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Can phosphorus fertilisers alone increase levels of soil nitrogen in New Zealand hill country pastures?

Saman Bowatte[1,3,]*, Russell Tillman[1], Andrew Carran[2] and Allan Gillingham[2]
*[1]Institute of Natural Resources, Massey University, Private Bag 11222, Palmerston North, New Zealand; [2]AgResearch (Grasslands), Tennant Drive, Private Bag 11008, Palmerston North, New Zealand; [3]Laboratory of Soil Biology and Chemistry, Graduate School of Bio-Agricultural Sciences, Nagoya University, Nagoya, 464-8601, Japan; *Author for correspondence (e-mail: sbowatte@agr.nagoya-u.ac.jp)*

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Abstract

In New Zealand grazed pastures, nitrogen (N) fixation by clover is the traditional method of supplying N to the grasses that make up the bulk of the pasture sward. In order to stimulate satisfactory clover growth, phosphorus (P) fertilisers are applied at levels which are generally more than adequate for grass requirements. These legumes then provided N through biological nitrogen fixation. However, studies conducted in New Zealand hill country pastures have revealed that these pastures are still highly N responsive. These results draw attention to a key issue with respect to N fertility in hill country pasture and the question arises as to the value of large P fertiliser applications to overcome N deficiency through clover growth. Here we used modelling approach to evaluate the effectiveness of adding P fertilisers to stimulate clover growth for improving soil N status in hill country pastures and to explore why the hill pastures are N responsive. In addition an attempt was made to explore the potential of fertiliser N in hill pastures based on the current model outcomes and the measured values of pasture production under non-limiting N.

Introduction

In New Zealand grazed pastures, nitrogen (N) fixation by clover is the traditional method of supplying N to the grasses that make up the bulk of the pasture sward. Nitrogen fixed by clovers is contained initially in the growth of the clover plant itself. Eventually however, most of the fixed N is recycled back into the soil, either through the breakdown of plant litter, roots and nodules, or by urine and faecal return from grazing animals (Sears 1953). The N then becomes available for uptake by grasses. In hill pastures this simple cycle becomes much more complex as the grazing animals develop slope and aspect related patterns of grazing and excretion (Gillingham and During 1973). These result in zones of nutrient enrichment and depletion that become progressively more important with time in contrast to the more random and time averaged returns of nutrients on flat sites.

Widespread and severe phosphorus (P) deficiency limited the growth of legumes and N inputs in hill pasture until aerial application of fertiliser became practical in the latter half of the 20th century. Today, phosphorus fertilisers are applied in order to stimulate satisfactory clover growth (Roach et al. 1996). The legumes then provide N through biological nitrogen fixation. In a long-term grazing trial conducted at Te Kuiti, New Zealand (Roach et al. 1996) demonstrated the sensitivity of hill country pasture production to reduction in P fertiliser input. They observed that withholding P fertilisers for 10 years resulted in 29–35% less annual pasture production, 54–72% less legume production and reduced plant available soil N status.

The level of biological N fixation by pasture legumes can vary greatly. Annual N fixation in developed lowland pastures in New Zealand is around 184 (range 107–392) kg N ha^{-1} (Hoglund et al. 1979) and N fixation through symbiotic fixation in unimproved North Island hill country was only around 13 kg N ha^{-1} (Grant and Lambert 1979).

Other studies conducted in hill country pastures (Luscombe 1980; Ball and Field 1982; Lambert and Clark 1986; Clark and Lambert 1989; Gillingham et al. 1998; Blennerhassett 2002) have revealed that despite the inputs of legume N these pastures are still highly N responsive. These results draw attention to a key issue with respect to N fertility in hill country pasture and the question arises as to the value of large P fertiliser applications to overcome N deficiency through clover growth.

The aim of this paper is to use a static nutrient budget modelling approach to evaluate the effectiveness of adding P fertilisers to stimulate clover growth for improving soil N status in hill country pastures and to explore why hill pastures are N responsive. First a simple model will be developed for hill country N cycle and then it will be used to compare soil N status in hill country pastures under low and high P addition. Secondly, model predictions will be used to assess the current P fertiliser policy and the potential for N fertiliser use in hill country pastures.

