An approach for simulating the soil-grassland interface in pastoral farming systems

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Abstract: Recycling of nutrients from the soil is one of the key determinants for the sustainability of grazing ecosystems. In this paper, a concise soil model, which is a part of a general grazing system simulation framework, is described. The model works in conjunction with a grassland model which also interacts with animal and herd models. The objective of the model is to simulate nitrogen (N), phosphorus (P) and water available for plants in a simple but mechanistic way. The model has 14 state variables, of which the most important are the N and P available to plants and the soil water content. The model functions with daily timesteps. All degradation processes are affected by soil moisture and temperature. Easily degradable plant litter and animal excreta are simulated as inputs to a pool of minerals available to plants. Structural litter is not simulated and the input of mineral is incorporated through the potential mineralization of organic matter. Rain and fertilisation are other inputs to the pool of N and P available to plants. The water submodel treats the soil as a multi-horizon-layered system with a variable number of layers, each one with variable thickness. The content of soil moisture is calculated from the combined effect of precipitation, runoff, irrigation, soil evaporation, and transpiration by plants and downward movement. Groundwater influence is not considered. The general structure of the model and preliminary results are described in the paper.

1. INTRODUCTION

Soil is a key component of grassland ecosystems because their sustainability depends on the amount of nutrients that can be extracted and recycled from it. Simulation of nutrient cycles is necessary for an appropriate description of the grassland system. The flow of energy and the functioning of living species depend on the flow of nutrients, especially water (Halm et al., 1972). Minerals are transported through biological processes such as plant uptake and utilisation by water. Therefore, biogeochemical and hydrologic cycles of the pasture ecosystem are virtually inseparable (Wilkinson and Lowrey, 1973).

Many water and mineral dynamics soil models are currently available (Keulen and Seligman, 1987; Verberne, 1992; Supit et al., 1994; Parton et al., 1994; Wight and Skiles, 1987; Jones et al., 1984). In the most complex ones, a lack of appropriate data for parameterisation is a major obstacle (Herrero et al., 1997). Therefore, a simple (easy parameterisation) but mechanistic approach (capable to simulate basic dynamics) has been followed to simulate nitrogen (N), phosphorus (P) and water available to plants.

This paper describes the general structure and dynamics of the soil model. Interfaces with plant and animal models are considered in order to describe nutrient cycles in grazing ecosystems.

2. DESCRIPTION OF THE MODEL

The soil model diagram is shown in Figure 1. It consists of water and mineral submodels, which are described as follows.
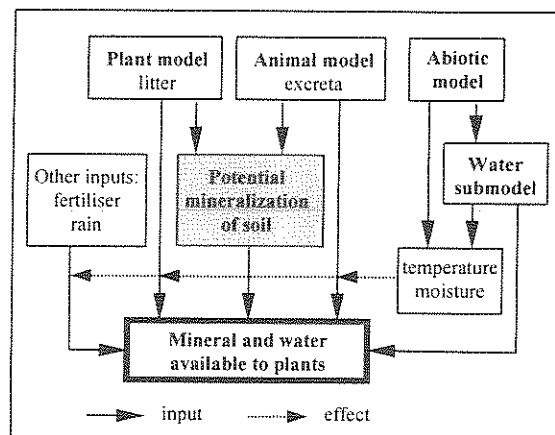

Figure 1. Diagram of soil model

2.1 The water submodel

The water submodel simulates water content in soil. It treats the soil as a multi-horizontal-layered system with a variable number of layers, each one with variable thickness. The processes represented are precipitation, runoff, irrigation, soil evaporation, plant transpiration and downward movement.

Run-off depends on precipitation intensity and duration, vegetation cover, soil type and surface slope. There is not a simple way to include all these processes into the model, but because run-off is an important feature of most areas, it has been incorporated following the work of Williams et al. (1985), which considers a soil water retention parameter.

The calculation of water losses due to evaporation and transpiration are based on the potential evapotranspiration,

calculated following the classical approach of Penman (1956).

Water infiltration from rain and irrigation occurs into the surface soil layer. Each soil layer can be filled with water until field capacity. Excess water drains to the next soil layer or below root zone.

We assume that there is not groundwater influence, therefore capillary rise is not considered.

