Quantifying C Changes in Crop Rotations in Southwestern Saskatchewan

C.A. Campbell[1], R.P. Zentner[2], G. Roloff[3], B.-C. Liang[2] and B.G. McConkey[2]

[1]Agriculture and Agri-Food Canada, ECORC, Central Experimental Farm,
Ottawa, ON, K1A 0C6
[2]Agriculture and Agri-Food Canada, SPARC, P.O. Box 1030, Swift Current, Sask., S9H 3X2
[3]Departamento de Solos, Universidade Federal do Paraná, Brazil (on leave)

1. Introduction

Disregarding erosion, the amount of soil organic C in a given ecosystem is the net result of two processes: the input of carbon (C) through photosynthesis (primary production), and the loss of C via decomposition (respiration) (Janzen et al., 1997). Any factor which favours greater C input relative to decomposition will increase organic matter while stimulation of decomposition relative to C input will result in a net loss of organic matter.

The prairies account for about 80% of the arable agricultural land in Canada and it contains large reserves of C in soil. This makes the prairies a dominant player in C considerations. However, the size of this C pool may change in response to management practices (Janzen et al. 1997; 1998). Such changes are a concern because of their potential to influence soil productivity, and because they may influence the concentration of CO_2 in the atmosphere thereby affecting global warming through the "greenhouse effect". But soil organic matter can also act as a sink for C; therefore it can be an asset in mitigating the CO_2 component of the greenhouse gas effect (Bruce et al., 1998).

The concept of giving "C credits" for C sequestered in agricultural soils (C trading) was discussed in Kyoto in 1998, at the International Conference to debate global warming, but the latter concept was not yet approved. Nor is this concept likely to be approved unless scientists can provide credible evidence indicating that soil C sequestration can result in significant gains in C, and that such gains can be reasonably and accurately quantified.

The objectives of this paper were to quantify the trends in soil C that have been measured in a long-term crop rotation experiment conducted in southwestern Saskatchewan, and to discuss some of the challenges we face regarding quantifying C sequestration in prairie soils.

2. Quantifying C Changes in Soil

If we are to gain international acceptance that C can be sequestered in agricultural soils scientists need to develop "an agreed upon methodology for measuring changes in C stocks"

(Bruce et al., 1998). Although changes in soil C can be measured directly, these changes are small compared to the size of stocks in the soil, changes occur slowly and, often, spatial variability of soil C is large. A direct measurement approach therefore becomes complex and may be impractical for this purpose (Bruce et al., 1998). Simulation modeling of soil C changes in agricultural soils is well developed for assessing long-term changes (i.e., >50-100 yr changes) (Paustion et al., 1997; Smith et al., 1998), but, quantifying short-term changes (<5-20 yr), which is necessary to determine the value of C sequestered for C trading purposes, is presently much less feasible.

2.1 **The CENTURY model**

Of several simulation models developed to describe C dynamics in soil (Smith et al., 1998), CENTURY, developed in Colorado by Parton et al. (1987), is the most widely used by North American scientists. However, it was developed to assess C changes over the long-term (>30 yr) and it is more reliable when used in this manner (Smith et al., 1998).

One of the main deficiencies of CENTURY with respect to its use for simulating short-term dynamics of soil C may be related to its inability to accurately estimate grain (and thus residue) yields (Kelly et al., 1997). This may be particularly true for crops grown in semiarid prairie climates. When we attempted to estimate grain yields of wheat grown on fallow (F-W) and continuous wheat (Cont W), for a 30-yr crop rotation experiment conducted at Swift Current, Saskatchewan, Canada, the results though very good for F-W, were poor for stubble-crop wheat (Fig. 1). Since residue input is directly related to grain yields (Campbell et al., 1997) and since soil C is directly related to residue input (Rasmussen et al., 1980; Campbell et al., 1997; Huggins et al., 1998), then any model failing to estimate yields accurately is likely to be deficient in simulating soil C dynamics over the short term. Thus, it was not surprising that CENTURY did not accurately estimate soil C (Fig. 1).

Two obvious discrepancies are the failure of CENTURY to reflect the impact of 7 yr. (1989-1996) of above-average residue inputs for F-W (Fig. 1a), and that the soil C estimates were either showing a downward trend (Figs. 1a & 1b), or constancy (Fig. 1c) even though measured soil C was either constant or increasing over time. This may be an indication that CENTURY requires some modifications regarding the relative weighting currently given to the influence of crop residue inputs on soil C changes. The trajectory of trend lines in the CENTURY soil C estimates may also be related to the high initial values estimated by the model (4 Mg ha^{-1} higher than our estimate for 1967). Perhaps if the model was re-initialized so that the estimated starting C values were similar to the measured values, then the trajectory of the estimated and measured trends in C may be closer.

Despite the apparent shortcomings of CENTURY, we believe the soil C dynamics parameters of this model are generally sound. Consequently, once the production (C inputs) aspects are satisfactorily addressed, this model should provide a reasonably accurate simulation of even short-term, site-specific conditions.

2.2 EPIC model

We used EPIC model version 5300 (Williams, 1995) with the Baier-Robertson potential evapotranspiration approach to estimate available water, yield and C dynamics in selected rotations at Swift Current. Roloff et al. (1998*a,b*) provide a detailed discussion on how this model was used. In general, EPIC provided reasonable accuracy and precision in estimating yield trends in Cont W and F-W over the 30-yr period of study (Fig. 2a). Although these yield simulations were superior to those obtained for stubble-wheat with the CENTURY model, there is still room for improvement in estimating annual yield variability (Roloff, 1998*b*). Like CENTURY, EPIC was not effective in estimating trends in SOC (Fig. 2b). The model suggested C would decrease steadily with time in both F-W and Cont W rotations, this despite correctly simulating the above-average yield trends from 1989 to 1996 which likely caused the upturn in measured SOC (Fig. 2b). This suggests that EPIC also does not give sufficient weighting to the impact of crop residue inputs on build-up of SOC. As well, in EPIC, SOC may also be decomposing too rapidly. In any event, we believe that the C dynamics aspects of EPIC need further improvements, such as explicitly accounting for the various C pools and crop-specific residue decomposition rates. (Results of simulation with EPIC of soil and C loss by erosion are discussed later).

2.3 Other Models

While scientists are working to modify and improve models such as CENTURY and EPIC so that they may perform more effectively in simulating short- and long-term situations, what can we do? We propose, that a workable approximation may be to use a simpler method of estimating soil C dynamics by treating recent residue additions and pre-existing soil C separately, similar to the method proposed 50 years ago by Woodruff (1949). The proposed equation is:

.... (1)

where SOC_t is the total amount of soil organic C per unit mass of soil remaining in soil after t years (time measured to just before residue addition in the current year, example residue added in yr 10 is not included at t=10 yr), C is the amount of C in the soil on a mass basis initially (t=0), k is the annual rate of soil carbon decomposition, A_n is the C addition as plant residue in year n, p is a proportion of residue C (note $p_1+p_2=1$), and r is the annual rate of residue decomposition. The subscripts 1 and 2 refer to differing degrees of susceptibility to decomposition with 1 representing the more active and 2 representing the slower decomposing pool of the plant residue and the soil humus. Although in theory, the output from A would feed into C in equation 1, we overlooked this factor to keep calculations simple. We solved the A portion and C portions of equation 1 separately then added the results (Campbell et al., 1999).

The advantage of using equation 1 is that values for A (related to residue inputs) are usually available, or can be readily estimated from grain yields, harvest index and straw/root ratios. These yield data integrate climatic conditions, thus helping to make this approach robust.

Equations based on a 10-yr ^{14}C-labelled ryegrass residue decomposition experiment conducted in Britain (Jenkinson, 1977), and a similar experiment conducted with wheat straw in Saskatchewan, Canada by Voroney et al. (1989) suggest that cereal and grass residues decompose at similar rates in temperate climates. Thus, for hard red spring wheat (Triticum aestivum L.)straw decomposing in a fallow-wheat-wheat (F-W-W) rotation in southwestern Saskatchewan, Voroney et al. (1989) obtained the following 2-component first order decomposition equation in an Orthic Brown Sceptre clay soil:

$$y = 0.72e^{-1.4t} + 0.28e^{-0.081t} \quad \text{......} \quad (2)$$

where y is proportion of residue C remaining in the soil after t years since residue addition. In a Grey Luvisol, Waitville loam soil in northeastern Saskatchewan, they found the rate of decomposition was slightly faster than for the clay. Equation 2 is similar to one obtained by Jenkinson (1977) at Rothamsted. He reported:

$$y = 0.71e^{-2.83t} + 0.29e^{-0.087t} \quad \text{......} \quad (3)$$

These results suggest that we may be able to represent the two pool proportions for residue additions (p_1 and p_2) of equation 1 with those from equation 2. Further, this suggests that the latter may also provide good representation of plant residue decomposition for large areas of arable land growing cereals and grasses throughout temperate climates. The parameters for the active and slow decomposing pools of soil carbon (C_1 and C_2, respectively in equation 1) can be estimated from information in the scientific literature, as can values of k_2 (Table 1). Thus, we might estimate the rate constant for the slow decomposing fraction of soil humus from the mrt of the humic fractions (about 0.00066 yr^{-1} for chernozemic soils). We could also assume that the active fraction (C_1) is represented by the light fraction and microbial biomass C which, though variable through the year, averages about 20% in Swift Current soil (Campbell et al., 1999). Thus C_2 would be 80% of soil C in this soil. We could then estimate k_1 by solving equation 1 iteratively to match the measured C for F-W system. However, because in equation 1, the value of k must embody differences not only in inherent susceptibility to decomposition of soil carbon fractions, but also differences in the effect of soil moisture, temperature, etc., on rate of decomposition, estimates of k are empirical in nature. This is a disadvantage compared to process-based models where k and r are functions of moisture and temperature. Our rate constants are therefore only pseudo rate constants. We reasoned that k_1 for F-W-W must be less than for F-W (less frequent fallow and fallow favours decomposition). Similarly, k_1 for F-W-W will be greater than for Cont W.