Model development

This model was developed for a notional 1 ha hill country paddock. The paddock was assumed to be located on summer-dry hill country in Hawkes Bay, New Zealand at the AgResearch Waipawa research station. This notional north-facing paddock was assumed to have slope categories of flat site (f), easy (25°) slopes (e) and steep (45°) slopes (s). The relative areas (A) of these 3 slope categories in the paddocks were: A_f (flat sites), A_e (easy slopes) and A_s (steep slopes). Annual pasture production (DM, kg ha^{-1} yr^{-1}) on each slope were designated as $(\mathrm{DM})_f$, $(\mathrm{DM})_e$ and $(\mathrm{DM})_s$. The percentages (%) of clover in the sward on the three slope categories were designated as $(C)_f$, $(C)_e$ and $(C)_s$.

N fixation (kg N ha^{-1} yr^{-1}) by legumes (NFL) was assumed to be proportional to clover growth, although the proportionality constant (0.03 and 0.04) varied between flat sites and sloping sites (Ledgard et al. 1987). Thus for each slope category,

$$(\mathrm{NFL})_f = ((\mathrm{DM})_f)((C)_f/100)(0.03) \qquad (1)$$

$$(\mathrm{NFL})_e = ((\mathrm{DM})_e)((C)_e/100)(0.04) \qquad (2)$$

$$(\mathrm{NFL})_s = ((\mathrm{DM})_s)((C)_s/100)(0.04) \qquad (3)$$

The amount of N taken up (kg N ha^{-1} yr^{-1}) by pasture (NP) was calculated in the model from annual pasture dry matter production (DM) and herbage N concentration (%) (HN). Thus for flat sites,

$$(\mathrm{NP})_f = (\mathrm{DM})_f((\mathrm{HN})_f/100) \qquad (4)$$

Similar calculations were done for steep and easy slopes.

The measured DM production consisted of both grass and clover. Hence, to estimate N uptake (kg N ha^{-1} yr^{-1}) from soil (NS), the amount of legume-fixed N was subtracted from plant N uptake. As an example, for flat sites,

$$(\mathrm{NS})_f = (\mathrm{NP})_f - (\mathrm{NFL})_f \qquad (5)$$

The percentage pasture utilisation (PU) for each slope was used to estimate the amount of pasture N eaten (kg N ha^{-1} yr^{-1}) by the animals (NEA). The plant N not utilised by animals (kg N ha^{-1} yr^{-1}) was considered to be added to the soil organic matter through the litter (LN). Thus for flat sites,

$$(\mathrm{NEA})_f = (\mathrm{NP})_f((\mathrm{PU})_f/100) \qquad (6)$$

and,

$$(\mathrm{LN})_f = (\mathrm{NP})_f - (\mathrm{NEA})_f \qquad (7)$$

It was assumed that 10% of the N eaten by animals (NEA) was retained in animal products

(NAP, kg N ha^{-1} yr^{-1}) and the rest was excreted (NEX, kg N ha^{-1} yr^{-1}). For flat sites,

$$(\mathrm{NAP})_f = (\mathrm{NEA})_f(10/100) \qquad (8)$$

$$(\mathrm{NEX})_f = (\mathrm{NEA})_f - (\mathrm{NAP})_f \qquad (9)$$

Similar calculations were done for steep and easy slopes.

The dung and urine distribution is uneven in hill country pasture paddocks. An example of estimating the dung and urine N deposited on each site is presented below.

The total amount of excretal N added to the paddock (TEN, kg N ha^{-1} yr^{-1}) is given by

$$\begin{aligned}\mathrm{TEN} = &[(\mathrm{NEX})_f(A)_f/100] + [(\mathrm{NEX})_e(A)_e/100] \\ &+ [(\mathrm{NEX})_s(A)_s/100]\end{aligned} \qquad (10)$$

Dung and urine (DU) return to a particular site (e.g., kg N ha^{-1} of flat site yr^{-1}) from the total excretal N returned to the paddock (TEN) was calculated using the percentage excreta return to each site and the percentage land area (A).

