Biogeochemistry 5: 165–181 (1988)

Development of a simulation model of sulfur cycling in grazed pastures

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Key words: S cycling, pasture modelling, organic S, nutrient modelling, CNP interrelationships

Abstract. A simulation model of S, P and N cycling in pastures was constructed as a conceptual and predictive tool to examine a range of possible fertilizer managements for improved pastures on the Northern Tablelands of N.S.W.. The model successfully simulated pasture yield and clover content for a four-year superphosphate trial. It was used to calculate C and S fluxes between various pools for pastures with and without fertilizer S. Under a non-limiting P regime, which was S deficient, the model predicted a 3.6-fold increase in tops growth due to S fertilizaton, a 13-fold increase in sheep liveweight gain, and a 5-fold increase in wool production. These effects were due to a greater proportion of assimilate contributing to tops growth, and a much higher proportion of clover in the diet.

Introduction

The sulfur cycle in a grazed pasture is a complex system involving the interface of soil, plants, animals, soil fauna and micro-organisms. Processes within the overall cycle include the recycling of S, within animals (Doyle & Moir 1979), leaching of S from plants to the soil (Tukey 1970), mineralization of plant S (Till & Blair 1978), and cycling between organic and inorganic forms within the soil (Freney et al. 1971, 1975; Freney & Williams 1983). Cycling rates vary greatly between one part of the system and another.

Work with organic carbon has shown half-lives in various pools ranging from a few minutes in situations of microbial grazing (Fenchal & Harrison 1976) to almost 2000 years for "chemically stabilized organic matter" (Jenkinson & Rayner 1977). The same range of half-lives could be expected for S. While the S associated with chemically stabilized organic matter is technically cycling, its slow turnover rate makes it practically unavailable to plants in the short term.

Till & May (1970) used specific radioactivity data to estimate the size and turnover rates of the various S pools in a pasture system grazed at 10 sheep ha^{-1}. Their data indicate that approximately two-thirds of the S in the grazed pasture system is present in organic S forms. Active cycling was occurring in all segments of the system with the exception of an organic fraction which constituted 35.7% of the total S in the system (Table 1).

While it is possible to estimate pool sizes and some transfer rates through radiotracer techniques, direct measurement of many of the processes is difficult in a grazed pasture. For this reason, the group at Armidale has expanded a previous computer model of P cycling in pastures (PMOD) (Blair et al. 1976) to incorporate the turnover of C, S and N.

Much of the information for the model has come from previously conducted experiments which were not primarily aimed at determining fertilizer response, but instead examined such parameters as herbage growth rates and animal performance. These basic data were expanded into a model of organic matter cycling and combined with data on the nutrient concentrations in each organic matter pool, to provide a means of calculating nutrient flux rates from one pool to another. The model, which consists of about 2,500 lines of FORTRAN code, is intended to extend the results of field experiments to a wider range of sites and seasons, and simulates improved phalaris/white clover (*Phalaris aquatica* L./*Trifolium repens* L.) pastures on tableland areas of N.S.W.. Full details of model construction and validation are presented elsewhere (McCaskill 1987) and only a summary of key process is presented here.

Model construction

Organic matter cycle

Organic matter pools and fluxes simulated by the model are depicted in Fig. 1. Carbon is assimilated from the atmosphere by grass and clover through

Table 1. Proportion of total S in the various pools within a pasture system grazed at 10 sheep h^{-1} (Till & May, 1970).

Pool	Proportion %
Fertilizer	3.6
Animal	0.8
Plant (living)	9.7
Plant and animal litter and excreta	8.3
Soil	
Plant available	9.2
Organic S (cycling)	32.7
Organic S (apparently inert)	35.7