2.4 **Testing the Woodruff-type Equation**

We tested equation 1 using data from a long-term crop rotation experiment that is being conducted at SPARC at Swift Current, Saskatchewan. The 30-yr study was initiated in 1967 on land that had been cropped to F-W since 1922 with primarily P fertilization (Campbell et al., 1983; 1992; Campbell and Zentner, 1993). Thus, this soil would have been somewhat degraded at start of the experiment. This study was conducted with stubble-mulch shallow tillage after the 1940's. There are 9 treatments and we discuss eight.

2.4.1 **Swift Current Rotations**

The rotation treatments and their fertilizer regimes are described in Table 2. We collected grain yields from all seeded plots and straw yields from specified plots (Table 2) annually, and we measured soil C and N (only C discussed) in all rotation phases periodically (viz., 1976, 1981, 1984, 1990, 1993 and 1996). We did not measure soil C at the initiation of the study in 1967, but estimated it to be about 30.5 Mg C ha^{-1} in the 0-15 cm depth (Campbell et al., 1999). The latter was the value for F-W in 1976 and we reasoned this system was at steady state because it was cropped to F-W for over 50 yr prior to our experiment. We only discuss C in the 0-15 cm depth because at no time was there a significant change of C in 15-30 cm depth (Campbell et al., 1999). Bulk density was only measured at start of the study. It was assumed to be constant throughout the years, being 1.22 Mg m^{-3} for the 0-15 cm depth.

The values used in equation 1 were derived as follows: Where straw was not measured, we estimated straw values from grain-to-straw equations that we developed over the life of the study (Campbell et al., 1999). We converted straw yields to total residue C inputs by assuming root-to-straw ratio = 0.59 (Campbell et al., 1977) and C content of residues = 45% (Millar et al., 1936). We used the constants derived by Voroney et al. (1989) for the Sceptre clay to calculate the dynamics of residue C decomposition because the location of this experiment was only 60 km from Swift Current, while the Waitville experiment, though similar in texture to the Swift Current study, was located several hundred km from Swift Current. Thus, the A_1, A_2, r_1, r_2 values are those for equation 2 and they were used to estimate residue C dynamics for all rotation phases separately then values were averaged over rotation phases (Campbell et al. 1999).

As stated earlier, C_1 and C_2 for this soil were taken as 20% and 80% of the C, respectively and k_2 assumed to be 0.00066 yr^{-1}. These values were used for all treatments. Because we observed a close similarity between soil C trends over the years for the degrading treatments (F-W and three F-W-W systems) (Campbell et al. 1999), we averaged soil C measurements over these four treatments (Fig. 3). Similarly, we averaged values for three aggrading systems [Cont W (P), W-Lent (N+P) and F-Rye-W (N+P)] (Fig. 3). We then used iterative calculations with equation 1 and these two curves to estimate approximate values for k_1 (the only remaining unknown) in degrading and aggrading systems. This process suggested the k_1 value for F-W would be about 0.02 yr^{-1}. We then assumed the value for F-W-W would be 0.01 yr^{-1} and for aggrading systems 0.001 yr^{-1}.

Most of the eroded C has not been lost by decomposition; this C is merely relocated in the landscape. Thus, we used EPIC to estimate C lost by erosion over the 30-yr period (Table 3) and added these values to the measured C values before comparing these sums to the estimated soil C values derived with equation 1 (Fig. 4).

Equation 1 estimated the trends in SOC consistently well, though it tended to underestimate the measured + erosion values for W-Lent(N+P). This may be an indication that the narrower C/N ratio crop residues in the latter system (Campbell et al., 1992) supports a more efficient conversion of residue C to SOC than does wider C/N ratio material such as for monoculture wheat. Unlike results for CENTURY and EPIC, the trends in SOC estimated by equation 1 showed a flat response in the 1980's when droughts in 1984, 1985 and 1988 resulted in very low yields, and then a consistent trend to higher SOC values in the wet 1990's. In a few instances the measured data appeared to be unreasonably high or low (see ? on Fig. 4). We suspect that the (?) points reflect texture differences at this site as reported by O'Halloran (1986). Campbell et al. (1996) have shown a direct relationship between C gains in response to adoption of no-tillage management and clay content of soil in a study conducted in southwestern Saskatchewan. As stated earlier, soil texture varies from loam to silty clay loam at this site.

Note that if we estimate C gains using equation 2, and assume that no soil C decomposition occurred, then the estimates fit the measured data for F-Rye-W (N+P) and W-Lent (N+P) almost exactly (Fig. 5). This implies that soil humus decomposition is very low in these two systems or, conversely that some of our assumptions for lentil and for fall rye using spring wheat based model (equation 2) are not appropriate.

Generally the measured soil C was of two patterns (Fig. 3). In the degrading (fallow-spring seeded crop) systems, SOC was generally constant until 1990, then increased sharply in response to a 7-yr period of above-average yields (residue input). For the aggrading systems there was an early gradual increase, due to change from over 60 yr of F-W (poor fertility) to continuous cropping (with good fertility); then values levelled off in the droughty 1980's, then increased sharply due to high yields in the 1990's. These results strongly suggest that crop residue inputs play a very significant role in influencing short-term soil C dynamics, perhaps an even more significant role than soil decomposition mechanisms. These results further underscore the need for the more process-related models, such as CENTURY and EPIC, to improve their estimates of crop production and to re-examine the parameter values they use in weighting the relative contribution of crop residue inputs to soil C changes as compared to the contribution of soil processes such as mineralization, immobilization and denitrification. The W-Lent and F-Rye-W systems suggest that the mineralization may not be great in the frigid semiarid prairie conditions of western Canada.

We calculated the change in SOC between the start of the experiment and the last date sampled, for the various rotations, and compared values derived by measurements and those estimated by equation 1 (Table 4). We also calculated a mean annual rate of increase in SOC over the life of each experiment. The measured and estimated SOC changes and rates of change were generally similar and generally confirmed our expectations regarding the influence of management on SOC changes. Based on our estimates, SOC changes range between 0.06 Mg ha^{-1} yr^{-1} in F-W to 0.22 Mg ha^{-1} yr^{-1} in well-fertilized continuously cropped systems (Table 4).

3. **Challenges Remaining to Quantifying Soil C on Prairies**

If we are to estimate soil C changes effectively over time and space on a regional or larger basis, we will need to use models that are less empirical than Woodruff-type models; models that are more process oriented, like CENTURY. However, our results suggest that CENTURY has a shortcoming with respect to its ability to estimate C inputs in stubble crops, at least it does for Canadian prairie conditions. Although EPIC model may do a better job of estimating residue C inputs, its submodel for estimating soil C appears to be weak. Both models were unable to simulate the increases and decreases in soil C due to periods of above- or below-average production, even when they were able to estimate yields effectively. This suggests that they may not be giving sufficient weighting to the contribution of input crop residues to soil C changes (as compared to the weighting being given to soil C decomposition processes). Certainly, the Woodruff-type equation was much more effective in simulating these weather (yield)- related trends, probably because accurate estimates of C inputs were used in the model. Perhaps the process-based models have over-emphasized the impact of soil processes such as mineralization, immobilization, and denitrification and have not given enough weighting to residue C inputs. These concerns need to be addressed by modelers designing and developing such models.

The Woodruff-type equation performed well when it was provided with adequate data to characterize a site. However, it suffers from shortcomings related to our limitations in modifying the rate of soil and residue C decomposition as a function of weather factors. Secondly, unless we know the k-values in particular, for a specific soil, it is difficult to decide what this value should be. The assumed value of k_2 seems reasonable enough (0.00066 yr^{-1} for chernozems). The rate constants for the active fraction (k_1) may vary with soil texture, inherent fertility of the soil, tillage and weather factors, and we have no method of predicting to what extent these rate parameters should be modified to satisfy these variables. Nonetheless, we can certainly use data from the scientific literature and intuitive reasoning to estimate appropriate coefficients for use in this equation. Then, using known values or estimates of residue C inputs we could at least make a credible estimate of relative changes in soil C. This would then guide us in deciding whether measured values, with their propensity for large variability, are reasonable. This is important because we often use the measured values to calibrate process-based models and, if the calibration is faulty, later extrapolations made with these models will be even more faulty.

Finally, we suggest that the Woodruff-type of calculation can be used to estimate effects of agronomic treatments on soil C changes over short-term (<20 yr). This can be a useful tool in providing an initial estimate of the influence of agronomic practices on soil C sequestration.

4. Conclusions

If the concept of "C credits trading" is to gain credibility as part of the solution in mitigating the "greenhouse gas" phenomenon for which CO_2 is partly responsible, scientists must be able to provide reasonable evidence that soil C changes in the short term (<20 yr) can be measured accurately.

Although process-based models, such as CENTURY and EPIC, are required for accurate estimation and extrapolation of soil C changes, the versions of both models that we tested appear to have serious limitations when used for modelling short-term C changes. CENTURY appeared to be weak in estimating residue C inputs of stubble-seeded crops in the semiarid prairie, and both models do not appear to give sufficient quantitative emphasis to the contribution of residue C inputs to soil C changes; instead they seem to overestimate C losses by decomposition and oxidation processes.

We suggest the use of simpler models, similar to that developed by Woodruff (1949), which describes SOC changes as a function of two, 2-component systems: (a) a residue decomposition component, and (b) a soil decomposition component. This type of model could be used together with measured or estimated (from grain yields) residue C inputs and appropriate constants for residue decomposition to estimate C changes due to residue inputs. Soil C decomposition from C-dating results and proportion of C in light fraction and microbial biomass were also used in the model, to simulate C changes in soil humus. This method has some limitations, but could be used to show the direction of C change in soil over time, and to calculate a first estimate of the magnitude of C change. Improved versions of the process-based models are however required to make accurate regional or National extrapolations of C changes in agricultural soils in the short term.