The time step for integration is one day. The only state variable of the model is the volumetric water content in the different soil layers considered. Water potential can be easily calculated from moisture content using the single parameter equation of Gregson et al. (1987). The driving variables are: mean, maximum and minimum daily temperatures, precipitation, relative humidity, wind speed, photoperiod, sunshine hours and angot values. The water submodel has 38 rate variables and 26 parameters that in many cases have default values.

The soil moisture content (W_z, m³H₂O m⁻²soil) is expressed by the two following equations for layer 1 and other layers respectively:

$$\frac{dW_1}{dt} = RAIN + IRR - RUN - EVA_1 - TRA_1 - INF_1$$

(1)

$$\frac{dW_z}{dt} = INF_{z-1} - EVA_z - TRA_z - INF_z$$ (2)

Where: W_z is actual soil moisture content in layer z (m³H₂O m⁻²soil); RAIN is precipitation (m³H₂O m⁻² soil day⁻¹); IRR is irrigation (m³H₂O m⁻²soil day⁻¹); RUN is runoff (m³H₂O m⁻²soil day⁻¹); EVA_z is actual soil evaporation in layer z (m³H₂O m⁻²soil day⁻¹); TRA_z is actual plant transpiration in layer z (m³H₂O m⁻²soil day⁻¹); INF_z is infiltration in layer z (m³H₂O m⁻²soil day⁻¹).

2.1 The mineral submodel

The mineral submodel simulates inorganic N and P available to plants.

Organic residues to the soil are usually higher in grassland than in crops. These are higher under grazing than under mowing as a result of the return of dung, urine and plant litter (Hassink, 1994). Therefore, these inputs help to simulate changes in minerals obtainable by plants in one stable ecosystem where climatic conditions and ungulate animals are the main causes of disturbance.

As can be seen in Figure 1., the model details availability of mineral to plants. Degradation processes are affected by soil temperature and moisture, which are obtainable from abiotic and water submodels. Easily degradable plant litter from the plant model and excreta from the animal model are simulated as inputs to the pool of mineral available to plant. Degradation dynamics of structural litter are not

simulated and are assumed through potential mineralization of soil. This approach is supported by soil conditions in natural pasture ecosystems, where the organic matter pool is relatively stable for each type of soil (White, 1987). Rain and fertiliser are other possible inputs to the pool of mineral available to plant.

The mineral submodel has 12 state variables, 59 rate variables and 19 parameters. As in the water submodel, most parameters have default values and the time step is one day.

The N available to plant (NApl) is modelled (Figure 2) on the basis of the potential mineralization of soil (Stanford & Smith, 1972; Stanford et al., 1973), which has been defined as a fraction of the organic nitrogen pool that is susceptible to mineralization. Therefore, only direct mineralization during the first stage of plant litter and animal excreta decomposition, have to be simulated. The N available to plant is calculated from the following differential equation:

$$\frac{dNApl}{dt} = Nsom + Nfa + Nfe + Nmr + Nms + Nu + Nr - LN - Np$$

(3)

Where: Nsom is the effective inorganic N mineralization from soil organic matter (g m⁻²); Nfa is N mineralization from faeces (g m⁻²); Nfe is N mineralization from fertiliser (g m⁻²); Nmr is N mineralization from metabolic root litter (g m⁻²); Nms is N mineralization from metabolic surface litter (g m⁻²); Nu is N mineralization from urine (g m⁻²); Nr is N from rain (g m⁻²); LN is leaching N from root zone (g m⁻²); Np is N uptake by plant (g m⁻²).

P is also modelled using potential mineralization of soil (Figure 2). However, to estimate P potential mineralization it is necessary to know previously the size of the P pool in stable organic matter, after which the surplus can be mineralised (Jones et al. 1984). The P available to plant (PApl) is calculated from the follow differential equation:

$$\frac{dPApl}{dt} = Psom + Pfa + Pfe + Pmr + Pms + Psr + Pss + Pr + ISP - OSP - LP - Pp$$

(4)

