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Tillage, crop rotation, and organic amendment effect on changes in soil organic matter

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"Capsule": *The models CQESTR and RUSLE were used to estimate carbon sequestration in agricultural soils.*

Abstract

Carbon sequestration in agricultural soils is controlled by the balance of added organic residues and microbial oxidation of both residues and native organic matter (OM) as moderated by management and tillage. The PC-based model CQESTR predicts decomposition of residues, organic amendments and soil OM, based on cropping practices. CQESTR uses RUSLE (Revised Universal Soil Loss Equation) crop rotation and management practice, crop production, and operation databases. These data are supplemented with residue nitrogen and soil OM, bulk density, and layer thickness. CQESTR was calibrated with soil carbon data from 70-year-long experiments at the Research Center at Pendleton, OR. The calibrated model provides estimates with a 95% confidence interval of 0.33% OM. Validation at 11 independent sites resulted in a matching of observed with calculated OM with a 95% confidence interval of 0.55% OM. A 12th site, with a history of severe erosion, provided a poor match. Published by Elsevier Science Ltd.

Keywords: Carbon sequestration; Organic matter; Agricultural soils; Tillage; Crop rotation

1. Introduction

Among the factors that control organic matter (OM) content of soils used for agricultural production, only crop rotations and management practices are under the control of a manager. Options available for rotations or tillage often have cultural, environmental, or economic restrictions. Within these limitations, a tool is needed for predicting the magnitude of changes in soil OM from current or planned practices. Ideally, this tool would be sensitive to local soils, climate, tillage systems, crops, crop rotations, fertilization, cover crops, and organic amendments. It would operate at the field level and utilize readily accessible data sets to assist farm-planning efforts to enhance soil OM. Available models with soil OM as a component part have been designed, more often than not, for the purpose of either cataloging soil carbon resources or investigating the detail of C and N cycles within the soil and within specific ecosystems (Smith et al., 1997). Each, of necessity, has different input data requirements that vary from rather generally available monthly average weather and annual biomass to highly specific individual residue and organic matter carbon isotope fractions. Routine application of these models for the purpose of evaluation of field management practices was not one of their design criteria and few if any lend themselves to that purpose. It is our goal to provide a model-based tool that uses readily available input data, for national or international use, in the field scale evaluation of management practices for purposeful manipulation of soil OM. The final decomposition product of crop residues and soil OM is CO_2, which is suspected of contributing to global climate change. Management to increase the storage of C as soil OM has multiple potentially beneficial environmental consequences in addition to the impact on CO_2.

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2. Materials and methods

Soil OM change is computed by the model CQESTR by maintaining a budget of organic carbon additions to a soil and losses of organic carbon through decomposition by microbes. The model requires the initial soil OM content for each soil layer of interest. The budget and identity for each organic input is maintained over a 4-year period of "composting". At the end of 4 years, the composted organic input loses its identity and is placed into the soil OM pool in an abrupt step function. Both the "composting" residues and the "mature" soil OM are decomposed daily using an exponential function driven by cumulative heat units, with appropriate empirical coefficients for the type of residue, nitrogen content and incorporation into the soil by tillage. The model uses daily time steps to calculate heat units that are initiated for each organic input, typically after crop harvest. Other soil amendments are tracked similarly.

2.1. Carbon budget with microbial-based carbon losses

CQESTR is based on the balance of crop residues or amendments added to a soil, the native OM of the soil, and the fraction of each that are lost to the continuing oxidation by microbial metabolism. In nature, each organic addition to soil decomposes and is slowly incorporated into the soil OM. In CQESTR, it takes approximately 4 years before the remnants of a residue are considered sufficiently composted to be added to the soil OM pool. This 4-year value was determined by best-fit calibration of the model with long-term soil carbon observations. Within the model, this transfer takes place as an abrupt step function on the date that composting is completed. Eq. (1) contains the components of the total soil C budget as used in CQESTR. The weight of all organically based C containing compounds (C_T) is computed on a daily time-step for multiple soil layers, using units of weight of crop residue or organic biomass per unit area within each layer.