References

Bruce, J.P., M. Frome, E. Haites, H. Janzen, R. Lal, and K. Paustian. 1998. Carbon Sequestration in Soils. Proc. Soil and Water Conservation Society's Carbon Sequestration in Soils Workshop, Calgary, AB. May 21-22, 1998.

Campbell, C.A. 1965. The use of naturally occurring ^{14}C to measure the persistence of organic components in soil. Ph.D. Thesis Dept. Soil Science, Univ. of Saskatchewan, Saskatoon, Sask.

Campbell, C.A., D.R. Cameron, W. Nicholaichuk, and H.R. Davidson. 1977. Effects of fertilizer N and soil moisture on growth, N content and moisture use by spring wheat. Can. J. Soil Sci. 57: 289-310.

Campbell, C.A., H. Janzen, and N.G. Juma. 1997. Case studies of soil quality in the Canadian Prairies: Long-term field experiments. pp. 351-397. *In* E.G. Gregorich and M.R. Carter (eds.) Soil Quality for Crop Production. Elsevier Science Publishers, Amsterdam, The Netherlands.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F. Selles, and D. Curtin. 1996. Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Can. J. Soil Sci. 76: 395-401.

Campbell, C.A., D.W.L. Read, R.P. Zentner, A.J. Leyshon, and W.S. Ferguson. 1983. The first 12 years of a long-term crop rotation study in southwestern Saskatchewan -- yields and quality of grain Can. J. Plant Sci. 63: 91-108.

Campbell, C.A. and, R.P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci. Soc. Am. J. 57: 1034-1040.

Campbell, C.A., R.P. Zentner, E. Gregorich, G. Roloff, B.C. Liang, and B. Blomert. 1999. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan - Effect of crop rotations and fertilizers (Can. J. Soil Sci. In preparation).

Campbell, C.A., R.P. Zentner, F. Selles, V.O. Biederbeck, and A.J. Leyshon. 1992. Comparative effects of grain lentil-wheat and monoculture wheat on crop production, N economy and N fertility in a brown Chernozem. Can. J Plant Sci. 72: 1091-1107.

Huggins, D.R., G.A. Buyanovsky, G.H. Wagner, J.R. Brown, R.G. Darmody, T.R. Peck, G.W. Lesoing, M.B. Vanotti, and L.G. Bundy. 1998. Soil organic C in the tallgrass prairie-derived region of the corn belt: effects of long-term crop management. Soil and Tillage Res. 47: 219-234.

Janzen, H.H., C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1997. Soil carbon dynamics in Canadian agroecosystems. pp. 57-80 *in* R. Lal, J. Kimble R. Follett, and B.A. Stewart, (eds.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage in the Canadian prairies. Soil and Tillage Res. 47: 181-195.

Jenkinson, D.S. 1977. Studies on the decomposition of plant material in soil. V. The effects of plant cover and soil type on the loss of carbon from ^{14}C labelled ryegrass decomposing under field conditions. J. Soil Sci. 28: 424-434.

Kelly, R.H., W.J. Parton, G.J. Crocker, P.R. Grace, J. Klir, M. Körschens, P.R. Poulton, and D.D. Richter. 1997. Simulating trends in soil organic carbon in long-term experiments using the century model. Geoderma 81: 75-90.

Martel, Y. 1972. The use of radiocarbon dating for investigating the dynamics of soil organic matter. Ph.D. Thesis. Dept. Soil Science, University of Saskatchewan, Saskatoon, Sask.

Millar, H.C., F.B. Smith, and P.E. Brown. 1936. The rate of decomposition of various plant materials in soils. Am. Soc. Agron. J. 28: 914-923.

O'Halloran, I.P. 1986. Phosphorus transformations in soils as affected by management. Ph.D. Thesis. Dept. Soil Science, Univ. of Saskatchewan, Saskatoon, Sask.

Parton, W.J., D.S. Schimel, C.V. Cole, D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51: 1173-1179.

Ramussen, P.E., R.R. Allmaras, C.R. Rohde, and N.C. Roager, Jr. 1980. Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. Soil Sci. Soc. Am. J. 44: 596-600.

Roloff, G., R. de Jong, C.A. Campbell, and V.W. Benson. 1998a. EPIC estimates of soil water, nitrogen and carbon under semi-arid temperate conditions. Can. J. Soil Sci. 78: 539-550.

Roloff, G., R. de Jong, R.P. Zentner, C.A. Campbell, and V.W. Benson. 1998. Estimating spring wheat yield variability with EPIC. Can. J. Soil Sci. 78: 541-549.

Smith, P., D.S. Powlson, J.U. Smith, and E.T. Elliott. 1998. Evaluation and comparison of soil organic matter models using data sets from seven long-term experiments. Special Issue Geoderma, 81: 1-225.

Voroney, R.P., E.A. Paul, and D.W. Anderson. 1989. Decomposition of wheat straw and stabilization of microbial products. Can. J. Soil Sci. 69: 63-77.

Williams, J.R. 1995. The EPIC model. Pages 909-1000 *in* V.P. Singh, (ed.) Computer models of watershed hydrology. Chapter 25. Water Resources Publications, Littleton, CO.

Woodruff, C.M. 1949. Estimating the nitrogen delivery of soil from the organic matter determination as reflected by Sanborn field. Soil Sci. Soc. Proc. 14: 208-212.

Table. 1. Some typical soil fractions and their decomposition rate-constants estimated from C-dating for Saskatchewan soils.

Soil	Soil zone	Humic fraction[†]	Proportion of Org C (%)	$^{1}/\text{mrt}$ (k) (yr^{-1})[‡]	Reference
Melfort sic	Black Chernozem	HA & Humin	71	0.00085	Campbell (1965)
		FA & acid extract	29	0.0021	
Oxbow cl	Black chernozem	Unhydrolyzed	50	0.00068	Martel (1972)
		Acid hydrolyzed	50	0.050	
Sceptre c	Brown chernozem	Unhydrolyzed	40	0.00063	Martel (1972)
		Acid hydrolyzed	60	0.0036	
Waitville l	Gray Luvisol	HA & Humin	83	0.004	Campbell (1965)
		FA	17	0.014	

[†] HA = humic acids and FA = fulvic acids

[‡] mrt = mean residence time

Table 2. Crop rotations and fertilizer applied to treatments at Swift Current, Saskatchewan

Rotation #	Rotation [z]	Fertilizer Criteria	Cropped Phase	Average N and P applied (kg ha^{-1} yr^{-1})					
				1967 - 76		1977-86		1987-96	
				N	P	N	P	N	P
11	F-(W)	N and P applied as required	Fallow	6.1	9.4	6.8	10.2	21.3	9.2
2	F-W-(W)	N and P applied as required	Fallow	7.4	9.4	6.4	10.2	22.3	9.2
			Stubble	19.5	9.4	32.1	10.2	43.6	9.2
1	(F)-W-(W)	P applied as required but no N applied except that in P fertilizer	Fallow	4.9	9.4	4.9	10.2	4.6	9.2
			Stubble	4.9	9.4	10.0	10.2	4.6	9.2
5	F-W-W	N applied as required no P applied	Fallow	3.4	0	2.0	0	21.0	0
			Stubble	10.1	0	22.6	0	31.4	0
4a	F-(Rye)-W[y]	N and P applied as required	Fallow	3.5	6.7	4.9	10.3	25.0	9.5
			Stubble	20.9	9.6	31.0	10.3	53.6	9.8
4b	CF-WW-WW	N and P applied as required	Fallow	-	-	4.9	10.0	11.0	6.6
			Stubble	-	-	4.9	10.0	34.1	7.5
3	F-Flx-(W)	N and P applied as required	Fallow	5.2	3.8	7.4	10.2	8.8	9.2
			Stubble	16.4	9.4	26.3	10.2	39.3	9.2
8	Cont (W)	N and P applied as required	Stubble	23.5	9.4	35.7	10.2	42.8	9.2
9	Cont (W)[x]	(fallow if less than 60 cm moist soil exists at seeding time: N and P applied as required)	Stubble	22.0	9.4	55.5	10.8	-	-
10	Cont (W)[x]	(fallow if grassy weeds become a problem: N and P applied as required)	Stubble	24.6	9.4	52.7	10.8	-	-
19	(W)-Lent	N and P applied as required	Lentil	-	-	26.0	10.1	10.7	7.4
			Wheat	-	-	24.6	10.1	31.6	9.2
12	Cont (W)[w]	P applied as required but no N applied except that in P fertilizer	Stubble	4.9	9.4	15.0	10.2	4.6	9.2

[z] Selected plots, indicated in parentheses, were sampled for straw weight at harvest. F = fallow; CF = chemical fallow; W = spring wheat; WW = winter wheat; Rye = fall rye; Flx = flax; Lent = grain lentil; Cont = continuous.

[Y] After 1984, rotation 4a was changed to chemical fallow-winter wheat-winter wheat (spring wheat whenever winter wheat failed to survive the winter). But in 1993 it was changed again to CF-Rye-W.

[X] During the first 12 yr, the criteria necessary for summer fallowing in these two rotations were met on several occasions but the action was not implemented. In 1979, these two rotations were changed to the spring wheat-lentil rotation.

[W] In 1980 and 1982 N was inadvertently applied to this rotation at rates of 70 and 40 kg N ha^{-1}, respectively.