Where: Psom is the effective inorganic P mineralization from soil organic matter (g m⁻²); Pfa is P mineralization from faeces (g m⁻²); Pfe is P mineralization from fertiliser (g m⁻²); Pmr is P mineralization from metabolic root litter (g m⁻²); Pms is P mineralization from metabolic surface litter (g m⁻²); Psr is inorganic P from structural root litter (g m⁻²); Pss is inorganic P from structural surface litter (g m⁻²); Pr is P from rain (g m⁻²); ISP is flow from secondary P (g m⁻²); OSP is flow to secondary P (g m⁻²); LP is leaching P from root zone (g m⁻²); Pp is P uptake by plant (g m⁻²).
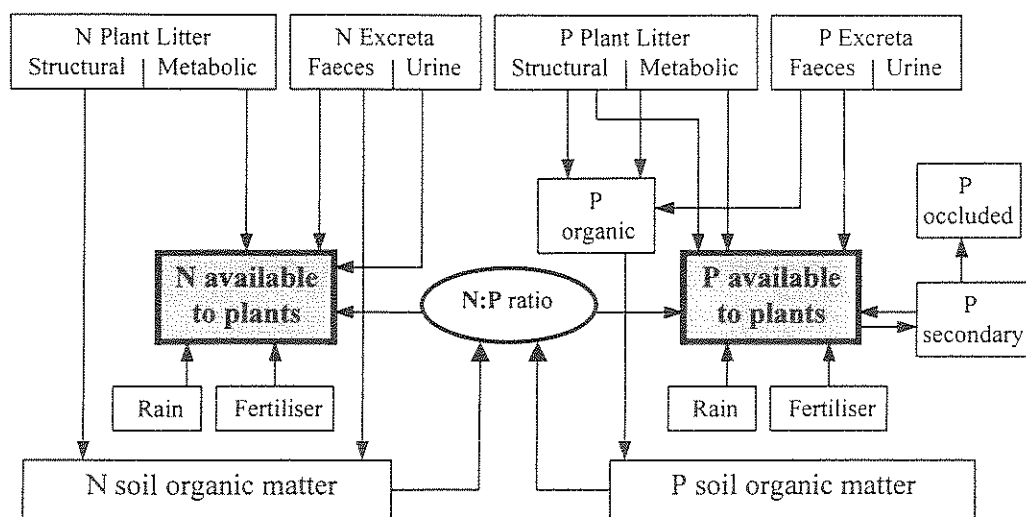
Figure 2. Dynamics of N and P in the model

2.1.1 Plant litter decomposition

Two different types of litter are considered depending on their position: surface and root litter. Lignin-to-nitrogen ratio controls the split of plant residue into a structural (slow degradation) and metabolic material (easily decomposable). The structural litter dynamic is not simulated and the mineral input from it is assumed to be reflected in the potential mineralization of soil.

When organic litter is decomposed essential elements are converted from organic combination to simple inorganic forms through microbial respiration (White, 1987; Hassink, 1994). The model assumes that 60% of carbon is lost through microbial respiration. Inorganic forms are released when the assimilated material is in excess of the growth demand of the microorganism that decomposes the organic material. The model considers that soil organic matter is maintained at a fixed C:N and C:P ratio according to the kind of soil.

N and P flow from metabolic litter depend on C flows. The model assumes that N and P are bonded with C, so the proportion of N or P present in metabolic litter is liberated for direct mineralization when CO_2 is produced during decomposition. However, this inorganic mineral can be immobilised when the ratio C:N or C:P in the flow from decomposition material to organic matter is less than the ratio in metabolic litter.

2.1.2 Potential mineralization from organic matter

Stanford and Smith (1972) proposed a mathematical model that was based on the hypotheses that only a fraction of the total N of soil is potentially mineralised (Parentoni et al. 1988). Evidence has shown that this procedure may give accurate predictions of N availability under field conditions (Smith et al., 1977).

The rate of N supply by stable organic matter is obtainable under ideal laboratory conditions. However, soil water and temperature greatly influence mineralization of soil organic nitrogen (Stanford & Epstein, 1974; Cameron & Kowalenko, 1976; Cassman & Munns, 1980), and the quantitative relationships involved have been incorporated in the model to predict the amount of N released to the plant under specific climatic conditions.

Phosphorus cycling is governed by its stability (low solubility), and its low mobility in soil. Only part of the P pool in soil organic matter can be mineralised. In the model 50% has been considered following data by Jones et al. (1984) for virgin soils.

