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Dynamics of C, N, P and S in grassland soils: a model

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Abstract. We have developed a model to simulate the dynamics of C, N, P, and S in cultivated and uncultivated grassland soils. The model uses a monthly time step and can simulate the dynamics of soil organic matter over long time periods (100 to 10,000 years). It was used to simulate the impact of cultivation (100 years) on soil organic matter dynamics, nutrient mineralization, and plant production and to simulate soil formation during a 10,000 year run. The model was validated by comparing the simulated impact of cultivation on soil organic matter C, N, P, and S dynamics with observed data from sites in the northern Great Plains. The model correctly predicted that N and P are the primary limiting nutrients for plant production and simulated the response of the system to inorganic N, P, and S fertilizer. Simulation results indicate that controlling the C:P and C:S ratios of soil organic matter fractions as functions of the labile P and S levels respectively, allows the model to correctly simulate the observed changes in C:P and C:S ratios in the soil and to simulate the impact of varying the labile P and S levels on soil P and S net mineralization rates.

Introduction

The elements C, N, P, and S are central to all biological processes and provide a key to our undertsanding of changes in the biosphere (Hutchinson 1970). Systematic study of the interaction of carbon, nitrogen, phosphorus, and sulfur transformations provides a valuable means of understanding the structure and functioning of ecosystems (Stewart 1984). With increased awareness of the connectedness of ecosystems in the biosphere, an understanding of the relationships among elements cycling within and between ecosystems is essential for understanding regional and global change in the environment. These changes include changes in temperature and rainfall patterns resulting from global increases in greenhouse gases and increases in atmospheric acidity (reviewed in Bolin & Cook (1983)). Concurrently, changes in agricultural management may influence the biogeochemical cycles of agroecosystems throughout large parts of the world. Management changes include changes in fertilizer and water management, changes in tillage and cropping strategies (Phillips et al. 1980), and changes in the distribution of crops. Alteration of macroclimate and management over

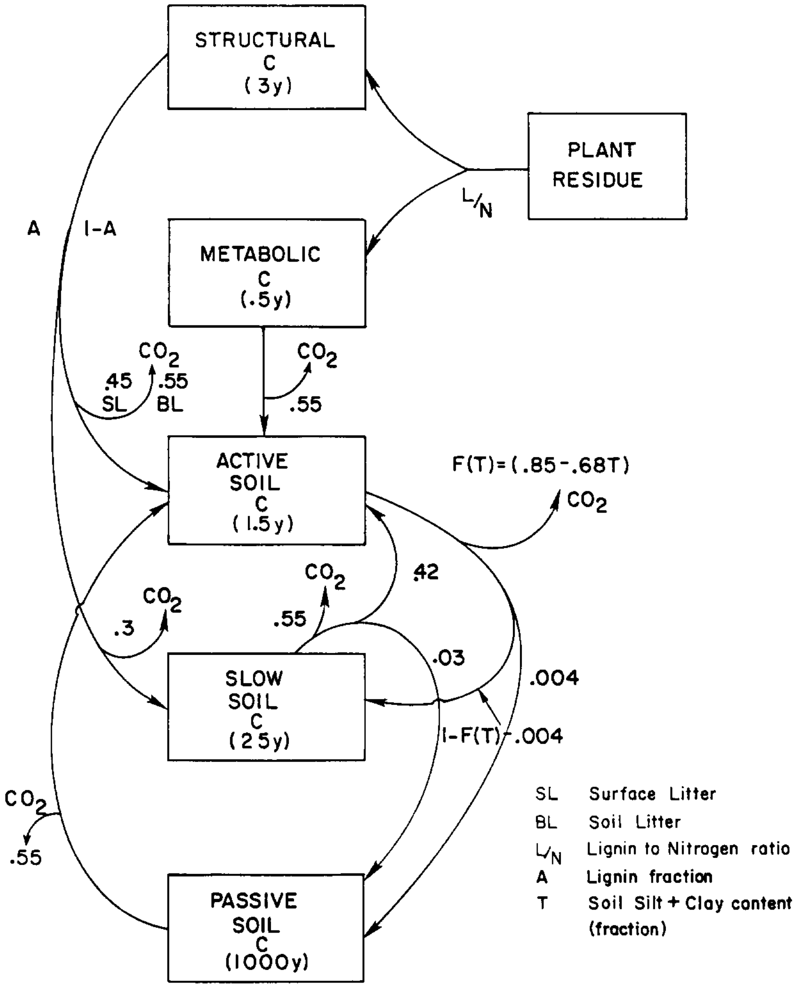

Fig. 1. Flow diagram for the carbon flow model.

large areas will affect the productivity and distribution of crops, erosion potential of soils, and storage and turnover of soil nutients (Fenster & Peterson 1979; Doran 1980). This paper will describe a model for simulating large–scale and long–term consequences of climate and management changes on C, N, P, and S dynamics in agroecosystems.

In recent years, a variety of models have been developed to simulate soil organic matter development (Paul & Van Veen 1978; Jenkinson & Rayner 1977; Van Veen & Paul 1981). These models have split organic matter and plant residue into different pools and consider the effect of soil erosion (Voroney et al. 1981) and soil texture on soil organic matter dynamics. There have been few attempts to model dynamics of element interactions. Recently, Hunt et al. (1983) proposed a conceptual model for interactions among

C, N, P and S. Differences in nutrient cycling patterns were related to fundamental chemical properties, to information from microbial physiology, and to current theories about the formation and decomposition of soil organic matter (Anderson 1979). Central to this conceptual model was the incorporation of a dichotomous system (McGill & Cole 1981) which makes a distinction between the behaviour of the specific bond classes C-C, C-N, C-S, C-O-S, and C-O-P. In this paper we have used these concepts to develop a model which simulates the changes in the composition of organic matter, availability and interactions among N, S, and P in soils under different cultivation systems (Bettany et al. 1980; Tiessen et al. 1982, 1983; Tiessen & Stewart 1983).

Model description

The model simulated soil organic matter dynamics in natural or cultivated systems and represents the dynamics of C, N, P, and S in the soil-plant system using a monthly time step. The model incorporates many of the concepts used in an earlier version of the soil organic matter model (Parton et al. 1983) which simulated long-term C and N dynamics using a yearly time step. In this paper, we describe the P and S submodels to supplement a detailed description of the C and N submodels (Parton et al. in press) and demonstrate operation of the total model with a focus on the interaction between the different elements. The dynamics of C, N, P, and S in cultivated wheat-fallow systems were simulated (spring wheat) for the northern Great Plains where they have been documented (Tiessen et al. 1982, 1983; Tiessen & Stewart 1983).