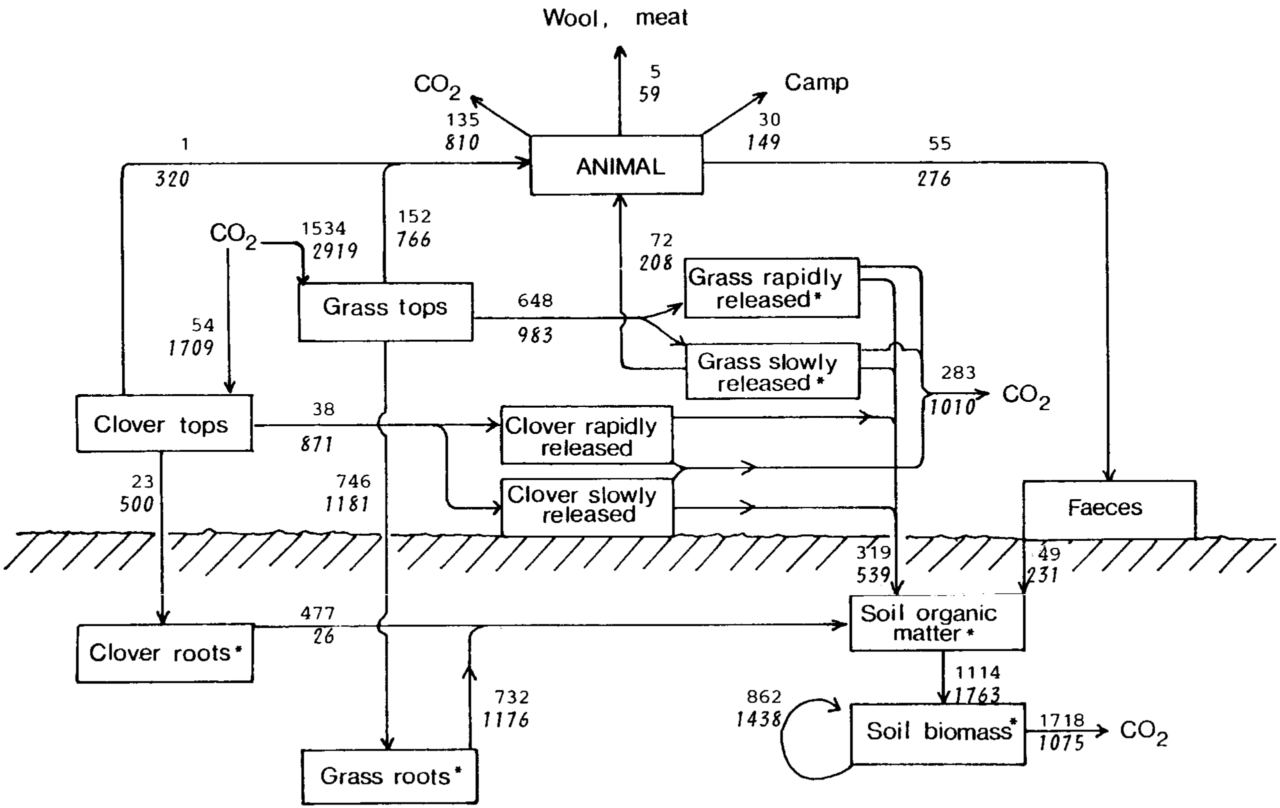

Fig. 1. Carbon pools and fluxes simulated by the computer model and calculated annual carbon fluxes (kg ha^{-1} yr^{-1}) over a 10-year period for a pasture system to which no sulfur is added (Roman type) and one receiving 43 kg S ha^{-1} yr^{-1} (italics). Pools marked "*" are simulated at various depths.

their above-ground tissue and a proportion of the assimilate is directed to plant roots. The gross tops growth rate (H_G, kg dry matter $ha^{-1} d^{-1}$) is calculated as a function of a genotypic potential growth rate, H_{max}, achievable under optimum growing conditions, with reduction factors ranging from zero to unity for temperature (f_T), light intercepted (f_L), moisture stress (f_θ) and S (f_S), P (f_P) and N (f_N) restriction:

$$H_G = H_{max} f_T f_L f_\theta \min(f_S, f_P, f_N)$$

H_{max} was found to vary seasonally when pasture growth data from Colman et al. (1974) were used in calibrating this section of the model. A maximial growth rate of 180 kg $ha^{-1} d^{-1}$ was used during the late winter- to mid-spring (August to October) and 80 kg $ha^{-1} d^{-1}$ during other months of the year. f_T is a function of temperature, also determined from the Colman data set, f_θ is a function of soil moisture (Smith & Johns 1975), and f_S, f_P and f_N are calculated from tissue nutrient concentration by functions of the form

$$f_x = 1 - \exp[-k(Ct - Ct_{min})]; \qquad Ct > Ct_{min}$$

where k is a curvature coefficient (kg plant material kg^{-1} nutrient), Ct (kg nutrient kg^{-1} plant tops) the nutrient concentration in plant tops, and Ct_{min} the minimum nutrient concentration of nutrient x required for plant growth. Values of k and Ct_{min} used for grass S were 3838 and 0.0015 respectively, which would predict no growth at 0.15% S and growth at 90% of maximal rates at 0.21% S.