Gillingham (1978) measured the dung P distribution in two hill country paddocks. His data were used to estimate the proportion of the excreta deposited on the whole paddock that were deposited on each slope category (E).

$$(\mathrm{DU})_f = [((E)_f/100)(\mathrm{TEN})]/((A)_f/100) \qquad (11)$$

$$(\mathrm{DU})_e = [((E)_e/100)(\mathrm{TEN})]/((A)_e/100) \qquad (12)$$

$$(\mathrm{DU})_s = [((E)_s/100)(\mathrm{TEN})]/((A)_s/100) \qquad (13)$$

Dung and urine output from a particular site due to animal transfer (ATN) was calculated as (e.g., for flat site):

$$(\mathrm{ATN})_f = -((\mathrm{DU})_f - (\mathrm{NEX})_f) \qquad (14)$$

with similar equations for the other slope categories.

Lambert et al. (1982) reported excretal N partitioning of 65, 71 and 78% in urine for unimproved, low P fertiliser, and high P fertiliser hill country pastures, respectively. The average of these values, 71% as excretal N in urine (UN) with 29% as dung N (DN), was assumed in these N balances. The bulk of dung N is in organic form (Haynes and Williams 1993). Thus, all N in dung was assumed to be incorporated into soil organic matter and released to soil slowly. The dung and urine N added to flat sites (kg N ha^{-1} yr^{-1}) was calculated as

$$(\mathrm{UN})_f = (\mathrm{DU})_f(71/100) \qquad (15)$$

$$(\mathrm{DN})_f = (\mathrm{DU})_f(29/100) \qquad (16)$$

with similar equations for the other slope categories.

Ammonia volatilisation was a major pathway of N loss from urine patches in hill country pastures. Experiments conducted in hill pastures (Bowatte 2003) indicated that the losses ranged from 21 to 51% of added urine N in two experiments. Thus, it was assumed in the model that 33% (mean of the volatilisation losses from two experiments) of added urine N is lost by ammonia volatilisation from hill pasture. The N lost through ammonia volatilisation (VN, kg N ha^{-1} yr^{-1}) for flat sites was calculated as

$$(\mathrm{VN})_f = (\mathrm{UN})_f(33/100) \qquad (17)$$

with similar equations for the other slope categories.

Generally, leaching has not been considered as a major N loss mechanism in hill country pastures (Sakadevan et al. 1993). However, the experiment conducted by Bowatte (2003) revealed that leaching could be a major N loss mechanism in some hill country sites, especially in stock campsites in flat sites. Based on these results the model assumed that 30% of added urine N to hill country flat sites is leached. No leaching was considered to occur from sloping sites in hill country, based on the low nitrification rates observed from steep soils (Bowatte 2003). The amount of N lost through leaching from flat sites (LN, kg N ha^{-1} yr^{-1}) is calculated as

$$(\mathrm{LN})_f = (\mathrm{UN})_f(30/100) \qquad (18)$$

To calculate net mineralisation in the model it was assumed that although the size of the mineral N pool may fluctuate widely from day to day, as a result of urine addition and various loss mechanisms, on an annual basis the pool size would be low and constant. In other words, inputs would equal outputs when summed over a year. With this assumption, net mineralisation N (NM, kg N ha^{-1} yr^{-1}) could be calculated as the difference between the other inputs to the mineral N pool (urine, atmospheric deposition) and the losses from that pool (plant uptake, volatilisation and leaching) according to the equation.

$$(\mathrm{NM})_f = (\mathrm{NS})_f - [[(\mathrm{UN})_f + (\mathrm{NAD})_f] - [(\mathrm{VN})_f + (\mathrm{LN})_f]] \qquad (19)$$

where NAD is N added by atmospheric deposition (kg N ha^{-1} yr^{-1}).

Model parameters

The model was parameterised using the data of three Massey University PhD theses (Gillingham 1978; Blennerhassett 2002; Bowatte 2003) that studied of New Zealand North Island hill country pastures. Bowatte (2003) studied fate of urine N in hill country pastures, and as noted earlier, estimates of urine N losses through volatilisation and leaching were based on those results. Annual pasture production (DM, kg N ha^{-1} yr^{-1}) under low and high P (Olsen P 10 and 28 μg/g soil, respectively) addition on each slope was as measured by Blennerhassett (2002) at the Waipawa AgResearch research site. Similarly, the percentage (%) of clover in the sward (C) was as measured by Blennerhassett (2002). Gillingham (1978) conducted a detailed study of P cycling in hill country. The N balance described in this paper was developed for a North facing notional 1 ha paddock, which was assumed to have the same proportion of flat, easy and steep slopes as one of the paddocks investigated by Gillingham (1978) in his detailed study of P cycling in hill country. The relative areas (A) of these 3 slope categories in the paddocks were: flat sites (A_f, 12%), easy slopes (A_e, 46%) and steep slopes (A_s, 42%).