In the soil organic matter formation model (see Fig. 1) plant residues are decomposed by microbes and the resulting microbial products become the substrates for humus formation. Polymerization of these compounds results in relatively high molecular weight compounds which are capable of various types of chemical and physical bonding with clay minerals and amorphous mineral colloids. The extent to which these compounds are stabilized in the soil appears to be related to the soil texture. The continued humification of these stabilized compounds forms lower molecular weight compounds which are more aromatic and progressively more biologically resistant (Anderson 1979). In the model, we divided the soil organic matter into three fractions:

— an active soil fraction consisting of live microbes and microbial products (2- to 4-y turnover time);
— a protected fraction that is more resistant to decomposition (20- to 50-y turnover time) as a result of physical or chemical protection;

- a fraction that is physically protected or chemically resistant and has a long turnover time (800–1200 y).

The plant residue is divided into structural (2-5 y turnover time) and metabolic (0.1 to 1 y turnover time) pools as a function of the lignin to N ratio of the residue. The model simulates the dynamics of C, N, P, and S for each of these state variables. Decomposition of each of the state variables was calculated by multiplying the decay rate specified for each state variable times the combined effect of soil moisture and soil temperature on decomposition. The soil moisture term is calculated as a function of the ratio of monthly precipitation to monthly potential evapotranspiration, while the soil temperature term is a function of the average monthly soil temperature at the soil surface (Parton 1984). The decay rate of the structural material is also a function of the lignin content of the structural pools, and the active SOM decay rate changes as a function of the soil silt plus clay content (low values for high silt and clay soils). Decomposition is also influenced by soil tillage. We assumed that decomposition rates for the month when tillage occur are increased by 25%, 50%, and 50% for active, slow, and passive SOM pools, respectively. These assumptions are conceptually based on data from Tisdale & Oades (1982). The respiration loss for each carbon flow is fixed for all of the flows except active soil organic matter which varies with the soil silt plus clay content (decreasing with high silt plus clay content).

The model also includes a plant production submodel which simulates the monthly dynamics of C, N, P, and S in the live and dead aboveground plant material, live roots, and structural and metabolic surface and soil residue pools. Maximum potential plant growth is estimated as a function of the precipitation (from planting to harvest time) and is reduced if sufficient N, P, or S is not available. The C:N ratio of new plant material is allowed to float from 30 to 35, the C:P ratio from 150 to 230, and the C:S ratio from 190 to 230. Plant production will be reduced if available N, P, or S pools are insufficient to produce plant material with a C:N, C:S, or C:P ratio less than or equal to the maximum value for these ratios (35, 230, and 230, respectively). Production will be reduced by the element that is most limiting and the C:N, C:S, or C:P ratios of other elements will be allowed to be as low as 30, 150, or 190 respectively, if there is excess nutrient available. The range of value of C:N, C:S, and C:P values are selected for the growth of wheat and will change for different crops (Westerman & Edlund 1985; Wagan et al. 1986). The reduction of plant production because of low availability of N, P, or S is an important mechanism of interaction of the cycling of the different nutrients.

Other processes represented in the model include growth of new plant material, nutrient uptake, live root and shoot death, removal of live shoots

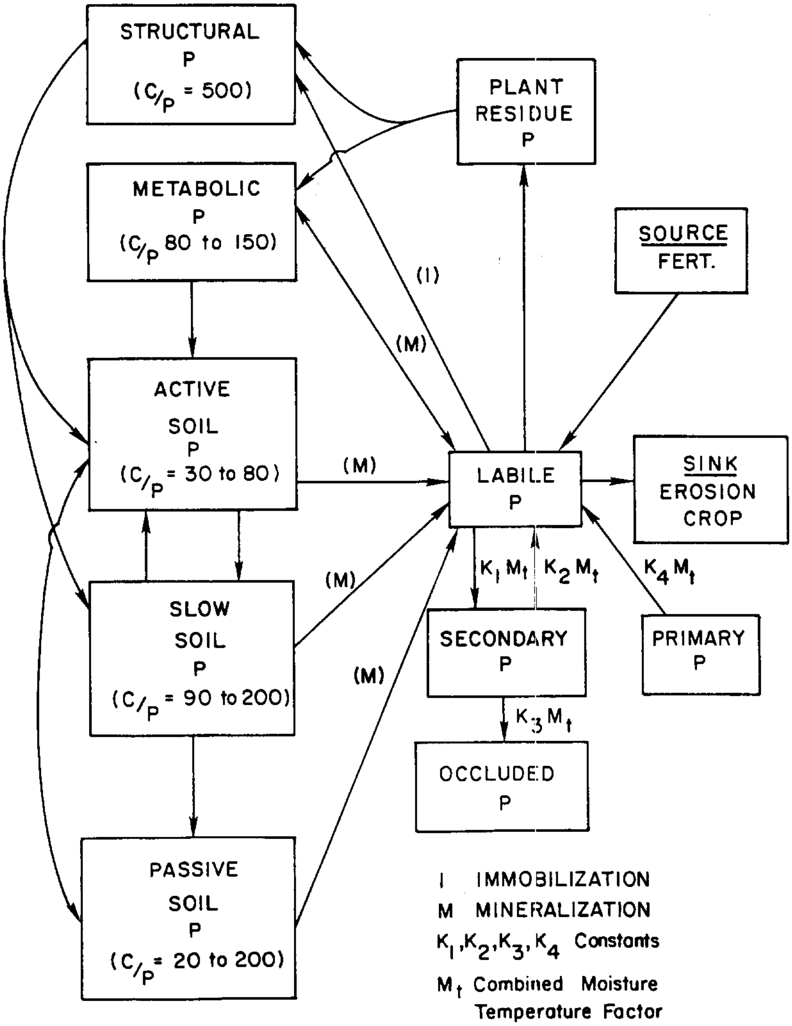

Fig. 2. Flow diagram for the P submodel.

and standing dead plant material, transfer of standing dead to surface litter, and mixing of surface litter into soil structural and metabolic litter pools. The flows of N, P, and S are calculated by multiplying the carbon flow rates by C:N, C:P, and C:S ratios of the state variables. When standing dead material is transferred into surface litter and live roots are transferred to belowground litter, the plant material is divided into metabolic and structural components as a function of the lignin (L) to nitrogen (N) ratio of the plant material (increasing structural fraction with higher L:N ratios).

Nitrogen submodel

The nitrogen submodel has the same basic structure as the carbon flow diagram and we assume that N is bonded mostly to carbon. We assume that the C:N ratio of structural (150), active (8), slow (11), and passive (11) soil fractions remain fixed. The N content of the metabolic pools is allowed to float as a function of the N content of the incoming plant residue. The N flows are assumed to be stochiometrically related to the carbon flows and are equal to the product of the carbon flow rate and fixed N:C ratio of the state variables that receive the carbon. The N attached to carbon lost in respiration (30–80% of the carbon flow) is assumed to be mineralized. Given the C:N ratios of the state variables and the CO_2 losses associated with each flow, decomposition of the metabolic residue and active, slow and passive soil organic matter fractions results in a net mineralization of nitrogen, while decomposition of structural residue results in immobilization of N. This model also uses simple equations to represent N inputs due to atmospheric deposition and soil and plant N fixation. The losses of N due to leaching, gaseous losses of N compounds, crop removal and erosion are also represented.

