Long-Term Effects of Crop Management in Wheat-Fallow: II. CENTURY Model Simulations

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ABSTRACT

There is increasing need to develop models to assess the long-term effects of management practices on soil and environmental quality, and to test these models across a wide range of environments. The CENTURY model was used to simulate long-term management practices for wheat (*Triticum aestivum* L.)-fallow agriculture. The objectives were to compare the accuracy of predicted vs. observed data and use the model to help interpret observed data and to determine the long-term impact of crop management on C and N stabilization in soil. The model simulated grain and straw yield and grain N uptake within ±10% of the observed data, and 0- to 30-cm soil C and N within ±5%. Improvement in performance requires addition of a dynamic plant growth submodel to represent the effect of soil N on C and N allocation to roots, straw, and grain. Soil C changes were a linear function of aboveground C inputs; an input of 200 g C m^{-2} yr^{-1} (4650 kg straw ha^{-1}) was required to stabilize soil C at its present level. Estimates of soil C stabilization efficiency ranged from 12 to 27% and was highest for the high N fertilizer treatment. Soil N stabilization efficiency was higher for organic N additions (37–46%) than for inorganic additions (18–26%). Inorganic N treatments had similar N removal in grain, higher other nonidentifiable N losses, but lower N stabilization in soil than organic N treatments. Soil N data suggest that mineralization of N from the 30- to 60-cm layer needs to be considered in the N budget, as nearly 39 g m^2 were mineralized between 1931 and 1986.

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Published in Soil Sci. Soc. Am. J. 58:530–536 (1994).

SOIL ORGANIC MATTER MODELS have been used extensively during the last 20 yr to help improve our understanding of soil organic matter (SOM) dynamics. The model developed by Jenkinson and Rayner (1977) suggested that SOM can be divided into active, slow, and passive pools, which have different turnover times (1, 30, and 1500 yr, respectively). Van Veen and Paul (1981) used an approach similar to Jenkinson and Rayner, but included the effect of physical and chemical protection of SOM, soil erosion, and soil cultivation in their model. In more recent years, Parton et al. (1987) included the effect of soil texture on SOM dynamics and developed a generalized nutrient cycling model that simulates C, N, P, and S dynamics (Parton et al., 1988). The most recent version of Jenkinson's model (Jenkinson, 1990) also includes soil physical protection by clay. The DNDC model (Changsheng et al., 1992) incorporates many of the concepts incorporated in previous SOM models including soil texture impacts on SOM dynamics, and has been used to study detailed nutrient cycling dynamics and trace gas fluxes using daily time steps.

Jenkinson and Rayner's model was tested using data from the long-term Rothamsted experiments (Jenkinson, 1990). Van Veen and Paul's model was tested using SOM data from Canada (Van Veen and Paul, 1981; Voroney et al., 1981), while CENTURY was tested

Abbreviations: SOM, soil organic matter; DECO, abiotic decomposition factor; ST/GR, straw/grain ratio.

using long-term SOM experiments in Sweden (Paustian et al., 1992) and soil organic C and N and plant production data from grassland soils in the U.S. Great Plains (Parton et al., 1987). There are a number of long-term studies that show SOM dynamics and plant production are manipulated by tillage practices and addition of chemical fertilizer and organic amendments (Rasmussen and Collins, 1991). We describe the use of the CENTURY model (Parton et al., 1987, 1988) to simulate the impact of different organic matter management practices on plant production, N cycling, and soil organic matter dynamics at the long-term (1931–present) residue management plots at Pendleton, OR. The study was set up to evaluate the impact of fertilizer additions and residue management on grain yield and soil quality for a wheat–fallow system. A complete description of the Pendleton site, the experimental design, and the results from the experiment are described in Rasmussen and Parton (1993).

Our major focus is the process used to adapt the model to the Pendleton site, the comparison of observed data with the model results, and an analysis of the long-term impact of crop management practices on C and N stabilization and N budgets. We used the model to help interpret the observed data, flagged apparent errors in the model, and identified specific research that is needed to improve our understanding of SOM dynamics.

