

# Comparing predictions of long-term soil carbon dynamics under various cropping management systems using K-model and CENTURY

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**Abstract:** There is a strong demand for accurate estimates of long-term changes in soil organic carbon (SOC) with different agricultural practices under different soil and climate conditions. A process and analytic model, K-model, including a non-compartmental algorithm of soil carbon decomposition, was developed to simulate the changes of SOC under different cropping and soil management practices. This study evaluates the performance of K-model by comparing its predictions on SOC with measurements and predictions of CENTURY model, which is widely used for the similar purposes. Both K-model and CENTURY can predict the dynamics of SOC when site-specific soil and climate data are used to initialize simulations. Very similar annual carbon decomposition rates were simulated by the single carbon pool K-model and the 3-carbon pool CENTURY model. However, compared with experimental measurements of SOC, K-model produces smaller root mean square errors and relative smaller errors than CENTURY ( $<0.1 \text{ kg C m}^{-2}$  vs.  $0.08\text{-}0.48 \text{ kg C m}^{-2}$ , and within  $\pm 5\%$  vs.  $\pm 5\text{-}45\%$ ), mainly resulting from smaller biases of predicted crop production. When detailed site-specific soil and climate data are not available for initialization and feeding the running of model, K-model can still reasonably predict the dynamics of SOC with its auto-correction function, but CENTURY produces poor results. In comparison with measurements, K-model has improved capacities to predict the effects of chemical fertilizer, manure application, residue management and fallow on SOC dynamics.

**Keywords:** K-model, CENTURY model, soil organic carbon (SOC), dynamics, rotation, fertilizer

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## 1 Introduction

Soil can be a sink or a source for atmospheric  $\text{CO}_2$ ,

depending on soil conditions and agricultural practices, such as fertilizer application, organic amendment, tillage and cropping system<sup>[1-8]</sup>. The variations of site conditions result in observations inconsistent with effects of the cropping and land management practices on soil carbon<sup>[9]</sup>. Furthermore, the short-term effects are normally inconsistent with long-term effects on soil carbon sequestration<sup>[10]</sup>. There is a demand for accurate estimates of long-term changes in soil organic carbon (SOC) with agricultural practices.

A number of models have been developed to describe the dynamics of soil carbon and nitrogen, and to predict changes in soil organic matter (SOM) and nitrogen content in response to management practices<sup>[10-15]</sup>.

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CENTURY model<sup>[13]</sup> has been widely used to simulate possible changes in soil carbon under various climate and soil management conditions<sup>[8,11,16,17]</sup>. It was developed to deal with a wide range of cropping rotations and tillage practices for analyzing the effects of management and global climate changes on productivity and sustainability of agroecosystems. According to the recommendation of local experts who are involved in the development of carbon trading protocol, the version 4.0 of CENTURY model was used in the study. It runs on monthly time step and integrates the effects of climate and soil driving variables and agricultural management to simulate carbon, nitrogen, and water dynamics in the soil-plant system. It can simulate complex of agricultural management systems including crop rotations, tillage practices, fertilization, irrigation, grazing, and harvest methods. Its SOM submodel is based on multiple compartments and is similar to other models of SOM dynamics<sup>[12,18,19]</sup>. This submodel includes three SOM pools (active, slow and passive), above and below ground litter pools and a surface microbial pool which is associated with decomposing surface litter, and requires different potential decomposition rates and coefficients for SOC transfer among different pools during decomposition.

The K-model is a new non-compartment SOM model developed for similar purposes, especially for confirming the relative changes of SOC for carbon trade. It is in the simplest form, and requires minimum number of kinetic parameters that can be determined from site soil measurements, particularly from the turn over time of SOM. The long-term SOC in K-model is represented by one-pool with single and continuously decreasing decomposition rate<sup>[20-24]</sup>. The maximum decomposition rate can be determined from experimental measurements, and is modified by soil water and temperature conditions, and by cropping and land management practices. It runs on daily time step for crop growth simulation, carbon decomposition and nitrogen transformation. Transports of water and nutrients in soil use smaller time steps determined dynamically by transporting rate and transportable amount. Table 1 presents main differences between K-model and CENTURY model. We conducted this comparison study in order to understand how well K-model performs on predicting SOC in comparison with the most popular and widely used model, CENTURY. This paper presents the results of the comparison study in two long-term experimental plots in Alberta, Canada.

**Table 1 Brief differences between K-model and CENTURY**

	K-model	CENTURY
Soil organic matter (SOM)	Non compartment Deal with whole soil profile Single pool (plant biomass and dead biomass) use continuous rate Constant distributions Single rate, influenced by: <i>Soil water, Soil temperature, C:N ratio, Depth, Soil texture, Soil disturbance.</i> Correcting initial value by: <i>Auto-correction function using a known value as reference</i>	Multiple compartments Deal with upper 20 cm Three pools Three rates coefficients for and transfer of C among pools, influenced by: <i>Soil water, Soil temperature, Substrate types, Soil texture, Soil disturbance.</i> Correcting initial value by: <i>run simulation to establish steady state</i>
Crop growth	Biological process, influenced by: <i>Crop types, Water availability, Nitrogen availability, Temperature, Radiation, Humidity, Wind speed, Cropping management.</i>	Numerical process <i>Crop types, Water availability, Nutrient availability, Temperature, Cropping management,</i>
Time step	Daily	Monthly
Climate data	Daily climate	Statistical monthly data

## 2 Study sites and methods

The Breton Plots were established in 1930<sup>[25]</sup> on a

Gray Luvisolic soil (Typic Cryoboralf) under boreal climate near Breton, Alberta, Canada (53°07' N, 114°28' W) with a mean annual precipitation of 547 mm and a

mean annual temperature of 2.2°C. The Breton Plots had been converted from a mixed aspen (*Populus* spp.)–spruce (*Picea* spp.) forest to cultivated agriculture land in three to ten years early. It was designed to compare two rotations, a two-year wheat-fallow (WF) rotation and a five-year wheat-oat-barley-hay-hay (WOBHH) rotation, under different fertilizer treatments. The “hay” was mixture grasses including legume ones for

forage. Three fertilizer managements, 1) no fertilizer, 2) manure, and 3) chemical fertilizer including nitrogen, phosphorus, potassium and sulphur, were used for this study. Table 2 presents the detailed information of treatments. Detailed information on soil and cropping management, climate, and crop yield was recorded. The SOC contents of the upper 15 cm soil layer were measured periodically.

**Table 2 Detailed information of the Breton and Lethbridge Plots**

Treatment	Rotation	Soil amendment	Starting year
Breton Plots			
NF5	Wheat-oat-barley-hay-hay	No	1930
MF5	Wheat-oat-barley-hay-hay	Applied manure 4.4 t C ha <sup>-1</sup> every five years before 1979, and 1.75 t C ha <sup>-1</sup> after oat and before wheat after 1979	1930
CF5	Wheat-oat-barley-hay-hay	Applied fertilizer 10 kg N ha <sup>-1</sup> every year before 1979, and 50-75 kg N ha <sup>-1</sup> in cereal year after 1979	1930
NF2	Wheat-fallow	No, return residue from 1966 to 1974.	1930
MF2	Wheat-fallow	Applied manure 4.4 t C ha <sup>-1</sup> every five years before 1979, and 1.8 t C ha <sup>-1</sup> in wheat year after 1979	1930
CF2	Wheat-fallow	Applied fertilizer 10 kg N ha <sup>-1</sup> every cereal year before 1979, and then 90 kg N ha <sup>-1</sup> in wheat year, and return residue from 1966 to 1974	1930
Lethbridge Plots			
CW	Continuous wheat	No fertilizer, return residue after 1953	1911
WWF	Wheat-wheat-fallow	No fertilizer, return residue after 1953	1911
WF	Wheat-wheat-fallow	No fertilizer, return residue after 1953	1911
FW2H3	Fallow-wheat-wheat-hay-hay	Applied fertilizer 80 kg N ha <sup>-1</sup> in wheat year, remove crop residue	1951

The Lethbridge Plots were established in 1910 on Brown Cherozemic soil (Canadian classification) under cold temperate grassland climate near Lethbridge, Alberta, Canada. The mean annual precipitation and temperature are 345 mm and 5.8°C, respectively. These plots were converted from native grassland to agriculture in 1910. Four crop rotations, continuous wheat (CW), wheat-wheat-fallow (WWF), wheat-fallow (WF) and fallow-wheat-wheat-hay-hay-hay (FW2H3), were used in this study (Table 2). No fertilizer was applied for CW, WWF and WF, and nitrogen fertilizer was applied in the wheat years of FW2H3. The SOC contents of the upper 15 cm soil layer were measured periodically from 1922 to 1993. The annual grain yields of CW, WWF and WF rotations were also measured in this period.