Phosphorus submodel

Considerable progress has been made in elucidation of specific parts of the P cycle (Chauhan et al. 1981; Stewart & McKercher 1981; Tiessen et al. 1984a) and the development of simulation models of the phosphorus cycle (Cole et al. 1977). We modified these models to simulate phosphorus flows in a model operating in monthly time steps (see Fig. 2). The primary mineral source of P in most soils is mainly apatite in the parent material. Secondary and occluded P minerals are formed from these phosphorites during the weathering and formation of soils. At the same time as physical and chemical weathering transforms primary P to secondary and occluded P forms, organisms in the soil and plant roots take up P from the solution. Phosphorus is incorporated into biomass and supports C assimilation and fixation. As more P becomes fixed through plant and soil microbial uptake, larger amounts become immobilized in organic matter to the extent that the organic accumulation depends directly on the P available for biological consumption (Cole & Heil, 1981). Microbial biomass is instrumental in the redistribution and/or accumulation of organic P compounds in soils. In the phosphorus submodel we followed the carbon submodel with respect to turnover times of the various active, slow, and passive fractions. The active

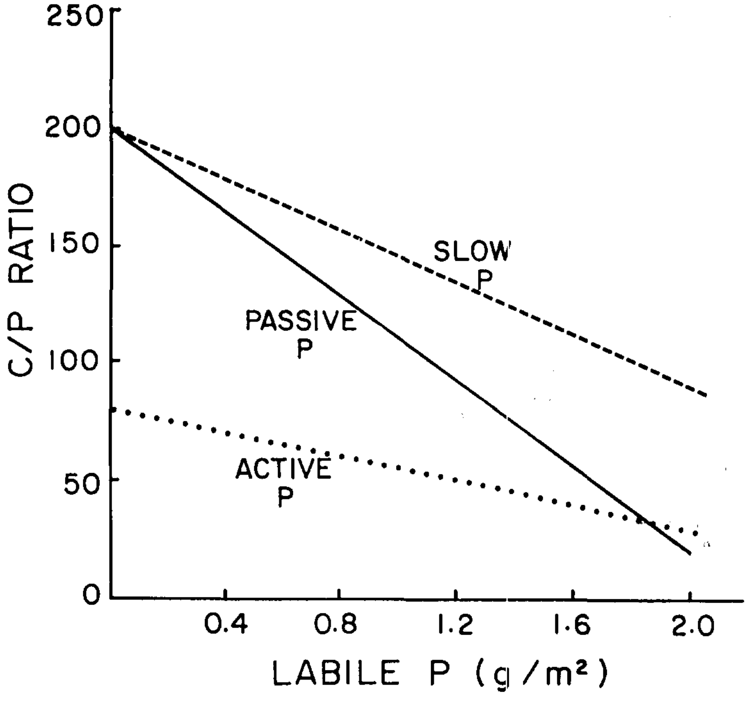

Fig. 3. Effect of the soil labile-P levels on the C:P ratio for the passive, slow and active soil organic matter.

soil P fraction consisting of microbial biomass and metabolites has C:P ratios ranging from 30 to 80. The most stable organic P forms were placed in the passive fraction, with C:P ratios ranging from 20 to 200, while intermediate forms in the slow soil fraction have C:P ratios ranging from 90 to200. Evidence for these transformations is found in the P fractionation data of Tiessen et al. (1982, 1983). The organic P flows are calculated by multiplying the carbon flow rate times the C:P ratio for the state variable receiving the carbon. The C:P ratio is fixed for the structural P box (500), while the metabolic P box receives the remainder of P in plant residue P that is divided between the structural and metabolic P.

The C:P ratio of active, slow, and passive soil organic pools varies as a function of labile P level where labile P is defined as orthophosphate which is isotopically exchangeable (Sibbeson 1984) or extractable with anion exchange resin (Sibbeson 1977) (see Fig. 3). The variation of C:P ratios as a function of labile P levels is based on data which show that C:P ratio of microbes varies as a function of labile P level and that under low levels of labile P, phosphatase enzymes are capable of directly mineralizing P from the system (McGill & Cole 1981). The net effect of these two processes is that

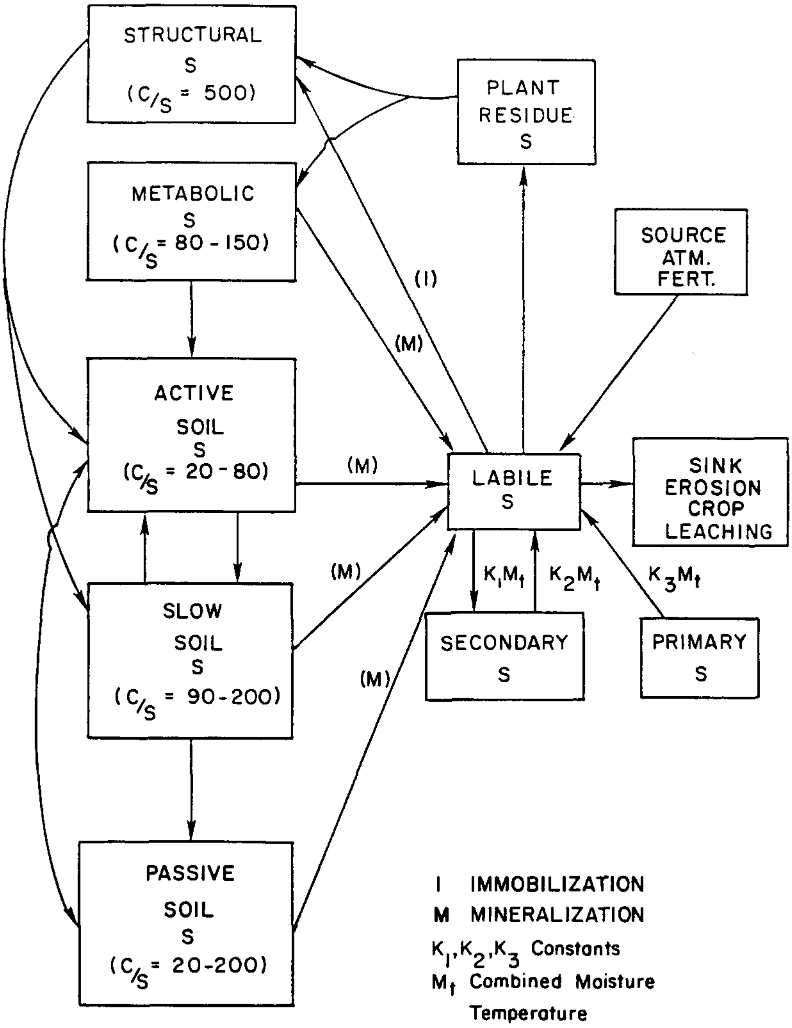

Fig. 4. Flow diagram for the S submodel.

the C:P ratio of new soil organic matter will vary as a function of current labile P level. This was also based on a comparison of C:P ratios in different soils (McGill & Cole 1981), which show that the C:P ratio can range from 60 to more than 200, with the lower C:P ratio in soils with high available-P levels.