MODEL DESCRIPTION

The CENTURY model was developed to simulate long-term (10–1000 yr) patterns in SOM dynamics (0–30-cm depth), plant production, and nutrient cycling (N, P, and S). The model uses a monthly time step and the driving variables include: monthly average maximum air temperature (°C at 2 m), monthly precipitation (cm), soil texture (sand, silt, and clay content), dead plant material nutrient and lignin content, and atmospheric and soil inputs of N. The flow diagram for the soil C model (Fig. 1a) shows that plant material is divided up into structural (difficult to decompose) and metabolic (readily decomposable) material and that soil organic matter is divided up into active, slow, and passive SOM. Active SOM included live microbes and microbial products and makes up 2 to 5% of the total soil C (minimum turnover time of 0.5 yr). Slow SOM has a longer turnover time (minimum of 10 yr) and is derived from resistant plant material (lignin) and physically protected SOM. Passive SOM has a long turnover time (minimum of 500 yr) and is physically and chemically protected from decomposition. The actual turnover times of each of the SOM pools is a function of the maximum turnover time of the specific SOM pool and DECO. The value of DECO is calculated by multiplying the soil moisture factor (function of precipitation and stored soil water) and the soil temperature factor (function of average monthly soil surface temperature). The turnover rate of active SOM is also a function of soil texture (higher for sandy soils), while the stabilization of active SOM into slow SOM is a function of the silt plus clay content (higher stabilization for higher silt plus clay contents).

The soil N submodel (Fig. 1b) has the same basic structure as the soil C flow diagram and N flows are calculated as the product of the C flow rates and C/N ratio of the material being created. The C/N ratios of the different SOM fractions change as a function of soil mineral N, with higher ratios for low mineral N levels (see Fig. 1b for range of C/N ratios). Turnover of the

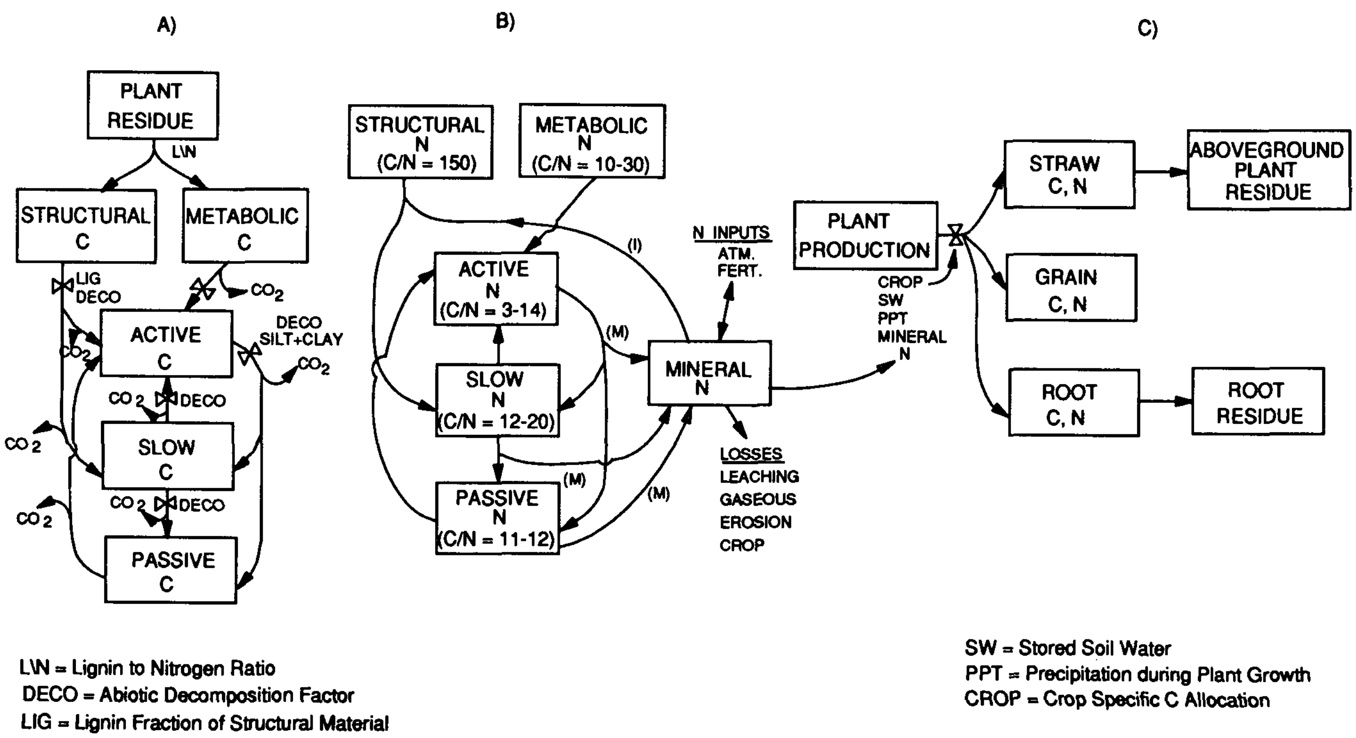

Fig. 1. Flow diagram for the CENTURY model: (a) soil C, (b) soil N, and (c) crop production.

active SOM creates most of the soil mineral N, while decomposition of structural plant material immobilizes substantial amounts of N. A complete description of the N cycling model and soil C model is presented by Parton et al. (1987).

