SIMULATING THE DYNAMICS OF SOIL ORGANIC MATTER IN LONG-TERM ROTATION PLOTS OF SASKATCHEWAN AND ALBERTA.

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ABSTRACT

This study used the Century soil organic matter (SOM) model to simulate the dynamics in soil organic carbon, nitrogen and phosphorus in long-term crop rotation studies established in Saskatchewan and Alberta.

Observed losses of organic C,N,P in the top 30 cm of a Brown Chernozem under fallow-wheat (FW) were 8.2, 1.7, and 1.0 g m^{-2} y^{-1}. Soil erosion was responsible for 47% of the organic-N losses. The Century model closely mimicked the direction and magnitude of SOM change, within 10% of measured values. Similar SOM declining trends were observed in a thin Black Chernozem under FW and continuous wheat (CW), although soil erosion losses were higher than in the Brown Chernozem.

Soil organic matter increased in the Brown Chernozem under CW and in the Black Chernozem under zero-tillage. Under no-till, the organic C,N and P accumulated at an average rate of 101.7, 5.3, and 2.0 g m-2 y-1. In comparisson, the Century model predicted a depletion of organic-C and N in the Brown Chernozem under CW and of organic-C under no-till. Model sensitivity analyses indicated that the rate of erosion and the fixed rate of organic matter decomposition had greater effects than plant biomass production on soil organic matter levels. Under aggrading SOM conditions, the Century model predicted organic carbon accumulation only after the respiration rate for the slow organic matter fraction was reduced by 50%.

Introduction

Excessive tillage has induced a decline in soil organic matter (SOM) in agricultural soils across the Canadian Prairies (McGill et al., 1982). Crop rotation systems, however, control the amount and dynamics of SOM within a given soil association (Campbell et al., 1990). Most past SOM studies have reported on the amount of total organic matter found in one particular year in surface soil layers (0-15 cm) for different crop rotations (Campbell et al., 1991), or on the relative SOM concentration (%) over a defined period (Freyman, 1982; Biederbeck et al., 1984).

The impact of agronomic practices on soil quality is usually assessed by monitoring SOM levels for long periods. The SOM level is assessed at the landscape level (Gregorich and Anderson, 1985) and in smaller size research plots (Campbell et al., 1991). Most scientists rely on information gathered from long-term research plots to extrapolate the regional effects of crop rotations on soil quality in Alberta (McGill et al., 1986; Freyman et al., 1982), in Saskatchewan (Zentner and Campbell, 1988; Zentner et al., 1987; Biederbeck et al., 1984 and Campbell et al., 1991) and Manitoba (Poyser et al. 1957). These valuable SOM studies, however, require human and monetary resources and take several years before the scientist and public can obtain reliable information.

Computer programs have been developed that simulate SOM dynamics in grasslands (McGill et al., 1981) and agricultural soils (Parton et al., 1987; Bouman, 1989; Molina 1989 and Jenkinson 1987). These programs can be tested to learn their predictive ability under different environments. Once a model is verified, it becomes an important tool to rapidly assess SOM changes in agro-ecosystems. As a result, simulation models may become practical desision tools in agricultural extension to promote better land use and soil conservation planning. Within this context, the objective of this study was to test the Century model's capability to simulate SOM dynamics in long-term crop rotation studiesin Saskatchewan and Alberta.

Materials and Methods

Crop rotations

The long-term rotations described in this study were established at two sites located in Saskatchewan and one site in Alberta. These sites encompass a variety of crop rotation systems, soil types and weather conditions. The soil-crop management systems discussed herein involve fallow-wheat (FW) and continuous wheat (CW) rotations managed under conventional tillage, and continuous barley grown under zero-tillage (CB-ZT) management. These rotation plots are part of larger studies established by Agriculture Canada and the University of Alberta.

Additional information on crop varieties, type and frequency of cultivation and fertilization at Swift Current, Saskatchewan, is described by Biederbeck et al. (1984) and Zentner and Campbell (1988). Details about management practices implemented at the Indian Head, Saskatchewan, have been described by Greer (1989), Zentner et al. (1987) and Campbell et al. (1991). At Ellerslie, Alberta, continuos barley (CB) *(Hordeum vulgare)* was fertilized with urea and triple superphosphate. A blanket application of fertilizer supplied adequate S and K for crop growth (Nyborg et al. 1991, personal communication). Table 1 shows additional information about the selected research plots.

Soils

The soils at Swift Current and Indian Head were a Brown Chernozem (Swinton, SiL) and a thin Black Chernozem (Indian Head, HC), repectively (Ayres et al., 1985 and Canada Soil Survey Committee, Subcommittee on Soil Classification, 1978). The soil at Ellerslie was a Black Chernozem (Malmo, CL).

Soil sampling

The Brown and Black soils were sampled during the summer of 1990. At Swift Current, six cores were taken in the middle of each rotation plot. These cores were pooled together to obtain three subsamples per plot. The genetic horizon thickness (Ah, Ap, and part of B) was recorded for every soil core before dividing it in 0-15 and 15-30 cm segments. At the Ellerslie site, soil samples were taken by hand in 1980, 1983 and 1990 from the 0-15 and 15-30 cm depths within the CB-ZT system. Soil samples were air dried, sieved to two mm and stored for further chemical analysis. Soil bulk densities for all treatments and sites were estimated from uncompressed soil cores. At Indian head, soil samples were taken from the 0-7.5cm, 7.5-15cm, and 15-30 cm depth (Greer, 1989).

Chemical analysis

Soil samples from the Brown and Black Chernozemic soils were ground further to 100 mesh before elemental analysis. The chemical analysis of soil samples taken in 1990 followed the same methods described in earlier studies (Biederbeck et al. 1984; Nyborg, 1991, personal communication).

Separate soil samples were used to measure total and inorganic C. Total C was measured by dry combustion and inorganic C by acid titration. Organic C (**Co**) was determined by difference. A standard reference for total C and inorganic C was analyzed with the 1990 soil samples. These standard references were obtained from the Canada Centre for Mineral and Energy Technology. The chemical analysis were highly reproducible. Standard deviation values of 0.06, 0.02 and 0.002 were obtained for references containing 4.8% total C, 0.92% inorganic C, and 0.18% total N, respectively.

Organic N (**No**) was determined by the Kjeldahl method of Bremner and Mulvaney (1982). Organic phosphorus (**Po**) was measured by the method of Saunders and Williams (1955). Total S was determined by plasma emission spectrometry in a HNO3/HClO4 digest. Inorganic S was determined by high performance liquid chromatography in a KCl (0.01 N) extract. Organic S (**So**) was determined by difference between total S and inorganic S. Microbial biomass-C was estimated by the chloroform fumigation extraction method of Joergensen and Brookes (1990). Soil erosion rates were estimated by the ^{137}Cs technique described by Pennok and de Jong (1987).

Experimental design

The experimental design at the three studied sites consisted of different replicated treatments established as completely randomized block designs. The rotations (FW and CW) selected from Swift Current are part of a twelve crop rotation study established in 1967. The same crop rotations were studied at Indian Head where eleven rotation-year treatments were established in 1958. The two zero-tillage treatments studied at Ellerslie are part of a 16 treatment trial with four replicates established in 1980 (Nyborg, 1990, personal communication). The purpose of the latter experiment was to study the effects of tillage, straw management and N fertilization on soil organic matter and crop productivity.