The P attached to C lost as a microbial respiration (30 to 80% of the carbon flow) is assumed to be mineralized, so that decomposition of metabolic plant material, active, slow, and passive soil organic matter (low C:P ratio) generally results in the mineralization of labile P. Decomposition of structural plant material which has a high C:P ratio (500) requires the immobilization of P from labile P.

The flows represented by the model (see Fig. 2) include weathering of primary P (K_4M_t), formation of secondary P (K_1M_t), solubilization of secondary P (K_2M_t), and formation of occluded P (K_3M_t). M_t is the combined moisture – temperature decomposition parameter and the value of K_1, K_2, K_3, and K_4 are 0.05, 0.0022, 0.000001, and 0.0001 per month, respectively. The model is also set up to consider the addition of P fertilizer, the removal of P in plant residues and grain and erosion losses.

Sulfur submodel

Progress has been made in developing a conceptual sulfur cycle in soil and in understanding its effect on soil organic matter composition in native grassland and cultivated fields (Bettany et al 1980; Freney & Williams 1983). In addition, separate laboratory studies have clarified the mode of operation and dynamics of processes (Saggar et al. 1983; Maynard et al. 1983) important to the transformation of S in soil ecosystems. We have used existing data and computer models to develop a simplified sulfur flow model as part of our soil organic matter model (Fig. 4). The S cycle has characteristics similar to both the N and P cycles since it has organic matter that has carbon bonds (similar to the N cycle) and ester bonds (typical of the P cycle). The main source of S in most soil is the weathering of a variety of primary minerals. Secondary S is formed as a result of adsorption of S on clay minerals and iron and aluminum oxides. At the same time that chemical weathering transforms parent S to secondary forms, organisms in the soil and plant root take up S from soil solution SO_4 and start the formation of soil organic matter compounds that contain S. Microbial processes are instrumental in the redistribution and accumulation of organic S compounds in soil. The organic components of the S model uses the same structural and turnover rates as the carbon model. Plant residues include a structural component with a C:S ratio of 500:1 and metabolic material whose C:S ratio varies with plant residue – S concentration. Labile S concentration has a key role, as it controls the eventual composition of the material in the active, slow, and passive components of soil organic matter. The C:S ratio of the active component ranges from 20 to 80, based on the work of Saggar et al. (1981), who attempted to measure the C:S ratios of microbial biomass and labile organic matter fractions (Anderson et al. 1981). Labile S is defined as SO_4 extractable with 0.01 *M* $Ca(H_2PO_4)_2$. The

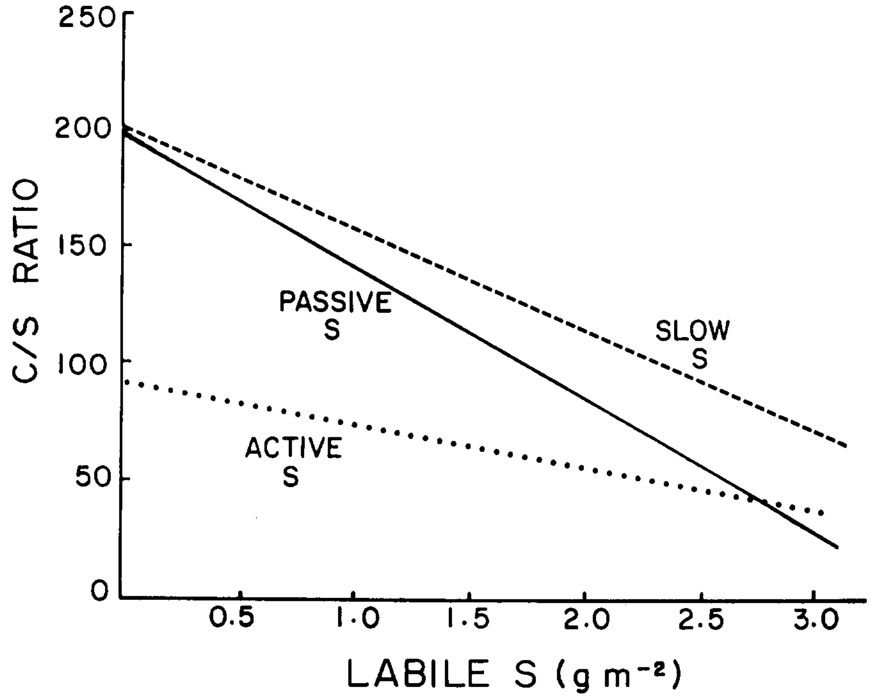

Fig. 5. Effect of soil labile S levels on the C:S ratio for the passive, slow and active soil organic matter.

C:S ratio of the slow fraction remains in the 90 to 200 range, reflecting the turnover of microbial metabolites and the formation of humic—like materials (Anderson 1979). The passive SOM will vary more widely than the other two boxes (20 to 200). The C:S ratio varies as a function of the soil labile S soil solution concentration (low ratios for high concentration, Fig. 5). The variation of C:S ratios for the different fractions are based on the observed C:S ratios for different particle size SOM fractions (Anderson et al. 1981; Anderson & Paul 1983) and data from a relatively unweathered soil, such as a Mollisol, where the C:S ratio will be relatively narrow (50:1 to 60:1), whereas in an Oxisol, the ratio will be much wider (150:1 to 200:1). These ratios reflect:

- the storage of excess SO_4 as ester sulfate under conditions where labile S is high enough to repress hydrolase activity and
- the incorporation of this relatively ester-rich (Mollisols) or ester-poor material (Oxisols) into aggregates which protect a portion of the organic matter from degradation (Tisdale & Oades 1982).

The organic flows are calculated by multiplying the carbon flow rate times the C:S ratio for the state variables receiving the carbon. The split between structural and metabolic S is calculated using the same algorithm as in the N and P submodels.

The S attached to C lost as microbial respiration (30 to 80% of the carbon flow) is assumed to be mineralized, so that decomposition of active, slow, and passive soil organic matter (low C:S ratio material) results in the mineralization of labile P, while decomposition of structure material (high C:S ratio) requires immobilization of S from the labile S pool. The S model also includes the weathering of parent P ($K_3 M_t$), the formation of secondary S ($K_1 M_t$), and the solubilization of secondary S ($K_2 M_t$) and has set the value of K_1, K_2, and K_3 equal to 0.001, 0.200, and 0.0005 per month, respectively (Fig. 4). The model allows for the addition of S due to fertilization, the loss of S contained in the plant residues and grain removed from the system, and the loss of S associated with erosion of soil organic matter.