The amount of N and P mineralised to the pool of available minerals to plants depends on the ratio N:P in soil organic matter that has to be constant in the model.

2.1.3 Animal excreta decomposition

When herbage is consumed by grazing animals, very small proportions of the total mineral intake are retained in animal products. Therefore, these are present in organic and/or inorganic forms in excreta, depending on the particular mineral. Thus, returned nutrients may be in readily plant-available forms or in forms that require mineralization before they are available for plant uptake. Significant mineralization of organic plant P occurs during passage through the animal digestive tract and, in addition, much of the N is excreted as urea, which is rapidly converted to the readily plant-available NH4 and NO3 forms. Consequently, the amount of N and P returned in animal excreta is more rapidly available to plant than are N and P in decaying plant residues (Wilkinson & Lowrey, 1973; Scholefield et al., 1993; Haynes & Williams, 1993).

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The model considers that N is excreted thorough urine and faeces in different proportions which are dependent on the quality of diet (Haynes and Williams, 1993).

Because the bulk of the N in faeces is in organic form it must first undergo microbial mineralization before it is released in mineral form. However, N mineralization from the plant material is slower after the animals have digested it, because faeces contain a large proportion of C in undigested fibres (Haynes & Williams, 1993). The model considers that the amount of N mineralization from faeces is closely related to the total N content of faeces and that the process is affected by moisture and temperature (Floate, 1970).

The percentage of N in diet determines the quantity of N present in urine. Urea is the main component of urine and its degradation to ammonium is quicker than with commercial urea (Sherlock & Goh, 1984). Loss of ammonium from urine patches depends also on temperature and moisture (Haynes & Williams, 1993).

As opposed to N, in which urine is an important pathway of excretion, faeces represents a predominant pathway in which P returns to the soil (Barnett, 1994). Only traces of P are normally detected in the urine.

The proportion of inorganic P in faeces increases as total P intake increases, but the content of organic P remains relatively constant. The inorganic faecal P content was found to be as effective as a P source as readily soluble fertiliser, however, the organic P content was not available, at least in the short term (Haynes & Williams, 1993). Therefore, the model assumes all organic P through potential phosphorus mineralization. The physical breakdown of the dung is the controlling factor in the movement of inorganic P from faeces into the soil and the weather is the main factor that affects the dung breakdown.

2.1.4 Other inputs and outputs

Rain and fertiliser are the other components to consider when establishing the pool of mineral available to plant.

The quantity of nutrients in the rainfall is derived from the mineral concentration and quantity of rainfall (Allen et al., 1968). Contribution of N and P from rain are assumed in the model as same as Hanson et al. (1988) and Allen et al. (1968) respectively.

Efficiency of N fertilisation depends on ammonia losses and the magnitude of the loss varies with weather conditions. Ammonia losses are incorporated to the model following the approach of Fenn and Hossner (1985). P fertiliser is considered in the model as a comparison with rock phosphate. Here, the triple superphosphate is adopted as a pattern. Therefore, all triple superphosphates are incorporated to the pool of available P. However, with the other P fertilisers, the relative agronomic effectiveness (RAE) is considered (Leon et al., 1986).

The P weathering has not been estimated in the model because of insufficient data are available on rates of P weathering (Newman, 1995).

The inorganic P that is available to plant is inconsistent, and part of it is interchangeable with other form of inorganic P called secondary. However, not all the secondary inorganic P can return to the pool of P available to plant because part goes to the occluded pool (Parton et al., 1987).

For leaching, the model follows the approach by Burns (1974) which considers that water and mineral entering into soil are completely mixed with the water and mineral present in soil. Therefore, leaching depends on infiltration flow that comes from the water submodel.

3. PRELIMINARY RESULTS

First results have been obtained using climate and soil data from Rio Grande do Sul in Brazil to obtain the parameters required by the model.