Simulation of Soil Organic Matter dynamics

The Century model was used to simulate **Co**, **No**, **Po** and **So** dynamics in the long-term crop rotation plots. Some of the input data representing soil and management parameters are shown in Appendix 1. This simulation model has been described previously (Parton et al., 1987). Briefly, the soil organic matter is divided into pools with different turnover rates: active SOM (1.5 y), slow SOM (25 y) and a passive SOM fraction (1000 y). A plant production subroutine generates a potential plant biomass residue (shoot and roots). The plant residue is divided into a metabolic (0.1-1 y) and a structural pool (1 to 5 y) before being transferred to the soil. The split of plant residue into structural and metabolic is controlled by the lignin (L) to nitrogen (N) ratio using $Fm = 0.85 - 0.018\ L/N$, where Fm= the fraction of residue that is metabolic.

The plant production submodel is a linear function that relates total plant biomass to amount of precipitation received during the growing season and amount of water stored in the soil at seeding time. The maximum potential plant biomass production is achieved without nutrient limitation. Plant production is limited if the available N,P or S pools are insufficient to produce plant material with C:N, C:P or C:S ratios less or equal to the maximum values of these ratios (i.e. 35, 230 and 230, respectively for winter wheat).

Initial model input parameter values for SOM

The initial SOM values for model simulation were defined on the basis of the **No** concentration (%) estimated in 1967 in the Brown Chernozem (Biederbeck et al. 1984). The initial input parameter values for **Co**, **Po** and **So** were estimated by assuming C/N=10.45, C/P=48.74 and C/S= 24.48. These ratios were defined after fitting the model output to the observed **Co** (four observations made in 1976, 1981, 1985 and 1990), **Po** (two observations made in 1982 and 1990) and **So** (one observation made in 1990). A similar approach was followed for data obtained at Indian Head since **No** concentration (%) was the only measurement made from the research plots in 1961 (Greer et al., 1990). Initial conditions for **Co**, **No**, and **Po** content at Ellerslie were defined on the basis of chemical analysis of archived soil samples. During simulations, the original maximum and minimum C/P and C/S input ratios for the slow pool were modified to accomodate the element ratios found in all three studied sites. The new range for C/P [RCES2(2)] and C/S [RCES2(3)] ratios were set between 40-200 and 20-200, respectively (Appendix 1).

Statistical analysis

Two statistical methods were used to test the Century model's capability to simulate measured data. The correlation coefficient (**r**) between observed and predicted values was used to test the ability of Century to predict the direction of SOM change. A paired t-test was used to compare the statistical differences between the mean observed and predicted values of various time series. The difference in magnitude between predicted and observed data for each point in time was expressed as % of observed [(Observed-Predicted)/Observed] * 100.

Sensitivity analysis

Sensitivity of a model to a given parameter can be defined as the rate of change in the model output with respect to the change in the value of a specific input parameter while keeping all other parameters constant. The sensitivity index (SI) is used to quantify the effects of such changes (Ng and Loomis, 1984):

$$SI = 100/N \sum_{i=1}^{N} [(X_{ni} - X_{ci})/X_{ci}] * (\%CH)^{-1}$$ where,

N= number of points in the output, X_{ni}= new value of output for the ith point with altered value of the initial parameter; X_{ci} is the value of output for the ith point in the control simulation run, and %CH is the absolute value of change in the input parameter expressed as a % of its value in the control simulation. Thus, a SI value =+0.1 would mean that for each one% change in the input parameter, the output increases by 0.1%.

The sensitivity of Century to changing fifteen input parameters was studied in a series of simulations (Table 2). Each parameter was altered by ± 50%. Results of those altered simulations were compared to results from a control simulation. The control simulation consisted of a data set used for the FW rotation in Swift Current. The sensitivity measures for **Co** were calculated for years 1 to 23 of the simulations.

Results and Discussion

The following section does not attempt to provide a detailed discussion of the main mechanisms and processes affecting the observed SOM levels in the studied rotations. Instead, it emphasizes the abilities of Century to mimic SOM change over the medium term (5 - 10y) and longer periods (>10y).

Soil Organic Matter Under Fallow-Wheat

Organic-N decreased by 7.5% in the 0-30 cm of the Brown Chernozem under FW after 23 y of cultivation (Figure 1A). The mass of **Co**, **No** and **Po** declined at an average rate equivalent to 8.2, 1.7 and 1.0 g m^{-2} y^{-1}, respectively (Table 3). The decrease in **No** and **Co** was best described by a linear function (r^2=0.94 and 0.96, respectively). Similar trends of change were observed for all elements in the 0-15 cm depth (data not shown). In comparison, Biederbeck et al., (1984) reported an increasing tendency in the concentration of **Co** and **No** for the same FW rotation between 1976-1981.

In the thin Black Chernozem, organic-N was the only element measured at the beginning of the experiment (Greer et al. 1990). For the period 1961-1987, the losses of **No** were almost 5 times higher than in the Brown Chernozem and were equivalent to 9 g m^{-2} y^{-1} (Table 3).

Based on the initial conditions for SOM defined earlier in this article, Century closely predicted the observed changes of SOM under FW in the Brown soil. On average, Century predicted the trend and magnitude of change for **Co**,

No, **Po** and **So** within 3.5, 6.8, 1.6 and 4.3%, respectively, over a 23 y period (Figures 1A,B,C). Only **Co**, **No**, and **Po** data sets, however, are considered to be true tests for the model since Century was forced to predict the single **So** observation made in 1990.

At Indian Head, Century simulated **No** changes under FW with great precision (Figure 1B). The measured **No** data set provides the only 'real test' for Century since changes in **Co** and total **S** were made 'to fit' single observations made in 1987. Inorganic sulphur is usually less than 2% of total S in non-saline soils, and therefore, total S is assumed to represent **So**. Differences between observed and simulated **Co** and **So** were reduced to <2% by fine tuning the model output with different C/N and C/S input ratios of the active and slow SOM pools.

Century predictions for the FW rotations at Swift Current and Indian Head were better than those reported earlier for FW rotations in the Great Plains of North America and for crop rotations in Sweden. Parton et al., (1982) reported that Century tended to overestimate the total SOM change observed during 25 years of cultivation under FW in Sweden. Cole et al., (1989) reported that the relative differences between observed and predicted **Co** under FW varied between 60 and 72% for 10 sites located across the Great Plains. Noteworthy, the latter authors did not consider soil erosion losses during their simulations. Hence, the wide differences between predicted and observed SOM levels may be related in part to differences in potential soil erosion rates among the 10 studied sites. The use of an erosion rate input value (PSLOSS) during our simulations helped to improve the predictions of SOM change under FW.

The losses of **No** due to erosion can be estimated using the erosion rate values estimated from ^{137}Cs data (Table 3). On average, 47% of the total **No** losses from the Brown Chernozem under FW are attributed to erosion. The latter assumed that eroded soil particles had an average N concentration of 0.16% (N% varied between 0.178% in 1967 and 0.14% in 1990). Other **No** losses may be associated to crop uptake, leaching, denitrification and volatilization. Similar estimates can be made for **Co**. Based on a t-test, the mean thickness for the A horizon in FW was less than for CW (14 cm versus 17 cm, respectively). The latter supports the high erosion rates measured for the FW rotation. At Indian Head, erosion was responsible for 70% of the total **No** lost between 1961 and 1987. Soil erosion was an important factor affecting the SOM dynamics in soils under FW (Table 3). De Jong and Kachanosky (1988) have suggested that 50% of the soil organic carbon is lost through erosion from selected crop-fallow and crop-crop fallow fields in Saskatchewan.

