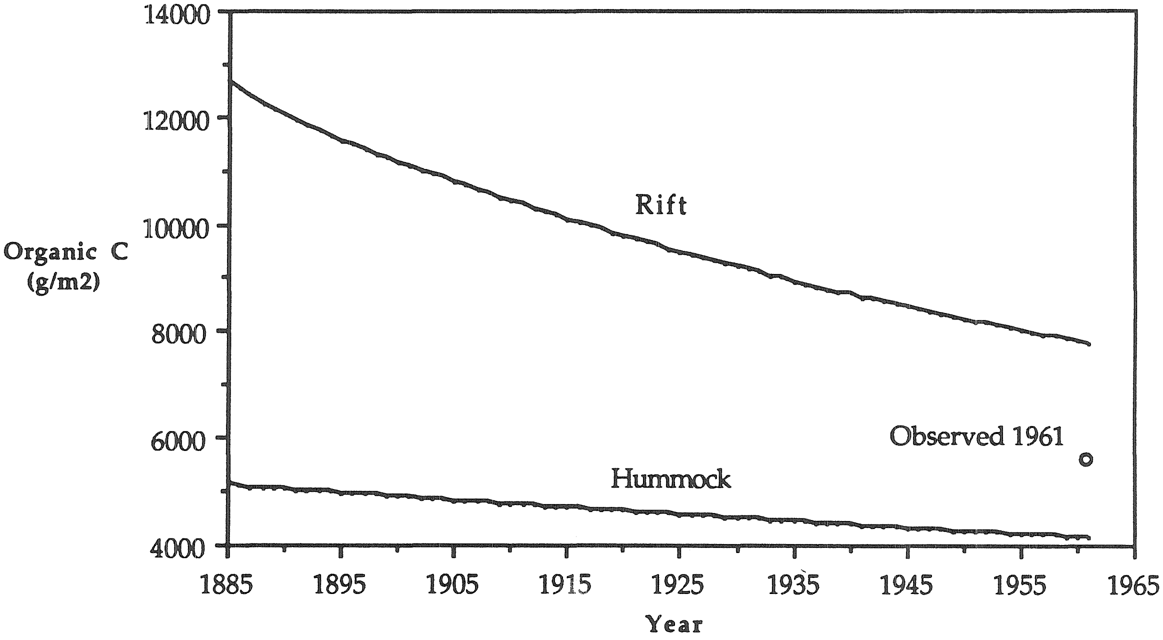

Figure 1. Simulated Organic C content in the 0 to 15 cm layer after 76 years of FW rotation

Figure 1. indicates that the OC level in 1961, estimated from observed N levels using C to N ratio of 10 to 1, falls within the simulated range of OC levels probable for a lacustral clay soil after 76 years of FW cropping. Such evidence confirms that the unpublished data total N levels on this site in 1961 are indeed plausible.

Simulating SOM levels after 26 years of crop rotation

Soil OC, estimated from the 1961 total N values, was allocated among the active, slow and passive pools in proportions similar to those present after the 76 year simulation (Appendix A). Simulations of the rotation treatments were then generated with soil erosion, at the rate measured by Greer (1989), and without soil erosion (Table 1.).

Table 1. Observed and Predicted Organic C content (g m^{-2}) in the spring of 1987 for the 0 to 30 cm layer.

Rotation	Observed OC	Predicted OC with Erosion	Predicted OC without Erosion
FW	6355	6603 (4)*	8278 (30)
FWW (+straw)	6329	7274 (15)	8680 (37)
FWW (-straw)	6332	7048 (11)	8400 (33)
FWWHHH	6432	7439 (16)	8393 (31)
cont.W	6553	7411 (13)	8834 (35)

* Overprediction as a percent of observed

Simulations of OC with soil erosion were, from 4 to 16% higher than the observed levels. Disregarding soil erosion as a mechanism of OC loss caused the predicted levels to be 30 to 37% greater than the observed. Predictions of total N followed a similar trend as OC predictions, both with and without soil erosion (Table 2.). However, the agreement between observed and predicted levels was somewhat poorer than those seen for OC.