Model results and validation

This section demonstrates that the model did a reasonable job of simulating the formation of soil organic C, N, P and S during a 10,000-year run and simulating the impact of cultivation on C, N, P, and S soil dynamics. To validate the model we used data that show how soil C, N, P, and S change under different cultivation practices in a typic Cryoboroll (Tiessen & Stewart 1983; and Anderson et al. 1981), data that show the effect of adding inorganic P on grain yield and P uptake (Wagar et al. 1986), and data showing the impact of plants on S mineralization in the soil (Maynard et al. 1985). Data on C, N, P, and S content in different soil particle sizes allows us to approximate the P, N, and S content of different soil organic matter fraction included in the model.

We used soil C, N, P and S data from the Blaine Lake Soil Association (Typic Cryoboroll) to demonstrate the impact of cultivation on dynamics of the elements. The C, N, P and S soil data (0 to 20 cm) from the Blaine Lake (Typic Cryoboroll) native soils (Tiessen et al. 1983; & Anderson et al. 1981) were used to initialize the C, N, S and P levels in the soil and data from 60 to 90 year cultivated Blaine Lake soils (Tiessen & Stewart 1983) were used to validate the simulated impact of cultivation on soil C, N, P, and S levels in the (0 to 20 cm depth). We emulated the observed cultivation history by simulating conventional tillage (two cultivation events during the fallow year) for a spring wheat system where wheat was planted in late April, harvested the following September and then followed by a year of fallow. No straw removal was simulated and mineral fertilizer was not added until after year seventy of the simulation (4, 0.7, 0.5 $\mathrm{g\,m^{-2}}$ N, P, and S were added at planting after year 70).

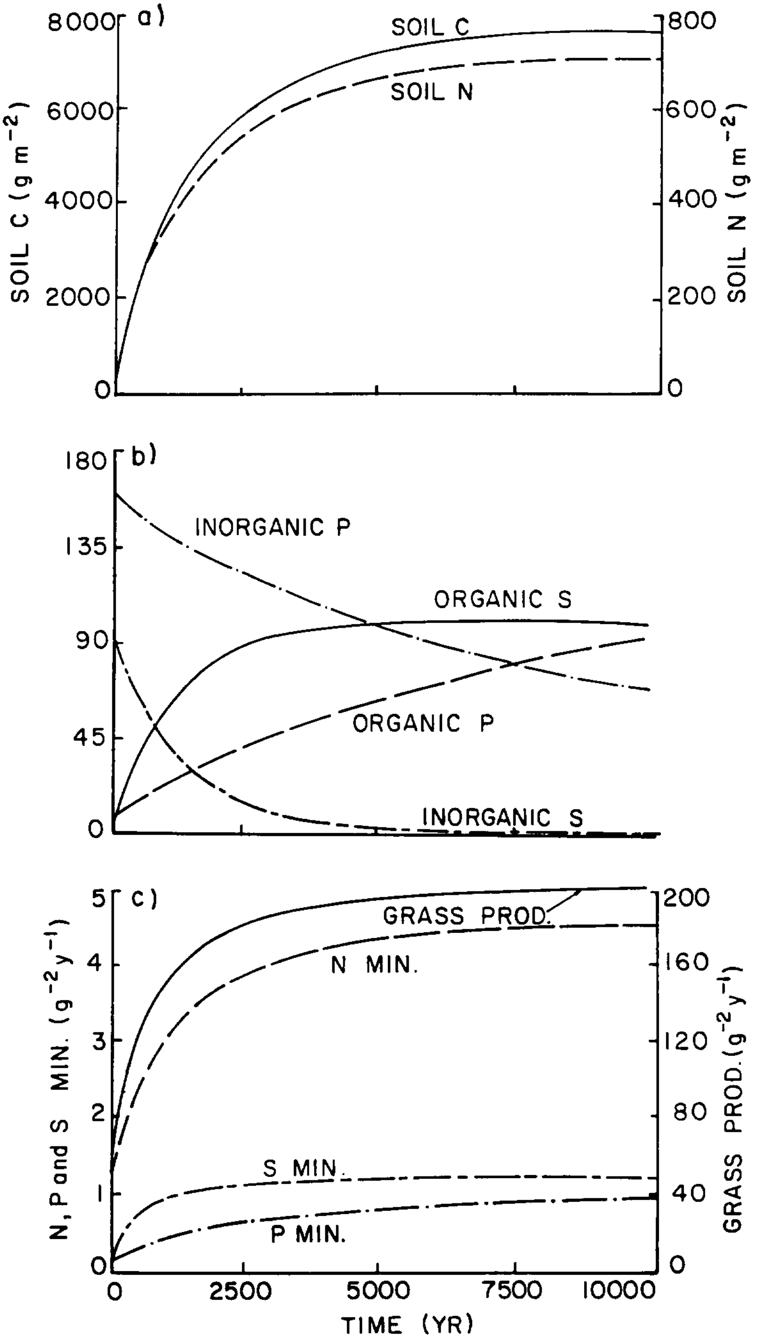

Fig. 6. Simulated pattern for soil (0 to 20 cm) C and N (a), and inorganic and organic P and S (b) and grass production and N, P and S mineralization (c) for a 10000 year model run.

Soil formation simulation

We simulated the formation of soil organic C, N, P, and S for the Blaine Lake uncultivated soils in a 10,000 year simulation. We assumed that the observed total P and S in the uncultivated soil began in "parent material" or primary minerals. N inputs to the soil were estimated by the model. The 10,000 year simulation time period was chosen to approximate the time period that soil formation has been occurring under grasslands following glaciation. Note that we assume that losses of P and S from the soil were minimal because of the dry environment (37 cm annual precipitation).

The results for soil C and N (0 to 20 cm) show (Fig. 6a) that greater than 80% of the final soil C and N levels have been reached by year 2500 and that most of the remaining increase in soil C and N occurred from year 2500 to 5000. The organic S levels (see Fig. 6b) followed a similar pattern with organic S being formed as a result of the relatively rapid weathering of primary S minerals. This contrasts with P dynamics where the weathering rate of primary P minerals were five times slower than for S. Total inorganic P levels declined to less than 45% of the initial level after 10,000 years with the inorganic P being equally split between secondary P and primary P. The slow weathering of primary P minerals results in a fairly steady increase in the organic P levels. Organic P levels in the active and slow SOM pools reached 80% of their final levels after 4000 years and most of the increase from year 4000 to 10,000 resulted from immobilization of P into the passive SOM fraction. This is important since turnover of the passive SOM fraction is quite slow and mineralization of nutrients (N, P, or S) from this fraction contribute less than 1% of total net mineralization. Thus, P weathered from the parent material after year 4000 is largely unavailable for plant growth. This same pattern was observed for organic S with 80% of the active and slow SOM S being formed by year 900 and most of S weathered from the primary minerals after this time going into the passive SOM pool.