According to Century, the biontic oxidation of soil C to CO_2 was responsible for 41% of the total **Co** losses. The model suggests that the greatest proportional **Co** losses originate from the active pools under FW in the Brown and thin Black Chernozems (Table 4). These results are supported by findings of Carter (1986) and McGill et al., (1986). The latter authors reported that microbial biomass is more dynamic and reflects changes faster than the total soil organic matter.

Soil Organic Matter Under Continuous Wheat

Soil samples taken at different time intervals showed a trend of **No** and **Co** accumulation in the Brown Chernozem under CW. This trend was better represented by the **No** data and both elements showed a high variabililty throughout the years (Figure 2A). Organic carbon and nitrogen increased on average by 12% since data were first recorded. The measured changes of these two elements could be described by a linear function (Figures 2A,B).

The increase in SOM content under CW in the Brown Chernozem was not paralleled in the thin Black Chernozem. In the latter soil, **No** decreased by 25% in the 0-30 cm depth after 26 years of CW, however the amount of **Co**, **No** and total **S** was higher under CW than in the FW rotation. Divergent SOM trends between the Brown and thin Black Chernozem under CW are associated with differences in rates of soil erosion. Measurements of ^{137}Cs indicate soil losses from the Brown Chernozem under CW were 2.4 t ha^{-1} y^{-1} compared to 23.9 t ha^{-1} y^{-1} from the thin Black Chernozem (Table 3). Seventy and 72% of **No** was lost via erosion from the thin Black Chernozem under FW and CW, respectively.

In the present study, all crop residues were returned to the thin Black Chernozem under CW. Century predicts a depletion in **No** between 1961 and 1987 if either all, or two thirds of the straw residue is removed at harvest (data not shown). This is consistent with trends in **No** measured for the same period (Table 3). Campbell et al. (1991) reported that removal of straw from a FWW rotation tended to decrease the amount of **No** but not of **Co** in the first 15 cm of the same thin Black Chernozem. Their conclusion was based on the assumption that soil was not lost via erosion from the studied plots. At present, it is not known the exact causes for the high soil erosion at the studied sites, although we suspect that soil removed by tillage may play an important role. The high soil erosion losses measured for the FW and CW rotations at Indian Head and for FW at Swift Current, permit to conclude that high rates of soil erosion significantly deplete SOM.

For the Brown Chernozem, Century slightly underpredicted the temporal changes of **Co** and **No** under CW by 5%. Although these differences were relatively small and not significantly different, the model predicts a depletion of **Co** and **No** after 23 y of cultivation (Figures 2A,B). In contrast, the analysis of soil samples showed a trend to increase SOM. As a result, the correlation coefficient (**r**) between observed and simulated **Co** and **No** was -0.91 and -0.99, respectively.

For the thin Black Chernozem, Century predicted the decline of **No** under CW within 13% at the end of 26 y simulation. The temporal dynamics of **No** provides the only 'real test' to determine the ability of Century to simulate data from the CW rotation at Indian Head. **Co** and **So** were not measured in 1958 or 1961 and their initial values were estimated with the assistance of Century by assuming initial C/N and C/S ratios of 11.19 and 64.35, respectively (Table 3).

In a Swedish soil, Century closely mimicked the direction and magnitude of **Co** change (Parton et al. 1982). Noteworthy, the latter authors increased the microbial respiration rate from 60 to 80% in order to improve the fit over a 25 y period. Another published report showed the difference between observed and measured **Co** varied between -38 to 117% after 30 to 43 y of CW at 8 sites across the Great Plains (Cole et al. 1989). As explained earlier, such wide prediction differences may, in part, be associated with neglecting to include soil erosion losses.

Soil Organic Matter Under Zero-Tillage

After seven years of no tillage at Ellerslie, the amount of **Co**, **No** and **Po** in the 0-15 cm of soil accumulated at an average rate of 101.7, 5.3 and 2.0 g m^{-2} y^{-1}, respectively. According to ^{137}Cs measurements, no soil erosion has occured in the CB-ZT plot (Table 3). These results are similar to those reported earlier for **Co** in crop rotations under zero-tillage (Dormaar and Lindwall, 1989; Carefoot et al., 1990). Some biochemical and microbial factors causing accretion of SOM under zero-tillage were discussed earlier by Aulakh et al., (1984) and Doran (1980).

Century predicted the change of **Co**, **No** and **Po** within 9, 3, and 8%, respectively after seven years of CB-ZT. The model mimicked the direction of temporal change of **No** (r=0.68) and **Po**, but it did not predict the correct trend for **Co** in the CB-ZT plot (r=-0.97, n=3) (Figure 3). For the latter, the model predicted a loss of **Co** from the three SOM pools, with most loss occurring in the active fraction (Table 4). This predicted trend is inconsistent with other studies that examined the dynamics of the soil microbial biomass-C in aggrading soil systems (McGill et al., 1986). Conversely, **No** increased by 60% in the active fraction and remained constant in the slow and passive pools (data not shown). The predicted decline of **Co** could not be explained. The present authors are not aware of any previous report using the

Century model to describe SOM dynamics under zero-tillage systems.

Plant Biomass Production

Century did not predict the correct trend of **Co** and **No** change in the Brown Chernozem under CW, and of **Co** in the Black Chernozem under zero-tillage. If the model represents the true processes and components controlling the dynamics of SOM, this discrepancy may be related to the amount of simulated plant residues returned to the soil and/or to the rates of CO_2 flow from each of the SOM pools.

We used Century to simulate the crop primary production and to compare these values with those estimated from crop yields reported earlier by Zentner and Campbell (1988) and Zentner et al., (1987). The basic function of the plant growth submodel was to provide an input of plant residue for the SOM calculations. Hence, predictions of annual plant production are less important than obtaining a good estimate of the average plant production input over the study period.

Table 5 shows the partition of plant-C for wheat and barley: 74% of total plant C was allocated into aboveground biomass (30% in grain and 44% in straw) and 26% into roots. In comparisson, Century allocates 80% of the total C into aboveground biomass (32% in grain and 48% in straw) and 20% into roots (Table 5). The model predicts the amount of straw and grain-C more closely than root-C.

The total long-term average plant biomass-C production ranged between 129 and 321 g $m^{-2}y^{-1}$ in all soils. The same data indicates more grain and straw were produced annually under CW than under FW in both the Brown and thin Black Chernozem. In all soils, the average production of straw residue varied between 57 and 124 g C m^{-2}, root-C ranged between 34 and 73 g m^{-2} y^{-1}, and grain-C varied between 38 and 124 g m^{-2} y^{-1}. The overall plant biomass production was consistently lower in the Brown Chernozem (Table 5). Differences in plant production among sites reflect differences in crop varieties, fertilizer rates, tillage systems and climatic conditions.