Root growth rate R_G (kg dry matter $ha^{-1} d^{-1}$) is calculated from the tops growth rate and a root/shoot ratio, R_S, which varies with the plant's nutrient status according to pot trial work by Davidson (1969):

$$R_G = R_S H_G; \qquad R_S = 0.3 + [1 - \min(f_S, f_P, f_N)]$$

Root growth is partitioned into a user-specified number of soil layers and scaled so there is a greater rooting density in upper layers and those with a higher available water content. A constant specific root length of 21 cm mg^{-1} root was used for both legume and non-legume pasture components, based on measurements made on container grown plants by Evans (1970), Godwin (1981) and Cornish et al. (1984).

Above-ground biomass may either be consumed by livestock or become senescent at a rate dependent upon the soil moisture restriction factor and frosting. For the non-legume component, the function used for senescence (r_s, d^{-1}) is

$$r_s = 0.00126 + 0.00133/f_\theta - 0.005 \min(0, T_{min})$$

where T_{min} (°C) is the night minimum temperature. The soil moisture section of this function was based on a relationship from Cayley et al. (1980) and the frosting component derived from the data set of Colman et al. (1974). Feed availability data from a grazed field trial of Hamilton (1973) were used to calibrate the senescence function. No changes were made except for the spring flush period when senescence rates were modified. More detailed work with perennial ryegrass (*Lolium perenne*) has shown that the senescence of reproductive material is delayed during the spring flush until after maturity (Parsons et al. 1983; Johnson & Parsons 1985). To allow for this effect, the senescence rate of reproductive material was halved from October 15 to November 20, then increased by 0.06 + r_s until the end of the year. Senescent grass and clover material is added to the standing dead and litter pools, from where it decays by linear kinetics at rates reported by Hutchinson & Roper (1985). It is assumed that 80% of material is respired above the ground surface and the other 20% added to the top soil layer.

Feed selection by sheep from the grass, clover and dead pools and the digestibility of selected material were calculated by functions from Grimes et al. (1967), Hamilton et al. (1973) and Curll (1982). Indigestible material leaves the sheep as faeces, 35% is directed to camp areas and the remaining 65% to the pasture. Australian Merino sheep have a very strong night camping habit which results in strong net organic matter and nutrient fluxes to higher areas of the pasture (Hilder 1964). Sheep faecal material is relatively resistant to decay (compared with cattle faeces), and has a half-life of about one year (Bromfield & Jones 1970; Boswell 1983).

Soil organic matter consists of a small amount of easily decomposable material and a large proportion which cycles extremely slowly. A previously published organic matter model (Van Veen & Paul 1981; Van Veen et al. 1984, 1985) was used as the basis of the pasture organic matter submodel. Organic matter is divided into five non-living and two living or biomass components, each with their own maximal release constant (shown in Table 3). Actual decomposition rates are calculated by multiplying the maximal release constant by temperature and moisture reduction factors similar to those used by Van Veen & Paul (1981). From most rapidly released to most resistant, the non-living subpools are:

1. readily decomposable plant residue,
2. slowly decomposable plant residue,
3. clay-protected plant residue,
4. unprotected recalcitrant, and
5. clay-protected recalcitrant.

Most soil biomass is protected from predation by clay protection, except in the topsoil where there may be more biomass than the soil's capacity to protect it (Van Veen et al. 1985). Unprotected biomass decomposes at a much faster rate than the biomass protected by clays. Dead root and litter material entering soil organic matter is partitioned into pools 1 and 2 from where it may be consumed by biomass or transferred to the slower-cycling clay-protected and recalcitrant forms. A constant 40% carbon content is assumed for all plant material entering organic pools (Dalal 1979). In addition to consuming the non-living organic pools, the biomass also consumes itself.

Nutrient dynamics

The structure of the S, P and N model, depicted in Fig. 2, is based on that for organic matter but contains additional paths for nutrient uptake, fertilizer release and leaching. Plant nutrient uptake is simulated by a method based on diffusion theory developed primarily for phosphorus by Nye (1966), Bagshaw et al. (1972) and Barber (1984). Using this approach, the effective diffusivity of a nutrient in soil (D_e, $cm^{-2} sec^{-1}$) is expressed as

$$D_e = f_i \theta D_s / b$$

where f_i is a dimensionless impedence factor for solution flow through soil which can be predicted from θ and the clay content (Porter et al. 1960; Rowell et al. 1967), θ is the volumetric water content (ml water cm^{-3} soil), D_s the diffusivity of the nutrient in solution ($cm^{-2} sec^{-1}$), and b the ratio of plant available nutrient to that in solution (mg sorbed + water-extractable nutrient, mg^{-1} + water-extractable nutrient).