Table 3 Organic C lost by erosion[z] from selected rotations, estimated by EPIC model at Swift Current, Saskatchewan

		Period sampled					
Rotation	Erosion Losses	1967-76	1977-1981	1982-1984	1985-1990	1991-1993	1994-1996
F-W (N+P)[y]	Soil lost during period (Mg ha^{-1})	12.14	9.69	9.35	18.75	11.88	11.88
	C lost up to end of period (Mg ha^{-1})	0.20	0.38	0.53	0.83	1.03	1.25
F-W-W (N+P)[y]	Soil lost during period (Mg ha^{-1})	10.51	9.02	7.49	15.60	8.99	8.99
	C lost up to end of period (Mg ha^{-1})	0.18	0.33	0.45	0.73	0.89	1.06
F-Rye-W (N+P)[y]	Soil lost during period (Mg ha^{-1})	4.51	2.49	1.94	5.29	3.18	3.18
	C lost up to end of period (Mg ha^{-1})	0.09	0.13	0.17	0.27	0.33	0.40
Cont W (N+P)[y]	Soil lost during period (Mg ha^{-1})	2.82	1.28	1.68	4.30	2.55	2.55
	C lost up to end of period (Mg ha^{-1})	0.05	0.08	0.11	0.18	0.23	0.29

[z] This includes both wind and water erosion. Wind erosion was usually up to 10% higher than water erosion for fallow-containing systems except those with fall rye where water erosion was twice that of wind erosion. Continuous cropping systems had water erosion four times that of wind erosion.

[Y] The weighted mean annual soil loss was 2.3, 1.9, 0.6, and 0.5 Mg ha^{-1} yr^{-1} for F-W, F-W-W, F-Rye-W and Cont W, respectively.

Table 4. Measured and estimated [Z] SOC gained from start of experiment to last measurement (1967-1996)

tation	Measured	Measured plus Eroded C	Equation estimate	Mean annual SOC change based on Measured data	Mean annual change based on equation estimates
ift Current (1967-96)		MgC ha^{-1}		MgC ha^{-1} yr^{-1}	
W (N+P)	3.4	4.6	1.8	0.11	0.06
W-W (avg N+P, +P, +N)	2.8	3.9	3.1	0.09	0.10
Rye-W (N+P)	6.9	7.3	4.9	0.23	0.16
nt W (N+P)	9.5	9.7	6.5	0.32	0.22
nt W (+P)	3.6	3.9	4.1	0.12	0.14
Lent (N+P)	8.5	8.8	6.6	0.28	0.22

[z] Carbon change estimated by equation 1 and erosion estimated by EPIC model.

Figure Legends

Fig. 1. Measured and simulated (by CENTURY model) grain yields of hard red spring wheat and corresponding measured plus eroded (from Table 3) C and simulated SOC in 0-15 cm depth in (a) F-W and (b) Cont W receiving N and P, and (c) Cont W receiving P, from a 30-yr crop rotation experiment at Swift Current, Saskatchewan. In this and other figures, the SOC values represent the mean for all phases of the rotation in the years sampled and the bars are standard error of the mean (S_x). SOC value for 1967 was assumed to be the same as the 1976 value for F-W (N+P).

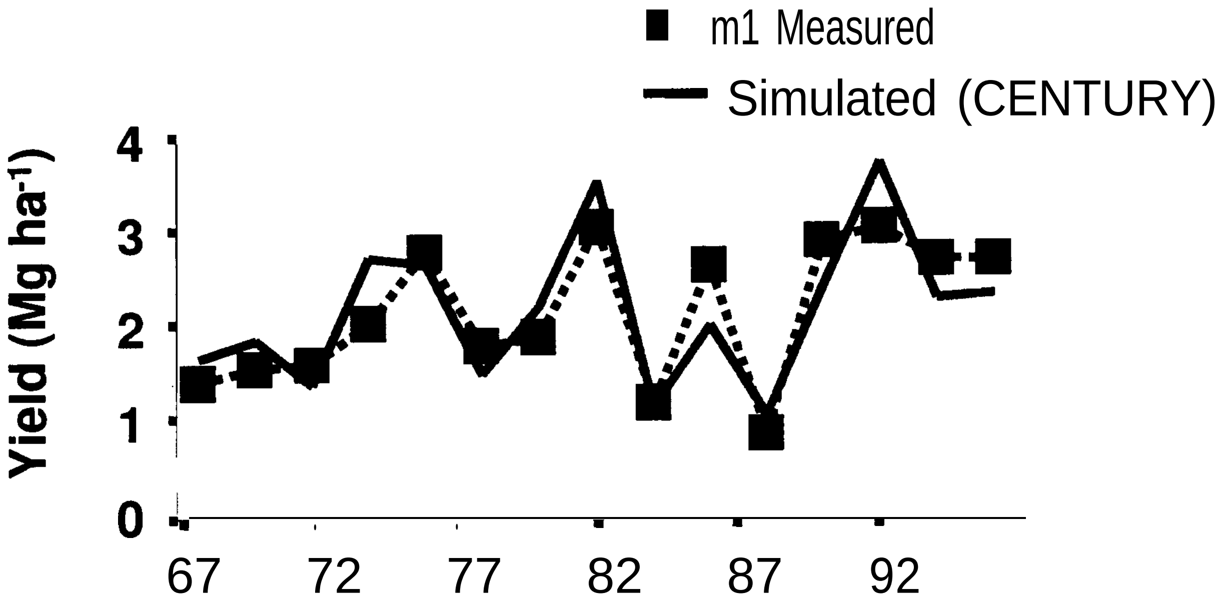
Fig. 2. (a) Measured and simulated (by EPIC model) grain yields for the same rotations assessed in Fig. 2a. (b) Corresponding measured plus eroded (from Table 3) C and simulated (EPIC) SOC for rotations assessed in Fig. 2b.

Fig. 3. Pattern of change in SOC for selected aggrading and degrading systems at Swift Current compared to the typical pattern of change in residue C inputs.

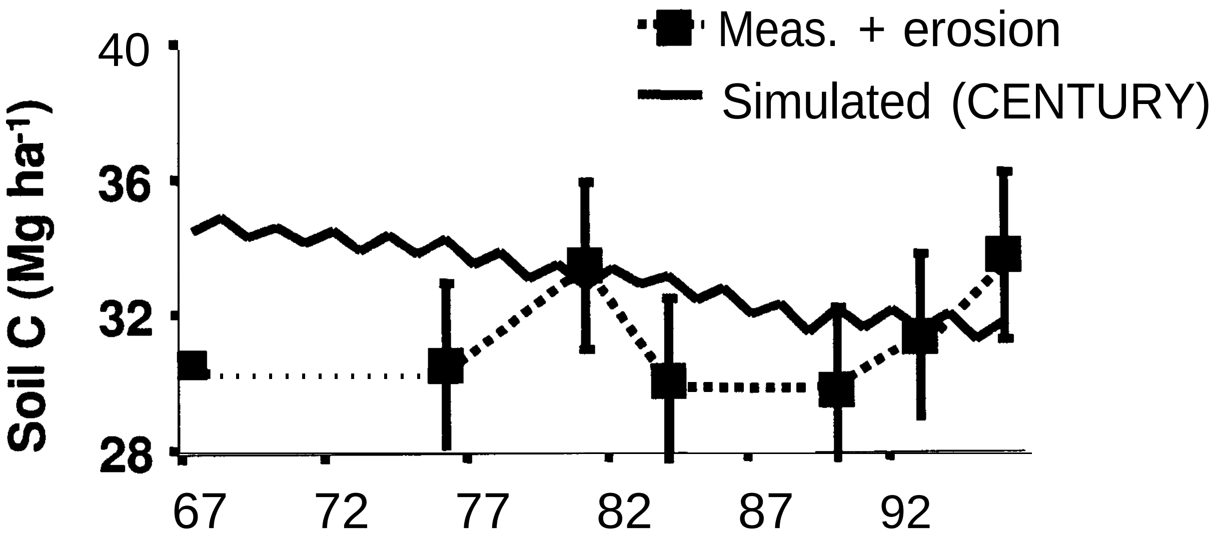
Fig. 4. Comparison of measured SOC and estimates made using a Woodruff-type equation for various rotations from the Swift Current 30-yr crop rotation experiment. In using the Woodruff-type equation we employed the Voroney et al. (1989) constants for straw decomposition in the Sceptre clay as the basis for the A components, and constants derived from C-dating (k_2) and proportion of soil C in light fraction plus biomass C for C_1 and remaining C as C_2. We estimated k_1 by iteration against measured data. S_ represents the standard error of the mean for the measured values. Eroded C, estimated by EPIC model (Table 3) were added to the measured C values before comparing to the simulated values. [(a) = F-W (N+P) and mean of F-W-W (N, P, and N+P); (b) = Cont W (P) and Cont W (N+P); (c) = F-Rye-W (N+P) and W-Lent (N+P)].

Fig. 5. Comparison of measured plus estimated eroded C versus estimates of C gains calculated from Voroney et al. (1989) residue C decomposition model (Equation 2) with no allowance made for C lost via soil decomposition, for the F-Rye-W (N+P) and W-Lent (N+P) rotations at Swift Current.

F-W (N+P)