In general, Century correctly predicted the relative differences in plant production between crop rotations, i.e. greater plant biomass-C under CW than under FW. The amount of plant-C was always underpredicted except for the thin Black Chernozem under FW. Noteworthy, the total simulated plant biomass was about 30% lower than the long-term reported values (Campbell et al., 1984; Zentner et al., 1977). Under zero tillage, the amount of C in straw and roots was also underpredicted by 29% (Table 5).

These results suggest the simulated **Co** decline in the Brown Chernozem under CW may be related to an inferior amount of plant residues generated by the plant production submodel. Subsequent simulations attempted to increase plant biomass production. The input parameter value for WPPB was increased from 12 to 18 (WPPB=18 represents biomass production in newer higher yielding wheat varieties, Parton, 1991 personal communication). As expected, this simulation increased plant biomass production (Table 5). The amount of predicted **Co** and **No** was, however, slightly lower than that simulated with WPPB=12 (Figure 4). Increasing plant production for the CW rotation alone is not a valid process since the same wheat varieties were grown under FW and CW in the Brown Chernozem. Century predicted the correct trends and amounts of SOM change in the Brown Chernozem under FW without altering the input parameters for plant production.

A similar analysis was made when simulating plant production in the CB-ZT system. Although a different crop (barley) was grown under zero-tillage, the initial model simulations used input parameters associated with wheat production. Under such conditions, the model underestimated total plant production by approximately 33% (Table 5). In view of these results, the input parameter values for plant lignin (FLIGNW) and the slope for plant biomass production (WPPB) were altered to simulate barley biomass output. Decreasing the FLIGNW value from .15 (wheat) to .08 (barley) and increasing WPPB from 12 to 18 increased total plant biomass by 7% relative to that obtained for the wheat simulation (Table 5). Increasing plant biomass production did not change the simulated decline in **Co** under zero-tillage (data not shown). This strongly suggests the predicted **Co** decline under zero-tillage was not associated with low inputs of plant residues.

In summary, Century underpredicted the amount of plant residue production in most rotations. Altering the model plant production function increased the output of plant biomass. The increase in long-term plant production did not change the declining predicted trend for **Co** and **No** in the Brown Chernozem under CW and for **Co** in the Black Chernozem under zero-tillage.

Soil Microbial Biomass

The active soil organic matter pool of the Century model represents live soil microbes and microbial products (Parton et al, 1987). This active biotic component catalyses biochemical processes to release plant nutrients and gases to the atmosphere. Hence, comparison of measured soil biomass-C with the simulated active fraction is useful in testing the model's capacity to describe the dynamics of active microbial pools in agricultural soils.

The microbial biomass size measured in the Brown Chernozem in 1990 was smaller than in 1982 (Table 6). The microbial biomass-C in the 0-30 cm of the native Brown Chernozem was 2.7 times larger than in cultivated samples. Cultivation of the Brown Chernozem since 1921 has resulted in a 60% reduction of the total soil microbial biomass. In the cropped rotations, the microbial biomass-C represents 0.6% of **Co**. No difference in biomass size was observed between the FW and CW rotations in the Brown Chernozem (Table 6). Noteworthy, the biomass-C in the 1982 was estimated in fresh soil samples, whereas, the 1990 samples were air dried and preincubated before chloroform fumigation.

These results show a faster decline of microbial biomass-C than of **Co** in degraded Chernozems. According to McGill et al., (1986) losses of microbial biomass in degrading soils are faster than losses of total soil organic matter. Our results support such hypothesis and further suggest that the rate of loss of soil biomass-C is three times faster than the loss of total **Co** from the Brown cultivated soil. The microbial biomass-C in the thin Black Chernozem under CW was larger than under FW, and was 3 to 6 times larger than in similar rotations of the Brown Chernozem (Table 6). Differences in microbial biomass for the thin Black Chernozemic soil are discussed in more detail by Campbell et al., (1991).

For the thin Black Chernozem, Century correctly predicted the relative differences in biomass-C and the size of microbial pool between the FW and CW rotations within 4 and 41%, respectively. The model overpredicted the soil microbial biomass by 150% in the native Brown Chernozem at steady-state and between 140 and 680% in the FW and CW rotations, respectively. Although no difference in biomass size was observed between FW and CW, the model predicted 1.7 times more biomass-C under CW (Table 6). If the active fraction of Century represents the microbial biomass plus its metabolites, the large differences between observed and predicted biomass-C must be associated with non measured microbial metabolite carbon.

A separate attempt was made at improving the model's prediction. The initial input value for the active soil organic matter pool was decreased from 173 g C m^{-2} (3% of total **Co**) to 74 g C m^{-2} (1% of total C). Such efforts proved to be unsuccesfull. The new predicted active SOM only changed by 0.5% as compared to the control run (data not shown). Overestimating the size of microbial biomass directly affects the net mineralization rates for N, P and S and indirectly affects plant primary production.

The above results suggest that the following model parameters may not define the true rates of biochemical processes taking place in the Brown Chernozem under CW:

a) the transfer of C from plant components to the active SOM fraction, b) the parameters or functions transfering C among soil pools, c) the model fixed decomposition rates for each soil state variable. Within this context, Monreal and McGill (1989) used kinetic analysis to study the cycling of soluble C in a climosequence of soils. They indicated that the rate of transfer for ^{14}C-cystine within and from active soil microbial compartments was different among native and cultivated Chernozemic soils and between two crop rotations in a Gray Luvisol. Such kinetic study defined biontic and abiotic components and reactions controlling the cycling of soluble carbon. In their model, the active soil microbial biomass was defined on the basis of metabolic processes . The latter concept is different to that presented by Century and helps to explain the model's difficulty in simulating the size and dynamics of the microbial biomass in native and cultivated Brown Chernozem. Noteworthy, the temperature and soil moisture functions controlling the maximum rate of SOM decomposition may not represent the climatic effects on biotic activities in soils of the semi-arid region of Saskatchewan.

In summary, Century predicted the size and trends of the microbial biomass-C in the thin Black Chernozem under FW and CW. The model largely overestimated the microbial biomass-C in the native Brown Chernozem and could not represent the relative sizes of the microbial pool within FW and CW. Such model anomalies may be associated with Century's oversimplified concepts of biotic and abiotic processes controlling the nutrient dynamics through the active SOM fraction.

Sensitivity Analysis

Century did not predict the trend of **Co** and **No** in the Brown Chernozem under CW and of **Co** in the Black Chernozem under zero-tillage. In the plant biomass production section we concluded that increasing plant production could not explain the declining simulated trends for the previous soils and rotations. We also found that the microbial biomass-C was largely overpredicted in the Brown Chernozem.

The purpose of this sensitivity analysis was to identify the potential model components or parameters responsible for such anomalous results. This step of model testing may also help to design future SOM research by concentrating on those variables associated with model weakness. Such information can be used later to refine the model.

During model sensitivity analyses, we grouped fifteen input parameters and variables according to their function (Table 2). In general, the sensitivity (SI) values are low and vary between -0.122 and 0.0559% (Table 7). Although all parameters were changed symmetrically by ±50%, except

RMVSTR, the absolute SI values were different between the two directions of change. The latter indicates there are non-linear relationships between model parameters. The direction of change in parameter values and their effect on predicted **Co** is consistent with the model postulates, i.e. an increase in WPPB (slope of plant production function) results in higher above-ground plant production (AGCACC). The negative sign for a SI value indicates a decrease from those obtained for the control run.