In hill country pastures, the stock tend to camp on flat areas of land and significant quantities of nutrients are transported to these areas through dung and urine from the steeper slopes where the sheep graze (Rumble and Esler 1968; Gillingham and During 1973; Rowarth and Gillingham 1990). Gillingham (1978) measured the dung P distribution in two hill country paddocks. His data were used to estimate the proportion of the total excreta deposited on the whole paddock that were deposited on each slope category. The measured proportions of total excreta deposited on each of the slope categories in the paddock of Gillingham (1978) were 67, 29 and 4 for flat sites, easy slopes and steep slopes, respectively. These same proportions were assumed for the present study.

The pasture utilisation (%) for the current N balance was taken from Gillingham (1978). He estimated the annual pasture utilisation as 79, 83 and 76 for flat sites, easy slopes and steep slopes, respectively. This pasture utilisation was measured in a paddock that had topography of 12% flat sites, 46% easy slopes and 42% steep slopes. Pasture utilisation in a second paddock that had 20% flat sites, 56% easy slopes and 24% steep slope was 77, 86 and 81%, respectively (Gillingham 1978).

The model assumed that under both low and high P levels, pasture utilisation, proportion of total excretal N deposited on slope categories, proportion of N leached, proportion of N volatilised, non-symbiotic N fixation, atmospheric N deposition, percentage of excretal N deposited in dung, percentage of excretal N deposited in urine and percentage of ingested N retained in animal products are the same. The parameters are summarised in Table 1.

The following parameters were identical for all model analyses.

Non-symbiotic N fixation = 13 kg N ha^{-1} yr^{-1}
Atmospheric N deposition = 3 kg N ha^{-1} yr^{-1}
Percentage of excretal N deposited in dung = 29%
Percentage of excretal N deposited in urine = 71%
Percentage of ingested N retained in animal products = 10%

Model output

Blennerhassett's (2002) data revealed that at the Waipawa site, addition of high rates of P fertiliser (500 kg ha^{-1} of triple super phosphate (20% P)) increased pasture growth and clover production (compare Table 1a and b). When these data are applied to the model's notional 1 ha paddock, under low P conditions pasture dry matter production was equivalent to 4744 kg ($5543 \times 0.12 + 6671 \times 0.46 + 2406 \times 0.42$). Similarly, under high P conditions dry matter production was

Table 1. Data used to parameterise the model.

Input	Flat sites	Easy slopes	Steep slopes
(a) Low P			
Land area (%)[a]	12	46	42
Pasture DM poduction (kg ha^{-1} yr^{-1})[b]	5543	6671	2406
N Concentration in herbage (% N)[b]	2.7	2.73	2.2
Clover in herbage (% by weight of total DM)[b]	5	11	0
Pasture utilisation (%)[a]	79	83	76
Proportion of total excretal N deposited on slope category (%)[a]	67	29	4
Proportion of urine N leached (%)[c]	30	0	0
Proportion of urine N volatilised (%)[c]	33	33	33
(b) High P			
Land area (%)[a]	12	46	42
Pasture DM production (kg ha^{-1} yr^{-1})[b]	6078	9022	2740
N concentration in herbage (% N)[b]	3.2	2.6	1.7
Clover in herbage (% by weight of total DM)[b]	1	14	0
Pasture utilisation (%)[a]	79	83	76
Proportion of total excretal N deposition on slope category (%)[a]	67	29	4
Proportion of urine N leached (%)[c]	30	0	0
Proportion of urine N volatilised (%)[c]	33	33	33

[a] Measured data of Gillingham (1978). [b] Measured data of Blennerhassett (2002). [c] Measured data of Bowatte (2003).

6030 kg ha^{-1}, which is a 27% annual increase. Also in the model, the increased clover production resulted in higher inputs through N fixation. A similar calculation as above showed that under low P the N input from legume fixation was 14 kg N in the low P 1 ha paddock and 23 kg N under high P conditions (Table 2). This is a 64% annual increase.

