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Nitrogen cycling in upland pastures of the U.K.

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Substantial areas of upland pastures occur in central Wales, the Lake District and Pennines, and over much of Scotland. Plant growth and N availability are limited by soil acidity, low temperatures and a short growing season. Grass heaths and heather moorland dominate the vegetation; grazing prevents the re-establishment of forest. The land is used mainly for hill sheep farming and game shooting; it is also an important source of water for urban and industrial use.

Comprehensive data on N cycling are sparse. Upland pastures have accumulated large amounts of soil organic N, 6–25 t ha^{-1} but only very small amounts, 20–60 kg N ha^{-1} are mineralised each year. Nitrogen in precipitation and dry deposition provides a total input of about 14 kg ha^{-1} organic and inorganic N, only part of which may be directly available for plant use. The annual input of mineral N in rainfall has increased by about 10 kg N ha^{-1} at Rothamsted this century; if this increase has occurred in upland pastures it could have significant effects. Biological fixation may add 5–10 kg N ha^{-1} annually; no fertilizers or manures are applied. Winter feed is unlikely to exceed 1 kg N ha^{-1}.

Periodic burning of accumulated vegetation is a principal output, averaging 4–6 kg ha^{-1} annually. Streams may discharge 3–6 kg mineral N ha^{-1} annually and also organic N detached from streambanks. Output as livestock and wool is proportional to grazing intensity; at 0.5 ewes per hectare the annual output would be 0.4 kg N ha^{-1}.

There are large differences in all items of the nitrogen cycle within a catchment, associated with inherent variations in soils, topography and climate. Consequently the N balance may be positive, negative or in equilibrium for different areas within a catchment and the internal variation may vitiate any evaluation of regional N balances.

1. Introduction

In the context of this paper upland pastures are defined as unenclosed moorland, with vegetation dominated by mountain grasses and heathers. Even though widespread on land more than 250 m in the west and north, such vegetation cannot be regarded as an ecological climax because most is maintained in its present state by grazing and burning. All but the highest ground would have been forest originally and could revert if left ungrazed. Upland pastures are used mainly for hill sheep farming, often in conjunction with grouse shooting. Other uses include hill cattle rearing and deer grazing as well as several non-agricultural uses, such as military training areas, water collection and recreation. A substantial area has been planted to coniferous forest.

In an examination of the use and N cycling of upland pastures, climate and soil properties have a predominant influence. The climate is wet and cold and has been described by Francis (1978). Mean annual rainfall may range from about 1000 to over 3000 mm; the average growing season from about 200 to 150 days or less. Soils are mainly acid because of the low base status of many of the rocks from which they have formed and also because of the strong leaching by rainfall (Anon. 1979). The surface soils are often peaty, and the thickness of peat may vary from a few centimetres in freely drained podzols to 2 m or more on flatter land in wet areas. In terms of world soil groups, podzols, gleys and climatic and basin peats predominate. Local variation can be considerable, often related to topography.

With the variation in soil properties and climate described above, there are difficulties in presenting a nitrogen cycle that is both accurate and comprehensive. In the sections on N reserves, input, output and N in circulation that follow, a range of values for components of the N cycle will be given, and an indication of the factors responsible for the variation. A detailed account of nutrient cycling in traditional hill sheep farming in the U.K. has been given by Newbould & Floate (1977).

2. N reserves

Substantial amounts of N are present in upland pastures, mainly as organic N in soils, plus N in vegetation and grazing animals. Total soil N may range from about 6 to 25 t ha^{-1}. The lower values would be typical of freely drained podzols on steeper slopes, the higher values from peat on flat or basin sites.

The amount of N present in vegetation depends on net accumulation, which is related to soil fertility and climate, and to the proportion consumed by grazing or lost by burning. After burning, N in vegetation would be lowest. Annual production of dry matter would range from 1200 to 2500 kg ha^{-1}, containing 20–60 kg N ha^{-1} (M. J. S. Floate, personal communication 1980). The amount of N accumulated in mature vegetation would depend on production and removal and could be expected to range from about 50 to 200 kg ha^{-1} (Gimingham 1972).

There is also a reserve of N present in grazing animals, which would depend on the stocking rate. For sheep grazing at 0.5 ewes per hectare, the total N would vary from about 0.4 kg ha^{-1} for the ewe alone in winter, to about 0.7 kg ha^{-1} in summer before lambs are sold. The N present in sheep at other stocking rates can be calculated *pro rata*. The reserves of N in grouse, deer and other grazing animals are likely to be insignificant by comparison with sheep, and have not been estimated. In higher pastures they may exceed those of hill sheep, but the amounts would be small.