The crop plant submodel (Fig. 1c) is fairly simple. Maximum aboveground plant production (MX_P, g m^{-2} biomass) is calculated as a function of the initial stored soil water at planting (H_2O_I, cm) and the precipitation that occurs while the crop is growing (PPT, cm) using the following equation:

$$MX_P = (H_2O_I + PPT)MX$$

where MX is maximum aboveground plant production per centimeter of water. Actual plant production is generally less than the maximum value depending on the availability of mineral N. Carbon and N are allocated into roots, grain, and straw according to a fixed allocation pattern. Other important inputs for the plant model are the minimum and maximum C/N ratios for the total crop. Table 1 summarizes the parameters used for the two wheat crop varieties simulated by the model (medium-tall variety from 1931 to 1966 and semidwarf varieties from 1967 to 1990). The crop aboveground parameters were determined by using the observed C/N and ST/GR ratios and adjusting MX to get the observed production for the two varieties. Note that the semidwarf variety has a lower ST/GR ratio and a higher minimum C/N ratio for the total plant. We also assured the allocation of C to roots would change (see Table 1) as a function of the relative N availability for the different treatments with high N availability treatments having lower C allocation to roots (Hansson et al., 1987). A complete description of the crop model is presented by Parton et al. (1988) and is the same version of the model used by Paustian et al. (1992) to simulate long-term SOM dynamics in Sweden.

One of the deficiencies of the present plant production model is that ST/GR ratio and C allocation to roots do not vary as a function of soil fertility and soil water status. Using observed plant data from the different varieties and treatments, we found that the ST/GR ratio increased with increasing N fertility for the medium-tall variety (1.84 to 2.17) and decreased for the semidwarf variety (1.81 to 1.58). These variations were not considered in the present formulation of the model and contribute to some of the observed differences between the simulated and observed data. The potential impact of changing C allocation to the roots was simulated in the model run by specifying higher allocation of C to roots for the low N fertility treatment. A dynamic C allocation model that responds to N and water stress would improve our ability to simulate SOM dynamics and N cycling for these different treatments.

METHODS

Model Runs and Initial Values

We used the version of CENTURY (Version 2.1) that was recently used to simulate the impact of different organic matter inputs for a long-term Swedish site (Paustian et al., 1992). The parameter values are the same as those described in the initial CENTURY publications (Parton et al., 1987). The parameter files used to run the model, the output files, and CENTURY Version 2.1 have all been saved and are available for distribution. Initial conditions for the different soil C and N pools (to represent levels in 1931) were determined by running the model to equilibrium conditions for the grassland and cultivating the system with a winter wheat system for the 40 yr prior to initiation of the experiment in 1931 (erosion rate = 0.30 kg soil m^{-2} yr^{-1}). All of the runs used the same initial condition for slow and active SOM pools; however, the passive SOM pool was adjusted (100–200 g C m^{-2} and 10–20 g N m^{-2}) so that the simulated initial total C and N levels for 1931 were equal to the observed values.

The model was used to simulate six of the nine treatments in the long-term study (Rasmussen and Parton, 1994). These included: fall burn (no. 6), control with no N addition (no. 0), no burn with 45 kg N ha^{-1} (no. 4), no burn with 90 kg N ha^{-1} (no. 5), pea vine addition (no. 9), and manure addition (no. 8). A more complete description of the fertilizer and organic matter additions are given in Rasmussen and Parton (1994). Monthly average maximum and minimum monthly air temperature and precipitation from 1931 to 1986 were used as driving variables for the model. We used a constant soil erosion rate for all of the treatments (0.30 kg soil m^{-2} yr^{-1}). The general equation used to simulate soil N fixation for the system was altered to increase the N inputs into the 0- to 30-cm layer. We justified this change because substantial N ($\approx$39 g m^{-2}) was mineralized from the 30- to 60-cm soil layer (Rasmussen and Parton, 1994), which should be available for plant growth. The present model does not simulate the dynamics of soil N below the 30-cm depth.