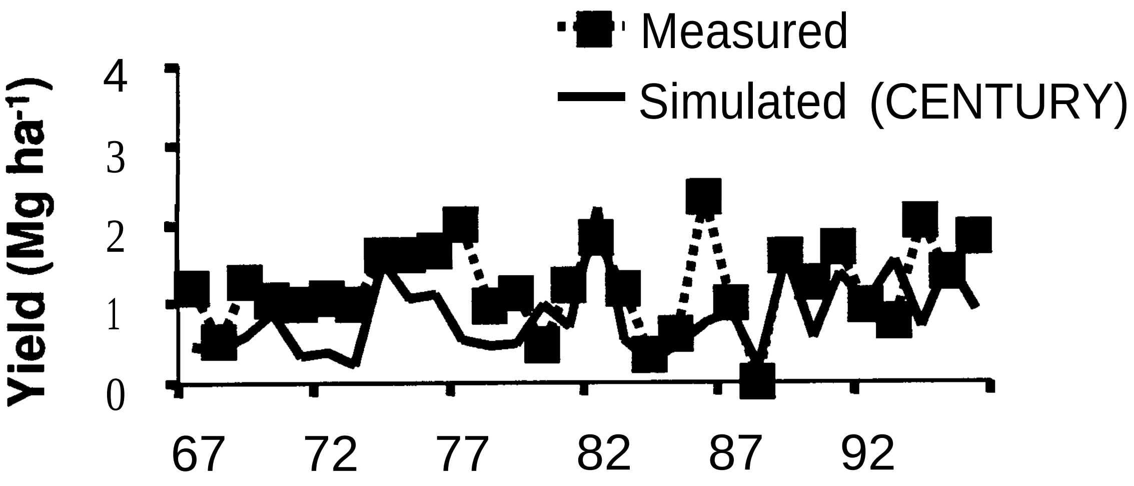


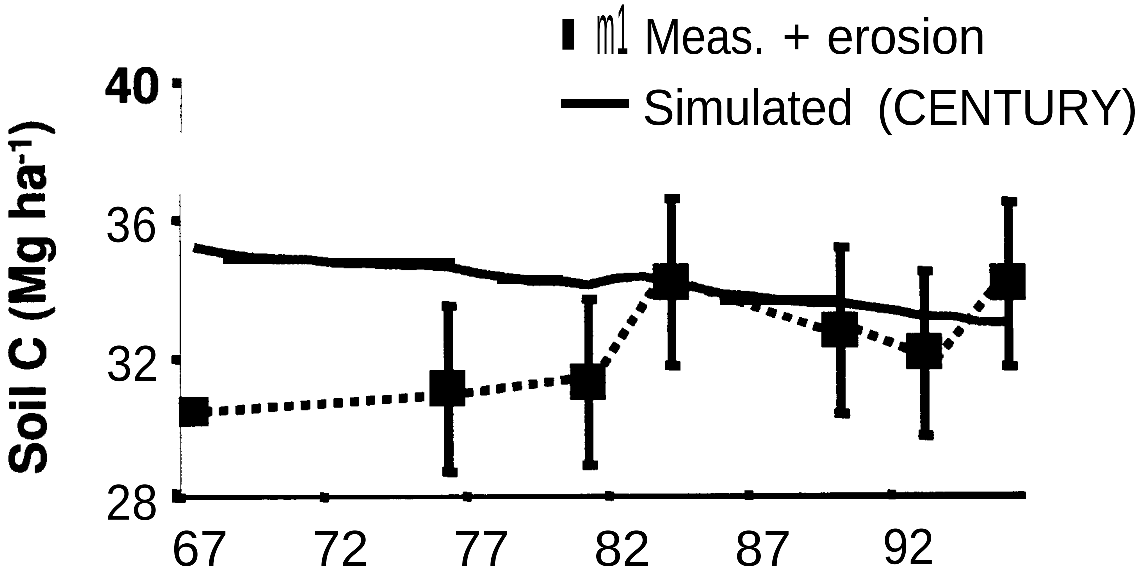
m1 Measured
Simulated (CENTURY)
Yield (Mg ha^{-1})
4
3
2
1
0
67
72
77
82
87
92



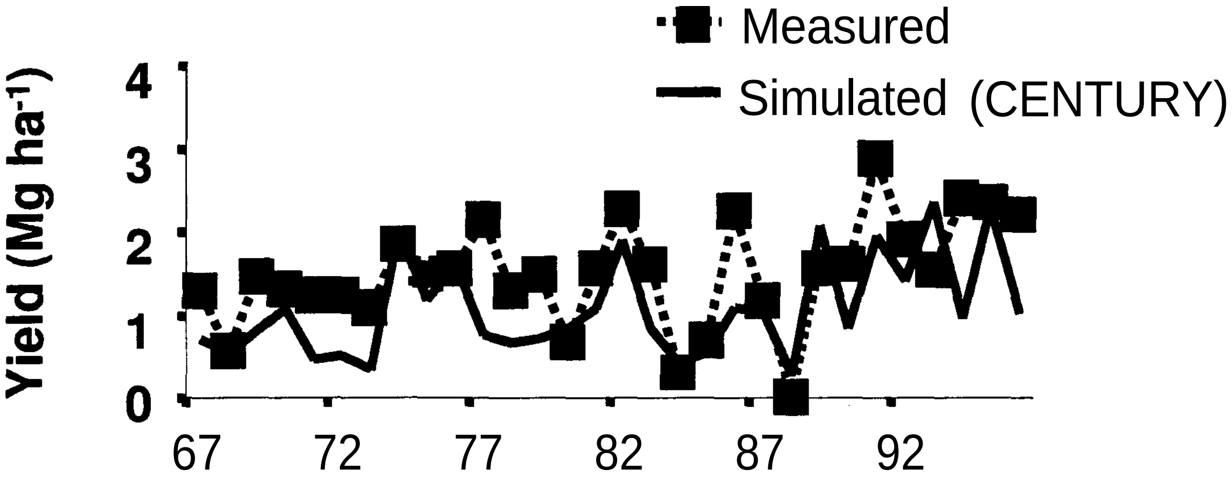
Meas. + erosion
Simulated (CENTURY)
Soil C (Mg ha^{-1})
40
36
32
28
67
72
77
82
87
92

Cont W (P)

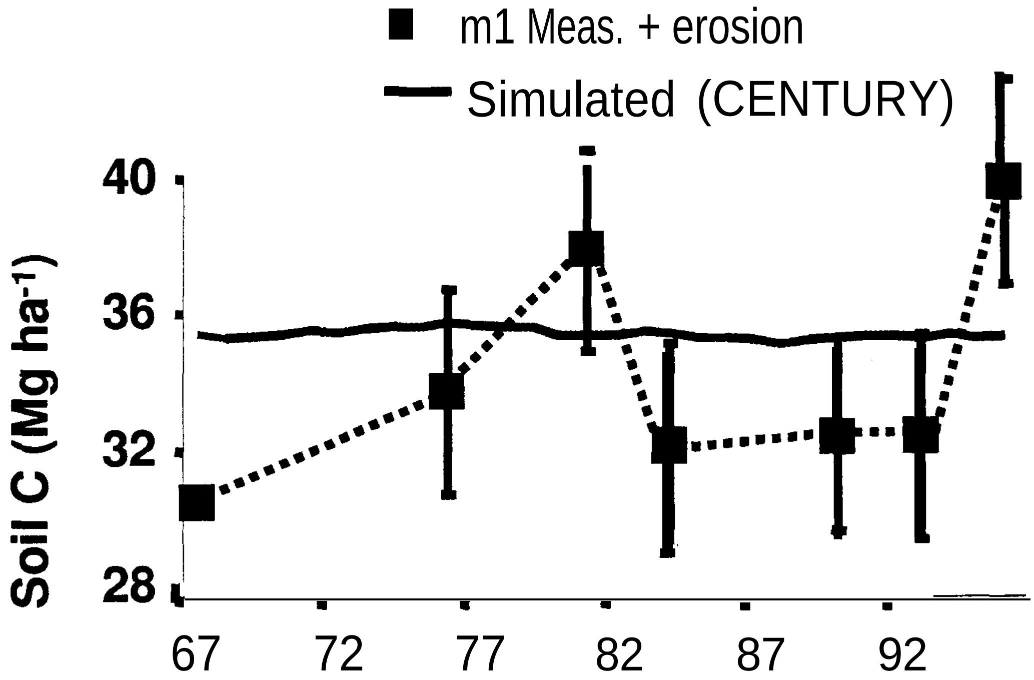

Measured
Simulated (CENTURY)
Yield (Mg ha^{-1})
4
3
2
1
0
67
72
77
82
87
92


Meas. + erosion
Simulated (CENTURY)
Soil C (Mg ha^{-1})
40
36
32
28
67
72
77
82
87
92

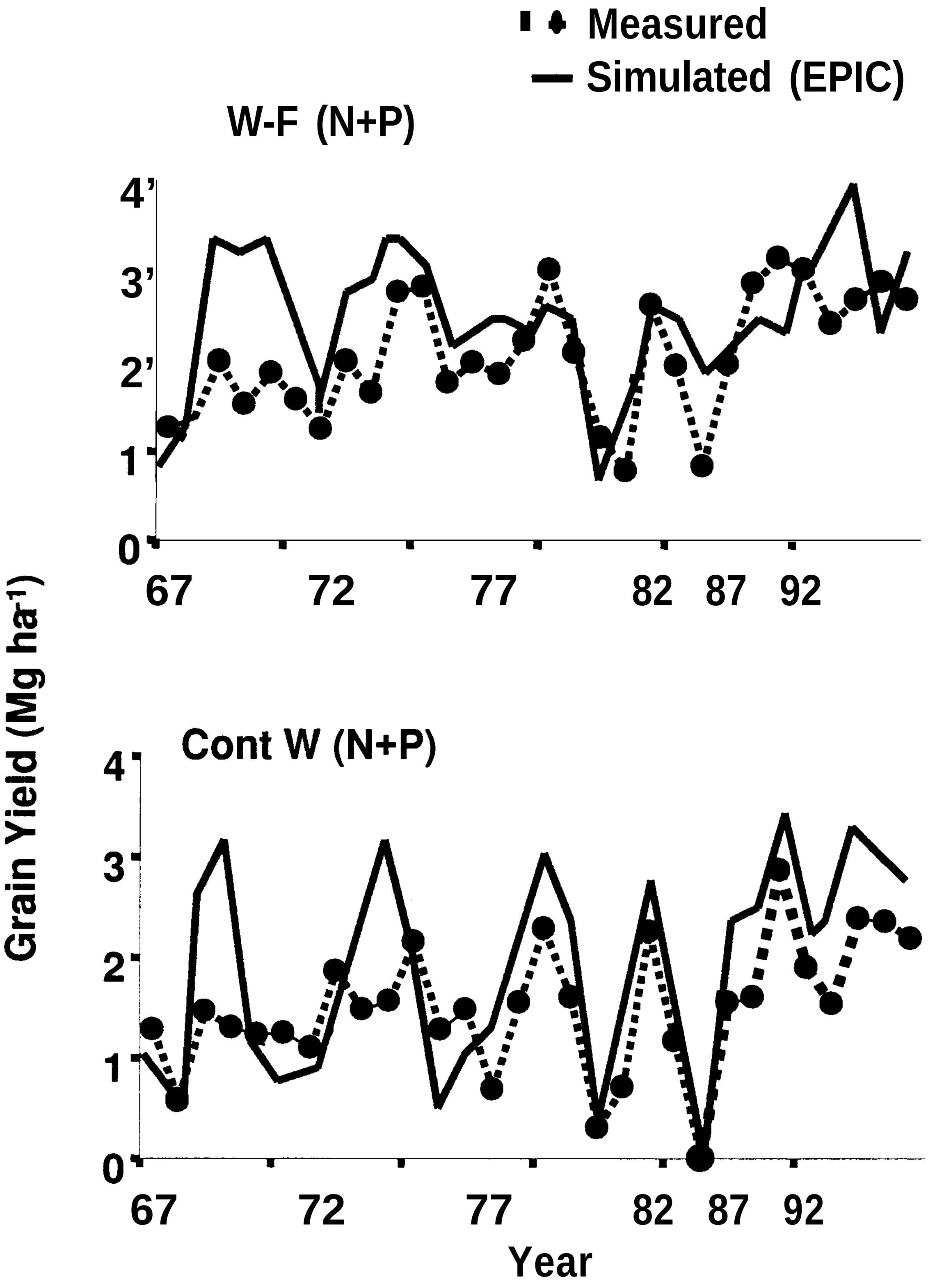
Cont W (N+P)