However, when the data (Figure 1) were used to construct a N balance (Table 2) for the notional 1 ha paddock it revealed that under both the low P and high P fertiliser regimes the overall predicted N balances remain negative, indicating all the annual N inputs are lost from the system and there is some mining of the reserves of N in the soil organic matter. This indicates that although adding P fertiliser increased N fixation, when this N goes through the animal cycle it also increased N losses.

Losses from the system occur in two ways. Processes such as volatilisation and leaching from urine patches represent an immediate, direct loss from the system. In contrast, animal transfer of N from sloped to flat areas does not necessarily represent a total loss from the system, as the N could still potentially be taken up by plants. If however, the annual input of N to flat areas is larger than the maximum amount of N that could be taken up by pasture, given the existing environment conditions, then some of this transfer to flat areas does represent an effective loss of N from the system. In addition, it is apparent that soil conditions in flat areas, particularly nitrification activity, are such that urine N transferred to these sites is at high risk of loss by leaching.

Discussion

The model outcome illustrates that the addition of P fertilisers to hill country pastures to improve soil N status is clearly questionable, particularly on steep slopes. Although on easy slopes clover production has increased as a result of P addition, and thereby increased the quantity of N fixed, on steep slopes clover production was not affected by P fertiliser as clover was not present in the herbage. This could be due to effects of extreme environmental conditions (moisture stress by higher solar radiation to north steep slopes) to clover growth. The N balances developed by this model, using the measured pasture production by Blennerhassett (2002) under low and high P fertility regimes, suggested that any increase in clover growth brought about by P fertiliser addition, had little effect on the residual N fertility of the soil. This is mainly because most N inputs are lost by animal transfer, and through volatilisation and leaching from urine patches.

A key to improving the efficiency of N is to reduce N transfer to flat areas through animal. If

Table 2. Modelled N balances for individual slope categories and for the overall paddocks taking into account that flat sites, easy slopes and steep slopes occupy 12% (A_f), 46% (A_e) and 42% (A_s) of the paddock area, respectively.

	Flat site	Easy slopes	Steep slopes	Paddock (1 ha)
(a) Low P				
Input (kg N yr^{-1})				
Legume N fixation	1	13	0	14
Non-symb. fixation	2	6	5	13
Atm. deposition	0	1	1	2
Total (kg N yr^{-1})	3	20	6	29
Output (kg N yr^{-1})				
Animal products	1	7	2	10
Animal transfer	−48	36	11	−1
Ammonia volatilisation	14	6	1	21
Leaching	13	0	0	13
Total (kg N yr^{-1})	−20	49	14	43
N surplus (Input–Output) (kg N yr^{-1})	23	−29	−8	−14
(b) High P				
Input (kg N yr^{-1})				
Legume N fixation	0	23	0	23
Non-Symb. fixation	2	6	5	13
Atm. deposition	0	1	1	2
Total (kg N yr^{-1})	2	30	6	38
Output (kg N yr^{-1})				
Animal products	2	9	2	13
Animal transfer	−58	48	9	−1
Ammonia volatilisation	17	8	1	26
Leaching	16	0	0	16
Total (kg N yr^{-1})	−23	65	12	54
N surplus (Input–Output) (kg N yr^{-1})	25	−35	−6	−16

this could be achieved the benefits would be twofold. Firstly, a greater proportion of the paddock would receive an input of urine N to offset the chronic N deficiency of hill country pastures. Secondly, the soil conditions on slopes are likely to be less conducive to rapid nitrification (Bowatte 2003) and subsequent loss of the applied N. Subdivision of paddocks and grazing management offer some potential for minimising N transfer to stock flat sites.

Consider two extreme, hypothetical situations. In the first, N inputs through fixation are assumed to be 50 kg N ha^{-1} yr^{-1}, pasture utilisation is 100%, loss in animal product is 10% of N ingested, N concentration in herbage is 3% and excretal N is returned more or less evenly to the grazing area, with no N losses from urine patches. In such a hypothetical situation, the only N loss from the system is in animal product. The 90% of ingested N not retained in the animal is returned to the soil, and can then be used to grow more herbage.

At a herbage N concentration of 3%, the 50 kg ha^{-1} of fixed N would support an initial pasture production of 1667 kg DM ha^{-1}. In the next cycle, the 90% (45 kg ha^{-1}) of remaining N would support a further 1500 kg DM ha^{-1} of pasture production. By continuing with this approach it can be demonstrated that, under these hypothetical conditions, the input of 50 kg ha^{-1} of fixed N could produce 16,667 kg DM ha^{-1}, before the entire N was lost in animal product. If environmental constraints were such that this amount of herbage could not be grown annually, then N would accumulate in the soil.