Table 2. Observed and Predicted Organic N content (g m^{-2}) in the spring of 1987 for the 0 to 30 cm layer.

Rotation	Observed ON	Predicted ON with Erosion	Predicted ON without Erosion
FW	601	648 (8)*	825 (37)
FWW (+straw)	601	725 (21)	869 (45)
FWW (-straw)	602	706 (17)	846 (41)
FWWHHH	611	725 (19)	821 (34)
cont.W	623	754 (21)	896 (44)

* Overprediction as a percent of observed.

Soil erosion has previously been eluded to as a contributory factor in the SOM balance, only where predictions of C and N levels were poor (Cole et al., 1988; 1989). Simulations on this site, where soil erosion over the management period was quantified, substantiate the importance of soil erosion as a factor in SOM dynamics.

Agreement was best in the FW rotation. All other rotations could not be adequately described during model initialization, therefore, more assumptions were required to simulate the FWWHHH, FWW (+straw), FWW, (-straw), and cont.W rotations (Appendix C). Increased uncertainty in the initialization step will undoubtedly reduce the accuracy of the prediction. However, previous model tuning using data from only FW rotations may also be a cause of the overpredictions observed on longer, more complicated rotations (Parton et al., 1988).

It is not possible to state precisely why CENTURY consistently overpredicts OC and ON on these rotations. However, recognizing the probable causes of overprediction may be useful in further fine tuning this model.

Monthly removal of SOM with eroded soil is approximated by multiplying the soil loss rate by the OC concentration in the simulated layer. This type of calculation will underestimate the OC removed since: (1) erosion removes the surface soil, which has a much higher SOM concentration than the whole soil layer, and (2) eroded material, from certain soil types, may be significantly enriched in SOM (Begg, 1982; Moss, 1935).

Consistent overpredictions may also result from low SOM decomposition rates. Moisture and temperature functions, developed for the U.S. Great Plains, are built into the model to moderate the decomposition rates (Parton et al., 1987). It is reasonable to suggest that the microbial populations and, therefore, the optimal temperature and moisture for decomposition will be different in more northern soils. Decomposition is also controlled by silt and clay content. The heavy clay soils at Indian Head have greater than 90% silt and clay, which may be above the levels used for model development and initial validation (Parton et al., 1987; Cole et al., 1989).

Simulated Crop Production after 26 years of crop rotation

Above and below ground plant production also has a direct impact on the SOM balance. Plant production could not be directly tested since above and below ground plant dry matter was not measured during the rotation study at Indian Head. Estimates of the residue produced have been calculated (Campbell et al., 1989; Greer, 1989), however comparing estimated plant production with predicted plant production is of questionable value.

CENTURY, for the IBM PC, assumes that C produced as grain (Cgrain) is 32% of the total C produced as dry matter in each crop year. The mean annual Cgrain, predicted after a 26 year simulation, can then be compared to the observed mean annual grain yields, assuming that the grain produced on this site from 1960 to 1984 was 40% C (Table 3.).

Table 3. Observed and Predicted mean annual C production as grain (g m^{-2} yr^{-1}) over 26 years of crop rotation.

Rotation	Observed Cgrain	Predicted Cgrain with Erosion	Predicted Cgrain without Erosion
FW	44.8	28.9 (36)*	33.7 (25)
FWW (+straw)	58.6	41.5 (29)	42.7 (27)
FWW (-straw)	59.8	41.4 (31)	43.5 (27)
FWWHHH	61.9	36.7 (41)	38.1 (38)
cont.W	72.4	50.0 (31)	52.9 (27)

* Underprediction as a percent of observed.

CENTURY substantially underpredicted the C produced as grain. Underprediction of Cgrain was fairly consistent among the FW, FWW (N+P;+straw), FWW (N+P;-straw), and cont.W rotations, suggesting that either the proportion of C fixed as grain, or the amount of plant production was consistently low. Cgrain in the FWWHHH rotation was further underpredicted, possibly as a result of insufficient build up of the mineralizable SOM during the grass years of the model. Alternatively, immobilization of N in the crop years after grass may be excessive, thereby limiting available N and crop yield (C.V. Cole, personal commun.).