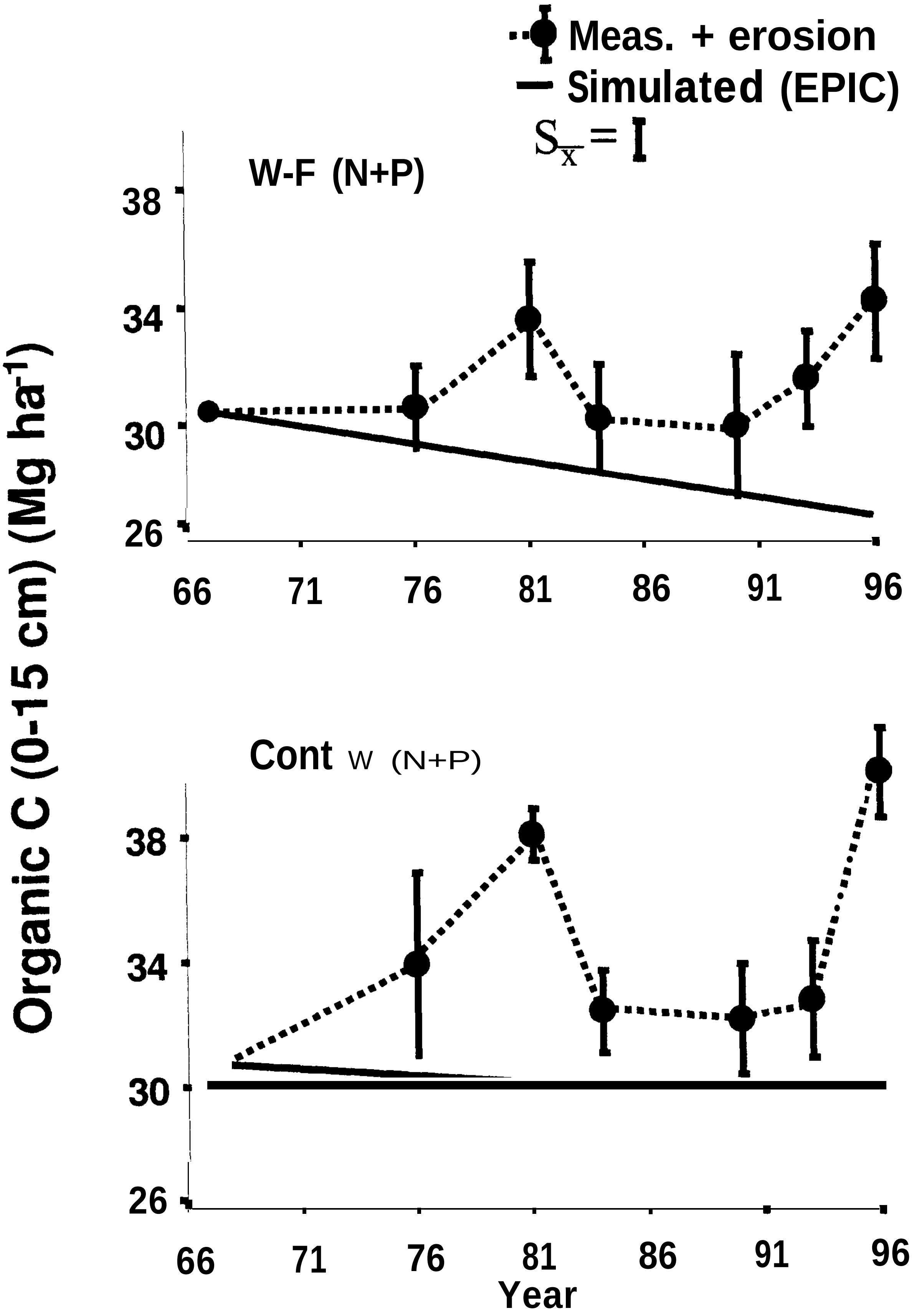


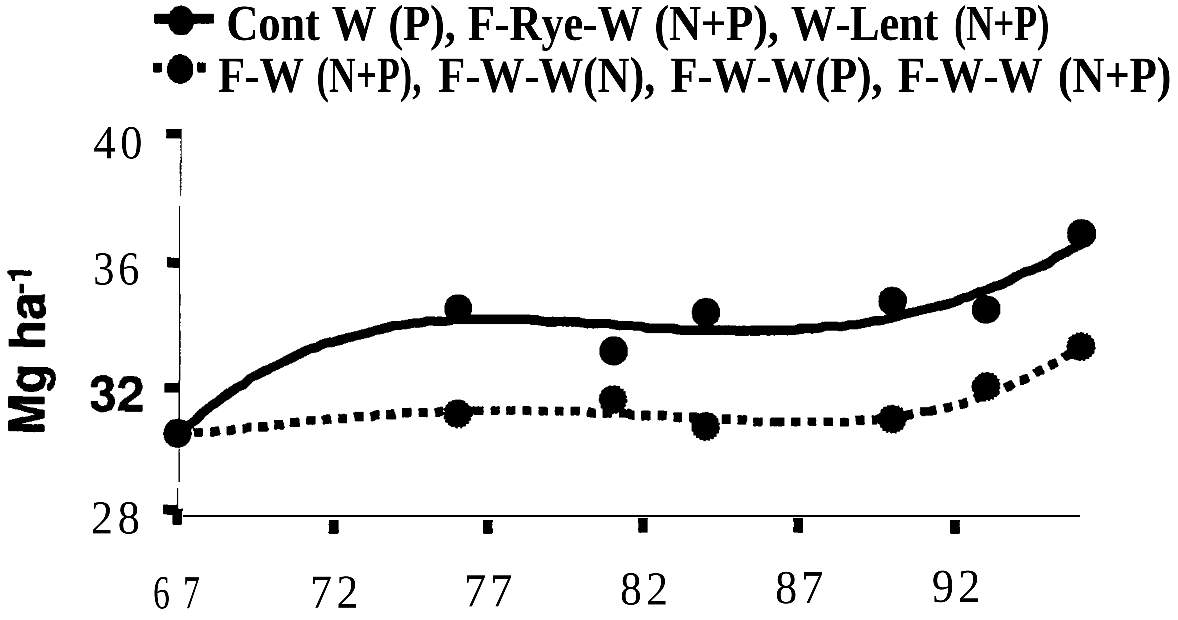
Measured
Simulated (CENTURY)
Yield (Mg ha^{-1})
4
3
2
1
0
67
72
77
82
87
92



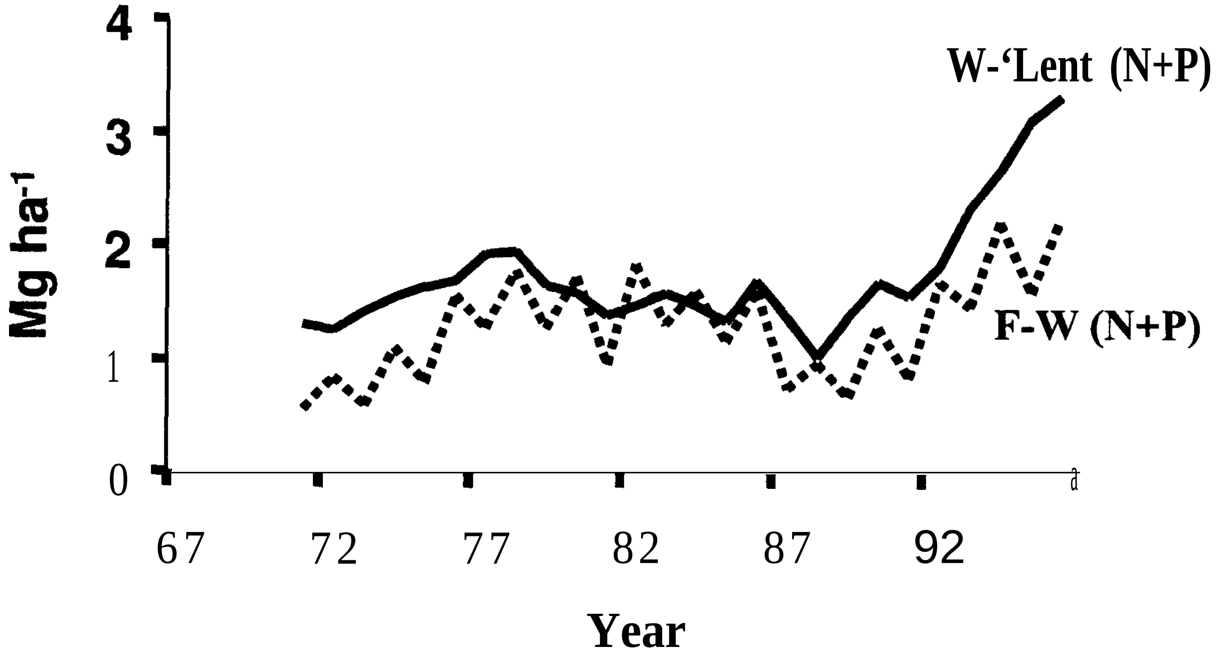
m1 Meas. + erosion
Simulated (CENTURY)
Soil C (Mg ha^{-1})
40
36
32
28
67
72
77
82
87
92