The selected input parameters were ranked in descending order according to their effect on **Co** after 23 y of cultivation (Table 7). The analysis showed that erosion rates have the largest impact on model output. The effect of erosion rates on model output was much larger than the effects caused by: the amount of plant residues, plant lignin/N ratio, rate of N and P fertilization, number of cultivations or the proportion of the straw residue that is removed from the field at harvest. The fertilization rate of P and S together with pH had no effect on **Co** and **No**.

Under conditions of soil erosion, the parameter PSLOSS and BULKD exerted the largest effect on predicted **Co** (Table 7). This is consistent with the model structure since the rate of SOM change and soil loss is proportional to BULKD. The latter points out the importance of determining bulk density and erosion rate values when simulating SOM dynamics with Century. In the present work, erosion was estimated for every site and crop rotation using the ^{137}Cs technique. Century overpredicts measured **Co** if erosion is not considered in the calculations.

Under conditions of no or little soil erosion (<2.4 t ha^{-1} y^{-1}), the parameters representing CO_2 flows (P_1CO_2b and P_2CO_2) become the main controlling factors and cause greater effects on **Co** than the plant production parameter WPPB (Figure 3). These CO_2 input parameters are fixed in the model. The parameter P_2CO_2 (controls the CO_2 outflow from the slow SOM pool) has a greater effect on **Co** than P_1CO_2b (rate of CO_2 flow from active pool). Decreasing the respiration rate for the slow pool by 50% improved the predictability of **Co** and **No** change in the Brown Chernozem under CW (Figure 3).

These results suggest that SOM decomposition rates are slower in CW than in FW. Greater amounts of light fraction found under CW than in FW also supports this explanation (Greer, 1989; Janzen, 1991, personal communication). The light fraction includes SOM that is not associated with clay minerals and has a density <2 g cm^{-3}. It is hypothesized that lower surface soil moisture under CW may decrease the microbial respiratory activity on plant litter and therefore contribute to a faster accumulation of SOM. Further research is needed to elucidate the processes affecting the accumulation of light fraction and its role in controlling the accretion of SOM under CW.

Under zero-tillage, the Black Chernozemic soil accumulated SOM, however, Century predicted a decrease in **Co**. As for the CW rotation, decreasing the rate of CO_2 flow from the active and slow SOM pools improved model performance by predicting the measured trend of **Co** accretion under CB-ZT (Figure 4). The oxidation of SOM under zero-tillage is slower than in conventional tillage by favouring longer anaerobic periods. Under low oxygen tension, the oxidation of organic substrates involves facultative and strict anaerobic organisms. In addition to reducing CO_2 production, active soil microbes in no-till systems synthesize and cause an accumulation of organic acids, alcohols and other intermediates of metabolism (Parson and Smith, 1989). Such microbial metabolic controls are not described explicitly by Century. The moisture and temperature functions controlling maximum decomposition of SOM are not adequate to compensate for lower C respiratory activity in the studied CB-ZT systems.

Century was developed and parameterized with data sets obtained mainly from grassland and wheat-fallow rotations under conventional tillage systems of the Great Plains (Parton et al, 1987; Cole et al, 1988). Our data shows that Century performed better when simulating SOM dynamics under FW than under CW and CB under zero-tillage. Hence, the original fixed input decomposition rates for the active fraction may not represent the rate of microbial substrate utilization, microbial growth and turnover rate under different crop rotation systems.

In summary, the sensitivity analysis showed that the rate of soil erosion and soil bulk density have the largest effect on the amount of **Co** remaining in degrading soils. Under conditions of no soil erosion, the rates of CO_2 flow from the active and slow soil organic matter pools have a greater effects on **Co** and **No** than the amount of plant residues returned to the soil. Reducing the microbial respiration rate by 50% helped Century to simulate accretion of **Co** and **No** in the Brown Chernozem under CW and of **Co** in the Black Chernozem under zero-tillage.

Concluding Remarks

We have examined changes in SOM in long-term crop rotation studies in Saskatchewan and Alberta. The mass of soil organic matter decreased in FW rotations due to the combined effects of soil erosion and biological oxidation. Soil erosion was responsible for up to 60% of the SOM decline. Organic matter accumulated in soils under crop rotations with little or no soil erosion and where greater amounts of crop residues were returned to the soil.

The Century model describes well the dynamics of **Co, No** and **Po** in degrading fallow-wheat systems. It did not represent the aggrading conditions for **Co** and **No** found in a Brown Chernozem under CW, or for **Co** in a Black Chernozem under CB-ZT.

A model sensitivity analysis indicated that input parameters representing the rate of CO_2 flow have greater effects on **Co** than the amount of plant residues returned to the soil. Century predicted **Co** accretion under CW and CB only after the respiration rate for the slow SOM pool was reduced by 50%. These results indicate that the original fixed input parameters for CO_2 do not represent the true values for describing SOM dynamics in crop rotations of the Canadian Prairies. Future model simulations with data sets from long-term rotations at Lethbridge, Breton and Vegreville will offer wider environmental conditions to further test the Century model.

ACKNOWLEDGMENTS

We thank the National Soil Conservation Program for financial contribution, and Drs. Vern Cole and William Parton for their assistance with the Century model. We also greatfully acknowledge Paula Brandt and the PFRA staff at Swift Current for soil sampling, Derek Chao for his technical asistance and the help of Connie Sauder for the preparation of this manuscript.

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Table 1. Soil and crop management practices in three long-term rotations of Saskatchewan and Alberta.

Site	Great Group	Year	Rotation	Fertilizer applied (kg $ha^{-1}y^{-1}$) N	P	S^1
Swift Current	Brown	1967	FW^2	3.5	4.6	1.7
			CW^3	29.5	9.4	10.7
Indian Head	Thin Black	1958	FW^4	0.0	0.0	0.0
			CW^5	39.0	10.0	5.5
Ellerslie	Black	1980	$CB\text{-}ZT^6$	56.0	15.0	10.0

1. Sulphur added as a result of N and P fertilization with 11-51-0, 11-48-0 and 34-0-0.
2. Rotation 11, plots 25,45 and 58. Conventional tillage.
3. Rotation 8, plots 26, 38 and 61. Conventional tillage.
4. Rotation 2, conventional tillage.
5. Rotation 9, conventional tillage.
6. Continuous barley in a zero-tillage system.

Table 2. Model variables and input parameters used in the sensitivity analysis.

Parameter	Description
	<u>Group1</u>. <u>Plant</u>
A. FLIGNW(1)	Fraction of lignin in aboveground residue
B. WPPB	Slope in regression equation estimating plant biomass production in wheat.
	<u>Group 2</u>. <u>Soil</u>
C. BULKD	Soil bulk density
D. PSLOSS	Rate of monthly soil loss
E. pH	Soil pH (H_2O)
	<u>Group 3</u>. <u>Soil and crop management</u>
F. CULTRA(2,1-12)	Fraction of surface litter transferred to the top soil layer for each cultivation month.
G. CULTMO	List of months when cultivation takes place (number of cultivation)
H. RMVSTR	Fraction of straw removed at harvest
I. Fertilizer-N	Rate of N fertilization
J. Fertilizer-P	Rate of P fertilization
K. Fretilizer-S	Rate of S fertilization
	<u>Group 4</u>. <u>Internal model parameters</u>
L. p1CO2b	Controls CO2 flow from the active pool
M. p2CO2	Controls CO2 flow from the slow pool
N. p3CO2	Controls CO2 flow from the passive pool
O. DT	Model time step

Table 3. Temporal change in Co, No, Co/Po and Co/So in various soils and crop rotation systems.