Simulations with erosion had lower Cgrain yields than those simulations without erosion. When soil erosion removes SOM, the pool of available nutrients is reduced, which, in turn, lowers plant production, thereby feeding less residue back to the SOM pools. Over time the removal of SOM through soil erosion along with the accumulated reduction in plant residue additions, will cause ever lower SOM levels, available nutrients, and grain yields.

CENTURY's ability to simulate this synergistic relationship may be very useful in evaluating the longterm cost of soil erosion on grain yield. For example, mean Cgrain predicted in the 26 year FW rotation was 4.8 g m^{-2} yr^{-1} lower where soil erosion did occur (Table 3.). This translates into approximately 1.8 bu ac^{-1} lost on every year of the rotation, or \$5.40 ac^{-1} yr^{-1} assuming wheat was \$3.00 bu^{-1}. A word of caution, however; before this type of analysis is applicable to an "on-farm" level, the importance of soil loss versus soil redistribution within fields must be addressed.

Conclusions and Recommendations

Simulations generated for the site from breaking to 1961, suggest that the unpublished total N levels taken by Spratt (1961) are indeed possible. Using these initial N levels, OC was estimated and used to initialize the CENTURY model. Predicted OC and ON for rotation treatments were within 4 to 21 % of the observed levels when erosion was considered as a factor. Simulations assuming no soil erosion, overpredicted final OC and ON by 30 to 45%. Quantification of soil erosion is, therefore, required to more adequately simulate SOM dynamics using CENTURY.

Simulated C produced as grain was underestimated by 25 to 41%. Fairly consistent underprediction on the FW, FWW (N+P;+straw), FWW (N+P;-straw), and cont.W rotations suggests that the proportion of C produced as grain may be too low. Soil erosion reduced the simulated Cgrain produced as a result of lower SOM, causing less available nutrients, and less plant production. Using this relationship it may be possible to calculate the longterm cost of soil erosion on grain yield, assuming that the Cgrain production function can be validated.

Appendix A

Model Input Parameters for the Indian Head site

	Input Variable Name and Value	Sources of Data
Initial OC	SOM1CI(1) = 268.3 SOM2CI(1) = 3144.0 SOM3CI(1) = 4971.7	Initial soil organic carbon in the active, slow and passive pools, respectively. Estimated from Organic N (Spratt, 1961 unpublished data) times 10.32 for the 0 to 15 cm layer. OC in the 15 to 30 cm layer was assumed to be equal to the mean level observed by Greer (1989).
Soil Erosion	IERODE = 1 or 0	1 for erosion, 0 for no erosion.
	PSLOSS = 0.06, 0.288, 0.203, 0.204, 0.252, 0.199	soil lost (kg m^{-2} mo.$^{-1}$) for 1st 76 years of cultivation, FW, FWW (N+P;+straw), FWW (N+P;-straw), FWWHHH, cont.W, respectively. *NOTE*: Soil erosion was estimated using the WEQ and USLE for 1st 76 years of cultivation.
	EDEPTH = 0.3	depth of soil layer in meters.
	BULKD = 0.99, 1.17, 1.11, 1.12, 1.10, 1.11	soil bulk density (Mg m^{-3}) for 1st 76 years of cultivation, FW, FWW (N+P;+straw), FWW (N+P;-straw), FWWHHH, cont.W, respectively.
Cultural Practices	CLTANY = 1	1 for cultivation to occur.
	CULTMO (1 to 4) = 5, 6, 7, 8.	months in which cultivation will occur during a summerfallow year.