The pattern of aboveground plant production for the simulation (see Fig. 6c) is similar to the soil C and N patterns with 80% of the final plant production levels being reached by year 1500. During the first 800 years both N and P restricted plant growth. After year 800 P and S did not restrict plant growth. After year 800, N was the limiting nutrient and increases in plant production reflect the increases in soil N mineralization rates (see Fig. 6c) which increased because of the incorporation of atmospheric N into SOM. The patterns of increasing N, P, and S mineralization rates with time (see Fig. 6c) reflected the increases in active plus slow N, P, and S since geater than 95% of the N, P and S mineralization came from the active and slow SOM fractions.

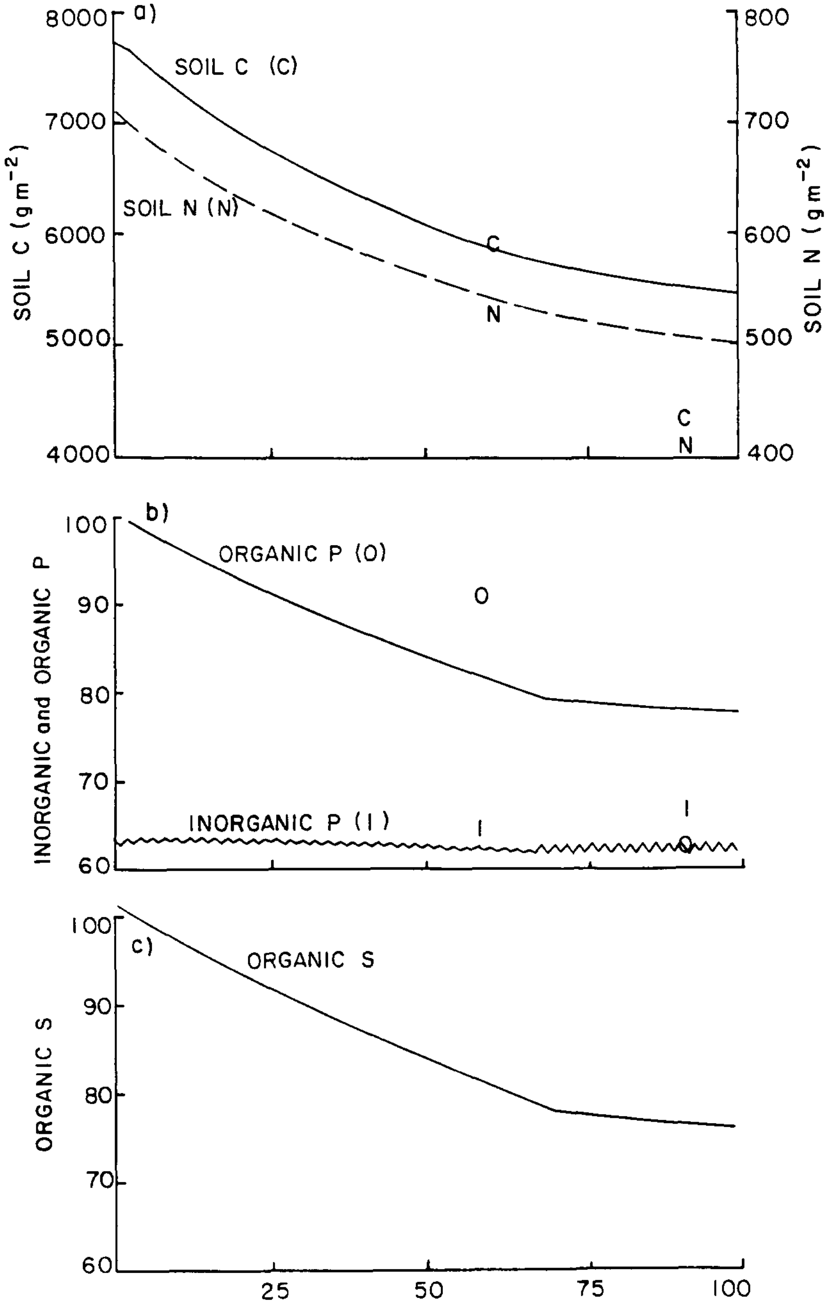

Fig. 7. Simulated impact of cultivation on soil (0 to 20 cm) C and N (a), organic and inorganic P (b), or soil S (c).

Simulated soil C, N, P and S levels after 10,000 years and observed soil C, N, P and S data for the Blaine Lake soils showed differences less than 15%. This is not an independent validation since some of the observed values were used to estimate parameters in the model. In particular, the soil N fixation rates were adjusted so that the equilibrium SOM C levels would be similar to the observed level, and the weathering rates of parent S and P were estimated by using the observed levels of parent P and S in the Blaine Lake soil. The simulated plant production level of 200 $g\,m^{-2}$ compares with an estimated average plant production of 200 $g\,m^{-2}\,yr^{-1}$ for the Blaine Lake site (Sims & Copland 1979).

Cultivation simulations

The simulated impact of cultivation soil C, N, P, and S level (see Fig. 7) was to decrease organic C, N, P, and S levels such that after 60 years of cultivation, simulated soil organic C, N, P, and S levels had been reduced by 23, 25, 18, and 20%, respectively. The observed organic C, N, and P levels after 60 years were similar to simulated levels of C, N, and P (see Fig. 7) and suggest that organic P and S losses with cultivation are less than C and N losses. Unfortunately, we do not know organic S levels for the Blaine Lake soil, however, data from another soil similar to this soil (Bettany et al. 1980) showed that S losses with cultivation were 4% less than the C losses. The comparison of the observed and simulated organic C, N, and P levels after 90 years of cultivation suggests that the model underestimated the loss of C, N, and P. This discrepancy is probably caused by the fact that the model assumed no erosion losses. The observed soils data suggested that erosion soil loss were minimal for the first 60 years and substantial after 60 years of cultivation. The simulated inorganic P levels remained fairly constant through the simulation and compared well with the observed inorganic P levels, although, again the model underestimated inorganic P levels after 90 years of cultivation. Inorganic P was split equally between parent P and secondary P, with labile P comprising less than 5% of the inorganic P.

Variable C:S and C:P ratios

One of the important assumptions in the P and S submodels is that the C:P and C:S ratios are controlled by the labile P and S levels, respectively. The simulated C:P and C:S ratios for the cultivated Blaine lake soils (see Fig. 8) show that C:P and C:S ratios of the slow and active SOM decreased during