$$C_T = (C_{OM} - D_{OM}) + (C_R - D_R) + (C_A - D_A) \qquad (1)$$

The weight, C_{OM}, is the amount of OM present in a soil layer at some starting time plus that added periodically from sufficiently composted residue (C_R) or organic amendments (C_A). Carbon is lost from the soil by the daily decomposition of C_{OM} (D_{OM}), decomposition of C_R (D_R), and decomposition of C_A (D_A). No attempt is made to estimate any temporary storage of CO_2 as a dissolved gas in soil water as the magnitude and time scale of this process was considered too small for the model spatial and time scale. Net loss, or gain, of C_{OM} is determined by the cumulative daily loss (D_{OM}) and the periodic (in the model) contributions of ($C_R{-}D_R$) and ($C_A{-}D_A$). The term C_T is a dynamic value, varying with the month-to-month additions of residue and daily decomposition losses. The soil OM, C_{OM}, is a relatively static variable. The daily amount of decomposition, D_{OM}, is small, but omnipresent, and both $C_R{-}D_R$ and $C_A{-}D_A$ are small after the 4-year composting time used in CQESTR.

Several environmental factors that can influence OM content are not included in the CQESTR model. Loss of surface soil to erosion by wind and water is not considered, nor is the effect of addition of soil from these sources. Worms, insects, and small mammals may consume a fraction of residues. This non-microbial consumption depends strongly on local fauna population, climate, type and amount of surface residue, and time residue has been on the soil surface. CQESTR does not attempt to predict this consumption. If non-microbial consumption is significant, independent estimates of it must be subtracted from the residue mass input to CQESTR for improved OM predictions.

2.2. Decomposition equation

One decomposition equation is used in CQESTR, however, because of event specific environmental parameter values, each residue decomposes differently. The equation contains a universal decomposition rate (k), the degree day thermal driver for decomposition (CDD), and four residue or environment dependent terms that modify decomposition rate. The terms include a residue nitrogen content factor (fN), a water index (fW), a soil texture index (fX), and a biomass or residue type factor (fB). The calibrated values that can be used for these factors are listed in Table 1. The residue nitrogen term (fN) provides different decomposition rates for nitrogen rich (i.e. legume) and nitrogen poor

Table 1
Values of parameters in the decomposition equation used in CQESTR[a]

Factor description and grouping	Variable name	Value
Fundamental rate constant	K	−0.0004
Nitrogen 0 rate (fN)	fN0	0.8354
Nitrogen 1 rate (fN)	fN1	1.2635
Nitrogen 2 rate (fN)	fN2	1.9770
Nitrogen 3 rate (fN)	fN3	3.4040
Nitrogen 4 rate (fN)	fN4	3.4040
Surface dry (fW)	Sc	0.21
Surface wet (fW)	Sf	0.32
Buried dry (fW)	Bc	0.80
Buried wet (fW)	Bf	1.00
Crop residue (fB)	Frf	1.00
Roots (fB)	Rf	0.35
Composted or digested (fB)	Cdf	0.60
Soil organic matter (fB)	Omf	0.019
Soil texture (fX)	Txf	1.00

[a] Residue decomposition parameters (K, fN, fW) values from Douglas and Rickman (1992).

(i.e. cereal) residues. The value of the water index (fW) is determined by the location of the residue either buried or laying on the soil surface and the presence or absence of a growing crop. The texture index is not functional in the current code. Its value will range between 0 and 1, as the water and residue type indices do, depending on documentable clay and sand content impacts on soil OM as reported by Parton et al. (1987). The biomass type term (fB) distinguishes among fresh residues, root material, previously composted or digested material, and native soil OM. Values for fB were determined by calibration with the long-term soil organic matter observations from the Pendleton research center (Rasmussen et al., 1989). Values used for each of these indices are listed in Table 1. Residue remaining (Rr, in units of weight of residue per unit area) is computed uniquely for each addition to each layer from an initial residue amount (Ir, same units as Rr) and the amount of heat accumulated from the time of residue addition to the soil (CDD, in units of °C with a base temperature of 0 °C) by Eq. (2):