Model Testing

We compared observed and simulated straw and grain yields, grain N uptake, and soil C and N levels. The comparison of observed and simulated straw yield (Fig. 2c) show that the model does a respectable job of simulating the straw yield (r^2 = 0.73), with the exception of yields for the medium-tall variety, which were underestimated by the model. We calculated the number of times that the difference between the model results and the observed data was less than $\pm$10% of the observed data for the straw and grain yield and grain N uptake as a practical index of how well the model performed. The

Table 1. Parameters used in the CENTURY crop production model for two wheat varieties.

Wheat variety	Aboveground production (MX)	Whole plant C/N ratio		Portion of plant N in grain	Straw/grain ratio	Portion of total production in roots†
		Maximum	Minimum			
	g biomass cm^{-1} H_2O			%		%
Medium-tall	14	60	44	60	1.9	25
Semidwarf	22	80	46	60	1.6	20

† Low fertility treatments (control and fall burn) assigned a 30% allocation to roots for the medium-tall variety, and 25 and 30%, respectively, for the semidwarf variety.

results for straw yield showed that 53% of the time the errors were less than ±10%.

Grain yields (Fig. 2b) were simulated more consistently by the model (r^2 = 0.94) with errors in grain yield being less than ±10% of the observed data 70% of the time. The major discrepancies were that the model tended to underestimate medium-tall variety yield for all treatments (Fig. 2b) and tended to overestimate yield for the semidwarf variety high-N treatment (not shown in the figure). It is possible that the overestimate of simulated production with the N treatment occurred because plant production was limited by available P or S, which were not simulated for these model runs. In the manure and pea vine treatments, P and S are added as an integral part of the organic material. The model is capable of simulating P and S dynamics; unfortunately there is insufficient soils data at the site to parameterize the P and S submodels. The general pattern of lower grain and straw yields for the medium-tall variety was possibly caused by an underestimate of N mineralization by the model or an underestimate of N input to the system. Extra N was added to the system to compensate for the deep soil N mineralization; however, the pattern of N mineralization with depth was not dynamically represented (we assured a constant addition of extra N). If N from the deep soil layer was initially released more rapidly, this could contribute to the observed deficiency of N for the medium-tall variety grown from 1931 to 1966. Grain N uptake was simulated (Fig. 2a), with observed vs. simulated r^2 = 0.83 and model errors less than ±10% of the observed data 57% of the time. The major discrepancy was an underestimate of grain N uptake by the model for the manure treatment (Table 2).

In summary, the comparison of the observed and simulated grain yields, grain N uptake, and straw yields show that the model can simulate these variables with errors less than ±10% of the observed data for more than one-half of the observations (70, 57, and 53%, respectively). These results suggest that it would be necessary to add a dynamic C allocation model if we want to substantially improve the prediction capability of the plant growth model. Specifically, we need to simulate the impact of nutrient availability on C allocation to roots, the ST/GR ratio, and N allocation to the different plant parts. The CERES-WHEAT model (Richie and Otter, 1985) could be modified to include these needed improvements and combined with the CENTURY soil organic matter submodel.

Model results and observed data for soil C and N show that soil C and N levels decreased for all of the treatments except the manure addition site. The decrease was greatest for the fall-burn treatment, followed by the control, the low and high N rates, and the pea vine addition. The comparison of the observed and simulated soil C levels (Fig. 3) shows that the observed vs. simulated r^2 = 0.77, that model errors were less than ±5% of the observed data 57% of the time, that model results were within the 95% confidence interval of the observed data for 80% of the observation, and that the major differences between the treatments were represented by the model. The comparison was more variable for the earlier dates (1942–1951) because of less accurate techniques to measure soil C (one correction coefficient was used to convert the old data [1931, 1944, and 1951], but it is possible that the correction coefficient should vary by treatment). The most significant difference between the model and the observed data is an underestimate of soil C for the fall-burn treatment. Two possible causes are overestimated C loss due to fall burning of the