Measured
Simulated (EPIC)
W-F (N+P)
Cont W (N+P)
Grain Yield (Mg ha-1)
0
1
2
3
4
67
72
77
82
87
92
Year


Meas. + erosion
Simulated (EPIC)
$S_{\overline{x}}$ =
W-F (N+P)
Cont W (N+P)
Organic C (0-15 cm) (Mg ha^{-1})
38
34
30
26
66
71
76
81
86
91
96
Year



Mean Soil Org. C

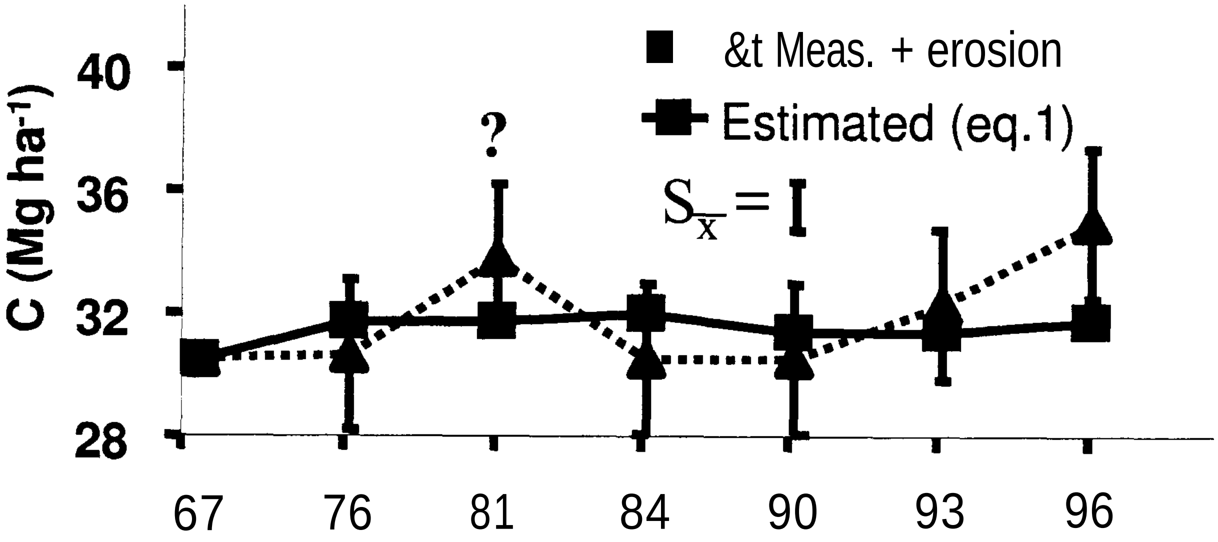


C Input (5-y running mean)

Swift Current

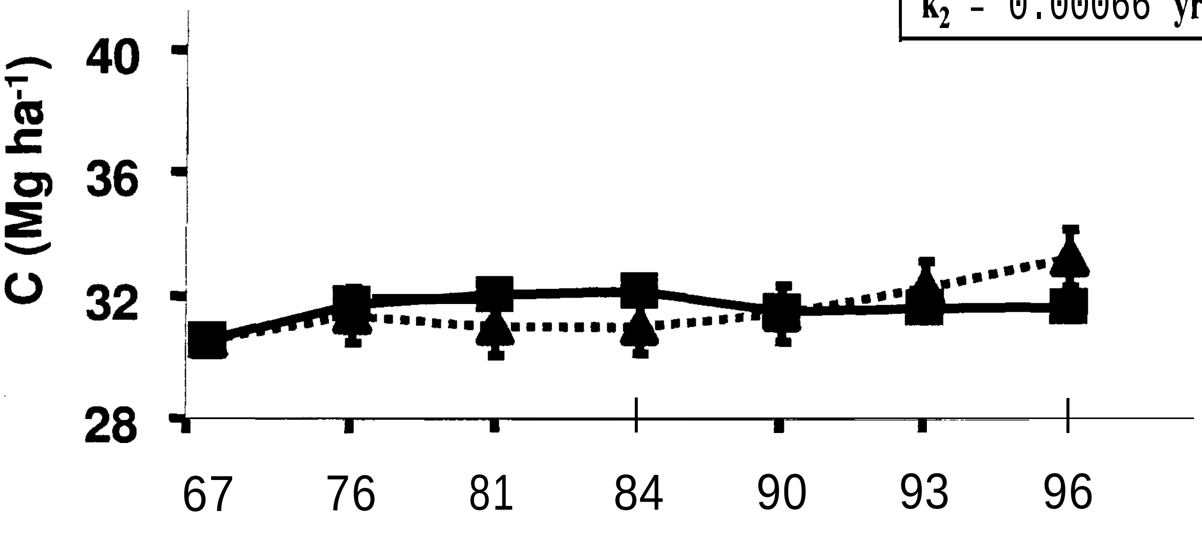
C_1 = 0.20
k_1 = 0.02 yr^{-1}
C_2 = 0.80
k_2 = 0.00066 yr^{-1}

F-W (N+P)



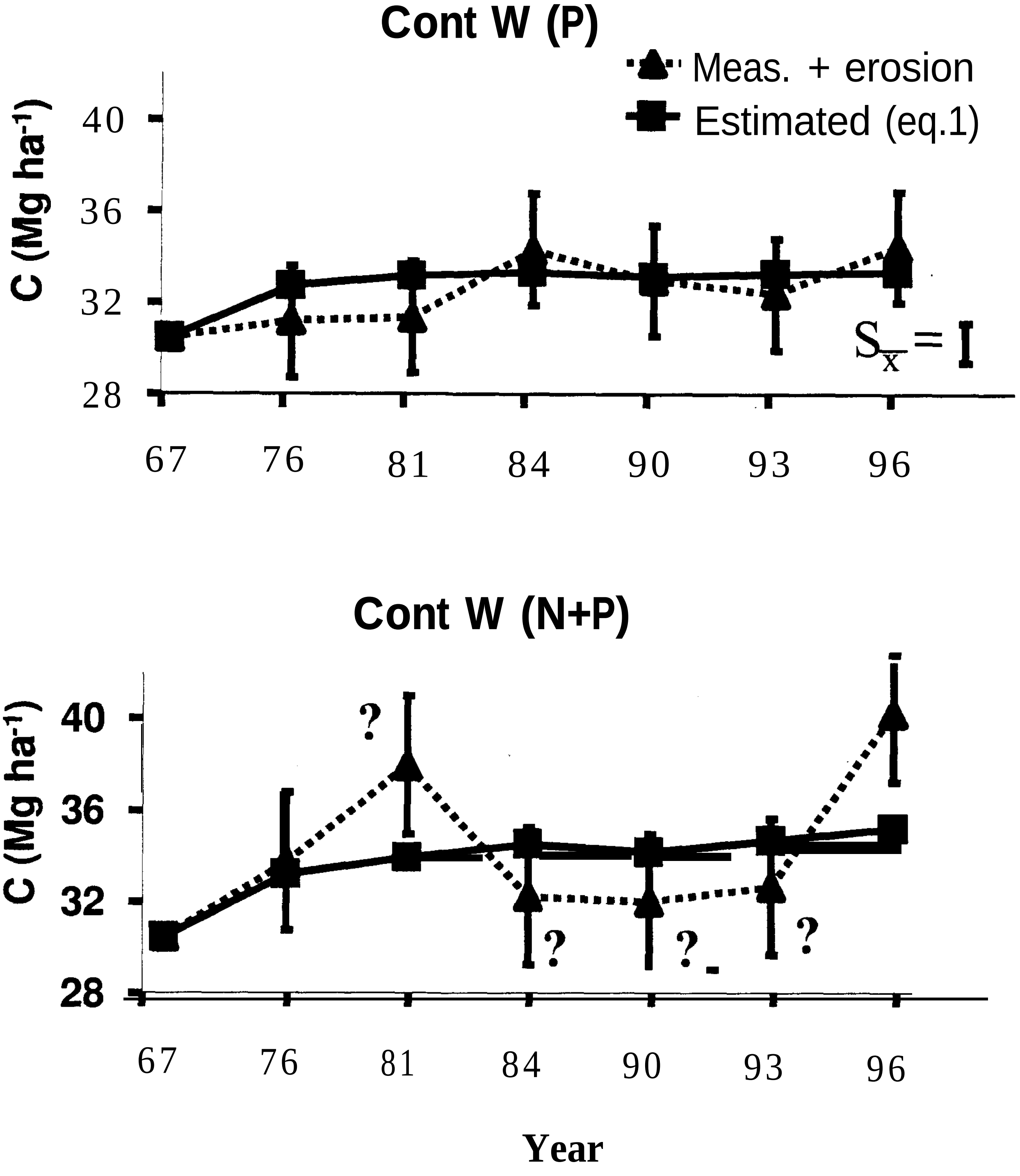
C_1 = 0.20
k_1 = 0.01 yr^{-1}
C_2 = 0.80
k_2 = 0.00066 yr^{-1}

F-W-W (N+P,N,P)