$$\mathrm{Rr} = \mathrm{Ir} \times \exp(k \times \mathrm{fN} \times \mathrm{fW} \times \mathrm{fX} \times \mathrm{fB} \times \mathrm{CDD}) \qquad (2)$$

where exp is the exponential function. The basic decomposition algorithm was taken from the existing residue decomposition model named 'D3R' (Douglas and Rickman, 1992).

2.3. Residue additions, tillage, and soil data

Both crop rotation and tillage information are required for the layer-by-layer computations performed by the model. Crop residue or amendment data include residue biomass, including roots, applied to or remaining in a field after harvest, dates of all additions, and nitrogen content of the added materials when applied. Dates of all tillage operations, fraction of pre-tillage residue weight remaining on the soil surface after each tillage, depth of tillage and the fraction of the surface disturbed by each are required.

Environmental data unique to each site includes average daily air temperature expected throughout the time of interest, number and thickness of soil layers, organic matter content and bulk density of each layer, and the average number of days for about an inch (2.5 cm) of rain to fall after a residue is added to a soil. Most of this information is automatically extracted from the c-factor (crop rotation and management practices), crop, and operation databases that are used or created by the Revised Universal Soil Loss Equation (RUSLE), (Renard et al., 1997). One need provide only the RUSLE crop rotation and management practice 'c-factor (*.rus)', crop (croplist.dat), and operations (oplist.dat) files that describe rotations and management practices of interest for the field sites of concern. CQESTR will automatically extract the data it needs when the file names and directory locations are provided. For irrigated sites the water index is set at its wettest value.

The availability of the monthly mean air temperatures from the c-factor files eliminates the need for independent sources of temperature data. Daily average air temperature is estimated by fitting the annual temperature trend provided by the average monthly temperatures. Daily values are estimated using the mean temperature as the estimate for the 15th of the month. A temperature for each day following or preceding the 15th was estimated using the weighted average of the rate of temperature change between preceding and following months. Weighting was based on the number of days from the date to the preceding or following month.

Only residue nitrogen content and thickness, starting OM content, and bulk density of soil layers of interest are additional required inputs to the CQESTR model. A small database of possible ranges of nitrogen contents for some common crops is provided as a part of the model. Wheat straw nitrogen content of 0.40% N was used for the calibration. Nitrogen content of the strawy manure added to the plots was estimated to be 0.75%. An Internet source of nutrition information for specialty crops is provided by Speedy and Waltham (1998). It lists crude protein content of hundreds of plant species produced under a wide variety of growing conditions. Nitrogen content for these plants may be estimated by assuming that protein is 16% N (Lehninger, 1970).

Up to five soil layers of any depth may be tracked with CQESTR. Normally, the number and depth of layers used will be determined by the availability of soil OM measurements for comparison. Tillage depths, provided in RUSLE operations files, are used to incorporate surface residues into appropriate depths. Complete mixing is assumed. Currently bulk density changes are not included in CQESTR computations.

Soil layering and initial OM content must be provided by the operator. The soil series present, their natural horizon depths, and the expected ranges of OM content by horizon are available in the county-by-county national soil survey (USDA-NRCS, 1997), or may be assessed by field sample analysis. Specific OM data from local samples are preferable for individual field projections. General OM contents are usable for trend projections. Local NRCS offices may provide more recent references to current local OM data as they become available.

2.4. Model operation

The "decomposition" of residues or OM discussed here, refers to the computed change in residue mass predicted by CQESTR. For the first 1000 degree days of decomposition of each residue or amendment, referred to as rapid-phase decomposition, the decomposition rate is computed using the initial nitrogen content to determine a value for fN, location of the residue in the soil (either buried or on the soil surface) to determine a value for fW, and biomass type for a value for fB. After the rapid-phase decomposition is completed (with the passage of 1000 degree days), the nitrogen factor (fN) is reduced to its minimum value (fN0) for all future decomposition of that residue, regardless of its initial N content (Table 1).