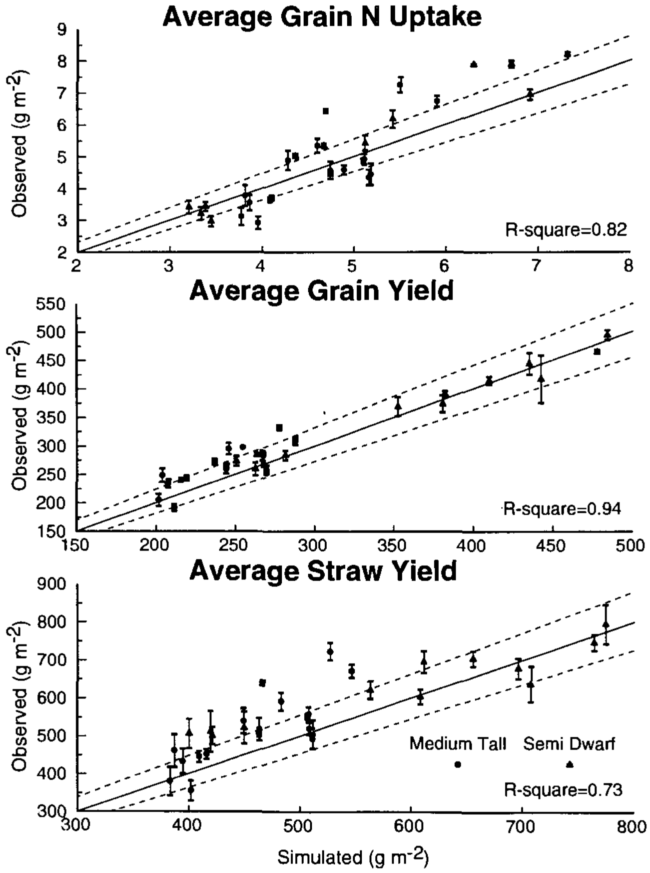

Fig. 2. Comparison of observed and simulated (a) grain N uptake, (b) grain yield, and (c) straw yield for treatments at Pendleton, OR, site. The 95% confidence intervals are provided and the 1:1 theoretical line, ±10% lines are also shown.

Table 2. Observed and simulated N budget for the different treatments from 1931 to 1986. Standard errors are provided for the observed data when it can be calculated.

	N additions		Cumulative N loss for 1931–1986				Soil N change, 0–30 cm for 1931–1986	
			Grain removed		Other N losses			
Treatment	ATM† + soil	Fertilizer	Simulated	Observed	Simulated	Observed	Simulated	Observed
	g N m^{-2}							
Fall burn (no. 6)	72	–	103	88 ± 2.0	63	70	−92	−86 ± 7.4
Control (no. 0)	72	–	98	93 ± 3.2	45	43	−69	−64 ± 11.4
Low N fertilizer (no. 4)	72	103	138	137 ± 3.6	66	73	−26	−35 ± 14.8
High N fertilizer (no. 5)	72	148	157	153 ± 0.6	73	103	−7	−36 ± 13.0
Pea vine (no. 9)	72	104	124	135 ± 2.2	58	64	−2	−23 ± 22.2
Manure (no. 8)	72	270	157	194 ± 1.1	112	101	+79	+47 ± 11.3

† ATM = atmospheric N deposition.

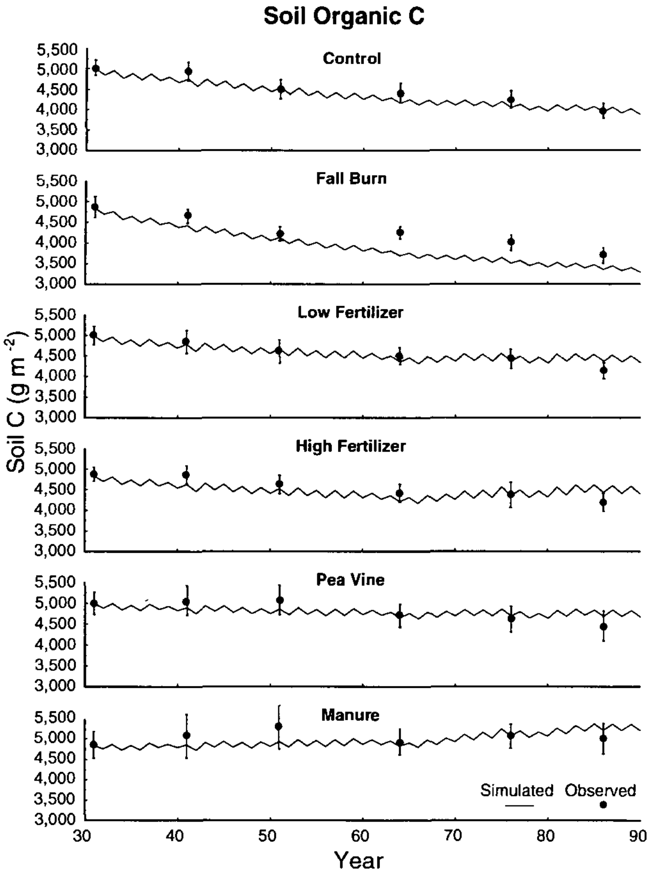

Fig. 3. Comparison of observed and simulated soil C (0-30 cm) for the (a) control, (b) fall burn, (c) low fertilizer, (d) high fertilizer, (e) pea vine, and (f) manure treatments at Pendleton, OR, site. The 95% confidence intervals are provided for the observed data.

