Developing simplified synergistic relationships to model topsoil erosion and crop yield.

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ABSTRACT

Topsoil is highly enriched with organic matter, which provides a valuable source of plant nutrients as well as a favorable rooting environment. Over time, erosion processes selectively remove the organic matter-rich fine fraction which causes a measurable reduction in soil productivity. Assessments of past erosion are of little value in predicting future losses in productivity since the synergistic lowering of soil organic matter through lower residue inputs is not considered. Dynamic computer models, which simulate the plant/soil system, can project the long run future costs of soil erosion on crop yield. A simplified erosion-crop yield model was developed by first defining the most important soil productivity variables, then quantifying the effect of erosion on each variable. The model predicted a declining trend in grain yields similar to that observed on soil scalping experiments.

INTRODUCTION

Cultivation systems having frequent tillage and little residue cover enhance the process of topsoil erosion. As erosion removes the organic matter-rich topsoil, soil productivity declines. Attempts to predict the cost of topsoil erosion on grain yields have used measurements of past erosion (Lyles 1975), simplistic proxy variables like solum depth (Christensen and McElyea, 1988) and complex computer models which simulate the plant-soil system (Williams et al., 1983; Shaffer, 1985).

Interactive computer models, although being the most robust, are often very complicated and poorly validated, especially under western Canadian conditions (Greer et al., 1991; Cassel and Fryrear, 1990). It was felt that the relationships between erosion and soil properties which directly control crop yield, could be more simply described. The objective of this paper is to describe the logic and tools used to develop a simple interactive relationship between topsoil erosion, soil available N, and crop yield.

MATERIALS AND METHODS

We began with the premise that crop yields in Saskatchewan are most often limited by available water, available N and available P and that erosion affects the ability of the soil to supply these factors. The task of logically connecting erosion to each soil property or process and each soil property or process, in turn, to crop yield was attempted using the STELLA® II temporal modelling environment.

STELLA® II is a numerical integration program which uses flow chart-like diagrams to track the changes in connected variables over time. Describing the logic between variables is far less complicated than programming in standard computer languages since creating a 'Flow' diagram is very similar to conceptual models of the soil system (eg. Anderson, 1991; van Veen and Paul, 1981). Formulating and testing logic using this software requires little programming experience.

STELLA® II uses four simple building blocks to create a flow diagram or model. "Stocks" are assigned to any item which accumulates or depletes over the time step modelled. Stocks are built up or depleted by "Flows" of items into or out of a stock. "Converters" are commonly used to provide detailed logic or convert one item into another. However, a converter can also replace a stock if the stock changes instantaneously from one time step to the next. Caution is advised when using converters in place of stocks since accumulations which attenuate the dynamic behavior of a system may be overlooked. "Connectors" simply link together the logic contained in Flows, Converters and Stocks. Connectors do not describe a flow from one item to another. They simply serve to connect the variables which impact each other. Further detail on attributes and applications of STELLA® II can be obtained from demo disks or software documentation available through High Performance Systems Inc., 45 Lyme Road, Suite 300 Hanover, NH 03755 USA, phone: 603-643-9636.