The value for the water factor (fW) is determined by the location of the biomass, either buried or on the soil surface, as controlled by the timing and type of tillage, and the presence or absence of sufficient water for maximum decomposition. In the arid US west and southwest, there are extended periods as a crop is growing and following harvest that decomposition is slowed by a lack of water. Decomposition continues at a maximum fW rate in these arid conditions, only after the arrival of fall rains, usually in early October. In CQESTR an average calendar date may be set to control the annual beginning of decomposition when projecting future effects of management changes. In the US central plains, southern, and eastern states with summer rainfall patterns, fW will be the larger of its possible values for the entire summer.

Each tillage operation conducted during a crop rotation buries additional amounts of each residue or amendment. The buried and surface amounts of each residue are decomposed using the rate appropriate for their location. Soil OM decomposition is computed separately for each soil depth that is being considered and for the residue on the soil surface.

3. Results

3.1. Calibration

RUSLE crop rotation and management (c-factor) files describing the production and tillage history for three wheat-fallow treatments that have been maintained for the past 70 years were created and used to run CQESTR repeatedly to obtain best fit values for the fB, and residue to organic matter transition time parameters. The three treatments were (1) minimum residue return using no nitrogen fertilizer and burning of the stubble before plowing for the fallow summer, (2) adding 90 kg N ha^{-1} for each wheat crop and plowing down the stubble for the fallow summer, and (3) adding 22 Mg ha^{-1} wet strawy manure and plowing it down with the stubble before the fallow summer. Fig. 1 illustrates the calibrated fit of the measured trend of organic matter content in the surface 30 cm layers for each treatment. The statistical 95% confidence interval is shown for the observed values. The points on the graph are the mean $+3x$, or the mean $-3x$, the standard error of the mean for each treatment at each date. Fig. 2 illustrates the goodness-of-fit for all reps of all three treatments for both 0–30 cm and 30–60 cm soil samples when CQESTR was run with the final set of fB and residue to organic mater transition time values. Using the residuals from the 144 computed and observed pairs of OM values from two depths and seven sample dates from the three treatments, the mean squared residual error for the model was 2.8. Based on the mean squared residual error, the model estimates have a 95% confidence interval of $\pm$ 3.3 g OM kg^{-1} soil (0.33% OM). This is the error of the model relative to the values used for calibration. Table 1 contains the calibration values of CQESTR parameters.

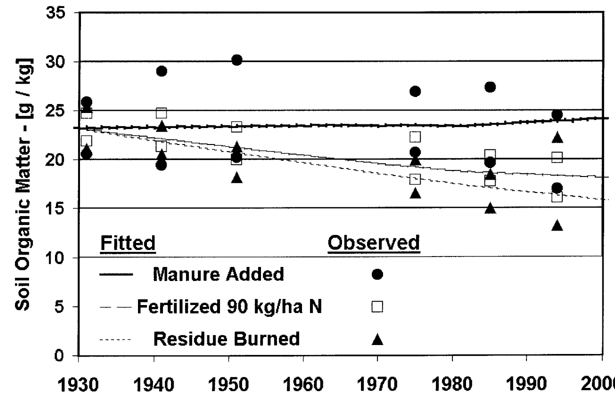

Fig. 1. Observed long-term organic matter changes in three wheat–fallow rotation treatments at the Pendleton Research Center, used to calibrate CQESTR. Observations are plotted as the high and low values from the 95% confidence interval for each treatment on each date. The solid lines are the computed changes in organic matter in the 0–30 cm soil layer using the calibrated model.