3. Inputs of N

(*a*) *Precipitation*

Nitrogen in precipitation and dry deposition provides a significant input into upland pastures. Contemporary annual inputs of total N of about 14 kg ha^{-1} have been recorded (Reid, 1979; H. G. Miller, personal communication 1980; A. Wild, personal communication 1980). However, care is needed in examination and interpretation of data as some include organic N, others are for mineral N only. The N in organic form is unlikely to be of immediate value as a plant nutrient, and would need to be mineralized before being available for uptake by plant roots. Much of the inorganic N in precipitation is added when vegetation is dormant and the soil wet. Under these conditions nitrate anions may remain in solution and move through or over the soil directly into stream flow. Ammonium cations may be almost all retained by cation exchange on to the ubiquitous organic layer on the soil surface. It would appear, therefore, to be unwise to equate the total input of N in precipitation and dry deposition with plant-available N. No firm conclusions can be reached because of the paucity and variability

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of data, but examination of several sources suggests that an input of total N of 14 kg ha^{-1} may contain 7 kg of organic N, 3.5 kg of NO_3^--N and 3.5 kg of NH_4^+-N.

Examination of long-term trends at Rothamsted shows that mineral N has increased about threefold this century, from about 5 to 15 kg ha^{-1} (A. Wild, personal communication 1980). While this increase is insignificant in the N balance of lowland areas, a similar increase in upland pastures could have significant long-term effects.

(*b*) N_2 *fixation*

Biological fixation of N_2 is discussed by Newbould (this symposium); in unimproved upland pastures, free-living and associative symbionts may add 5–10 kg N ha^{-1} annually.

(*c*) *Fertilizers, manures and feedstuffs*

The input of N from fertilizers and manures is assumed to be nil on unimproved upland pastures. Where supplementary feed is given to hill ewes in winter and spring, the N input in hay and concentrates is unlikely to exceed 1 kg ha^{-1} each season (M. J. S. Floate, personal communication 1980).

4. Output

(*a*) *Livestock*

Livestock and wool are the principal economic products from upland pastures. The output of N depends on the stocking density, which may range from less than 0.25 ewes per hectare to over 1.5 ewes per hectare, and also on the number of lambs born. For a stocking density of 0.5 ewes per hectare and a lambing percentage of 80, the annual N output would be about 0.22 kg ha^{-1} as store lambs, 0.08 kg ha^{-1} as cast ewes and 0.10 kg ha^{-1} as wool, a total of 0.40 kg N ha^{-1}. This represents less than 10% of that consumed; the remainder is recycled in excreta (Floate 1981). There are also smaller amounts of N in any grouse, deer or hare carcases taken from the area.

(*b*) *Leaching and runoff*

A substantial portion of the annual precipitation is discharged in stream flow from upland pastures; this may contain N in several forms, both organic and inorganic. Few figures from catchment studies are available and those of Crisp (1966) and Reid (1979) suggest that the mineral N output in streamflow may be 3–6 kg N ha^{-1} annually. The amount of insoluble organic N in stream flow may be as much as five times greater than the mineral N (Crisp 1966); much of this is derived from erosion of peat alongside water courses and would be greater in times of peak stream flow. Much of the organic N can therefore be regarded as N displaced from soil reserves, of considerable age, and not strictly part of the current annual output.

(*c*) *Burning*

Burning of heather moorland is a long-established practice used to maintain the quality of the vegetation for grazing by sheep and grouse. Most of the N contained in the stems and leaves is lost and in very hot fires the organic layer on the soil surface may also be ignited with an additional loss of N. The effects of temperature have been investigated by Kenworthy (1964), Allen (1964) and Evans & Allen (1971); the effects were discussed by Gimingham (1972, 1981). As a result of a normal burn with temperatures of 550–650 °C, 68% of the N was lost in smoke from burning *Calluna*, and at 800–825 °C, a 'severe' burn, 76% of N was lost (Allen 1964). Some fractions may condense not far from the fire and smoke particles may be deposited not far downwind, but Evans & Allen (1971) found that only a very small proportion of the nutrients incorporated into smoke were returned to the ground in particles deposited within 120 m of the fire. Convection currents may carry fine particles into upper airstreams, leading to their loss from the area.

The quantity of N lost in any fire will depend primarily on the initial amount present, this being a function of the soil fertility, climate, and topography as well as of the age of the vegetation. It will also be related to the temperature of the burn, but this is largely a matter of chance depending on the dryness of the vegetation and the weather at the time of the burn. Annual losses of N due to burning have been given as 4–6 kg ha^{-1} (Anon. 1977), though, as explained above, losses may be substantially higher or lower than this. It should also be pointed out that not all upland pastures are burnt regularly. In wetter or higher situations slow-growing vegetation may be maintained in a relatively stable condition by grazing alone, so that losses of N would be less.