RESULTS AND DISCUSSION

Creating erosion - crop yield models

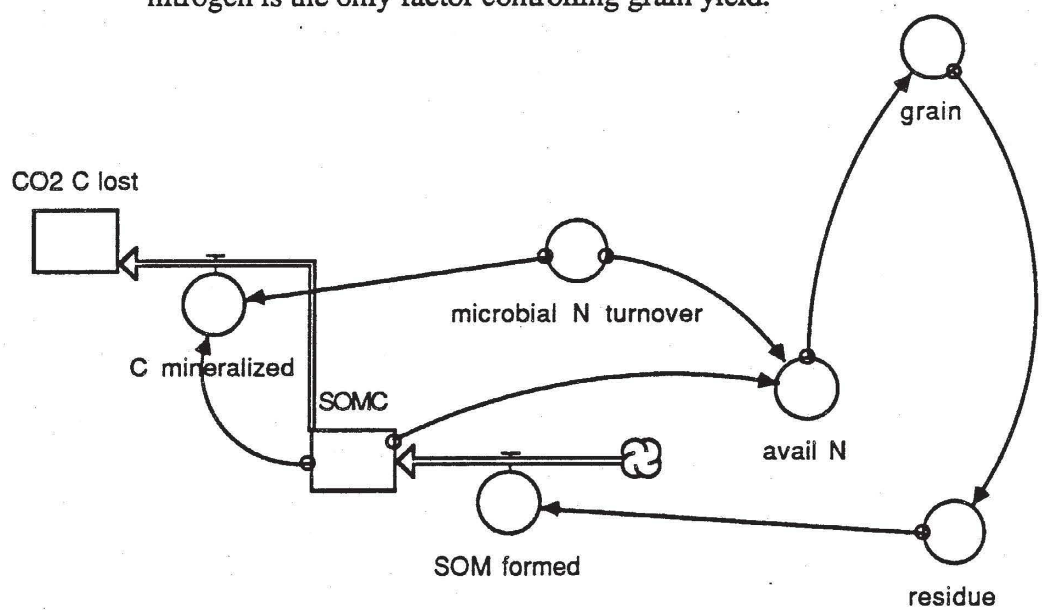
Most people associated with agriculture possess a mental model of the plant-soil system. This mental model is usually a collage of detailed personal experiences and theoretical knowledge and is often greatly skewed toward that person's particular expertise. Although mental models are useful in organizing knowledge, they cannot be used to describe dynamic behavior. Mental models normally lack quantification. They lack the numerical equations describing how experiences and knowledge are linked. Hence, the fundamental challenge in model building is in moving from a detailed mental model toward a quantified numerical model which describes the dynamic behavior of the plant-soil system.

Richmond et al. (1990) suggests moving directly to the most simplified description of the system by aggregating and selecting the processes which serve to condense the mental model to its essential elements. Zooming out to a "big picture" view of the system reduces the skew associated with individual experience and serves as a starting point to quantify the key interdependent relationships. Only after testing and describing the output of the initial "big picture" model, should other variables and numerical equations (complexity) be added. Discussion of model building guidelines is not the purpose of this paper (see Richmond et al., 1990 for further details). However, it is important to realize that adding model complexities which truly reflect the dynamic behavior is more valuable than including every process which is 'part of the system'.

Application of a simplified modelling procedure

A highly aggregated STELLA® II model of the plant-soil system, where soil available N is the only factor limiting crop yield, is shown in Figure 1. As a time step (one year) passes, some amount of the soil organic matter carbon (SOMC) is mineralized as a result of microbial N turnover. The nitrogen (N) made available depends on the amount of SOMC as well as the microbial turnover rate of organic matter. The grain and residue produced depend on the level of available N supplied by the soil in that year. This synergistic loop is completed when residue is connected to SOM formed.

Figure 1. A simplified STELLA® II model of the plant-soil system where available nitrogen is the only factor controlling grain yield.



As the model currently stands, grain yields and SOMC levels will equilibrate when the SOM formed from residue is equal to that mineralized from SOMC. This simplified model can now be expanded to include some key interactions between topsoil erosion and available N.

As the soil erodes, the surface layer is lost causing the SOLUM depth to decrease (Figure 2). Removing the surface layer of soil also results in some fraction of the total SOMC to be lost. Using the graphical feature in STELLA® II (Richmond et al., 1990, pp.112) it is possible to quickly describe a reasonable quantitative function between the relative depth of SOLUM removed and the fraction of the total SOMC in that amount of SOLUM (Figure 3).

Figure 2. A simplified STELLA® II model of the plant-soil system where available nitrogen and topsoil erosion are factors controlling grain yield.