3.2. Validation

The text "Soil Organic Matter in Temperate Agroecosystems" by Paul et al. 1997, provides a companion diskette which contains soil carbon, crop rotation, production, and tillage data from 30 long-term agricultural sites in the United States and Canada. Using the reported data, RUSLE c-factor files were created that described the rotations at several of the sites. CQESTR computations were performed for the intervals where C data were available. The comparison of computed and observed organic matter contents for the sites that have currently been run are shown in Fig. 3. The comparison provides a fit of computed and observed values with a standard error of regression of 0.28% OM or a 95% confidence interval of $\pm$ 0.55% OM. All of the sites with soil C observations at two or more dates and sufficient data for creating the required RUSLE files will eventually be prepared for comparison with CQESTR. The characteristics of the sites that have been completed are listed in Table 2.

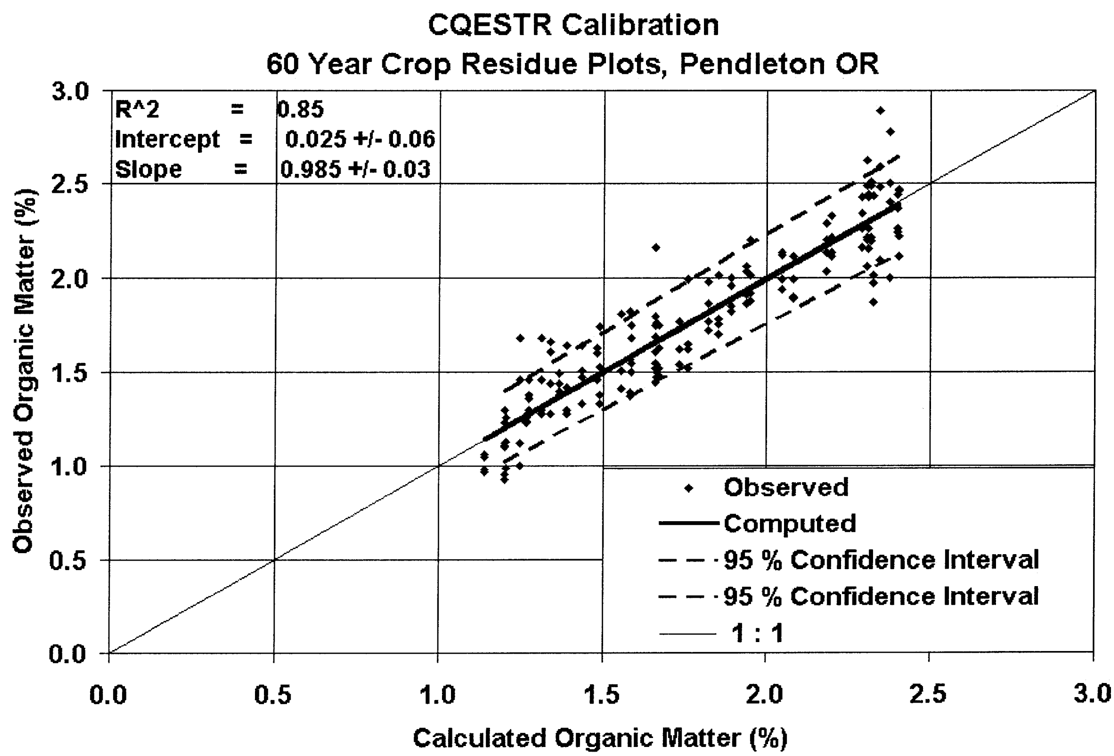

Fig. 2. Relationship between observed organic matter content for both the 0–30 and the 30–60 cm depth from the 90 kg N ha^{-1}, manure added, and residue burned wheat–fallow rotations from the Pendleton Research Center and the values computed using the calibrated CQESTR model. The model estimates have a 95% confidence interval of ± 3.3 g OM kg^{-1} soil (0.33% OM).