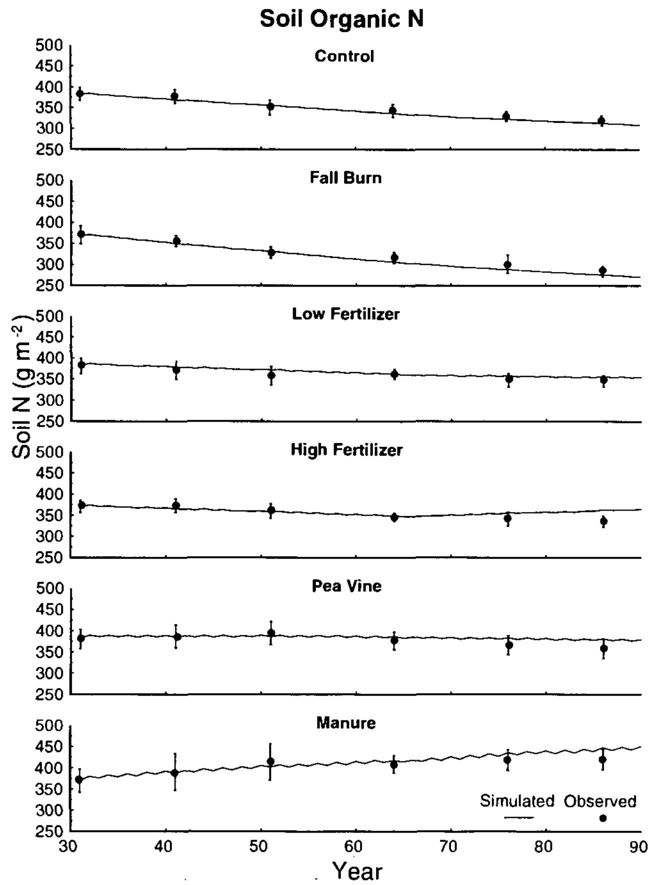

Fig. 4. Comparison of the observed and simulated change in soil N (0-30 cm) for the (a) control, (b) fall burn, (c) low fertilizer, (d) high fertilizer, (e) pea vine, and (f) manure treatments at Pendleton, OR, site. The 95% confidence intervals are provided for the observed data.

straw or an underestimate of the amount of C allocated to root growth. A third may be slower turnover of the C remaining after the burn.

The comparison of observed and simulated soil N levels was more favorable (Fig. 4) compared with the soil C data, with the observed vs. simulated $r^2 = 0.95$, model errors less than $\pm 5\%$ of observed data 93% of the time, and model results within the 95% confidence interval of the observed data for 93% of the observations. This probably results because soil N was measured using a comparable technique for the whole time period. The major discrepancy for the soil N data is that the model tended to overestimate soil N for the organic N addition and high fertilizer treatments. The model underestimated N removed in the grain for the manure treatment (Table 2), and thus, N removed from the system. This illustrates how errors in the plant production model can influence the soil submodel.

Nitrogen Budget

We calculated the N budget for the different treatments using soil N data and grain N removal from the system for the 1931 to 1986 time period (Table 2). The calculated budget was compared with the simulated N budget for the same time period. Atmospheric N additions and N mineralized from the 30- to 60-cm soil layers were estimated and assumed to be constant for all treatments. Organic and inorganic N additions were measured for the whole time period (Rasmussen and Parton, 1994). Nitrogen losses other than grain N removal were calculated by subtracting soil N change (0–30 cm) and grain N removal from total N input. Other avenues of N loss include erosion, soil and plant NH_3 loss, gaseous loss of NO_x, N_2 and N_2O loss, and leaching N loss.