Rotation	Year	Erosion ($t\ ha^{-1}y^{-1}$)	Co ($g\ m^{-2}$)	No ($g\ m^{-2}$)	Co/Po	Co/So
			Brown Chernozem[1] (0-30 cm)			
FW	1976	21.6	4802	507	N.D.	N.D.
	1981		4779	500	47.3	N.D.
	1990		4687	485	50.4	25.0
CW	1976	2.4	5452	523	N.D.	N.D.
	1981		5458	559	55.8	N.D.
	1990		5976	584	66.4	33.4
			Thin Black Chernozem[2] (0-30 cm)			
FW, CW	1961		9094[4]	813[3]	N.D.	N.D.
FW	1987	34.6	6190	569	N.D.	61.9
CW	1987	23.9	6420	612	N.D.	57.7
			Black Chernozem (0-15 cm)			
CB-ZT	1983	0.0	8790	705	102	N.D.
	1990		9502	742	116	N.D.

1. Experiment started in 1967 (estimated N=0.178% or 522 $g\ m^{-2}$ 30 cm^{-1}).
2. S reported as total S (Greer, 1989).
3. For 0-15 cm depth, N=0.362% (Greer et al., 1990), bulk density = 1.2 $g\ cm^{-3}$ (Greer, 1989).
4. Used Century to estimate initial C/N=11.19 and C/S=64.35 ratios.

Table 4. Changes in the active, slow and passive soil organic carbon pools in three soils.

Soil pool	Amount of Carbon (as percent of initial)				
	Brown Chernozem		Thin Black Cher.		Black Ch
	FW	CW	FW	CW	CB-ZT
Active	-38	10	-45	- 7	-24
Slow	-25	-2	-38	-18	- 2
Passive	-14	-2	-25	-18	0
Period	1967-1990		1961-1987		1983-90

Table 5. The long-term average estimated and simulated carbon content in plant materials.

Great group	Rota-tion		Grain yield[1] (g m^{-2})	Amount of C (g m^{-2})			
				Grain	Straw	Root	Total
Brown	FW	Observ	94.8	37.9[2a]	57[2b]	34[4]	128.9
		Predic	85.0	34.0	51[3]	21	106.0
	CW	Observ	135.4	46.5	81	48	175.5
		Predic	123.8	49.5	74	31	154.5
		Predic[5]	138.5	55.4	83	34	172.4
Thin Black	FW	Observ	112.0	44.8	67	40	151.8
		Predic	72.5	29.0	87	36	152.0
	CW	Observ	181.0	72.4	109	64	245.4
		Predic		55.2	83	35	173.0
Black	CB-ZT	Observ	311.0	124.4	124[2c]	73	321.4
		Predic	165.0	66.0	98	41	205.0
		Predic[6]	175.0	70.2	105	44	219.2

1. For the Brown Chernozem, grain yield reported for period 1967-1984 (Zentner and Campbell, 1988). For the thin Black Chernozem, grain yield was reported for period 1960-84 (Zentner et al., (1987).
2. Assumed: a) grain-C = grain yield x 0.4
   b) wheat straw-C = grain yield x 0.4 x 1.5
   c) barley straw-C= grain yield x 0.4 x 1.0
3. Predicted straw-C = aboveground C accumulator (AGCACC) - C in grain (CGRAIN).
4. Root-C=straw-C x F, where F=0.59 for Black soils (van Veen and Paul, 1981) and F=0.48 for the Brown Chernozem (Campbell et al., 1977).
5. WPPB was increased from 12 to 18 (represents use of higher yielding wheat).
6. Simulating barley plant production: FLIGNW=0.08 and WPPB=18.

Table 6. Observed and simulated microbial biomass-C in two long-term rotations plots in Saskatchewan.

Great Group	Rotation	Year	Microbial biomass-C (g m^{-2})			
			Estimated			Simulat.
			(0-15)	(15-30)	(0-30)	(0-30)
Brown	FW	1982	39.5[1]	8.1[2]	47.6	115
		1990	19.5	8.1	27.6	106
	CW	1982	45.2	9.7[2]	54.9	187
		1990	18.3	9.7	28.0	189
	Native[3]	1990	62.5	11.8	74.3	N/A
					65.2[4]	162[4]
Thin	FW	1987	81.5[5a]	71.6[5b]	153.1	147
Black	CW	1987	102.9	74.2	177.1	250

1. Readapted from Biederbeck et al., (1984). Assumed microbial biomass-C in 7.5-15 cm is the same as for the 0-7.5 cm depth.
2. Assumed that the maximum biomass-C in the 15-30 cm depth in 1981 is the same as in 1990, (the true value may be lower).
3. The thickness of sampled soil layers correspond to 0-17 (Ah) and 17-30 cm (part of B horizon).
4. Biomass-C in 0-20cm.
5. a) Biomass-C reported by Campbell et al., (1991); b) Biomass-C reported by Greer (1989).

Table 7. The effects of changing input parameters on the amount of **Co** remaining in the Brown Chernozem after 23 y of cultivation.

Model parameter	Parameter in Control run	Sensitivity Index SI (%)		Rank in decending order	
		+50	-50	+50	-50
PSLOSS	.18	-.0658	.0678	PSLOSS	BULKD
BULKD	1.22	.0201	-.1220	p2CO2	PSLOSS
FLIGNW	.15	.0025	-.0002	BULKD	p2CO3
WPPB	12.00	.0074	-.0352	p1CO2b	WPPB
pH	6.75	.000	.000	WPPB	RMVSTR
CULTRA	.40	-.0023	-.0060	Fert.-N	p1CO2B
CULTMO	4.00	-.0042	.0178	CULTMO	CULTMO
RMVSTR	.00	N/A	-.0306	FLIGNW	CULTRA
Fertil.-N	.70	.0043	.0045	CULTRA	Ferti-N
Fertil.-P	.92	.000	.000	p3CO2	p3CO2
Fertil.-S	.34	.000	.000	pH	FLIGNW
p1CO2b	.68	-.0200	.0224	Fert.-P	Fert.-P
p2CO2	.55	-.0523	.0559	Fert.-S	Fert.-S
p3CO2	.55	-.0019	.0020	DT	pH
DT	.083	.000	.000		DT

Appendix 1. Selected input parameters used during simulations.