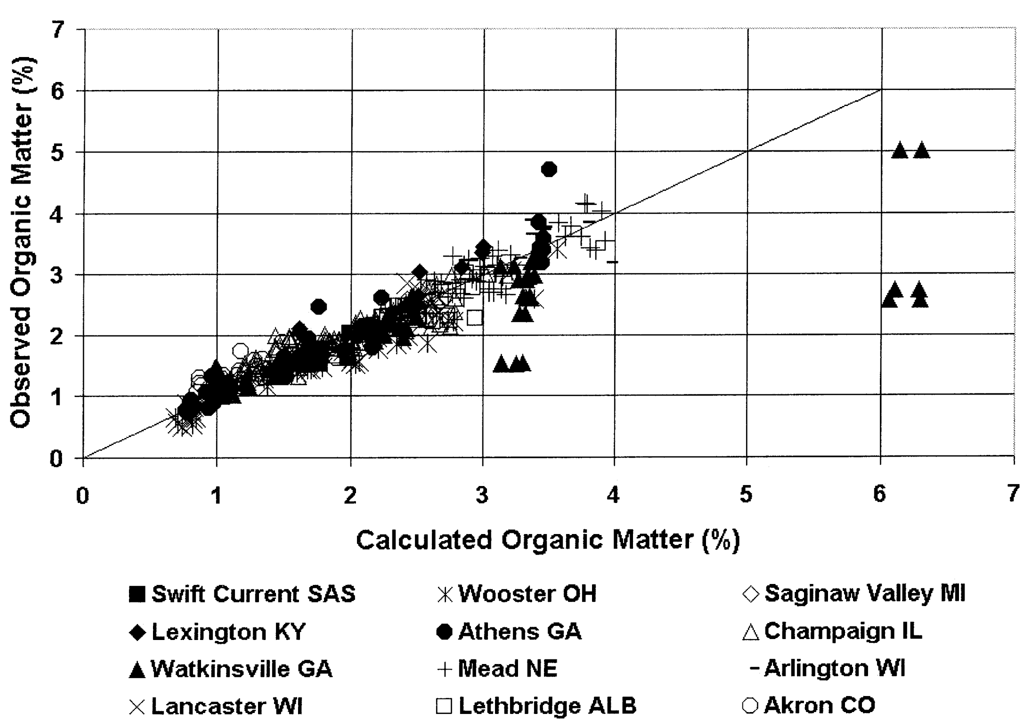

Fig. 3. Computed and observed organic matter content for multiple locations with different cropping and management histories. The linear fit of calculated vs. observed OM provides an $R^2=0.71$ with a slope of 0.93, statistically less than 1.00. The 1:1 line is shown in the figure. The standard error of linear regression was 0.28% OM resulting in a 95% confidence interval of ± 0.55% OM.

Table 2
Crop rotations, tillage practices, soil layers with organic matter data, and sampling dates for validation sites[a]

Site name	Crop rotation	Tillages	Soil layers (cm)	Earliest sample	Latest sample	Soil series/texture
Akron, CO	Wheat/Fallow	Conventional	0–5	1982	1989	Weld silt loam
		Reduced till	5–10			
		No till	10–20			
Arlington, WI	Corn	Conventional	0–15	1958	1991	Plano silt loam
	Corn	3 fertility levels				
Lancaster, WI	Corn	Conventional	0–15	1958	1999	Rozetta silt loam
		3 fertility levels				
Athens, GA	Sorghum/Rye	Conventional	0–5	1982	1990	Sandy clay loam
		No till	5–12			
			12–20			
Watkinsville, GA	Sorghum/Soybean,	No till,	0–4	1987	1991	Cecil and Pacolet
		light erosion,	4–8			
		severe erosion	8–20			
Champaign, IL	Corn	Conventional,	0–15	1904	1993	Flanagan
	Corn/Oats	2 fertlity levels				silt loam
	Corn/Oats/Hay	3 manured fertility levels				
Lethbridge, AL	Wheat	Conventional,	0–15	1910	1990	Sandy clay loam
	Wheat/Fallow	2 fertility levels				
	Wheat/Wheat/Fallow					
Lexington, KY	Corn	Conventional	0–15	1990	1990	Maury silt loam
		No till	15–30			
		4 fertility levels				
Mead, NE	Corn	Conventional	0–15	1979	1990	Sharpsburg silty
	Corn/Soybean/Corn/					clay loam
	Oat/Clover					
Swift Current, SAS	Wheat	Conventional,	0–15	1966	1980	Swinton loam to
		Annual				silt loam
		Wheat/Fallow				
		Wheat/Wheat/Fallow				
Wooster, OH	Corn	Conventional	0–8	1971	1980	Wooster silt loam
	Corn/Soybean	Minimum till				
	Corn/Oats/Meadow	No till				

[a] Data from Paul et al. (1997).