The observed grain N removal was highest for the manure treatment, followed by the high N fertilizer, low N fertilizer, pea vine, control, and burn treatments. A comparison of observed and simulated grain N removal shows that most of the treatments were well simulated. However, the model overestimated grain N removal for the burn treatment and underestimated grain N removal for the manure treatment. Observed soil N was lost from the 0- to 30-cm layer for all of the treatments except the manure treatment, with N losses greatest for the burn treatment followed by the control, high N, low N, and pea vine treatments. The simulated results generally compare favorably with the observed data. Soil N increase was overestimated for the manure treatment and soil N losses were underestimated for the high N fertilizer and pea vine treatments. The overestimation of the soil N by the model for the manure treatment probably results from an underestimate of N removal in the grain (25 g N m^{-2} error for soil N vs. -37 g N m^{-2} error for grain N removal).

Other N losses were lowest for the control treatment and highest for the high N fertilizer and manure treatments. A comparison of the organic and inorganic N treatments shows less loss from the organic N treatments, with the high N fertilizer treatment having almost as much N loss as the manure treatment despite having 122 g m^{-2} less N added. The comparison of the observed and simulated soil N losses showed fairly good agreement, with the exception that the model underestimated N loss from high N fertilizer treatment.

A general comparison of the inorganic and organic N addition treatments shows that inorganic N fertilizer increased N uptake by the plants and other N losses (NO_3 leaching, N_2O gas flux, etc.) while soil N stabilization decreased. Results also suggest that these patterns get more pronounced as the level of N addition increases. Paustian et al. (1992) presented long-term (31 yr) N budget results for different inorganic and organic N addition treatments in Sweden that are similar to those observed in this study. They also showed how varying the N content of the added plant material and combining inorganic and organic N treatments influences plant–soil N budgets. Decreasing the N content of the added plant material decreases other N losses, increases N stabilization in the soil, and reduces N uptake by plants. In fact, addition of very high C/N ratio material (wheat straw and sawdust) reduces N uptake by the plants even after 30 yr of adding plant material. The combined impact of adding high C/N ratio plant material to a N fertilizer treatment is a reduction in other N losses, increased N stabilization in the soil, and slightly reduced plant N uptake. The reduction of plant N uptake is greatest for high C/N ratio plant material. In general, a comparison of the observed N budgets with simulated CENTURY model results for the different N addition treatments presented here and by Paustian et al. (1992) show that the major treatment differences are represented by the model. Recent data from Reddy and Reddy (1993) support the model predictions that other N losses increase as the inorganic N addition rates increase.

Data from Mahler and Hemamda (1993) showed short-term (3 yr) N use efficiencies for adding green manure to spring wheat systems in Idaho. Plant N stabilization efficiencies ranged from 27 to 59% for added alfalfa and pea material, while soil N stabilization efficiencies were 27 and 19%, respectively. The soil N stabilization efficiencies were lower than those observed in this study, while our plant N stabilization efficiencies of 36 to 40% for manure and pea vine (Table 3) were between the values measured by Mahler and Hemamda (1993). Paustian et al. (1992) observed soil N stabilization efficiencies of 12, 30 and 68% for inorganic fertilizer, green manure and farmyard manure treatments, respectively. Plant N stabilization efficiencies observed by Paustian et al. (1992) were 65, 44 and 38% for inorganic N, green manure and farm yard manure treatments, respectively. Comparison of Paustian's values with similar treatments in this study (Table 3) shows that inorganic N additions increase N uptake by plants and reduce N stabilization by the soil, while values for both studies have similar soil and plant N stabilization efficiencies for the organic N treatments. The only major difference was much higher N stabilization for manure treatment in the Paustian et al. study, which probably results from higher lignin content (30 vs. 15%) of their manure (lignin promotes soil C stabilization).

Carbon and Nitrogen Stabilization

We attempted to calculate the soil C and N stabilization efficiencies for the inorganic and organic N addition treatments by comparing changes in soil C and N levels for these treatments with changes in control levels. We subtracted the change in the control soil C and N level over the 1931 to 1986 and 1931 to 1976 periods from similar changes in the organic and inorganic addition treatments, and then divided these changes by increased N and C that was added relative to the control treatment. The two time periods were selected in order to give an index of variability resulting from errors in the observed data and should represent the long-term stabilization efficiency since the treatments were in place for at least 45 yr. We calculated values for two time periods in order to get an estimate of how variation in the observed soil C and N levels would influence estimates of the stabilization efficiencies. We also calculated the percentage of the added N that was removed in the grain.