A total of ten simulations were formatted for each of CENTURY and K-model in the Breton (6 simulations) and Lethbridge (4 simulations) long-term experimental plots (Table 2). The same soil data were used by both K-model and CENTURY model (Table 3). The

monthly climate data used in CENTURY model were summarized from the daily data used for K-model. All crop rotations including the cropping management input data were the same for both models. Key parameters including initial soil and climate data were listed in Table 4.

For the Breton Plots, the simulating period was from 1930 to 2005. For both models, the measured daily climate data from 1930 to 2005 and measured soil data from a nearby native land in 1936<sup>[10]</sup> were used to initialize the six simulations of the Breton Plots (Table 3). For both models, nitrogen deposit rate was estimated as 8 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The simulations of CENTURY model were also set as native grassland for 10 years before 1930, but the total SOC in the upper 20 cm soil layer in 1930 were enforced to be the same as those in K-model.

For the Lethbridge Plots, the simulating period was from 1911 to 2000. The soil and climate data were not site-specific such as those used for the Breton Plots. The soil data used in the four simulations were extracted

from Agriculture Region of Alberta Soil Inventory Database (AGRASID) (Table 3). Daily climate data from 1961 to 1997, which were interpolated from data of nearby meteorological stations and provided by Alberta Agriculture, were supposed to present the climate pattern in the Lethbridge Plots. Therefore, the missing climate data for periods of 1911-1960 and 1998-2000 were consequently filled using the data from 1961 to 1997. Simulations of K-model used auto-correction function, because the non-site specific soil data were used, which can differ significantly from the initial SOC of native soil when the plots were converted to agriculture. The

measurements of SOC in 1953 for CW, WWF and WF, and in 1973 for FW2H3, were used as the reference values for the auto-correction function of K-model to estimate the initial SOC. The simulations of CENTURY model were set as native grassland for 10 years before 1911, and monthly climate data were the statistical results of daily data used for simulations of K-model. However, for CW, WWF and WF in 1911 and for FW2H3 in 1951, the total SOC contents of the upper 20 cm layers in CENTURY were enforced to be the same as those in K-model.

**Table 3 Soil data used for initializing the simulations in the Breton and Lethbridge Plots**

Layer number	Depth/cm	Sand content/%	Clay content/%	Bulk density/Mg m <sup>-3</sup>	Organic carbon content/%
Breton Plots, Alberta, Canada					
1	9	26	12	1.32	1.25
2	18	26	12	1.35	1.25
3	33	34	29	1.45	0.50
4	76	32	33	1.5	0.30
5	112	31	33	1.5	0.30
6	150	35	27	1.5	0.00*
Lethbridge Plots, Alberta, Canada					
1	15	45	20	1.25	1.76
2	33	30	35	1.40	2.00
3	50	35	25	1.50	0.00
4	100	40	25	1.50	0.00

Note: \*The zero values in organic carbon contents indicate that the soil layer had no measurable organic carbon.

**Table 4 Key parameters of K-model and CENTURY used in the simulations**

	K-model	CENTURY
Climate data	Measured daily data	Recalculate from daily data
Initial soil organic carbon (SOC)	Layer by layer for the whole profile	Upper 20 cm, integrated from corresponding depth, and partitioned into different pools based on its standard coefficient for grassland/cropped soil
Maximum crop production	-	350-450 g C m <sup>-2</sup>
Maximum light use efficiency	4.54 g C MJ <sup>-1</sup>	-
Maximum decomposition rate	0.23-0.65 yr <sup>-1</sup> , decreasing with the age of SOM	0.20 yr <sup>-1</sup> (active), 0.13 yr <sup>-1</sup> (slow), 0.0045 yr <sup>-1</sup> (passive)

The simulation results and field measurement data for the period of 1930-2005 for the Breton Plots and for the period of 1911-2000 for the Lethbridge Plots were used to evaluate the performance of K-model and CENTURY in predicting long-term SOC dynamics after the evaluations on predicting crop yields in both sites. The statistical methods, developed by Smith et al.<sup>[17]</sup>, consisting of a number of statistical tests for comparison

of data series such as modeled and measured long-term crop yields and SOC trends, were followed.

### 3 Results

#### 3.1 Predictions of crop yields

In the studied Breton Plots, crop straw was one of the main sources of organic carbon returned into soil, especially in the NF5, CF5, NF2 and CF2. Figure 1

presents the predictions of K-model and CENTURY in the straw yields. The K-model generally simulated the temporal variation of annual straw yields, although the magnitude of inter-annual variation were always smaller than measured ones for all tested cropping system. The CENTURY remarkably overestimated the straw yields of the WOBHH rotation as well as underestimated them in the WF rotation (Figure 1). Crop straw yields predicted by K-model did not statistically differ with measurements (Table 5), which would be a good precondition for

accurate estimations of SOC dynamics. The insignificant correlation, high root mean square errors (RMSEs) and significant bias between measured values and modeled results confirmed the relatively poor predictions of CENTURY in crop straw yields (Table 5). Because the crop straw was one resource of the organic carbon input into soil although the most straw was removed from the fields in the Breton Plots, the significant over- or under-estimations would result in the over- or under-predictions of SOC sequestrations.