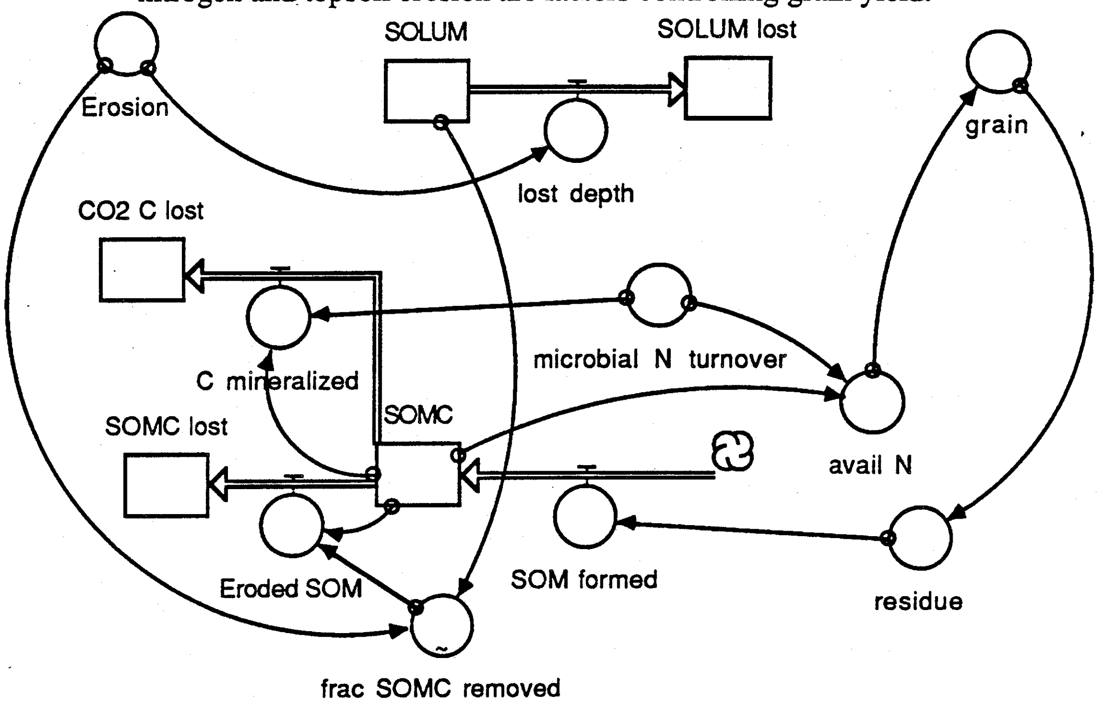


Figure 3. Graphical function quantifying the removal of SOMC as topsoil erodes.