In Figure 3 the monthly minimum, medium and maximum soil water content ($m^3 m^{-3}$) is presented for a period of 10 years in a silt loam soil.
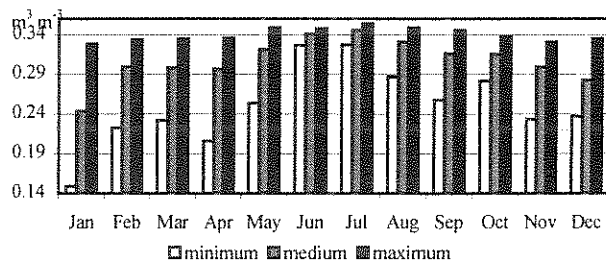
Figure 3. Simulated monthly minimum, medium and maximum soil water content during the period 1974-1984.

The highest medium water content in soils occurs in winter, from July to August. In this period, precipitation is very regular every year so minimum and maximum water contents are close to medium values. In winter, the limiting factor to plant growth is low temperature but not moisture.

In spring and autumn medium water contents are still high but the minimum values are lower because rain is more irregular in these periods.

In summer, the medium water content in soils is at the lowest levels, and most important, the variation between years is very big due to irregularity in precipitation. This is especially important in January. These results agree with the water balance observed in Rio Grande do Sul (Motta et al., 1970). Plant water availability is very limited in summer when temperatures are at highest values. This phenomenon is especially important in years with low rain

and explains the irregularity of pasture production in this region.

Harvested
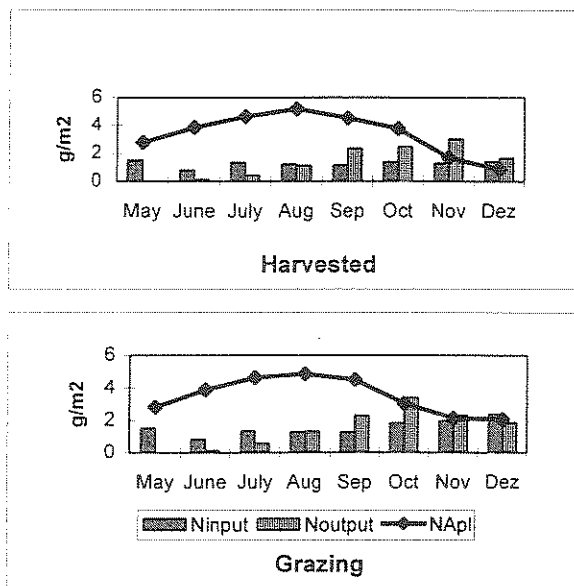

Ninput Noutput NApl

Grazing

Figure 4. Simulated N in the soil cultivated with Italian ryegrass.

In Figure 4 the result of simulated N available to the plant in the soil is shown on management conditions of harvesting and grazing.

In harvested management, three cuts were simulated following Gonçalves (1979) without fertiliser. In the grazing management, the conditions of simulated stocking rate increase from 100 kg/ha in July to 800 kg/ha in November.

The patterns of N available to plant curves are similar in both conditions of management. However, after October, the effect of recycling of N by animals is confirmed and the N in the soil tends to get to a steady state. The same conditions can be observed in Figure 5 with P. This fact is shown by the higher input of available minerals, mainly P.

The higher rate of Italian ryegrass growth in spring results in higher output of minerals from the soil. Therefore, during this time the mineral balance is negative, mainly in harvesting conditions. The opposite situation occurs in late autumn and winter, due to the establishment and low growth of Italian Ryegrass.

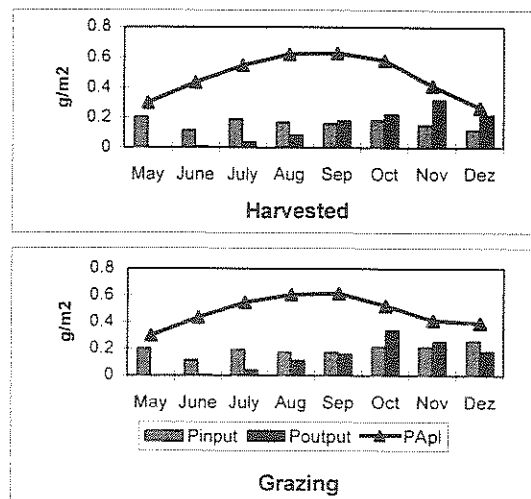The model is now in the test of parameter sensitivity and validation.

Harvested

Pinput Poutput PApl

Grazing

Figure 5. Simulated P in the soil cultivated with Italian ryegrass.

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