One further point in relation to burning and the nitrogen cycle is that in the season after burning, the soil surface is relatively unprotected, and more leaching and erosion may occur than normal. Losses of water by transpiration will be small and a higher proportion of rainfall will be available for leaching. On steep slopes, soil erosion may occur. Therefore additional losses of N may occur after burning, probably largely as particulate organic N in stream flow.

(*d*) *Denitrification*

Losses by denitrification or ammonia volatilization are likely to be insignificant except in localized areas of dung and urine deposition.

5. N in annual circulation

Apart from gross input and output, some N circulates within the soil–plant–animal system. The annual net uptake of N by herbage would be expected to range from 20 to 60 kg ha^{-1}; much of this would be derived from ammonium ions produced by mineralization of organic N in the soil. Recent incubation studies on peat at the Macaulay Institute for Soil Research have given similar results (B. L. Williams, personal communication 1981). Low soil temperature is probably the main factor controlling the release of N by mineralization (Floate 1970). The proportion of the annual herbage produced that is consumed by grazing livestock is on average about 20% for upland pastures; more would be grazed from better-quality grass-dominated herbage and a lower proportion from mature woody heathers.

On the basis of the plant N values from §2, N ingested by grazing livestock may range from about 2 kg ha^{-1} on heather-dominant vegetation to about 30 kg ha^{-1} on *Agrostis–Festuca* grassland. Most of the N ingested would be returned to the soil in faeces and urine; these aspects are further discussed by Floate (1981). The return of excreta is not uniformly distributed; there is often a transfer of fertility to dry or sheltered areas used frequently by sheep for resting (O'Connor 1981).

6. Discussion and summary

The amounts of N in reserves, input, output and in circulation are shown in table 1. The large reserve of N in soils of upland pastures that has accumulated under postglacial vegetation shows that there has been an annual average net input of N of the order of 1–3 kg N ha^{-1}. The present input from precipitation and dry deposition contains N that originates from industry, the combustion of fossil fuel, and from the application of organic manures to the land. Over most of the postglacial period, therefore, the input from precipitation and dry deposition would have been much less than at present. Biological N_2 fixation is another major input, but more field measurements are needed to establish accurate values; this input may have been higher during the pioneer stages of plant establishment.

Table 1. Summary of amounts of N cycling in upland pastures

	N / kg ha^{-1}	comments
N reserves		
total N in soils	6000–25000	low rate of breakdown
accumulated N in vegetation	50–200	related to species, age and climate
N in livestock 0.5 ewes per hectare	0.4–0.7	
1.5 ewes per hectare	1.2–2.1	
annual input		
precipitation and dry deposition, total N	14	
fixation	5–10	
fertilizers and manures	0	
feeding stuffs	< 1	
annual output		
livestock and wool 0.5 ewes per hectare	0.4	
1.5 ewes per hectare	1.6	
stream flow	3–6	plus organic N detached from stream banks
burning	4–6	affects leaching and erosion
denitrification	negligible	
annual circulation		
mineralization from soil N, plant litter, faeces and urine	20–60	all related to type of vegetation; the values given are not additive, but are representative of simultaneous activities
plant uptake	20–60	
returned in faeces and urine	2–25	

The output of N as livestock from the present system of hill farming is small; the output and circulation of N may have been higher in the past when the land was used more intensively as shown by the location of long-deserted dwellings and villages in upland areas. The evaluation of the significance of N in stream outflow is complicated by localized displacement of organic N from bank erosion and by mineral N originating from rainfall, which in winter has had a short residence time within the soil–plant system. Losses by burning are considerable, but vary according to the type and amount of vegetation present and to the severity of the burn. While the evidence points uncontroversially to a net accumulation of N in the past, the present situation is equivocal. Comprehensive data are not available. Where burning is done regularly, there is probably a cyclical balance, with an accumulation of N as vegetation matures and a sharp decline in the season of burning; overall there may be a slight decline, associated with increased leaching and erosion shortly after burning. Where burning is not done regularly, there may be a small net accumulation of N. However, in both burnt and unburnt upland pastures, there are substantial differences in all items of the N cycle within any catchment, associated with inherent variations in soils, topography and climate. Within any catchment there may be areas where the N balance is positive, negative or in equilibrium; the preparation of local or regional N cycles for upland pastures must account for internal variation, and any general conclusions must be interpreted with care.

Two broader issues are relevant to consideration of the N cycle in upland pastures. The first is that, despite the presence of substantial amounts of organic N in soils, the turnover is low; nitrate concentrations in streams emanating from upland pastures are very low, possibly even lower than in rainfall. Such areas provide large supplies of good-quality water. The second is that, if the increased quantity of N in rainfall recorded at Rothamsted and elsewhere is confirmed for upland areas, this could have considerable implications for the N balance.

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