The second hypothetical situation is identical to the first, except that none of the excreted N is returned to the grazed area. In this case, as none of the N is recycled, the input of 50 kg ha^{-1} of fixed N would support only 1667 kg DM ha^{-1} of pasture production. It is unlikely that environmental constraints would restrict pasture production to below this level, and so N would not accumulate in the soil. Any pasture production in excess of 1667 kg DM ha^{-1} would involve ‘mining’ the soil reserves, and would theoretically be unsustainable.

Clearly, any real life situation would fall between these two simplistic scenarios. However, this

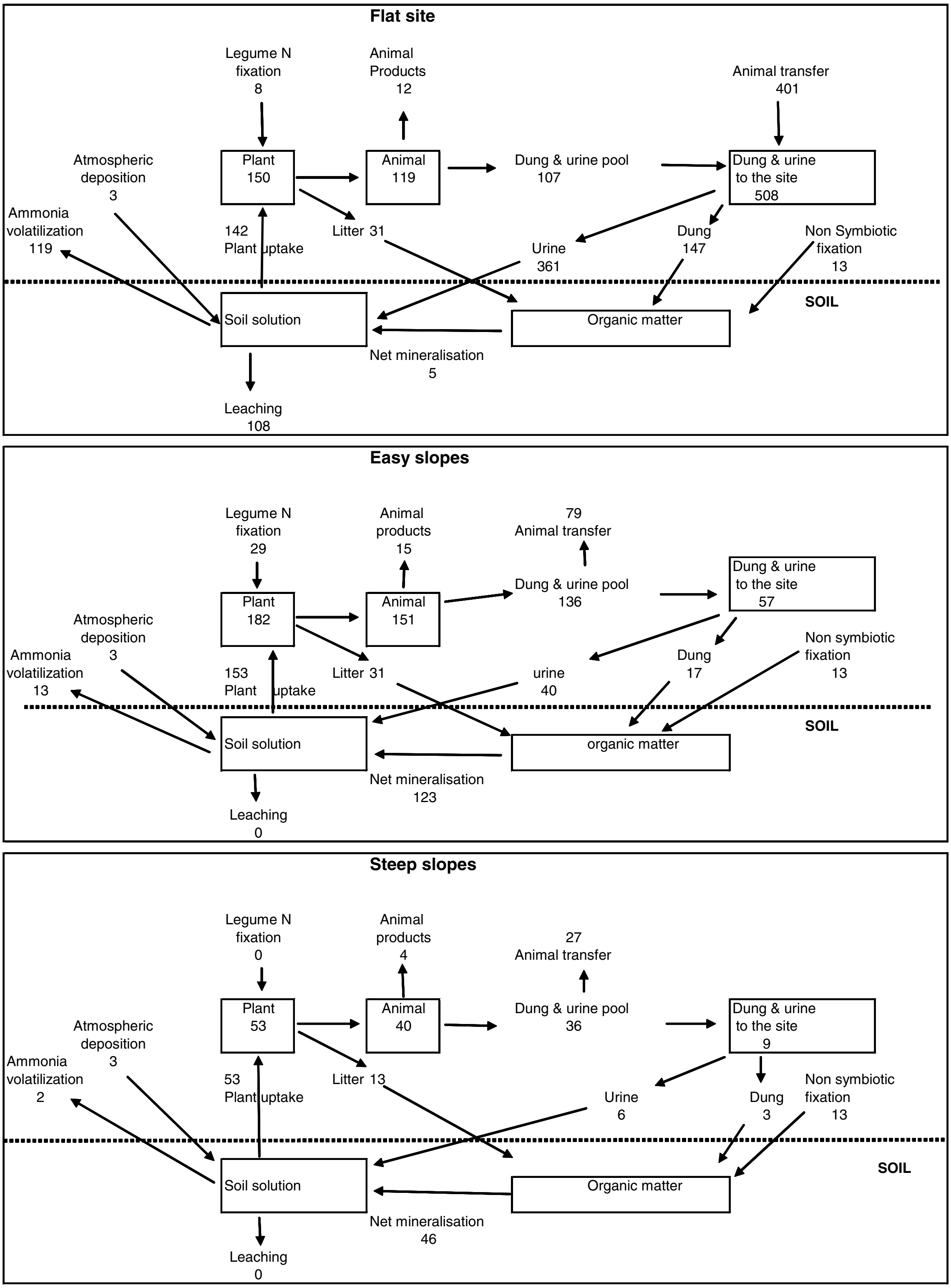

Figure 1. Modelled N cycles for 1 ha of flat site, easy slope and steep slope in hill country paddock with northerly aspect with low P fertiliser. All values kg N ha^{-1} yr^{-1}.

approach may provide a conceptual framework within which the insertion of more realistic data would enable the likely sustainable maximum pasture production in the absence of N fertiliser to be estimated and the potential for N fertilisers to be assessed.

To illustrate this approach, data on steep and easy slopes on north aspects from low P and high P regimes were considered within the conceptual framework outlined above. The results are presented in Table 3. Pasture utilisation on all slopes was assumed as in Table 1 and the proportion of excreted N that was transferred off-site was estimated from Figures 1 and 2. The N inputs through N fixation and deposition on each slope and aspect were as in Figures 1 and 2. Given these estimated N inputs and animal transfer rates, the predicted sustainable level of pasture production ranged from 986 kg DM ha^{-1} yr^{-1} on steep northerly slopes under low P regime to 4592 kg DM ha^{-1} yr^{-1} on easy northerly slopes under high P regimes.