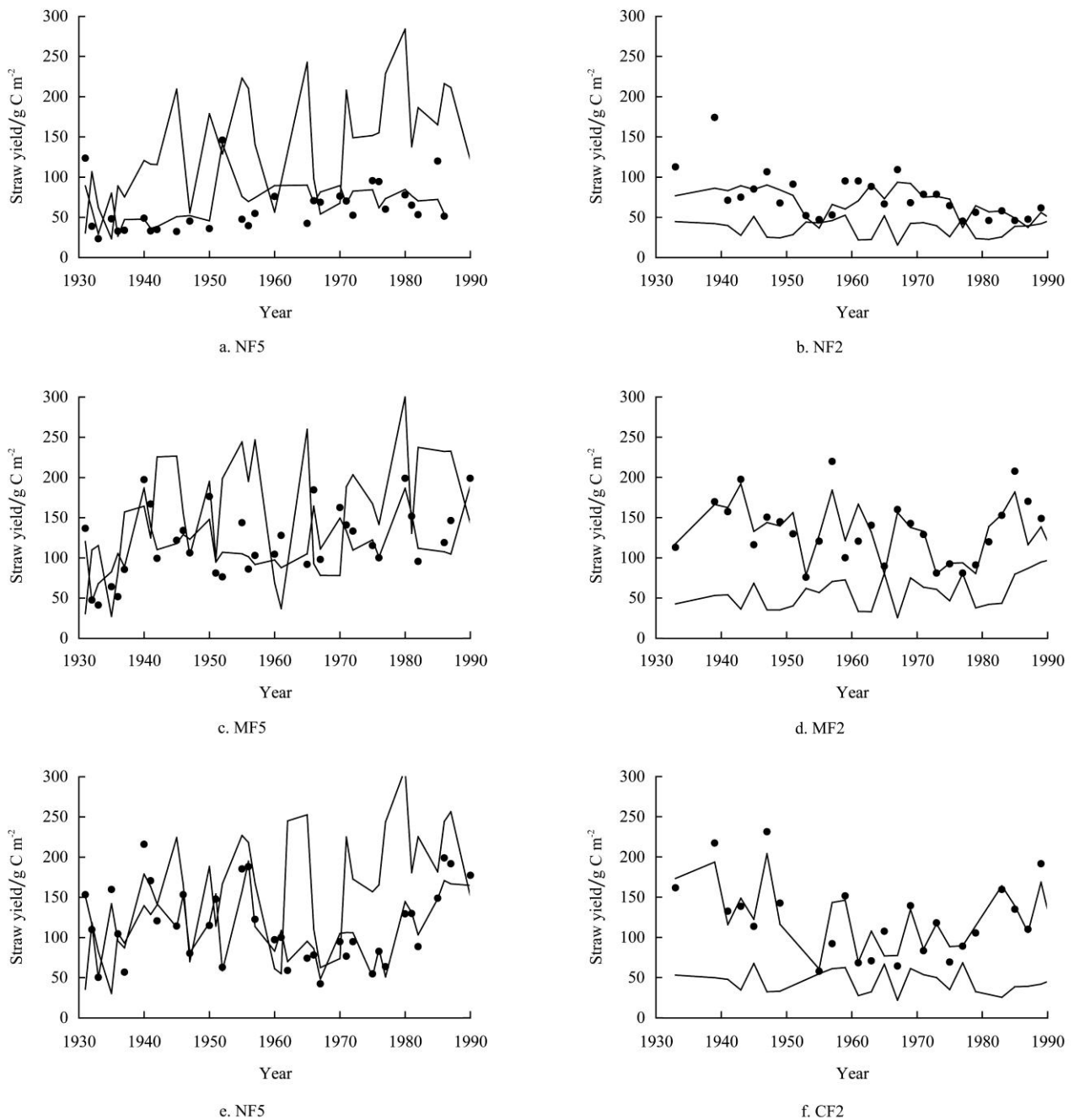


Figure 1 Measured and modeled crop straw yields of different cropping systems in the Breton Plots  
 Dots are the measured yields, and thin and thick solid lines are the modeled values of CENTURY and K-model, respectively

**Table 5 Results of statistical analysis for yield predictions in the Breton and Lethbridge Plots.** The straw yields ( $\text{g C m}^{-2}$ ), which may be the main part of carbon input by returning crop residues, are used in this analysis for the Breton Plots. Grain yields ( $\text{g C m}^{-2}$ ) were only available and measured crop data in the Lethbridge Plots.  $R^2$ , “Bias” ( $\text{g C m}^{-2}$ ) and RMSEs ( $\text{g C m}^{-2}$ ) present the correlation coefficients, the mean differences, and the RMSEs between modeled and measured data pairs. The negative values of “Bias” indicate that model overestimated the productions, otherwise, the underestimations occurred.

Treatment	K-model			CENTURY			Measured mean
	$R^2$	Bias	RMSEs	$R^2$	Bias	RMSEs	
Breton Plots							
NF5	0.55*	-3.20	20.81	0.05	-77.44 <sup>&amp;</sup>	107.66	60.85
MF5	0.78*	2.64	20.77	0.19	-38.31 <sup>&amp;</sup>	85.21	120.19
CF5	0.88*	0.83	16.41	0.17	-42.81 <sup>&amp;</sup>	89.24	116.41
NF2	0.42*	5.28	21.95	0.11	37.86 <sup>&amp;</sup>	48.95	74.33
MF2	0.76*	-0.61	19.22	0.12	74.37 <sup>&amp;</sup>	87.36	131.89
CF2	0.83*	-0.62	18.75	0.02	76.35 <sup>&amp;</sup>	89.98	122.08
Lethbridge Plots							
CW	0.31*	-8.34	23.80	0.22*	1.71	26.66	46.09
WWF	0.18*	2.09	28.21	0.27*	10.55	26.37	80.50
WF	0.04	5.74	29.51	0.35*	17.53	31.81	85.06

Note: \* The correlations between modeled and measured data are higher than 95% significance level.

<sup>&</sup> The average differences between modeled and measured data are different at 95% significant levels. It indicates that the predictions of a model are too far away from measurements.

Figure 2 illustrates the relationships between measured crop grain yields and modeled values of K-model and CENTURY in the Lethbridge Plots. Both models obviously underestimated the grain yields; particularly for WF rotation, with insignificant correlation, K-model did not represent the inter-annual dynamics of grain yield that indicated by the measurements (Figure 1 and Table 5). The RMSEs were smaller than 60% of measured means, and the bias between modeled grain yields and measured ones were not significant (Table 5). In statistical view, the predictions of both models were reasonable in the sense that differences from experimentally measured results were within the generally established limits of error. The grain yield could not directly affect the changes of SOC, and might partially indicate high or low yields of crop residues. However, the grain yield data were the only available crop production data for the Lethbridge Plots. The statistically acceptable predictions on grain yields mean that both models could simulate crop growth with certainly statistical confidence, and also provide indirectly references for judging the predictions of SOC dynamics.

In summary, the net primary production (NPP) and

root growth predicted by both models were not analysed because of the lack of data. However, the statistically acceptable performance of both models on predicting straw and grain yields could be good evidence to demonstrate the capability of estimating NPP, root and shoot growth. Eventually, K-model and CENTURY had statistically satisfied capability to predict crop growth, although the accuracies were not as good as expected, and both models provide good fundamental conditions for estimating the changes of SOC.

### 3.2 Predictions of SOC

Figure 3 illustrates the long-term dynamics of measured SOC and the predicted values by K-model and CENTURY in the upper 15 cm soil layer. The K-model correctly represented the dynamics shown by measurements, including the fluctuations caused by the changes of cropping management. The CENTURY model in general represented the trends of long-term SOC changes for some treatments but not for all.

For WOBHH rotation, K-model and CENTURY represented well for SOC dynamics of NF5 and MF5. The SOC increasing rate of CF5 simulated by CENTURY was more than double of the measured value ( $28.6 \text{ g C m}^{-2} \text{ yr}^{-1}$  vs.  $12.9 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), while it was correctly