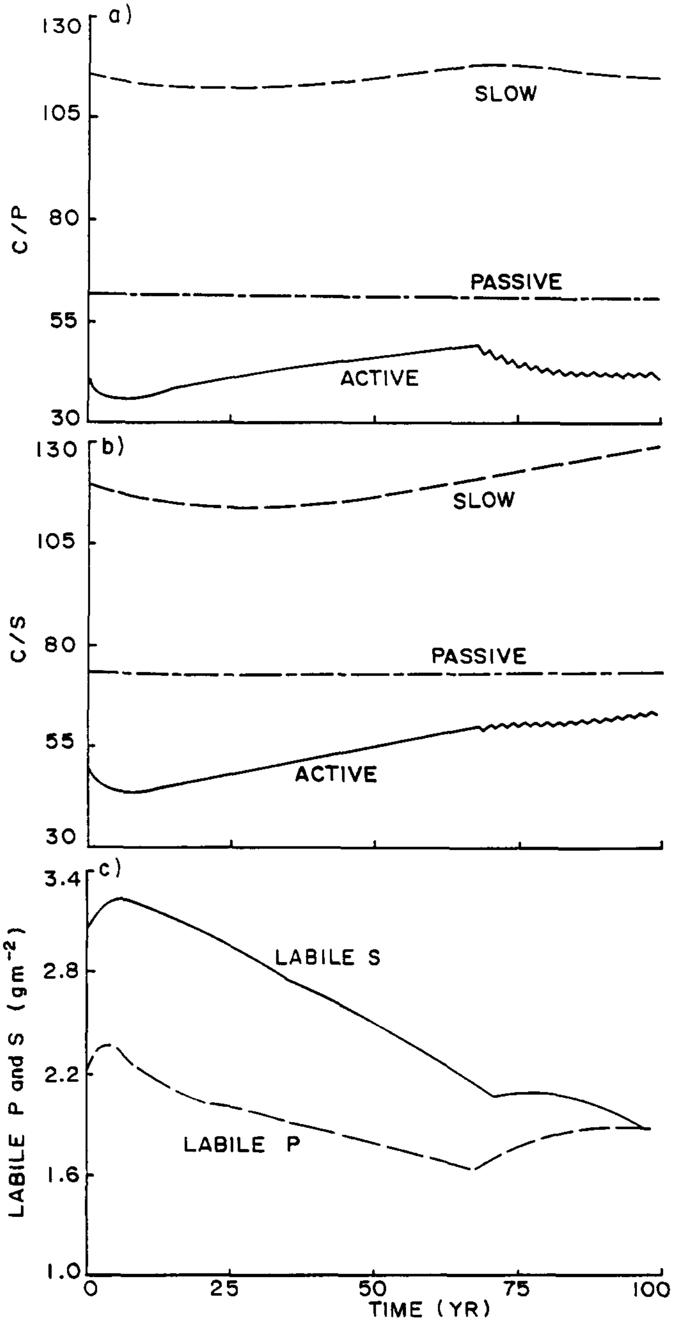

Fig. 8. The simulated effect of cultivation on soil organic C/P (a) and C/S (b) ratios and soil labile P and S levels (c).

the first ten years and then increased steadily for the next 60 years. These results were caused by the increase in the labile P and S levels during the first ten years (see Fig. 8c) and the steady decrease from year 10 to 70. The initial increase in the mineral P and S levels were caused by the enhanced mineralization rate associated with cultivation, while the decline after 10 years in the mineral P and S levels was caused by the removal of N, P, and S in the grain. After 70 years inorganic N, P, and S fertilizer were added, increasing the labile P pool and decreasing the C:P ratios of the slow and active SOM. The C:S ratios continued to increase, since insufficient S fertilizer was added to increase the labile S levels. The active SOM pool responds rapidly to changes in the P and S levels in the soil because it has a relatively fast turnover time (1 to 2 years). The C:P and C:S ratios of the passive SOM did not change during the 100 year simulation because of that fraction's long turnover time (1200 years).

The simulated total soil C:P ratio decreased from 78 to 70 during the 100-year simulation, while the C:S ratio decreased from 77 to 72. The decrease was caused by the rapid decline of the slow SOM pool which has the highest C:P and C:S ratios for the different SOM fractions. The result was that the fraction of the total SOM in the passive fraction increased during the simulation and thus causes the total C:P and C:S ratios to decrease. The simulated ratios were supported by observed data, which showed that C:S ratio was decreased to 71 ater 60 years of cultivation, while the C:P ratio decreased to 70 after 90 years of cultivation. The simulated total soil C:N ratio remained fairly constant (~ 11), while the observed C:N ratio decreased from 12.3 to 10.4. The observed values for the C:N, C:P and C:S ratios for the different SOM fractions were based on the assumption (based on carbon dating) that the fine silt and course clay particle-size soil fractions contain the old organic matter (Tiessen & Stewart 1983; Tiessen et al. 1984b; Anderson & Paul 1985), the slow SOM is primarily found in the sand and coarse silt soil fractions, and the fine clay contains the active SOM fraction.

An important impact of the C:P and C:S ratios changing as function of the labile P and S soil levels is that changes in the labile P and S levels cause changes in P and S mineralization rates. This was shown by Maynard et al. (1985) in an experiment including plants in soil incubations. Plant growth caused the S mineralization rate to be substantially increased. They hypothesized that the major impact of the plant was to reduce the labile S level, causing S mineralization rates to increase because of increased S enzyme activity. We simulated the S mineralization rate for planted and unplanted incubations of Maynard et al. (1985) for the Loom River soil (Table 1). The model correctly simulated the increased S mineralization rates in the planted

Table 1. Comparison of observed and simulated S mineralization rates from planted and unplanted soils. Observed values come from a paper by Maynard et al. (1985)

Treatment	Planted		Unplanted	
	OBS ($g m^{-2}$)	SIM ($g m^{-2}$)	OBS ($g m^{-2}$)	SIM ($g m^{-2}$)
Control	2.42	1.07	−0.49	−0.10
$+SO_4$	1.79	1.04	−0.29	−0.28

soils. The model does not specifically represent all the soil processes that cause increased S mineralization; however, impact of changing the labile S levels on S mineralization is represented by the assumption that the C:S ratios of the SOM fractions are controlled by the labile S level.

Fertilizer simulation

It is generally observed that after 30 to 60 years of cultivation with a wheat fallow system that crop production is reduced by nutrient availability. We ran five simulations in which fertilizer was added; N ($4 g m^{-2}$), P ($0.7 g m^{-2}$) and S ($0.5 g m^{-2}$) individually, N and P together (4 and $0.7 g m^{-2}$ N and P) and N, P, and S together (4.0, 0.7, $0.5 g m^{-2}$ N, P, and S). All fertilizer was added when the spring wheat was planted (see Fig. 9). Fertilizer additions were started in year 30. The impact of N, P or S individually after 30 years of cultivation was relatively minor (data not shown for P and S) with N additions resulting in a 5 to 10% increase (from year 30 to 90) in grain yield and P and S additions, causing a small increase in grain yield ($< 1\%$). The combined impact of adding N and P fertilizer (see Fig. 9) was to increase grain yields to the maximum level for years 30 to 60 followed by a decrease to control levels by year 80. The combined N, P, and S fertilizer runs suggested that the decrease during years 60–80 was caused by S limitations, as the addition of S allowed plant-grain yield to remain at the maximum level from year 30 to the end of the simulation. These results show that N and P limitations occur earliest after cultivation, and that all three nutrients will have to be added to maintain production at the maximum level for sustained periods (> 60 years) of cultivation. The addition of N, P and S fertilizer reduced the rate of decline of soil carbon with cultivation (Fig. 9b) and suggest that a near equilibrium for soil C, N, P and S levels would occur after 150 to 200 years of cultivation for the combined inorganic N, P, and S fertilizer run. The results of the fertilizer simulations are generally consistent with observed data from this region which show the P and N are the first