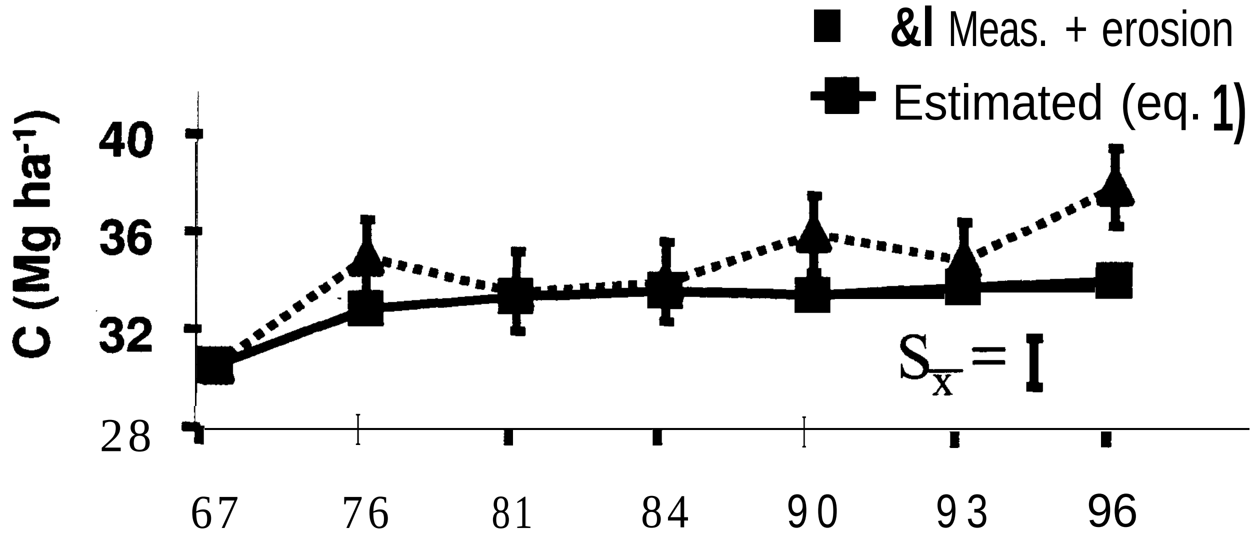
Swift Current

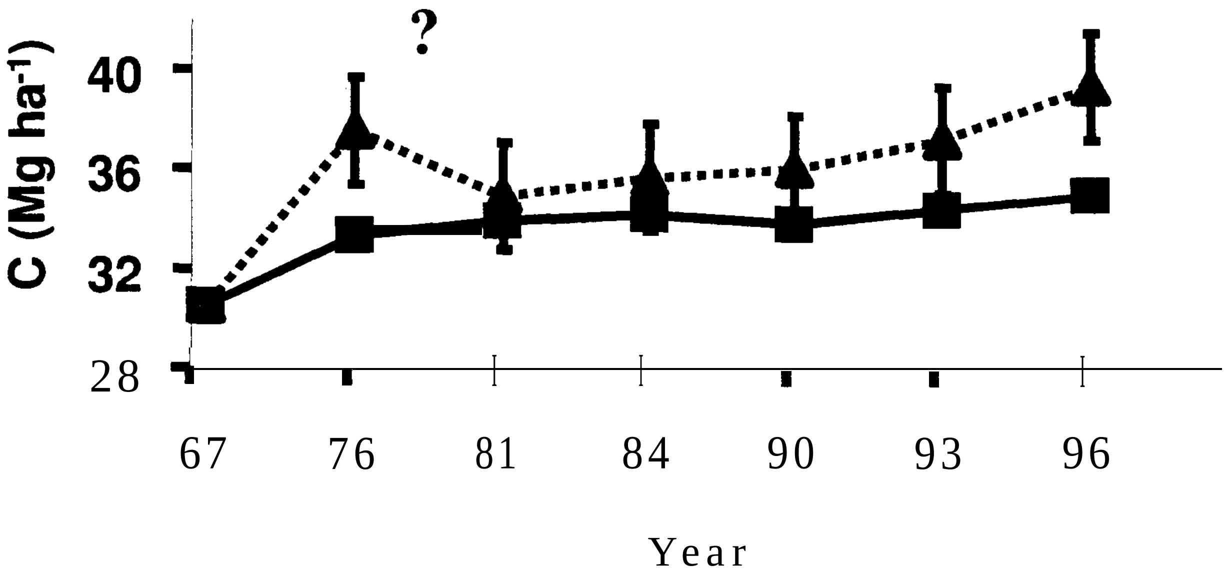
$C_1 = 0.20$
$k_1 = 0.001\ yr^{-1}$
$C_2 = 0.80$
$k_2 = 0.00066\ yr^{-1}$

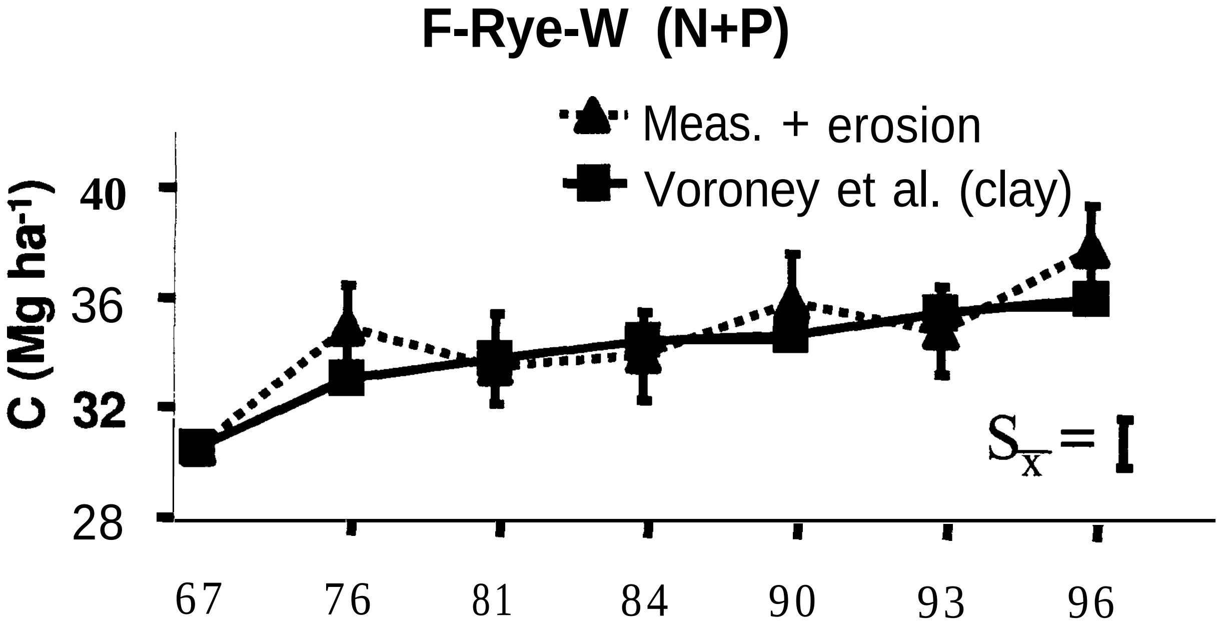


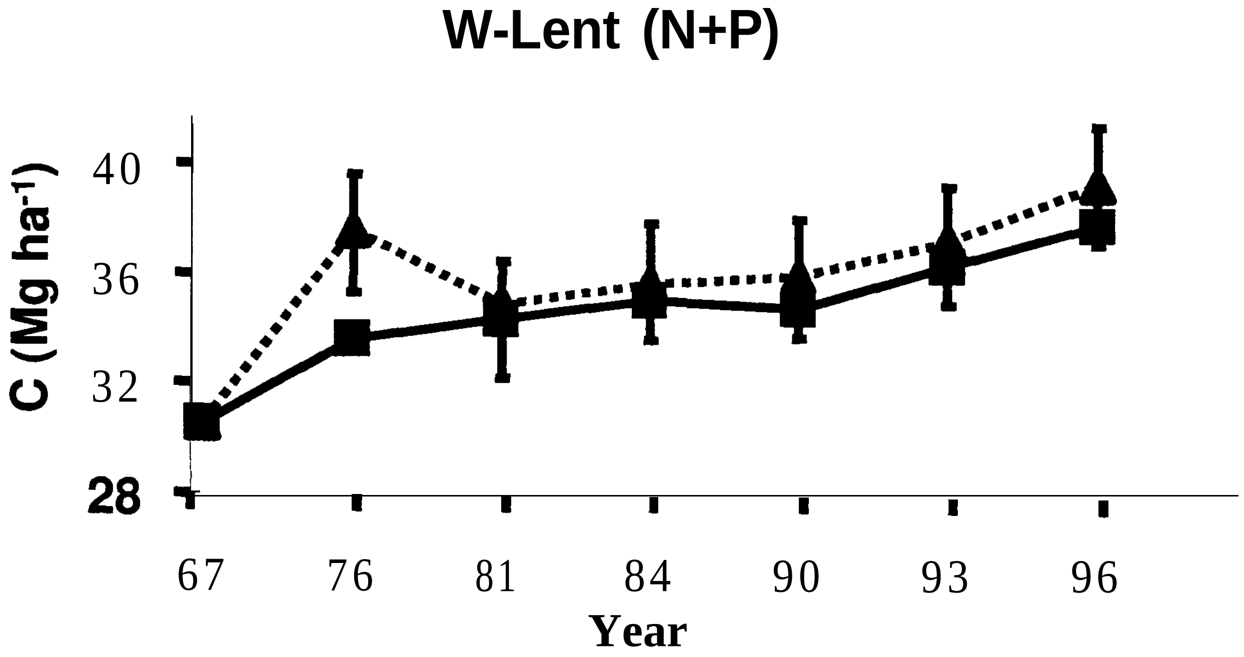
Swift Current

$C_1 = 0.20$
$k_1 = 0.001.\ \mathrm{yr}^{-1}$
$C_2 = 0.80$
$k_2 = 0.00066\ \mathrm{yr}^{-1}$


F-Rye-W (N+P)


W-Lent (N+P)


F-Rye-W (N+P)
Meas. + erosion
Voroney et al. (clay)
C (Mg ha^{-1})
40
36
32
28
$S_{\overline{x}}$ =
67
76
81
84
90
93
96


W-Lent (N+P)
C (Mg ha^{-1})
40
36
32
28
67
76
81
84
90
93
96
Year