The nutrient depletion pattern around a root hair zone is a function of the effective diffusivity, D_e, time and distance from the root. This depletion pattern may be simplified into an effective rooting radius (r_E, cm), within which all sorbed and water-extractable nutrients would be considered available. The concept can also be expanded to include the effects of inter-root competition and root hair length (r_h, cm), and the distance $r_E - r_h$ can be calculated as a function of D_e and rooting density. The effects on the diffusion pattern can be simplified by using a constant time period for nutrient uptake. Field observations by Garwood (1967), solution culture work by Shock and Williams (1984) and reports cited by Barber (1984) indicate that virtually all nutrient uptake occurs in the first 30 days of root life. A constant 30 day period was allowed for nutrient uptake and in each day's simulation one-thirtieth of the plant-extractable sulfur within the

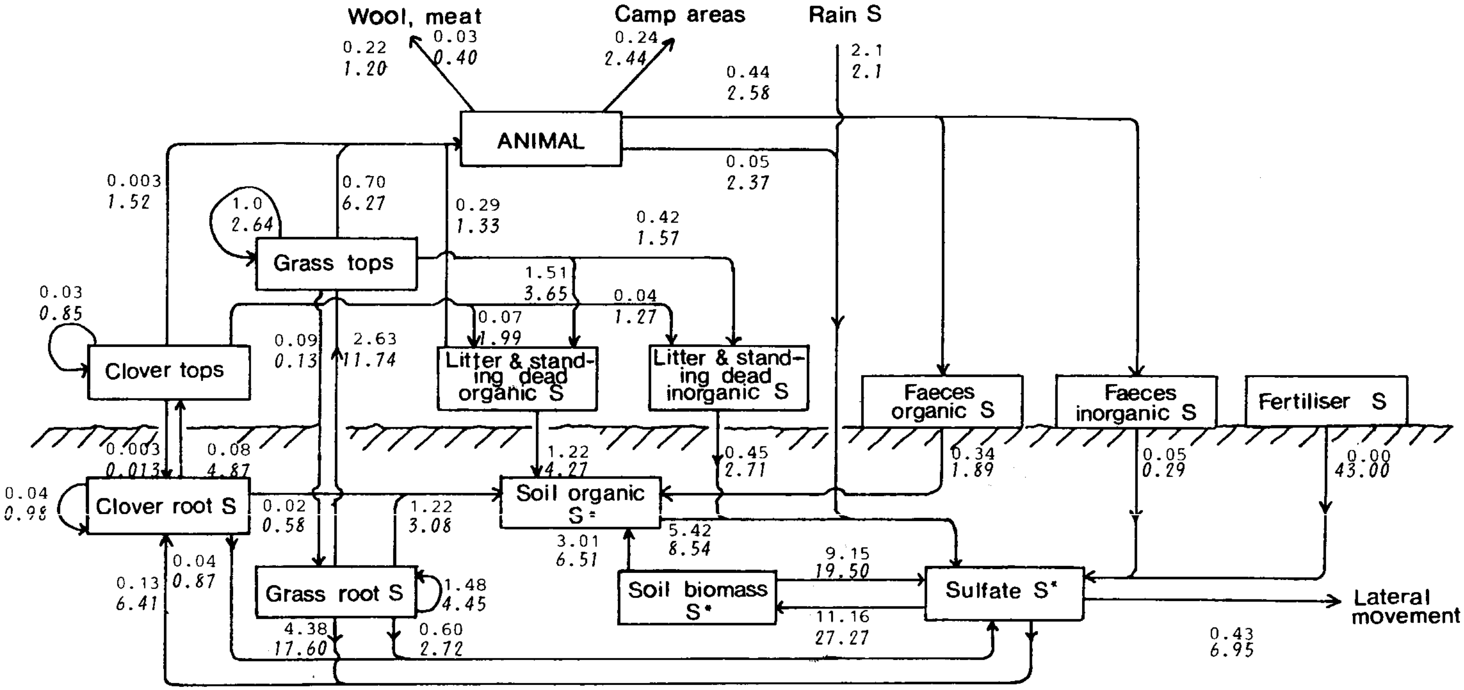

Fig. 2. Sulfur pools and fluxes simulated by the computer model and calculated annual sulfur fluxes (kg S ha^{-1} yr^{-1}) over a 10-year period for a pasture system to which no sulfur is added (Roman type), and one receiving 43 kg S ha^{-1} yr^{-1} (italics). Pools marked "*" are simulated at various depths.