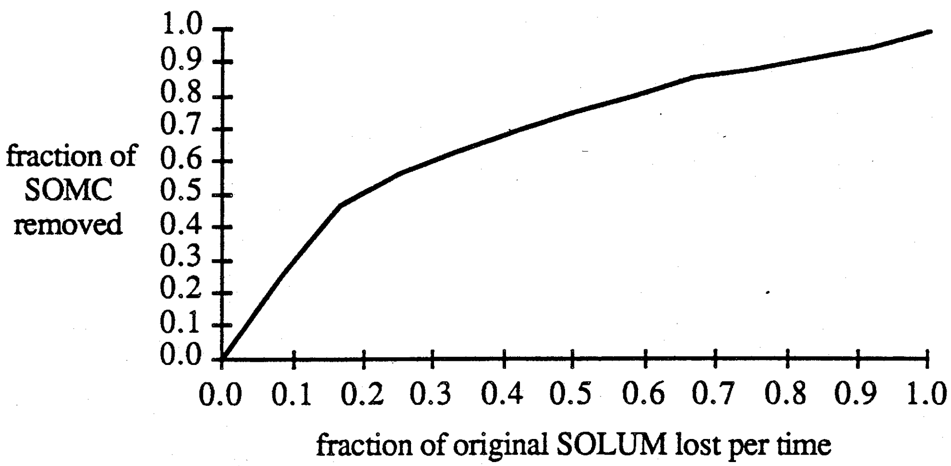
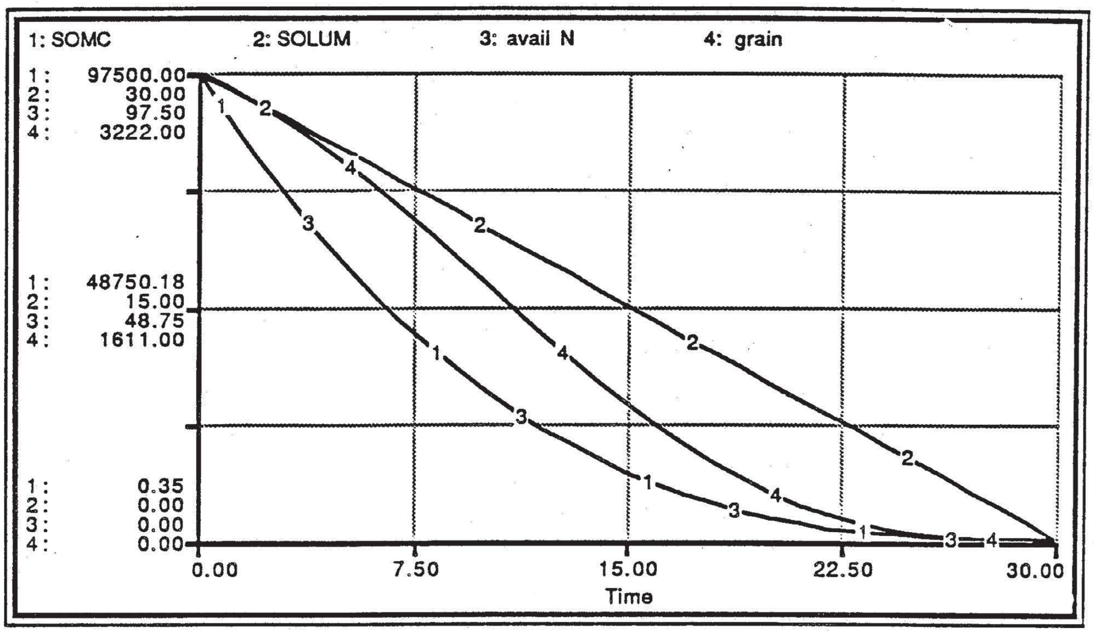


Figure 3 indicates that a greater fraction of the total SOMC is removed as the amount of the solum eroded increases. However, marginally more of the total SOMC is lost is with the first unit of solum lost. This function is based on the assumption that SOMC is always most concentrated in the surface layers. Such an assumption is valid even on soils where the entire solum has been lost, since SOMC present as residues is concentrated in the surface 10 cm. (Staricka et al., 1991).

When the model described in Figure 2 is initialized and run for a 30 year period, the following output is generated (Figure 4). Initial soil conditions required for the simulation are as follows: soil organic C (entire solum) = 2.5%, soil bulk density = 1.3 $Mg \cdot m^{-3}$, SOLUM = 30 cm, Erosion = 1 cm per year (130 $t \cdot ha^{-1}$).

Figure 4. Simulated changes in soil depth, organic matter C, available N and grain yield over thirty years with 1 cm of Topsoil Erosion per year.



The greatest loss of SOMC occurs as the first few cm of topsoil are lost. Continued erosion of the solum appears to remove less SOMC since deeper layers are less enriched in organic matter. Available N follows the same trend as SOMC with successive loss of topsoil. Intuitively, a declining trend in available N is expected. However, many studies have shown that the fraction of the total N mineralized is significantly lower in the deeper soil layers (Hadas et al., 1986; Greer and Schoenau, 1992). This will cause available N to decline at a faster rate than the total SOMC as the most readily mineralizable organic matter in the surface soil is lost.