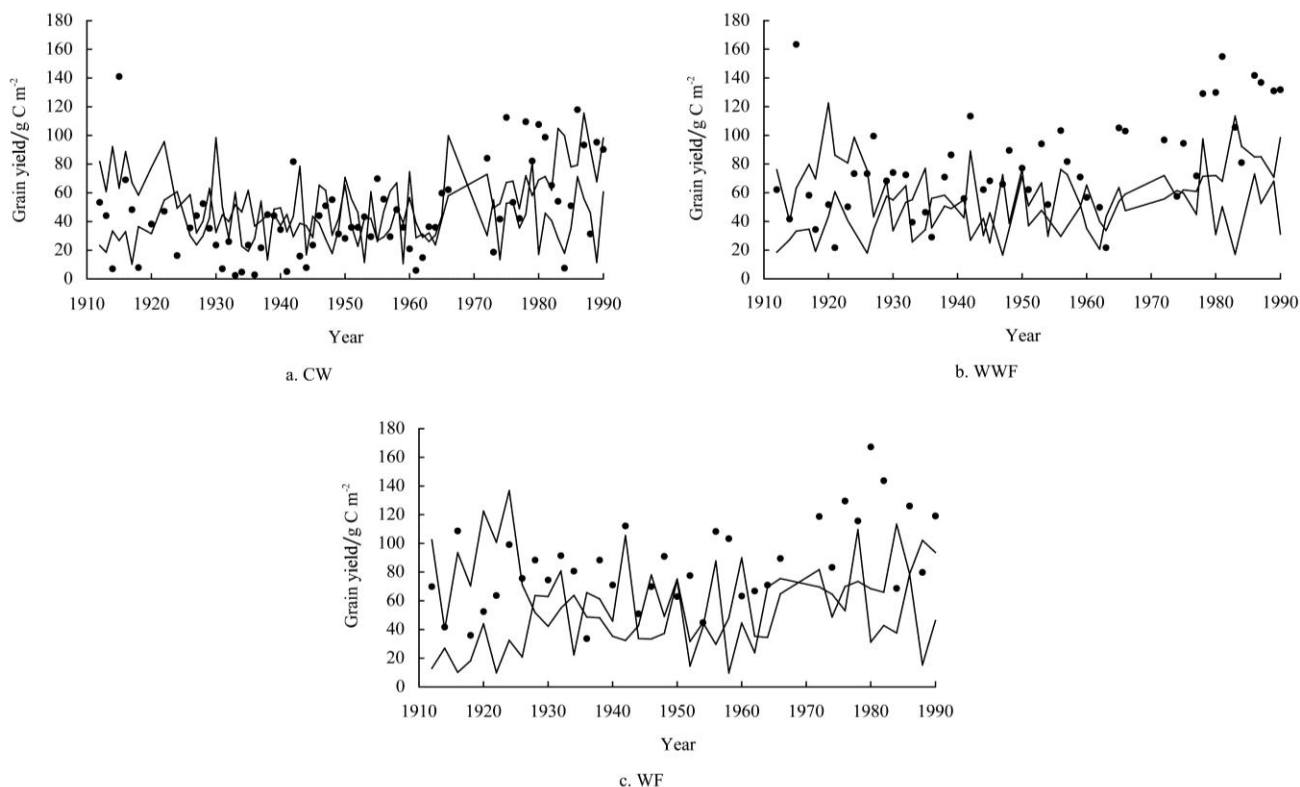
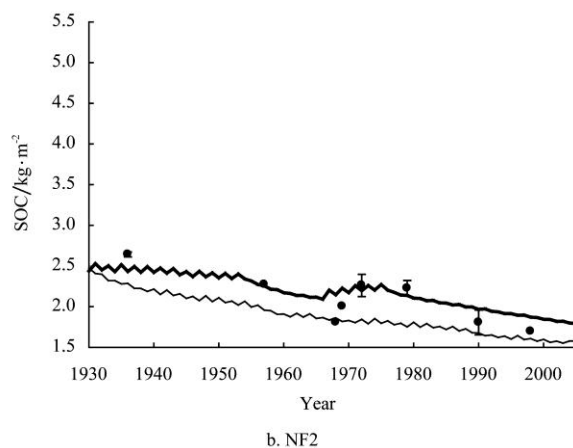
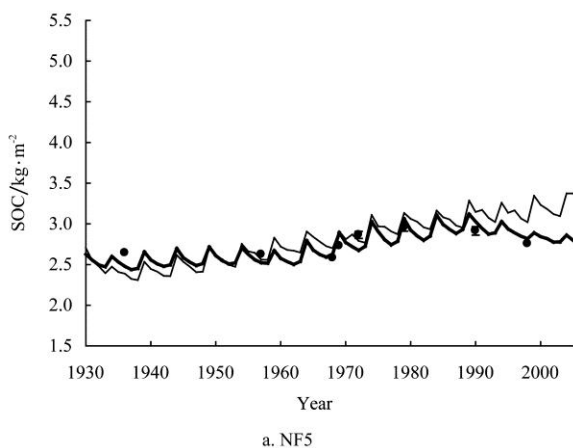


Figure 2 Measured and modeled crop grain yields of different cropping systems in the Lethbridge Plots. Dots are the measured yields, and thin and thick solid lines are the modeled values of CENTURY and K-model, respectively

predicted by K-model ( $11.4 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). However, K-model seems to over predict carbon loss in the CF5 during the relatively dry period between 1990 and 2005 (Figure 3; predicted loss of  $5.1 \text{ g C m}^{-2} \text{ yr}^{-1}$  vs. measured gain of  $7.5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ).

For wheat-fallow (WF) rotation, K-model predicted the decreases of SOC before 1966 for NF2 and CF2, followed by the increases resulted from switching clean harvest to return residue from 1966 to 1974 as shown by the measurements. In contrast, CENTURY did not predict the detailed variations of SOC shown by measured values, although the modeled rates of carbon

loss for NF2 and CF2 ( $12.1$  and  $5.4 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) were close to those of measurements ( $15.2$  and  $9.6 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) for the whole period from 1930 to 2005. For MF2 treatment, K-model predicted the steady increase of SOC ( $7.4 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) as indicated by measurements ( $7.8 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). The CENTURY predicted initial slow SOC loss and then fast increase of SOC, contradicting to the results of measurements and K-model predictions. The differences in carbon inputs and outputs in the upper 15 cm soil layer simulated by K-model and CENTURY (Table 6) may partially explain the differences in predicted SOC dynamics.



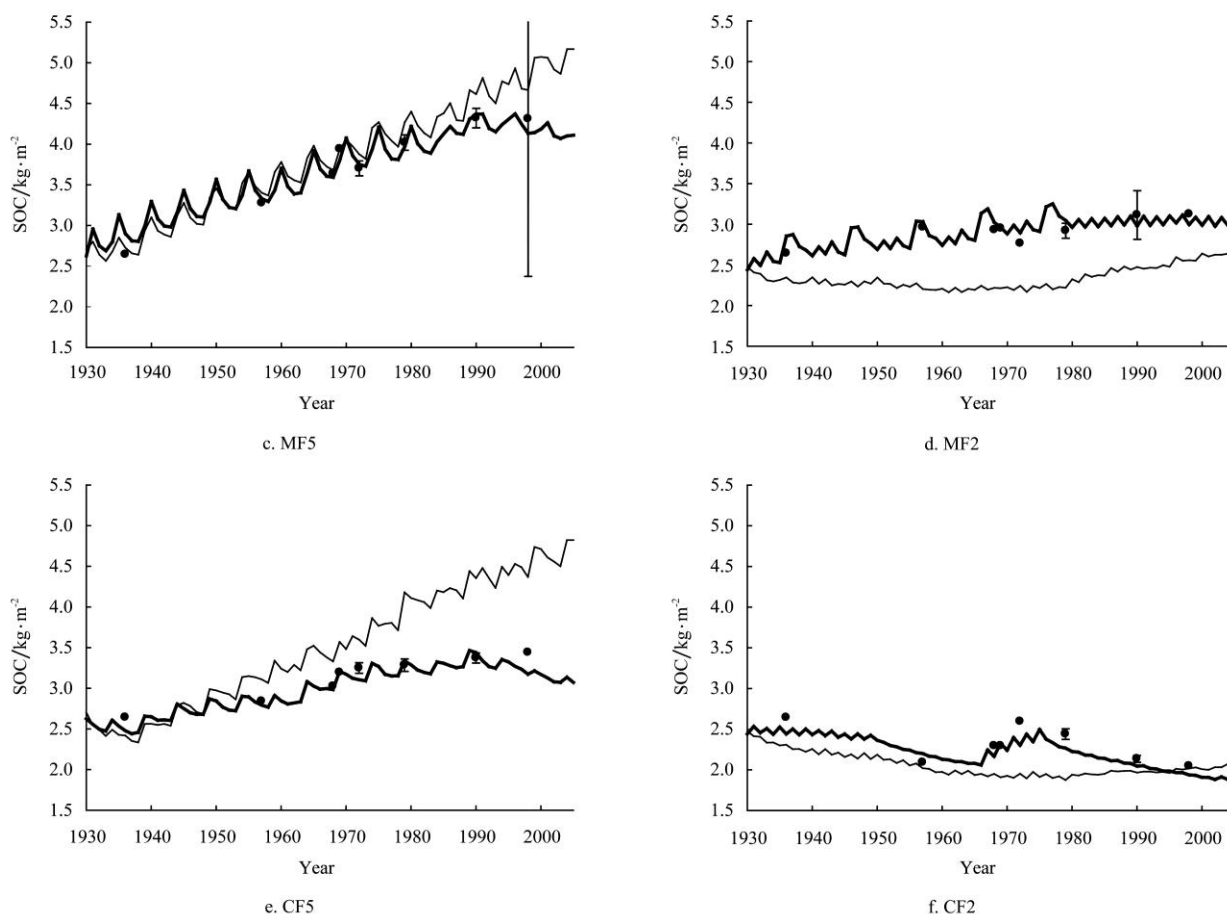


Figure 3 Measured and modeled soil organic carbon (SOC) in the upper 15 cm layer of the Breton Plots. Dots are the measurements, and thin and thick solid lines are the modeled values by CENTURY and K-model, respectively