effective rooting radius made available for plant uptake. To account for the efects of rhizosphere acidification, variation of b with distance from the root and other factors which are not fully described by diffusion theory (e.g. Silberbush & Barber 1984), r_E was multiplied by a calibration factor so that predicted tissue S and P concentrations matched those observed through a season by Hutchinson & King (unpublished data). For S, calibration factors of 0.26 and 0.24 were used for grass and clover respectively, and for P 0.42 and 0.38. These factors were increased three-fold during September and by a factor of 1.5 in October. The need for such empirical calibration of this section of the model indicates that there are still many poorly understood processes in nutrient uptake by pastures. Despite the empirical nature of this part of the model, the relationship between plant-available S concentration and the modelled nutrient restriction factor was similar to that which would be expected from field experiments (Fig. 3). Points above the fitted curve are from periods of little growth, and points below the curve from periods of rapid growth or immediately after S application.

Nutrient taken up by plants is distributed between above-ground and below-ground organs with the same concentrations in both components. Field trial evidence for maize reviewed by Jones (1983) and pot trial data for

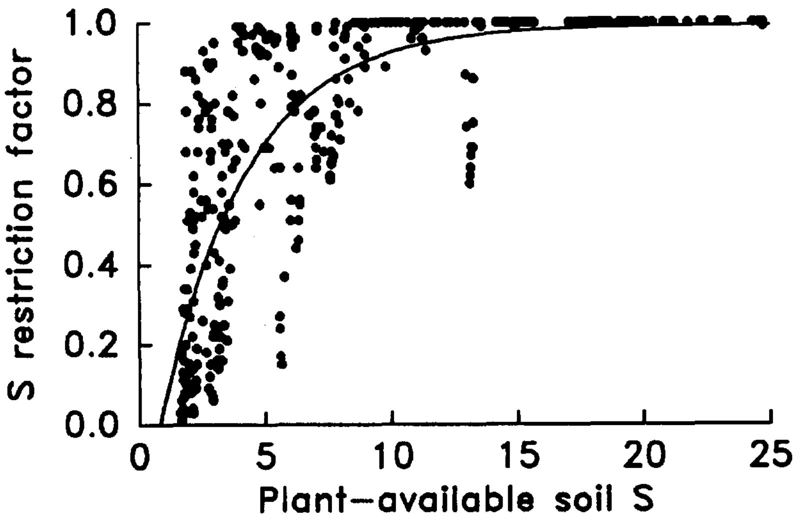

Fig. 3. The grass S restriction factor (f_s) calculated in a series of model runs (points), as a function of phosphate-extractable soil sulfate concentration ($[S_{av}]$, mg S kg^{-1} soil), where sulfate concentrations in the various soil layers are weighted according to rooting density. The line was fitted by a least-square procedure, and has the equation $f_s = 0.993(1 - \exp(-0.293([S_{av}] - 0.817)))$.

white clover (Godwin 1981) indicate that except for young plants, root P concentrations are similar to those in green shoot material.

Upon senescence, 45% of S, 60% of P and 60% of N can be resorbed from dying tissue (Colman 1971; Hutchinson et al. 1987). Nutrient in senescent tissue is split between inorganic and organic fractions in a 60/40 ratio following work by Bromfield & Jones (1972) on the leaching of P from hayed-off pastures. The same senescence principles are adopted for roots as for tops.

Organic nutrient is subdivided into two pools — non-living and biomass. Data from Saggar et al. (1981) and Chauhan et al. (1981) indicate that the S and P concentration in soil biomass varies according to the plant-available nutrient concentration. Functions of the form

$$C_b = a + b[1 - \exp(-cC_s)]$$

were used to determine the nutrient concentration of new biomass (C_b, kg nutrient kg^{-1} biomass C) from the plant-available soil nutrient concentration (C_s, mg nutrient kg^{-1} soil). For S, a, b and c coefficients predicted a C_b range of 0.007 to 0.021, with 90% of maximal biomass S concentration at 7.8 mg S kg^{-1} soil. Comparable values for P and N were 0.0172 to 0.0689 and 0.0856 to 0.258 respectively, with 90% levels at 14.8 mg P kg^{-1} and 77 mg N kg^{-1}.