4. Discussion

Assumptions basic to the operation of CQESTR are those used to create the residue decomposition model 'D3R' (Douglas and Rickman, 1992). First and foremost, is the use of thermal time (CDD) computed as cumulative degree days (the sum of mean daily air temperature greater than a base value of 0 °C) as the primary driver of residue and organic matter decomposition. Second is the use of nitrogen content of the residue-not soluble mineral nitrogen (NO_3) in the soil-to control the 'first stage' rate of decomposition. Once the first stage decomposition, which lasts 1000 degree days, was complete all remaining material decomposed as though it had the same low value for fN. Third is the use of a water index (fW) that is controlled by position of the residue relative to the soil surface. Residue on the surface decomposes slower than residue that is buried, as the surface residue can dry thoroughly and is exposed to direct sunlight. Fourth, organic materials differ in their rate of decomposition based upon the content of simple (sugars and proteins) or complex (lignins and polycyclic rings) compounds. Only the most general classification of a material is needed to place it in a sufficiently appropriate residue type category. Only four residue types (fB) were created: (1) fresh undecomposed plant or animal residue, (2) roots, (3) manure or composed residue, and (4) soil OM. Each has a type coefficient listed in Table 1, that reflects the relative difficulty of decomposition. Fifth, decomposing residue becomes soil OM only after a prolonged composting interval. For the purpose of determining trend and magnitude of change in soil OM, as controlled by microbial decomposition, no other parameters were utilized.

After a residue has been composted for an extended time and its original identity is lost, the remaining mass for that residue is transferred to the OM pool and decomposed with the fB value for OM, not the fB value of its original residue type. Values for the residue-to-OM transition time and the biomass type factors were determined by interactive manual fitting of the model to OM contents from the 0N, 90 kgN ha^{-1}, and biennial 22 Mg ha^{-1} manure treatments of the long-term crop residue experiment at the Pendleton Research

Center (Rasmussen et al., 1989). The treatments were all conventional moldboard plow and clean fallow tillage. Clean fallow tillage refers to a primary inversion tillage that leaves less than 15% residue cover on the soil surface followed by multiple mixing tillages (such as disc, harrow, or rod weeder) throughout the fallow period. The value of 4 years for this transition provided a best fit for the long-term soil carbon and wheat production observations used to calibrate CQESTR. Preliminary validations from locations other than Pendleton indicate no change is required for non-wheat residues (Fig. 3). Residue position (surface or buried) did not change the time for conversion from residue to OM for wheat straw.

There are major differences between computed and observed OM at the Watkinsville site. Causes for this difference appear to be related to extreme erosion and sampling in thin layers, only 1.5 cm thick. Further information about this site is being collected.

The model is being submitted to independent testing for further validation and evaluation of the interface for ease of use. Currently planned modifications include automating the rainfall dependence of beginning decomposition and calibrating to data sets that show organic matter dependence on soil texture. It is planned to be ready for public release in late 2001.

5. Conclusions

Limited testing shows the model CQESTR may be an acceptably accurate and easy to use tool for the prediction of trends in soil OM content in individual agricultural fields. Applications could range from examining the expected effects of planned changes in crop rotation and tillage practices on soil C to planning specific management strategies for maximizing soil C storage. Locations or regions could be compared for their potential for C storage using region specific crop rotations and tillage alternatives. The economics of C storage as soil OM can now be evaluated by comparing costs of converting to C-storing practices to the anticipated value of additional stored C.

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