**Table 6 Average annual budget of soil organic carbon (SOC) ( $\text{g C m}^{-2} \text{yr}^{-1}$ ) in the upper 15 cm soil layer in the Breton Plots**

Treatment	NPP	I <sub>c</sub>	H <sub>c</sub>	H <sub>c</sub> /I <sub>c</sub>	Rate	H <sub>c<sub>f</sub></sub>	H <sub>c<sub>c</sub></sub>	H <sub>c<sub>f</sub></sub> /H <sub>c<sub>c</sub></sub>
K-model								
NF5	385.53	95.48	91.37	0.96	4.11	-	-	-
MF5	388.50	178.18	156.78	0.88	21.41	-	-	-
CF5	386.14	122.61	114.85	0.94	7.77	-	-	-
NF2	140.81	38.95	48.16	1.24	-9.20	54.62	41.70	1.31
MF2	160.59	113.09	105.73	0.94	7.36	115.43	96.02	1.20
CF2	159.01	44.38	52.23	1.18	-7.85	60.48	43.98	1.38
CENTURY								
NF5	344.45	154.46	143.27	0.93	11.20	-	-	-
MF5	407.78	265.94	228.54	0.86	37.40	-	-	-
CF5	386.33	172.85	156.71	0.91	16.14	-	-	-
NF2	98.19	69.67	74.68	1.07	-12.51	77.14	72.21	1.07
MF2	137.80	114.93	110.75	0.96	4.19	128.39	93.11	1.38
CF2	146.86	81.29	86.13	1.06	-4.82	86.26	85.94	1.00

Note: NPP: Net primary production. I<sub>c</sub>: Total carbon input from crop and additional carbon application in the upper 15 cm soil layer. H<sub>c</sub>: Carbon loss through heterotrophic respiration process in the upper 15 cm soil layer. H<sub>c<sub>f</sub></sub>: H<sub>c</sub> in the fallow years. H<sub>c<sub>c</sub></sub>: H<sub>c</sub> in the crop years.

Figure 4 presents the results of statistical analysis using the method of Smith et al.<sup>[17]</sup>. Comparing the predicted SOC values of K-model with measured values, the correlations were all significant, and RMSEs and

relative errors were not statistically significant. The RMSEs were less than 0.1 kg C m<sup>-2</sup>, and relative errors were less than 5%. The statistical results showed that the SOC values predicted by CENTURY were significantly



correlated to measurements, except for MF2 and CF2. The RMSEs were less than  $0.2 \text{ kg C m}^{-2}$  and not statistically significant. The relative errors were less than 10% and not statistically significant for NF5, MF5 and NF2 treatments, but the relative errors were larger than 10% and significant for CF5, MF2 and CF2 treatments.

In summary, K-model and CENTURY have a good capacity to represent SOC dynamics of the Breton Plots.

Statistically, predictions of SOC by both models are acceptable. However, K-model correctly predicted the details of SOC changes upon changing residue management, while CENTURY did not. Considering the large RMSEs and significant relative errors nearly double those of K-model, the accuracies of CENTURY predicted SOC contents and SOC changes were less than those of K-model.

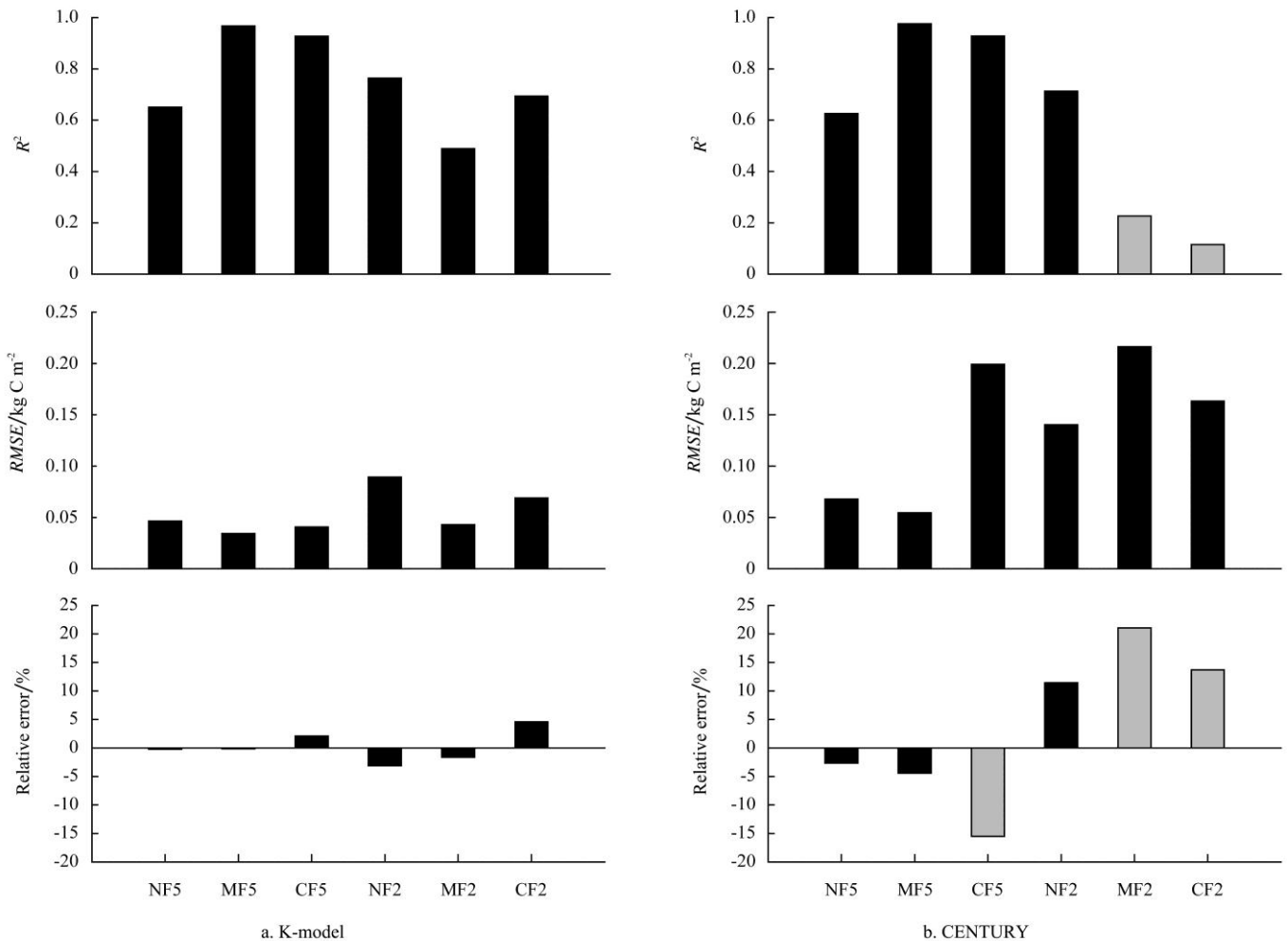


Figure 4 Correlations, root mean square errors (RMSEs) and relative error between measured and modeled soil organic carbon (SOC) in the upper 15 cm soil layer of the Breton Plots. Black bars indicate significant correlations or insignificant RMSEs and relative errors, and grey bars show insignificant correlations or significant RMSEs and relative errors

Figure 5 shows the dynamics of SOC in the Lethbridge Plots measured experimentally and predicted using K-model and CENTURY for the upper 15 cm soil layer. Modeled SOC changes by K-model generally reproduced the dynamics of measured results, especially the reverse of SOC loss after 1953 when the management changed from clean harvest to residue return (RR). However, K-model did not catch all measurements,

notably measurements in 1973 for CW, WWF and WF. These differences are most likely due to errors in the measurements. Data considering adjacent measurements in 1967 and 1980, the sudden decreases measured SOC from 1967 to 1973 and subsequent recoveries from 1973 to 1980 were more than  $101 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $112 \text{ g C m}^{-2} \text{ yr}^{-1}$ , respectively, almost equalled to total annual carbon inputs. These changes could only be

possible if for some reasons decomposition was exceedingly fast, or there was no carbon input from 1967 to 1973 and then carbon input returned to normal and decomposition stopped from 1973 to 1980. No logical

explanation could be found for the sudden drop in measured values in 1973. Therefore, the measurements in 1973 were not used in the statistical analysis.