Since biomass represents only 0.9 to 6.4% of organic carbon in the soil (Chauhan et al. 1981; Schimel et al. 1985), most nutrient in organic matter is held in the non-living component. Nutrient concentrations in organic matter tend to be higher in soils where there are higher levels of inorganic forms of these nutrients (Walker & Adams 1958, 1959; Probert 1977). Australian data for a limited range of soils indicate that a similar nutrient/C ratio is maintained during the organic matter build-up associated with superphosphate application (Williams & Donald 1957; Barrow 1969) but, in New Zealand where Jackman (1964) measured a wider range of soils, organic matter nutrient concentrations were stable only on low-adsorbing soils and became richer in S, P and N on the more strongly adsorbing soils. Since most Australian soils are of low adsorption capacity, long-term changes in nutrient/C ratios are ignored in modelling the non-living organic nutrient pool and any nutrient in excess of the starting nutrient concentration is released as net mineralization.

Model calibration

The model was calibrated against data from field experiments conducted by Wolfe (1971) and Hutchinson & King (1984) to set rates of organic matter decay and clover senescence. In the Wolfe experiment, grass and clover yields were measured under a crash-grazing regime over a four-year period at superphosphate rates of 0, 41, 125 and 375 kg $ha^{-1} yr^{-1}$. Correspondence between observed and predicted annual yields and clover contents are shown in Fig. 4. Comparisons with liveweight gain and wool production have also been made (McCaskill 1987).

Simulation results and discussion

The model was run over a 10-year period for a newly developed pasture with S inputs of 0 and 43 kg $ha^{-1} yr^{-1}$, and P inputs of 34 kg P $ha^{-1} yr^{-1}$ on both treatments. Stocking rates for the zero-S treatment were 3 sheep ha^{-1} during autumn–winter and 6 sheep ha^{-1} during spring and summer, and for the fertilized pasture, 10 and 15 sheep ha^{-1} respectively. These stocking rates are typical of those used in commercial practice for unfertilized and fertilized pastures in the New England Tablelands. Stock were removed whenever there was less than 500 kg ha^{-1} green dry matter, and attempts were made to reintroduce them every 30 days until more than this quantity of feed was available. No liveweight gain or wool production was calculated for the period sheep could not be supported. Predicted annual pasture growth rates, shown in Table 2, indicate a 3.6-fold increase in tops growth due to S applications. This was able to support a 13-fold increase in liveweight gain, and a 5-fold increase in wool production. Sheep could be maintained on the simulated pasture for an average of 274 days per year for the high-S treatment, but only 193 days per year without S. Forced removal on the high-S treatment was mainly during the first two years, which were relatively dry and organic N levels had not been built up through clover growth. Mean annual carbon fluxes, presented in Fig. 1, show that increased animal production was caused by two effects, 1) a greater proportion of assimilate contributing to tops growth, and 2) a much higher proportion of clover in the diet. A greater proportion of carbon was cycling above the soil surface, and beneath the ground surface higher organic matter inputs resulted in a net increase in soil organic matter at virtually all soil depths, and an increase in the proportion or organic matter in the more rapidly cycling pools (Table 3). In the 0–7.5 cm layer, the organic carbon concentration increased from 1.2 to 1.6% over the 10-year period. Sulfur turnover rates were also substantially increased, particularly those occurring above the ground surface (Fig. 2).

Previous models of S (Coughenour et al. 1980) and P (Cole et al. 1977) cycling in grassland have been designed more for calculating element flux rates than predicting nutrient response. The model presented here has been