	WHTSCH (1 to 4) = 5, 0, 0, 9.	months in which crop germinates, fall senescence occurs (for winter wheat), spring regrowth occurs (for winter wheat), and harvest occurs.
	RMVSTR = 0, 0, 0, 0, 0.67, 0.67.	proportion of straw removed for FW, FWW (N+P;+straw), FWWHHH, cont.W, FWW (N+P;-straw), and 1st 76 years of cultivation, respectively.
Meteorological conditions	PRECIP (1 to 12) = 2.02, 1.80, 2.44, 2.36, 4.90, 8.17, 6.04, 5.24, 4.24, 2.56, 2.33, 2.08.	Mean monthly precipitation (1891 to 1989) for January to December in cm (D. Anderson, LRRC, personal commun.).
	TMN2M (1 to 12) = -22.6, -20.4, -13.6, -3.2, 3.2, 8.6, 11.2, 9.8, 4.3, -1.7, -10.6, -18.4.	Mean monthly minimum air temperature at 2 m. (1891 to 1989) for January to December in °C (D. Anderson, LRRC, personal commun.).
	TMX2M (1 to 12) = -11.9, -9.2, -2.2, 9.6, 17.8, 22.1, 25.8, 24.5, 18.1, 10.9, -0.7, -8.2.	Mean monthly maximum air temperature at 2 m. (1891 to 1989) for January to December in °C (D. Anderson, LRRC, personal commun.).
Soil properties	PH = 7.5	soil pH (Moss and Clayton, 1940).
	SAND = 0.089	proportion of sand (> 0.05 mm) (Alway and McDole, 1907).
	SILT = 0.429	proportion of silt (< 0.05 and > 0.005 mm) (Alway and McDole, 1907).
	CLAY = 0.482	proportion of clay (> 0.005 mm) (Alway and McDole, 1907).
Length of simulated management	TEND = 76, 26	number of years the model was run for the 1st 76 years of cultivation, and all rotation treatments, respectively.

Appendix B

Input Parameters for FWWHHH Rotation

Input Variable Name and Value	Description and Assumptions
FDGREM = 0.00001	Fraction of standing dead plant material removed with grazing. Model would not allow this parameter to equal zero for Hay simulation.
FECF = 0.00001	Fraction of aboveground material returned as feces. Model would not allow this parameter to equal zero for Hay simulation.
FLGREM = 0.99	Proportion of aboveground plant material removed by grazing.
GFCRET = 0.01	Proportion of C added to the soil as aboveground plant material during grazing.
GREMON = 7	Month in which grazing will occur.
GRET(1, 2, 3) = 0.01, 0.01, 0.01	Proportion of N, P, and S added to the soil as aboveground plant material during grazing.
TEND = 3, 6, 9, 12, 15, 18, 21, 24, 27	Time of simulation, changed for each extension from FWW to HHH or vise versa.

Appendix C

Rotation	Assumption Required to Simulate Rotations
FWWHHH	- Three years under the native grass model approximates the brome-alfalfa Hay years of the rotation. - L/N ratios under native grass, estimated using annual precipitation, approximate those of brome-alfalfa Hay. - Removing 99% of the aboveground plant material by grazing estimates actual Hay removal by baling. - Soil erosion occurs only during the FWW years of the rotation. - CENTURY simulations can be extended from one system to another (ie. cereal grain to grass). -Erosion estimated by ^{137}Cs tracer approximate the amount of soil lost during 1961 to 1987. - Bulk density during the 26 years of rotation are equal to those measured in 1987.
FWW (+straw) and FWW (-straw)	- Applying all of the fertilizer in the simulated summerfallow wheat year approximates the actual fertilizer additions to both summerfallow and stubble wheat crops. - Fall and spring tillages during crop years, which are not possible in CENTURY simulations, did not affect the SOM. - Straw baling removes 67% of the straw produced. -Erosion estimated by ^{137}Cs tracer approximate the amount of soil lost during 1961 to 1987. - Bulk density during the 26 years of rotation are equal to those measured in 1987.
cont.W	- Fall and spring tillages during crop years, which are not possible in CENTURY simulations, did not affect the SOM. -Erosion estimated by ^{137}Cs tracer approximate the amount of soil lost during 1961 to 1987. - Bulk density during the 26 years of rotation are equal to those measured in 1987.
FW	-Erosion estimated by ^{137}Cs tracer approximate the amount of soil lost during 1961 to 1987. - Bulk density during the 26 years of rotation are equal to those measured in 1987.

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