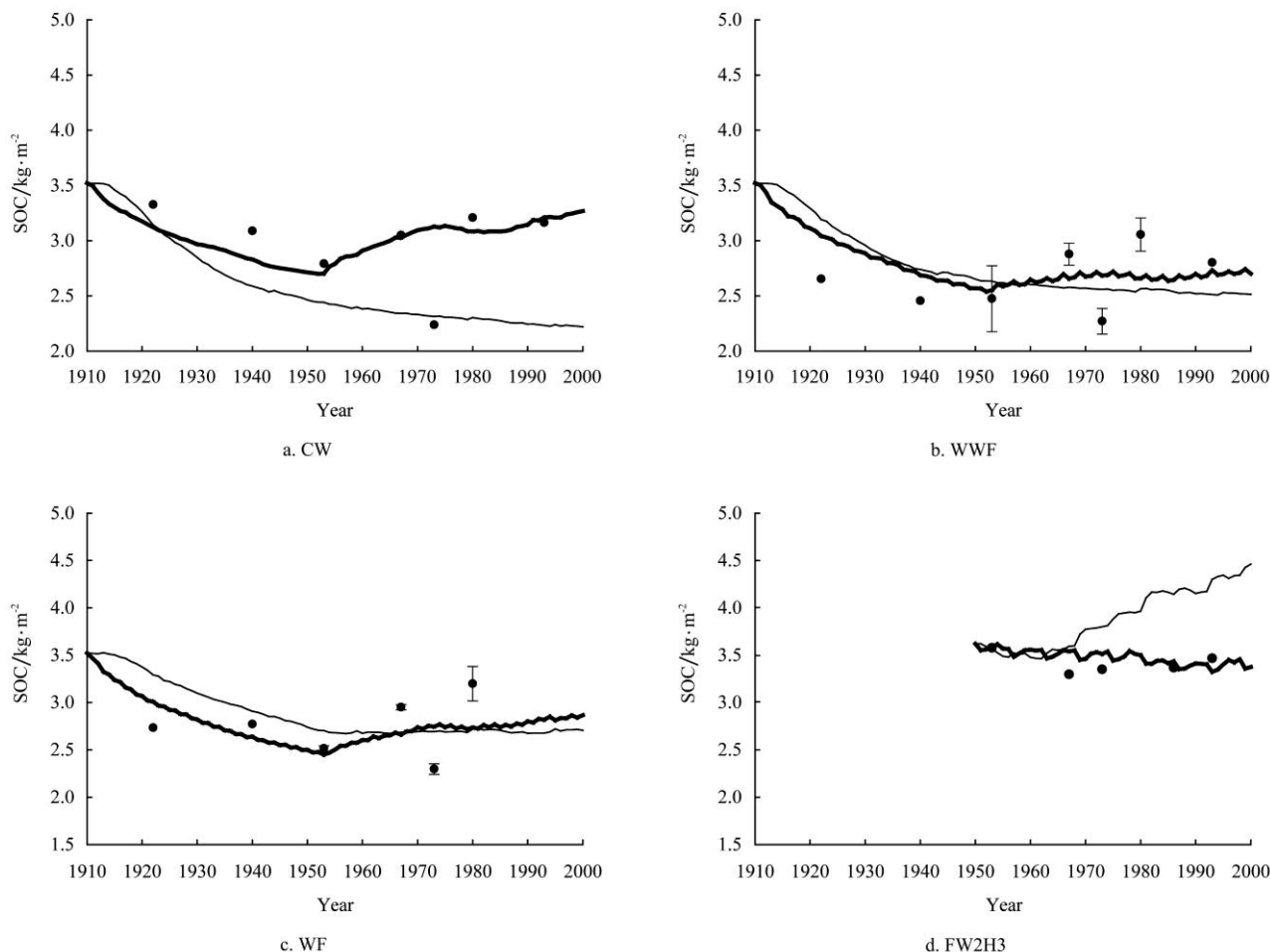


Figure 5 Measured and modeled soil organic carbon (SOC) in the upper 15 cm layer of the Lethbridge Plots.

Dots are the measurements, and thin and thick solid lines are the modeled values by CENTURY and K-model, respectively

The predicted SOC contents of CENTURY in the upper 15 cm layer did not follow the same dynamics as the measurements. The predicted SOC contents decreased continuously for CW, WWF and WF, completely missing the SOC recovery after 1953. For FW2H3, CENTURY predicted a much higher rate of SOC increase than measurements. The large differences on carbon inputs and outputs in the upper 15 cm soil layer simulated by K-model and CENTURY (Table 7) may partially explain the remarkable differences in their predicted SOC dynamics.

Figure 6 illustrates the results of statistical analysis comparing predicted SOC contents by K-model and CENTURY with measured values in the upper 15 cm soil

layer of the Lethbridge Plots. Correlations between measured and predicted SOC by K-model were all significant. The RMSEs were less than  $0.1 \text{ kg C m}^{-2}$  and not statistically significant. The relative errors were smaller than 5% and not statistically significant. These values are in the same range as those for the Breton Plots. However, the predicted SOC values of CENTURY were not statistically significantly correlated with measurements for all treatments. The RMSEs ( $0.15\text{--}0.35 \text{ kg C m}^{-2}$ ) were large but not statistically significant. The relative errors for CW and WWF were larger than 20% of measurements and significant, while they were not statistically significant for FW2H3.

**Table 7 Average annual budget of soil organic carbon (SOC) ( $\text{g C m}^{-2} \text{yr}^{-1}$ ) of the upper 15 cm soil layer in the Lethbridge Plots**

Treatment	Period	NPP	Ic	Hc	Hc/Ic	Rate	H <sub>Cr</sub>	H <sub>Cc</sub>	H <sub>Cr</sub> /H <sub>Cc</sub>	
										K-model
CW	HP	198.91	75.38	76.93	1.02	-1.54	—	—	—	
	NRR	203.19	24.07	42.56	1.77	-18.50	—	—	—	
	RR	195.08	122.34	108.37	0.89	13.97	—	—	—	
WWF	HP	237.10	66.94	67.51	1.01	-0.58	76.87	62.83	1.22	
	NRR	249.01	17.90	33.57	1.88	-15.67	—	—	—	
	RR	226.46	118.37	103.11	0.87	15.24	—	—	—	
WF	HP	190.73	61.14	67.32	1.10	-6.18	78.95	55.69	1.42	
	NRR	191.53	15.46	37.09	2.40	-21.62	—	—	—	
	RR	190.01	102.93	94.98	0.92	7.95	—	—	—	
FW2H3 (1951-2000)		272.34	100.74	90.75	1.11	9.99	147.26	81.01	1.82	
CENTURY										
CW	HP	191.50	56.55	82.49	1.46	-25.94	—	—	—	
	NRR	193.72	52.28	91.38	1.75	-39.10	—	—	—	
	RR	189.51	60.96	68.60	1.13	-7.64	—	—	—	
WWF	HP	209.72	48.42	73.87	1.53	-25.45	74.77	73.42	1.02	
	NRR	221.54	45.50	86.32	1.90	-40.82	—	—	—	
	RR	199.15	51.35	61.42	1.20	-10.07	—	—	—	
WF	HP	186.50	51.86	73.92	1.43	-21.43	79.94	67.90	1.18	
	NRR	188.72	47.28	86.08	1.82	-38.80	—	—	—	
	RR	184.51	55.96	63.60	1.13	-7.64	—	—	—	
FW2H3 (1951-2000)		308.28	210.23	195.42	0.93	14.81	219.89	207.94	1.06	

Note: NPP: Net primary production. I<sub>c</sub>: Total carbon input from crop and additional carbon application in the upper 15 cm soil layer. H<sub>c</sub>: Carbon loss through heterotrophic respiration process in the upper 15 cm soil layer. H<sub>Cr</sub>: H<sub>c</sub> in the fallow years. H<sub>Cc</sub>: H<sub>c</sub> in the crop years. HP: Whole simulated period from 1911 to 2000. NRR: Period without residue return. RR: Period with complete residue return.