The soil C and N stabilization efficiencies were similar for the two time periods (Table 3). Both the model and the data suggest that the high inorganic N treatments had higher soil C stabilization efficiencies than the other treatments, and that higher rates of inorganic N or organic additions had higher C stabilization efficiencies. This is consistent with data from Berg and Ekbohm (1991), which show high long-term C stabilization for litter material that has high initial N content. Both the model and the data suggest that the soil N stabilization efficiencies are higher for organic matter additions than for inorganic N additions. The model tended to overestimate soil N stabilization efficiency. Paustian et al. (1992) also showed that the model overestimated soil N stabilization for all of the treatments except the high lignin addition site, where the model underestimated N stabilization.

A possible reason for overestimation for the manure treatments is the model underestimation of grain N removal. The observed percentage of N removed in the grain (35–40%) is fairly similar for all of the addition treatments and is well represented by the model for the fertilizer addition treatments and underestimated for the organic addition treatments.

We compared changes in soil C for three periods (1931–1966, 1931–1976, and 1931–1986) with the aboveground C inputs using observed data and model results. Data from different time periods were used to give an index of variability in the soils data; all of the time periods had at least 35 yr to reach near-equilibrium conditions. Our results are consistent with other studies that show soil C levels increasing linearly with annual C input (Larson et al., 1972; Rasmussen et al., 1980; Paustian et al., 1992). The slope of the observed linear regression equation is 0.18 for actual data and 0.24 for model simulation (Fig. 5). This suggests that the model tends to overestimate the increase in soil C for a given C input. The observed slope is similar to the C stabilization efficiencies calculated in Table 3, which range from 0.12 to 0.27 and have

Table 3. Observed and simulated soil C and N stabilization efficiency for different treatments, 1931 to 1976 and 1931 to 1986 periods. Standard errors are presented for observed data when it can be calculated.

Treatment	Soil C stabilization efficiency			Soil N stabilization efficiency			Grain N removed	
	Observed		Simulated	Observed		Simulated		
	1976	1986	1986	1976	1986	1986	Observed	Simulated
	% of added C			% of added N				
Low Fertilizer	18 ± 14	12 ± 7	26	23 ± 12	26 ± 5	42	39	40
High Fertilizer	27 ± 12	25 ± 6	31	22 ± 6	18 ± 5	42	40	39
Pea Vine	12 ± 3	13 ± 5	21	42 ± 8	37 ± 9	64	40	25
Manure	19 ± 2	18 ± 2	25	46 ± 5	41 ± 3	55	36	22

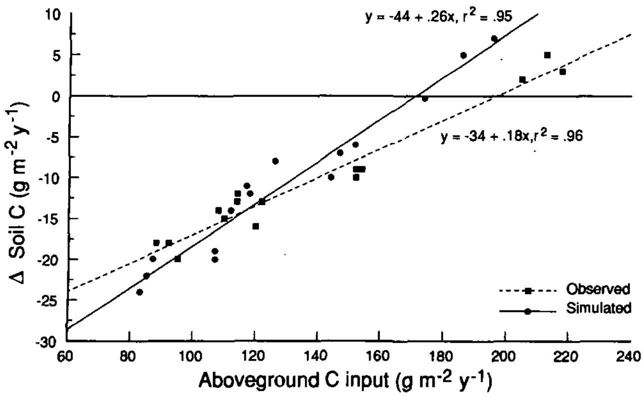

Fig. 5. Comparison of the observed and simulated change in soil C in the 0- to 30-cm zone from 1931 to 1966, 1931 to 1976, and 1931 to 1986 as a function of aboveground C input.

large standard errors. A comparison of these results with the graph of Paustian et al. (1992) for a site in Sweden shows that it requires more C input at Pendleton to attain a steady-state soil C level. This is probably because the Pendleton site has an alternating crop-fallow, while the Swedish site has annual small grain production. The Swedish site is also colder, which may change C turnover efficiency.

CONCLUSIONS

Comparison of model and observed data shows that the model can predict soil C and N change within ± 5% (57 and 93% of the time, respectively), and grain yield, straw yield, and grain N removal within ± 10% (70, 53, and 57% of the time, respectively). Improvement in the model's ability to simulate plant production variables would require incorporating the impact of soil N availability on C and N allocation to grain, straw, and roots. Apparent errors in the plant production model (underestimation of N removal for the added-manure treatment) lead to errors in the soil N submodel (overestimation of soil N stabilization). Soil N stabilization efficiency appears to be higher for organic N treatments, while grain N removal and soil C stabilization efficiencies appear to be higher for inorganic N fertilizer treatments. The major model errors are overestimation of soil N stabilization, underestimation of soil N losses for the N fertilizer treatments, and overestimation of soil N and C losses for the fall-burn treatment.

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