To demonstrate how these numbers were generated consider the data for steep northerly slopes under low P regime. At a herbage N concentration of 3% the input of 16 kg of N would support initial production of 533 kg DM. At 76% pasture utilisation with 10% of ingested N retained in animal and 68% of excreted N transferred to off-site, 7.3 kg N is returned to the soil and can then be used to grow a further 245 kg DM. Similarly in the next cycle another 3.4 kg N would support another 112 kg DM. This approach was continued until the entire N input was consumed (at 986 kg DM, Table 3). The same excel worksheet was used to estimate the N input required to maintain the potential yield. Different N input values were tested by trial and error until the required potential yield value (Table 3) was obtained.

These sustainable (in terms of N supply) production levels are very much less than the potential yields as estimated by Blennerhassett (2002) in the absence of any N limitation. These potential yields ranged from 8000 kg DM ha^{-1} yr^{-1} on northerly steep sites under low P regimes to 16,500 kg DM ha^{-1} yr^{-1} on northerly easy sites under high P. The estimated N inputs required to maintain these potential yields on a sustainable basis range from 128 to 240 kg N ha^{-1} yr^{-1} (Table 3).

The current N inputs are clearly very much smaller than those required to sustain maximum

Table 3. Comparison between sustainable levels of pasture production with current N inputs and theoretical maximum pasture production in different slope categories of hill country.

Slope category	Current estimated N inputs[a] (kg DM ha^{-1})	Proportion of ingested N that is transferred off-site	Sustainable level of pasture production with current N inputs (kg DM ha^{-1} yr^{-1})	Theoretical maximum pasture production if N is non-limiting[b] (kg DM ha^{-1} yr^{-1})	Estimated N input required to maintain theoretical maximum production (kg N ha^{-1} yr^{-1})
LPE	45	0.52	3182	13750	194
LPS	16	0.68	986	8000	130
HPE	67	0.54	4592	16500	240
HPS	16	0.58	1128	9000	128

LPE, Low P fertiliser treatment in easy slope; LPS, low P fertiliser treatment in steep slope; HPE, high P fertiliser treatment in easy slope; HPS, high P fertiliser treatment in steep slope. Pasture utilisations are 83 and 76% for easy and steep slopes, respectively.

[a] Values from Figures 1 and 2.

[b] Measured data of Blennerhassett (2002).