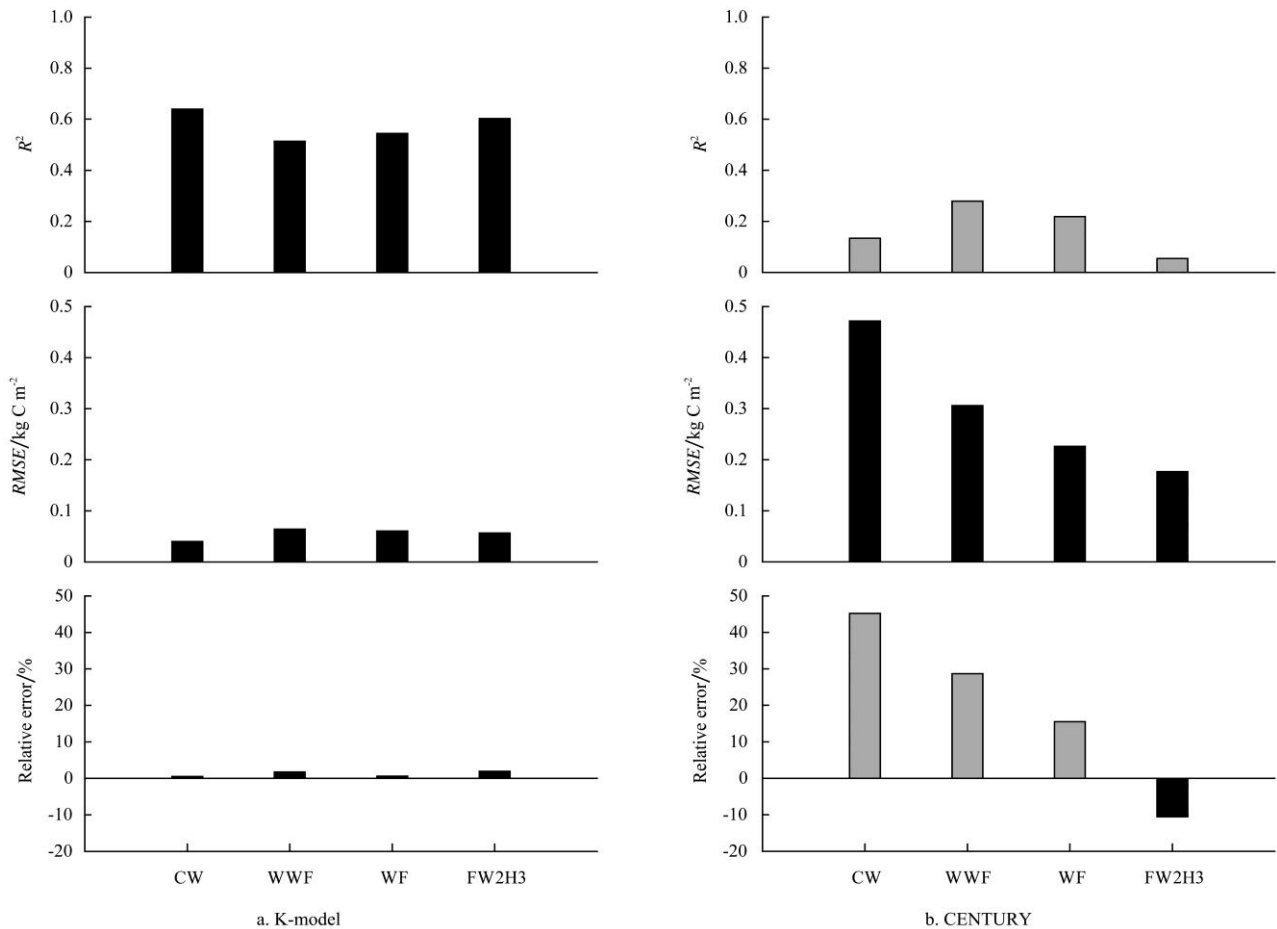


Figure 6 Correlations, root mean square errors (RMSEs) and relative error between measured and modeled soil organic carbon (SOC) in the upper 15 cm soil layer of the Lethbridge Plots. Black bars indicate significant correlations or insignificant RMSEs and relative errors, and grey bars show insignificant correlations or significant RMSEs and relative errors

In summary, K-model represented the SOC dynamics consistently with statistically acceptable accuracy for both of the Breton Plots and Lethbridge Plots. The predictions of CENTURY were relatively poorer than those of K-model. The CENTURY performed acceptably in representing SOC dynamics when site-specific soil and climate data are available, such as the case for the Breton Plots. However, when these site-specific data are not available, CENTURY has no means of compensating for the inaccuracies in the input data, and as a result, may fail in its predictions. The K-model, on the other hand, has the ability to compensate the uncertainties in the input data by using a single SOC value, measured at any time, as reference through its auto-correction function.

#### 4 Discussion

For both of K-model and CENTURY model, the relatively low accuracies on prediction crop growth led the predicted SOC contents and its changes by differing to measurements, although some of the differences (i.e. errors) were not statistically significant (Figures 1 to 4). One reason for the errors is that ecosystems such as agricultural and natural lands are very complex, and computer models do not have capability and possibility to represent the complex system identically because of insufficient knowledge and imperfect conceptualizations about ecosystem processes<sup>[8]</sup>. The other reason is the uncertainties in model parameterization and input data such as climate, soil data, and land management assumptions<sup>[26]</sup>. Therefore, the predicted values are acceptable if differences between simulated and measured results are not statistically significant at 95% or even at 90% confidence levels. However, the initial soil, climate and land management data (i.e. data before land were converted from native land to agriculture) are often unavailable, although they have important influences on measured and simulated SOC values. Sometimes, the initial data such as soil data may be available, but are often inferred from nearby native soils measured at some time much later; for example, the initial soil data for the Breton Plots in this study, significant errors can result from these estimates. Therefore, the initialization of soil

condition and land management before the simulation period is important for correctly predicting SOC dynamics.

For unknown initial conditions, CENTURY runs simulation to establish steady state of SOC using input soil data under native land management such as native natural grassland. The K-model assuming native soil before cultivation was at steady state and SOC changes from beginning of cultivation to beginning of experimental were estimated using the best available climate and management information. The K-model uses auto-correction function to adjust or estimate the initial values of SOC using any available SOC data as reference, because initial values of SOC are often not available, or are assumed in error as they are often estimated or taken from databases that contain information obtained from survey or measurements of unknown dates. The different methods for initializing SOC between K-model and CENTURY resulted in the differences of easily decomposable SOC at the starting time of simulations and subsequent simulating periods, although the total amount of initial SOC was enforced to be the same in both models.

Comparing the SOC changes simulated by K-model and CENTURY under no fertilizer and no organic amendment applications, estimations of average annual NPP of crops by K-model were higher than those by CENTURY for both Plots (Tables 6 and 7). Carbon inputs in the upper 15 cm soil layer ( $I_C$ ) simulated by K-model were much smaller than those by CENTURY for the Breton Plots, while lower values were predicted by K-model for the Lethbridge Plots. One reason for the difference in simulated carbon inputs may be that the two models simulated different depths of soil profile. The K-model simulated soil carbon for the whole soil profile where decomposition of SOC and crop root growth occurs. The CENTURY calculated soil carbon changes only in the upper 20 cm soil layer without considerations of lower horizons. Another reason may be that K-model and CENTURY use different carbon allocating functions. The K-model uses a dynamic allocation function influenced by water, nutrient, radiation and shading factors. It can allocate more carbon to root and deeper

soil layers in poor and/or dry soil conditions, and less carbon to roots and shallow soil layers in fertile and/or moist soil conditions. The negative effects of poor soil conditions on crop growth are partially offset by dynamically changing the explored soil volume for meeting crop requirements on water and nutrients. The CENTURY did not include this self-adjustment capacity of crops. The ratios of heterotrophic carbon losses to carbon inputs ( $H_C/I_C$ , Tables 6 and 7) were very close between the results of the two models. This also means that the single carbon pool of K-model and three carbon pools of CENTURY generated similar results on carbon decomposition. However, the single pool of K-model has a single rate controlling parameter that was much easier to determine than the three rate constants in CENTURY.