Adding another converter (NtSOLUM) between the SOLUM and microbial N turnover will allow N mineralization to be reduced as the solum is lost (Figure 5). Once again, a graphical function is used to described the loss in the % of the total N mineralized per year as the original solum is lost (Figure 6).

Figure 5. A simplified STELLA® II model of the plant-soil system where available nitrogen, topsoil erosion, and nitrogen turnover with depth are factors controlling grain yield.

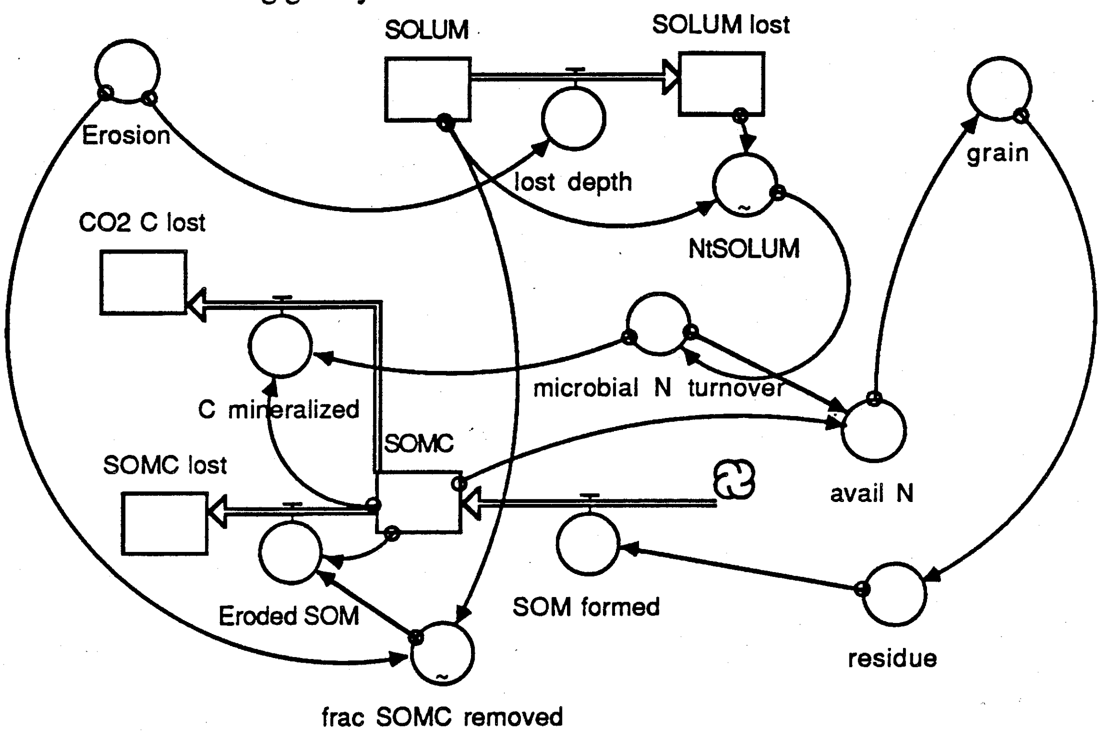
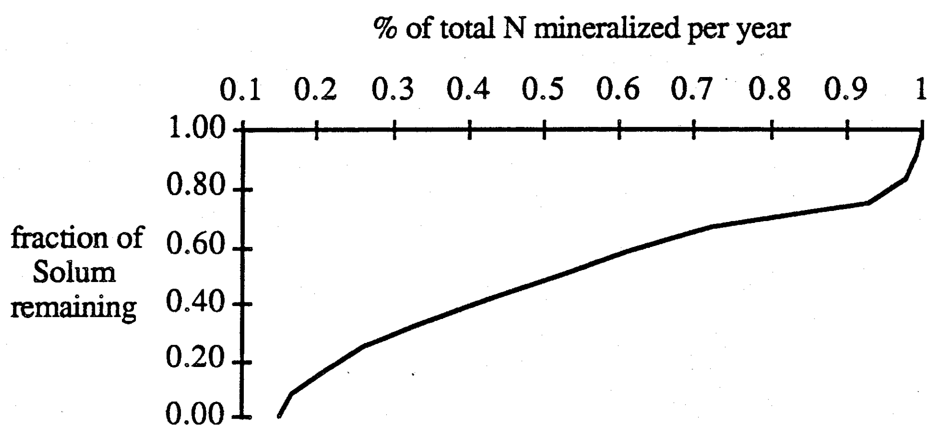
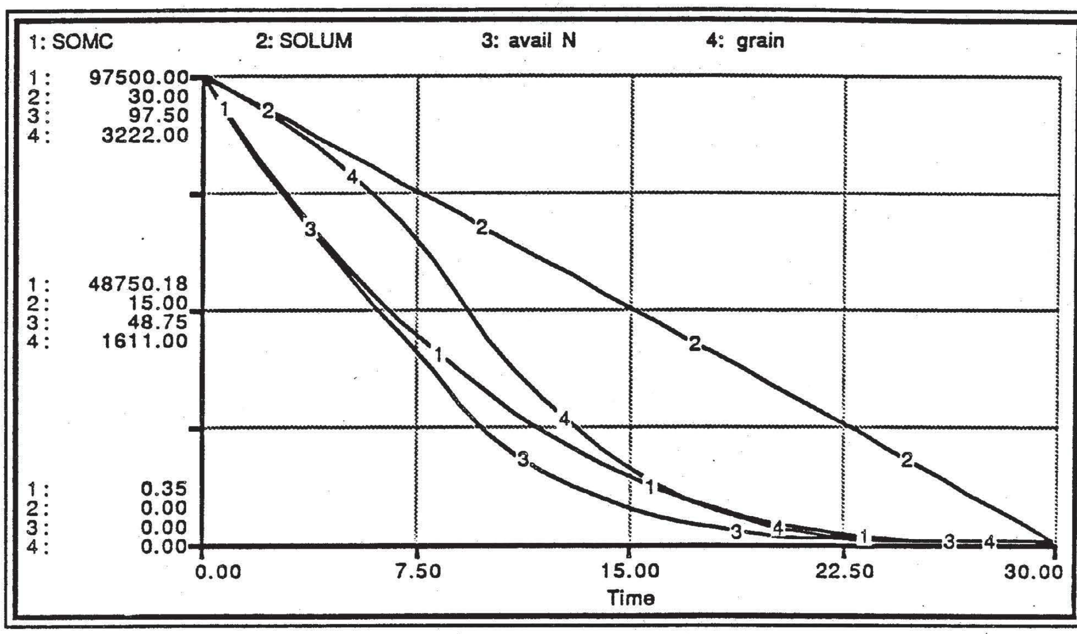


Figure 6. Graphical function quantifying the decline in N mineralization as solum depth erodes.



Running the new model with the same parameters reveals a more meaningful description of available N and crop yield as SOM erodes (Figure 7). Once the plow layer is lost the amount of available N declines at a faster rate than SOMC. This causes grain yield to decline very rapidly after 7 to 10 cm of topsoil is lost. Such trends in grain yields have been found on simulated erosion plots (Larney et al., 1992). However, further work is required to validate the role of available N in lowering grain yield on naturally eroding soils.

Figure 7. Simulated changes in soil depth, organic matter C, available N and grain yield over thirty years with 1 cm of Topsoil Erosion per year and N turnover decreasing with depth.



CONCLUSIONS

Simple synergistic relationships, when numerically modelled, are very useful in clarifying our perception of the complex plant-soil system. A firm grasp of the 'big picture' or the key factors controlling a system was required to aggregate factors and select essential processes. A simple model describing the impact of soil erosion on grain yield through its effect on soil organic matter and available N was developed. Questioning the temporal dynamics of the initial simulation prompted a more detailed description of N turnover to be added. This added complexity was tested and appeared to more closely describe the behavior of crop yield on scalped plots.

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