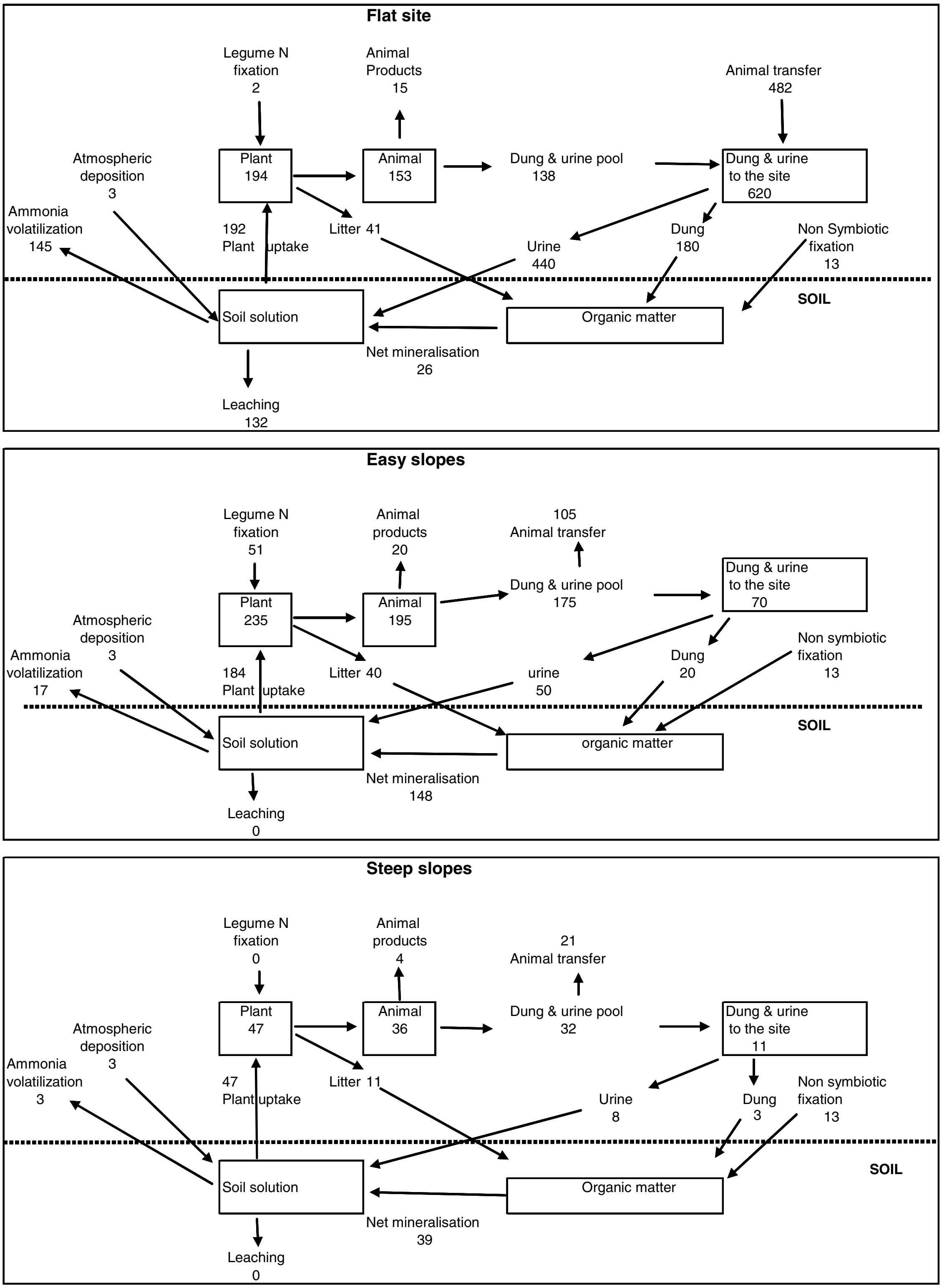

Figure 2. Modelled N cycles for 1 ha of flat site, easy slope and steep slope in hill country paddock with northerly aspect with high P fertiliser. All values kg N ha^{-1} yr^{-1}.

pasture production. More work is required to quantify inputs through N fixation, to determine the extent to which optimising soil fertility for legume growth can boost N inputs towards levels needed to enable near-maximum pasture production. However, it is obvious considering the wide gap between the current N inputs and the N inputs required for maximum pasture production, the potential for N fertiliser in hill pastures is huge.

Calculations such as these that are based on annual balances do not take into account seasonal nutrient transformations. Thus, even if annual N fixation could be boosted to the levels indicated as being required in Table 3, environmental constraints (such as soil temperature) would mean that mineralisation could not provide N at a sufficient rate to allow maximum pasture growth at some times of the year.

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