Considering these two reasons, the rate of SOC increased higher with larger amount of carbon inputs while the values of  $H_C/I_C$  were less than one. The SOC decreased faster with the smaller amount of carbon inputs when the ratios were greater than one (Tables 6 and 7). In general, in comparison with measurements, CENTURY overestimated rates of SOC change, as shown in Figures 3 and 4 and Tables 6 and 7, because of inaccurate estimations of carbon inputs. The K-model produced better estimations of SOC and its changes in no fertilizer fields.

In the Breton Plots, when chemical fertilizers were applied in the CF5 and CF2 treatments, estimates of NPP by K-model were similar to those of CENTURY (Table 6). Carbon inputs into the upper 15 cm soil layer estimated by K-model were much lower than those by CENTURY. The reasons for these differences on carbon inputs were discussed above. Moreover, the values of  $H_C/I_C$  are very close. Therefore, as shown in Figure 3, CENTURY produced higher rates of increase and lower rates of decrease with its higher carbon inputs, while K-model produced SOC changes that are close to measurements.

For the Lethbridge Plots, the predicted NPP of K-model was 22% lower than that of CENTURY in FW2H3, where chemical fertilizers were applied in wheat years of the rotation (Table 7). Carbon input in the

upper 15 cm soil layer simulated by K-model was half of that by CENTURY. Therefore, with the similar values of  $H_C/I_C$ , CENTURY model predicted almost double the rate of SOC increase in comparison with those shown by measurements and predicted by K-model. The overestimation of NPP by CENTURY, and the two reasons as discussed previously, accounts for the overestimation of SOC increase shown in Figure 5 and Table 7. Some other studies also demonstrated that CENTURY overestimated carbon stock with nitrogen fertilizer applications<sup>[8]</sup>.

There were about 5-14% differences on estimations of NPP by the two models when manure was applied (Table 6). The CENTURY had higher estimation in WOBHH rotation while K-model had higher estimation for WF rotation. The ratio of carbon input in the upper 15 cm soil layer to NPP for CENTURY was much higher than for K-model. In addition, the ratios of carbon loss to carbon input (i.e.  $H_C/I_C$ ) were similar for these two models. For MF5, CENTURY predicted higher carbon input, resulting in slight higher rate of SOC increase than those of measurements and the predictions by K-model. The significant relative errors between measurements and simulated values also demonstrate that CENTURY overestimated SOC changes. For MF2, the similar carbon inputs simulated by these two models (Table 6) resulted in similar rates of SOC changes. However, CENTURY predicted a decrease of SOC before 1979, and an increase thereafter (Figure 3), with lower overall rate of increase than measurements and results from K-model, for the whole simulating period. These differences on SOC changes also resulted in the large root mean square error and significant relative error for CENTURY (Figure 2).

Figures 3 and 5 shows that CENTURY model did not predict the increases of SOC resulting from RR in NF2 and CF2 treatments of the Breton Plots, and in CW, WWF and WF treatments of the Lethbridge Plots. The return of residue occurred for less than 10 years around 1970 in NF2 and CF2 treatments. Therefore, discussion about residue management will be concentrated on CW, WWF and WF treatments of the Lethbridge Plots.

Without fertilizer, the predictions of NPP by

CENTURY were slightly lower than those by K-model, and the differences were less than 13% for the Lethbridge Plots (Table 7). The predictions of NPP by the two models were higher before RR than after RR, but the differences were less than 11%. However, large differences existed between carbon inputs modeled by K-model and CENTURY. During the period of no residue return (NRR), carbon inputs consisted of root senescence and crop stubble. Carbon inputs in the upper 15 cm soil layer modeled by K-model were only 30% to 46% of those simulated by CENTURY (Table 7). With the similar of carbon loss to carbon input ratios estimated by both models, ranged from 1.77 to 2.40, indeed large differences in predicted carbon inputs lead to large differences in predicted carbon losses. As a result, CENTURY predicted larger decreases of SOC than K-model did (Table 7). During the period of complete RR, carbon inputs modeled by K-model were much higher than those by CENTURY. Comparing the carbon inputs in RR with those in NRR, K-model predicted increase of carbon inputs in RR by 87-100 g C m<sup>-2</sup> yr<sup>-1</sup>, while CENTURY model only predicted increases of 6-8 g C m<sup>-2</sup> yr<sup>-1</sup> after all surface residues were relocated into the upper 15 cm soil layer through tillage operations. Small amount of increases in carbon inputs in complete RR could not turn SOC from continuous decrease into increase, as shown by measurements and modeled results of K-model (Figure 5). In summary, CENTURY model did not predict the increases of SOC after crop residues were completely returned, because too little carbon was allocated into leaf and stem of crops. Higher allocation of carbon to leaves and stems by K-model allows it to produce predictions of SOC increase after RR that closely followed experimental measurements.

The K-model and CENTURY estimated similar heterotrophic carbon losses in fallow years in crops-fallow rotations, such as NF2, MF2, and CF2 of the Breton Plots, and WWF and WF of the Lethbridge Plots. However, the carbon losses modeled by K-model were much lower than those predicted by CENTURY in cropping years and were closer to measured values. The K-model thus correctly predicted SOC changes rates,

while CENTURY overestimated SOC loss overtime.

In fallow-crop-grass rotation (i.e. FW2H3 in the Lethbridge Plots), CENTURY doubled the heterotrophic respirations in fallow and cropping years in comparison with the K-model. However, the high NPP and the more than double carbon input estimated by CENTURY offset the large carbon loss and produced higher rate of SOC increase than measurements and modeled results of K-model.

## 5 Conclusions

When the site-specific soil and climate data were available to initialize simulations, both K-model and CENTURY have the capacity to represent the dynamics of SOC. Statistically, there were no significant differences between measurements and modeled results, although the RMSEs and relative errors of CENTURY were larger than those of K-model. When non site-specific soil and climate data were used to initialize simulations, considerable uncertainties are introduced because of the uncertainties in initial soil conditions and history of management, as well as errors that may exist in the climatic data, K-model can still represent the dynamics of SOC with no significant reductions in accuracy. The CENTURY, on the other hand, may produce poor results that significantly differ from measurements in the cold and dry agricultural ecosystem.

This study shows that K-model, in comparison with CENTURY, improved predictions of effects of chemical fertilizer, manure application, residue management and fallow on SOC dynamics. The possible reasons for these improvements were: 1) K-model simulated the SOC dynamics within whole soil profile where soil water, nutrient and aeration conditions allow root growth, while CENTURY only simulated the SOC dynamics of the upper 20 cm soil layer; 2) in comparison with CENTURY, K-model had strong capacity to adjust carbon allocation, as well as the root growth and root distribution within soil profile according to the soil texture, water, nutrient and aeration conditions, these adaptive adjustments of crop growth modeled by K-model reduces the negative effects of water and nutrient stresses on crop growth; 3) K-model allocated correct amount of carbon to leaf and stem which

allows increases in the SOC resulting from complete RR to be accurately represented, CENTURY, on the other hand, is not as flexible; and 4) K-model and CENTURY use different methods to deal with initial soil, climate and management.

The single carbon pool of K-model and three carbon pools of CENTURY did not generate large differences on carbon decomposition rates. However, K-model only requires a single decomposition parameter comparing with three parameters required by CENTURY. The less and easily measurable parameters and other data required by K-model improved the utility of model. Auto-correction function of K-model was helpful for accurate predictions if measurements are available to be used as references.

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