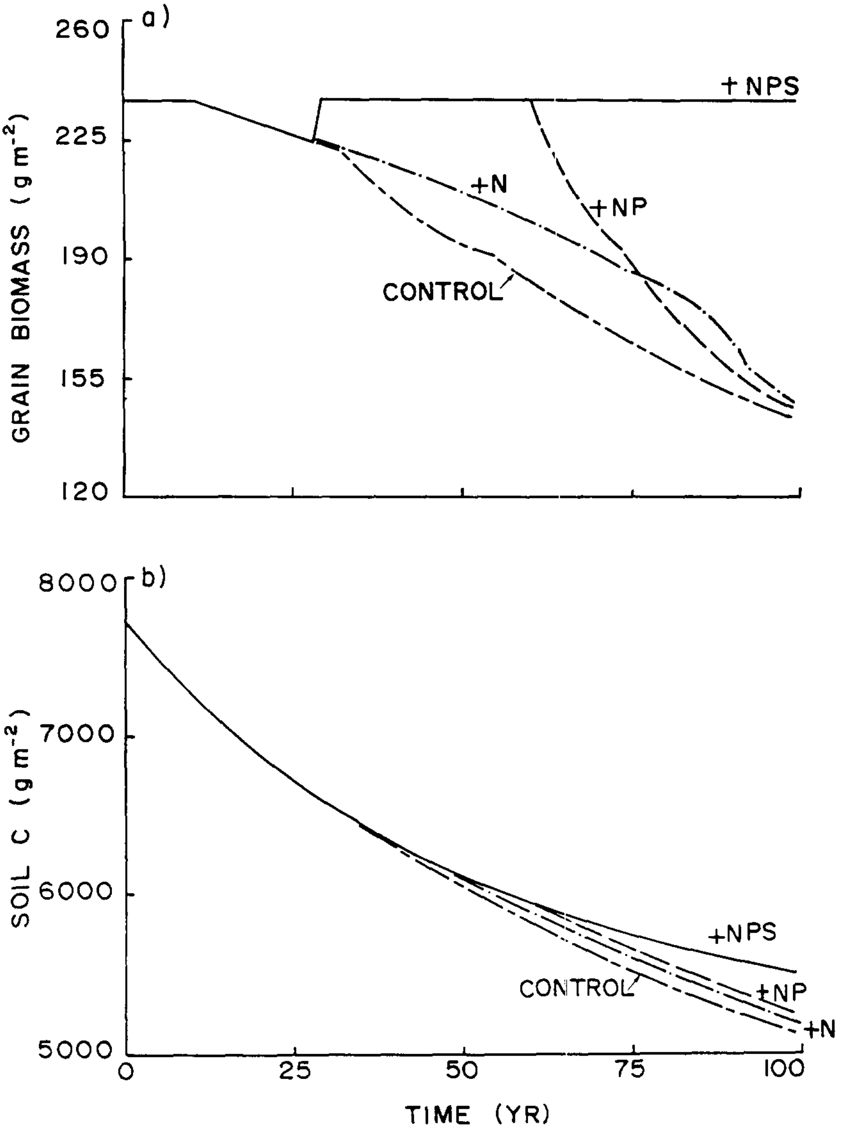

Fig. 9. Simulated effect of adding N, N and P and N, P and S fertilizer on grain biomass (a) and soil C (b).

limiting nutrients and S limitations become important when N and P nutrient limitations are removed by fertilizer additions.

We evaluated the model's ability to respond to P addition to the soil by simulating the addition of labile P fertilizer to a P deficient soil and comparing the results to observed data from Wagar et al. (1986). They used a variety

Table 2. Comparison of observed and simulated five year average grain biomass and grain P for a cultivated soil in Canada (Wagar et al. 1986), where 2 g P m^{-2} were added to the soil initially.

Treatment ($g P m^{-2} y^{-1}$)	Grain Biomass ($g m^{-2} y^{-1}$)		Grain P ($g m^{-2} y^{-1}$)	
	OBS	SIM	OBS	SIM
Control	213	210	0.74	0.64
+0.25	234	224	0.80	0.70
+0.50	243	235	0.90	0.75
+1.00	254	250	0.92	0.87
+2.00	265	260	1.04	1.08

of different P fertilizer additions to a P deficient soil where spring wheat was grown annually from 1979 to 1984. We estimated the initial conditions by cultivating of the Blaine lake soil for 60 years. Spring wheat was then simulated for five years with P addition treatments (see Table 2 for results). The treatment simulated was 2 g m^{-2} labile P added at the beginning of the five year run and different amounts of P fertilizer added annually at seeding (other nutrient limitations we eliminated by fertilizer additions). Table 2 shows that the observed and simulated five year average grain biomass and grain P for spring wheat were quite similar with the model having a slight tendency to underestimate P uptake in the grain. The model represented the changes in P concentration in the grain (simulated grain P concentrations increased from 0.3% to 0.42%) as the P fertilizer levels increased (observed P concentrations ranged from 0.35 to 0.39%).

Conclusions

Soil P and S cycles include both inorganic and organic fractions, and have organic fractions where the C:P and C:S ratios change as a function of the labile P and S levels, respectively. The primary source of soil P and S is weathering of P and S from the parent material. This contrasts with soil N cycles where most of the soil N (> 95%) is found in an organic form, the C:N ratio of SOM is fairly constant and the primary source of soil N is atmospheric deposition and biological fixation. Varying C:P and C:S ratios as a function of the available soil P and S levels is an important aspect of the model and allows it to simulate the impact of different levels of available P and S on the cycling of P and S in the soil. A key part of the floating ratio model is the assumption that the passive SOM fraction has the widest range of variation (20 to 200), followed by active SOM (20 to 80) and slow SOM

(90 to 200). The simplistic representation of the floating C:P and C:S ratios used in the model appears to yield similar results to the more mechanistic representations used elsewhere (Hunt et al. 1983).

The results from the long term soil formation simulations showed that the model adequately represented the weathering of P and S from the soil parent material and the formation of organic P and S in different SOM fractions. P weathered from the parent material after year 4000 was primarily immobilized into the old SOM fraction, which cyles at a very slow rate and thus acts as sink for the P mineralized by weathering after year 4000.

The cultivation run showed that the model correctly represented the changes in inorganic and organic C, N, P and S soil levels caused by cultivation. The model results suggest that the observed drop in the SOM C:P and C:S ratios is a result of an increase in the fraction of the SOM that is passive (the passive SOM has a low C:P ratio). The model also correctly showed that P and N are the primary limiting nutrients for the Blaine Lake soil and correctly represented the increase in grain biomass and P content resulting from the addition of P fertilizer to the soil. The model demonstrated the observed results that adding plants to the soil system causes the P and S soil mineralization rates to be increased.

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