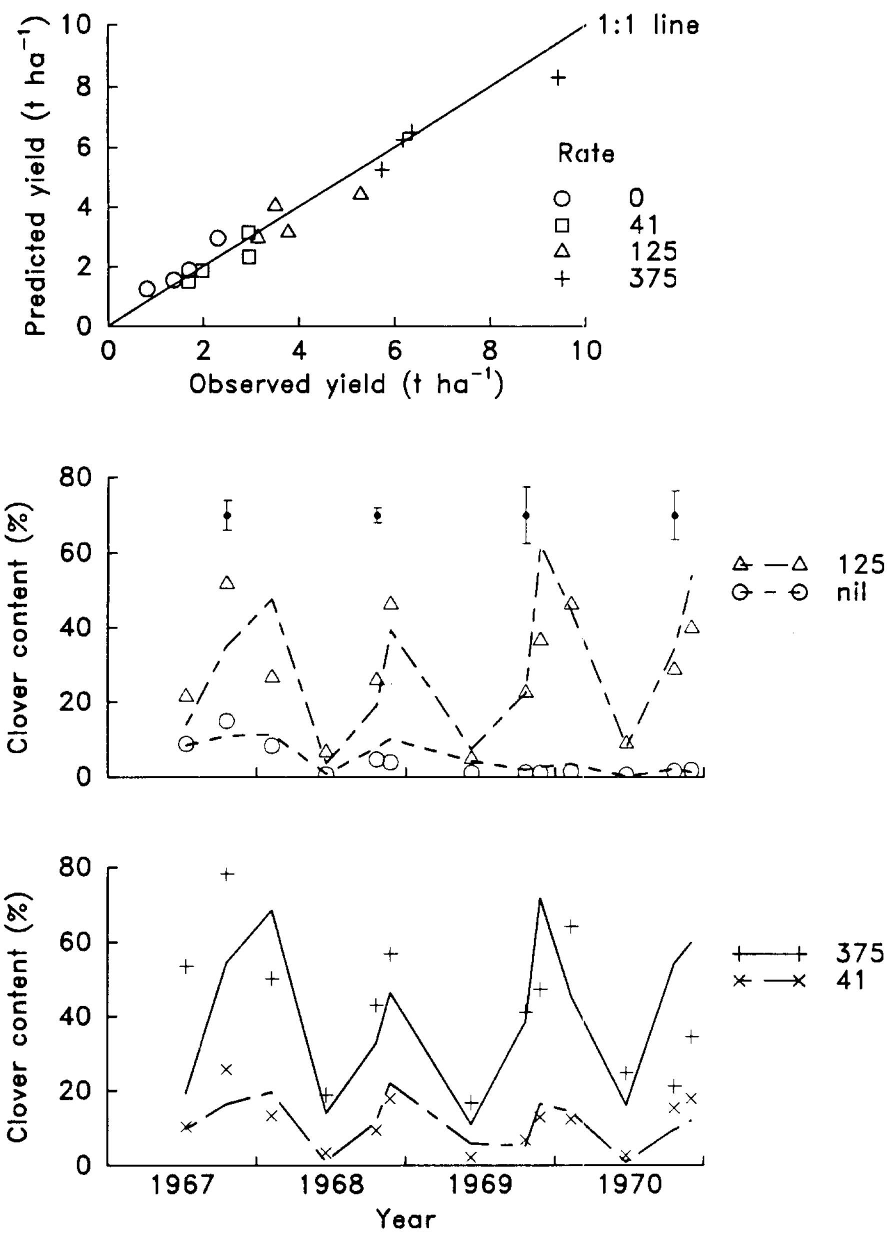

Fig. 4. Top: annual pasture yields observed by Wolfe (1971) and those predicted by the model. Middle and lower: observed and predicted clover contents at each harvest for the same experiment. Observed clover contents are represented by symbols and predicted by lines. Error bars indicate the 5% LSD for observed clover content (within year comparisons).

Table 2. Predicted annual pasture growth rates and sheep liveweight gain and wool and production over a 10-year period.

Year	Total growth kg ha^{-1} yr^{-1}		% Clover growth over year		Weight gain kg ha^{-1} yr^{-1}		Wool growth kg ha^{-1} yr^{-1}	
	No S	+S	No S	+S	No S	+S	No S	+S
1967	3285	5141	2.7	27.0	62.9	165.2	12.8	36.5
1968	2093	3734	12.9	41.9	9.3	110.1	5.3	19.4
1969	2184	6688	10.3	58.1	9.2	208.1	8.7	38.0
1970	2129	6809	3.7	51.7	11.1	216.9	6.5	31.3
1971	1802	7797	3.7	53.3	13.0	342.1	6.9	39.3
1972	1633	7503	0.8	34.6	8.0	284.1	5.5	38.3
1973	2143	9405	0.5	39.8	43.7	365.9	5.5	48.6
1974	1746	9122	1.0	40.6	16.3	412.4	8.7	51.0
1975	1661	8502	1.1	28.6	24.9	322.1	4.8	44.4
1976	1823	9292	0.3	38.1	7.4	315.7	6.6	47.8
Mean	2050	7399	3.7	41.4	20.6	274.3	7.1	39.5

designed with both aims in mind. As in the previous models, the greatest nutrient flux rates occurred between the soil biomass and plant-available pools. These high flux rates explain why ^{35}S-labelled fertilizer is so rapidly converted into forms unavailable to plants (Goh & Gregg 1982), and the plant-available pool quickly diluted with unlabelled S. At an S application rate of 70 kg ha^{-1}, Till (1976) found that only 27% of plant S taken up in the subsequent year was from the labelled source. Coughenour et al. (1980) estimated the flux rate into soil biomass pools as 66 kg S ha^{-1} yr^{-1} compared with 11 and 27 kg S ha^{-1} yr^{-1} for the no-S and high-S treatments used here. Plant available soil sulfate concentrations were much higher in the environment which these authors were simulating, and biomass S concentrations are sensitive to environmental S concentrations (Saggar et al. 1981). Cole et al. (1977) estimated P flux rates into the biomass pool as 24 and 32 kg P ha^{-1} for two sites, compared with 42 and 75 kg P ha^{-1} yr^{-1} respectively for no-S and high-S treatments here (full data not presented). Application of P fertilizer enhanced the flux rates in the simulations reported here. Thus, even though a variety of methods have been adopted for calculating biomass nutrient fluxes, estimates are within the range which would be expected considering the different environmental conditions.