	Brown		Thin Black		Black
PRAMETER	FW[1]	CW	FW	CW	CB-ZT
SOM1CI(1)	172	172	291	291	264
SOM2CI(2)	2485	5485	3410	3410	4008
SOM3CI(3)	2802	2803	5393	5393	4518
TEND	23	23	26	26	7
BULKD	1.22	1.16	1.02	.95	1.0
EDEPTH	.3	.3	.3	.3	.15
pH	6.75	6.75	7.5	7.5	6.1
PSLOSS	.18	.02	.288	.199	0
CLTANY	1	0	1	0	0
CULTMO(1)	5	-	5	-	-
CULTMO(2)	6	-	6	-	-
CULTMO(3)	7	-	7	-	-
CULTMO(4)	8	-	8	-	-
WPPB	12	12	12	12	12/18
FLIGNW(1)	.15	.15	.15	.15	.15
SAND	.3	.3	.089	.089	.20
SILT	.5	.5	.429	.429	.42
CLAY	.2	.2	.482	.482	.38
RCES1(1)	5	5	12	12	8.6
RCES1(2)	30	30	45	45	54
RCES1(3)	30	20	40	40	35
RCES2(1)	12	12	18	18	18
RCES2(2)	50	50	117	117	165
RCES2(3)	20	20	46	46	190
RCES3(1)	10	10	9	9	10
RCES3(2)	50	50	62	62	62
RCES3(3)	30	30	90	90	100

1. Parameters for FW represent those for the control run.

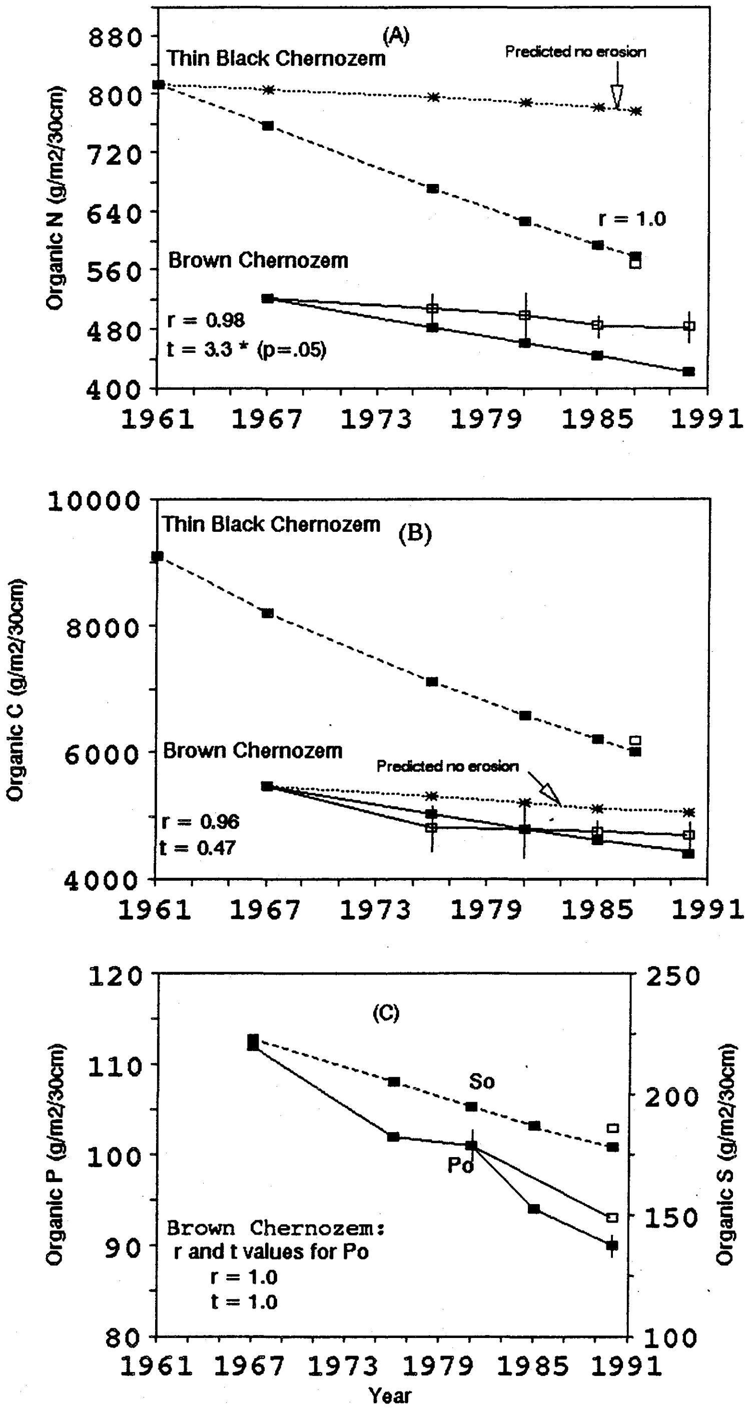


Figure 1. The dynamics of Co, No, Po and So in fallow-wheat rotations in two Chernozemic soils (□ = observed; ■ = predicted, I=standard deviation).

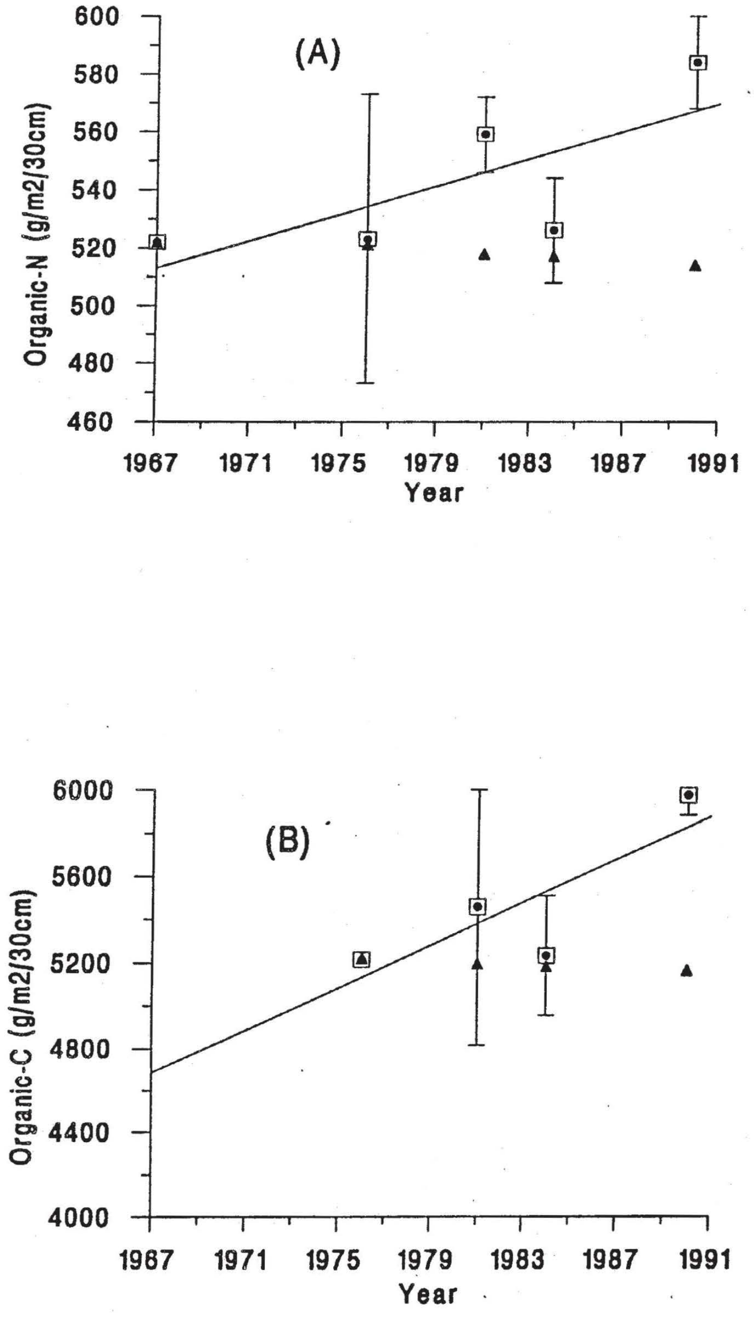
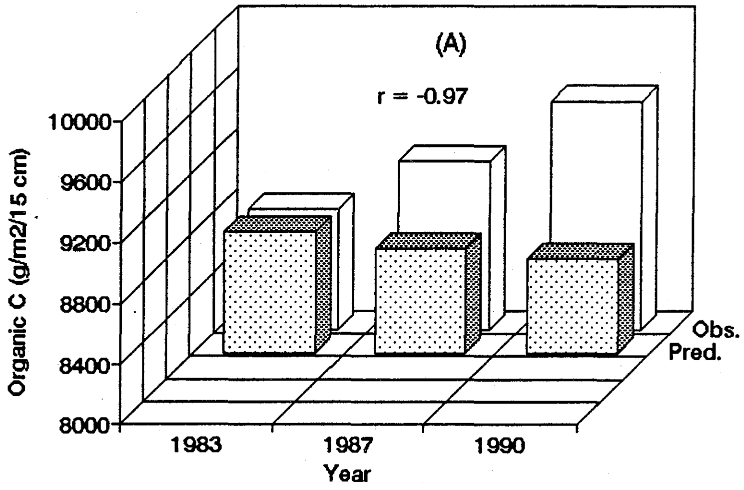