Traditional field research has aimed to test a range of management options over a number of sites and seasons. Monitoring is directed more at measuring treatment differences and, because of the large number of plots involved, is conducted relatively infrequently. Model construction and calibration revealed a need for more detailed reporting of factors such as plant and soil nutrient concentrations for a small number of extreme treatments.

Table 3. Changes in total soil organic matter and proportion of organic matter in the various pools at the beginning and end of a 10-year simulation with no added S and 43 kg S ha^{-1} yr^{-1}.

		Organic matter pool						
		Non-living					Living	
		1	2	3	4	5	Unprotected	Protected
Maximal decay constant (day^{-1})		0.031	0.0016	0.00011	4.5×10^{-5}	4.6×10^{-7}	0.7	0.0077
Initial conditions								
Depth (cm)	Total organic C (t ha^{-1})				%			
0.0–1.5	2.43	0.47	19.03	52.09	15.68	10.74	0.02	1.97
1.5–7.5	9.73	0.47	9.04	57.09	18.68	12.74	0.02	1.97
7.5–23.0	13.83	0.70	7.04	54.63	16.98	17.41	0.00	3.24
23.0–46.0	13.99	0.60	5.12	46.90	21.13	23.65	0.00	2.60
46.0–69.0	6.00	0.47	4.30	31.98	27.81	33.34	0.00	2.10
69.0–150.0	21.12	0.09	0.71	9.05	32.96	56.72	0.00	0.47
After 10 years @ 0/kg S ha^{-1} yr^{-1}								
Depth	Change in C (t ha^{-1})							
0.0–1.5	1.97	0.28	34.63	45.90	11.95	5.96	0.08	1.19
1.5–7.5	−0.62	0.22	4.28	60.02	20.04	13.61	0.00	1.83
7.5–23.0	−0.54	0.27	4.30	57.52	17.72	18.11	0.00	2.08
23.0–46.0	−0.34	0.24	2.92	49.59	21.36	24.24	0.00	1.66
46.0–69.0	−0.14	0.19	2.35	34.23	27.80	34.14	0.00	0.29
69.0–150.0	−0.21	0.06	0.66	9.62	31.96	57.26	0.00	0.44
After 10 years @ 43 kg S ha^{-1} yr^{-1}								
Depth	Change in C (t ha^{-1})							
0.0–1.5	4.28	0.72	57.33	28.79	8.63	3.64	0.17	0.72
1.5–7.5	−0.03	0.64	7.85	57.52	19.03	12.78	0.03	2.15
7.5–23.0	0.81	0.77	8.22	54.17	16.33	16.45	0.00	4.06
23.0–46.0	0.87	0.68	6.00	47.91	19.80	22.26	0.00	3.34
46.0–69.0	0.28	0.54	4.97	33.90	26.08	31.83	0.00	2.67
69.0–150.0	0.29	0.17	1.48	10.23	31.30	55.93	0.00	0.89

Data from such field experiments can be made more useful by a greater use of modelling in data analysis. The estimates of cycling and non-cycling organic sulfur presented in Table 1 were made through the use of a mathematical model, and further advances in nutrient cycling research will almost certainly involve a close involvement with modelling. The present trend for less field research with research being concentrated on processes involved in nutrient transfer emphasises the need to model subsystems. This will enable more complete interpretation of the data, and facilitate its use in a whole-system model. Other less criticial parts of the system where more experimental work would improve the model, include the enhancement of S mineralization by plant and soil esterases produced in response to nutrient stress, S movement in the soil profile, S uptake from depth, prediction of grass growth, and the germination, growth and senescence of white clover. Despite these areas where improvement is possible, the model has been an invaluable tool for integrating data and concepts into a means of testing the effects of climate and fertilizer management on production parameters.

Acknowledgements

We wish to acknowledge financial support from the Australian Wool Research Trust Fund (project L/6/815, "S in pastures"), ACIAR (project 8328, "P and S cycling in tropical cropping systems") and the University of New England, and thank Drs Ian Johnson and Peter Sale for comments on the manuscript.

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