Figure 2. The No and Co dynamics in a Brown Chernozem under CW (□=observed, Δ=predicted, I=standard deviation). A linear function described the observed No (r^2=0.55) and Co (r^2=0.67).



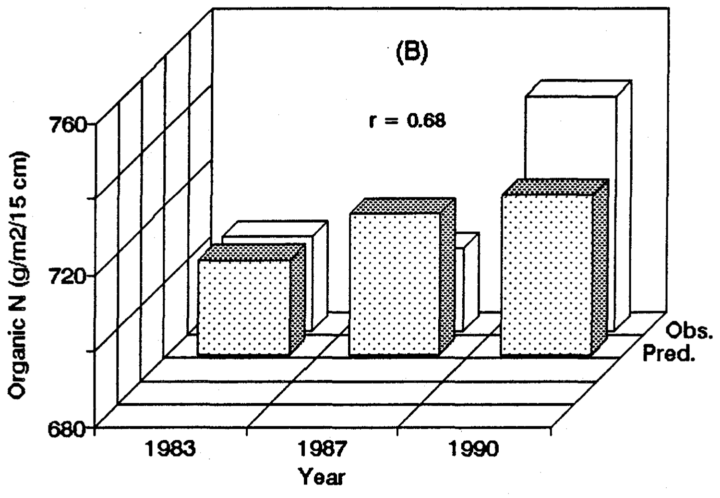


Figure 3. The dynamics of Co and No in a Black Chernozem under zero-tillage with no erosion and no straw removed.

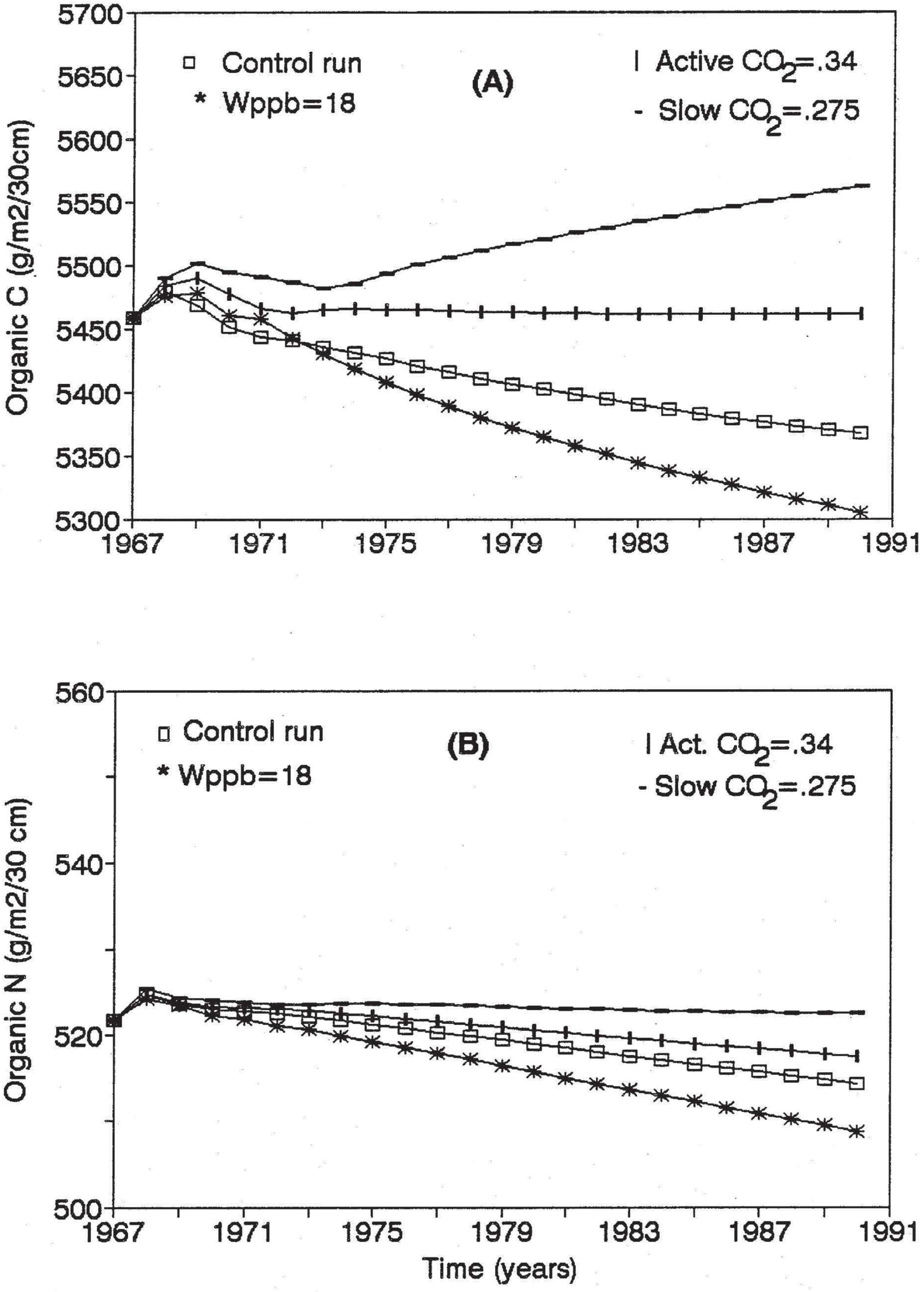


Figure 4. The effects of plant production and organic matter decomposition on model output for a Brown Chernozem under CW. (WPPB= slope value for calculating plant biomass production)