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The nitrogen cycle in upland agriculture: its understanding, control and use

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1 *Introduction*

Paradoxically, the air around us is composed mainly of nitrogen (N), yet it is this element which is the greatest limiting nutrient to agricultural productivity throughout the world. Although molecular N constitutes about 80% of the earth's atmosphere, it is chemically inert and therefore cannot be used directly by most living organisms. The conversion of N from the gaseous form into compounds suitable for uptake by living organisms is called N fixation and this is principally achieved by the chemical industry and by N-fixing bacteria. It is man's efforts to overcome this limiting factor to productivity which have led to the annual expenditure of vast quantities of energy, and to major problems in the pollution of the environment.

The production of one kg of fertilizer by the chemical industry currently requires an energy input equivalent to that provided by burning 2 kg of oil. The UK demand for nitrogenous fertilizers is on the increase, and Figure 1 clearly shows the consistent and upward trend in the use of N fertilizers, contrasting it with the trends shown for the 2 other principal nutrients used in agriculture. Unfortunately, large quantities of the nitrogen currently applied to agricultural land often miss the target crop, finding their way into aquatic systems and back into the atmosphere. It is estimated that farmers in the UK spend 400 million on N fertilizers each year and, because of this enormous financial commitment, together with the importance of N in polluting natural ecosystems, we need to be aware of the fate, efficiency, and environmental consequences of these compounds.

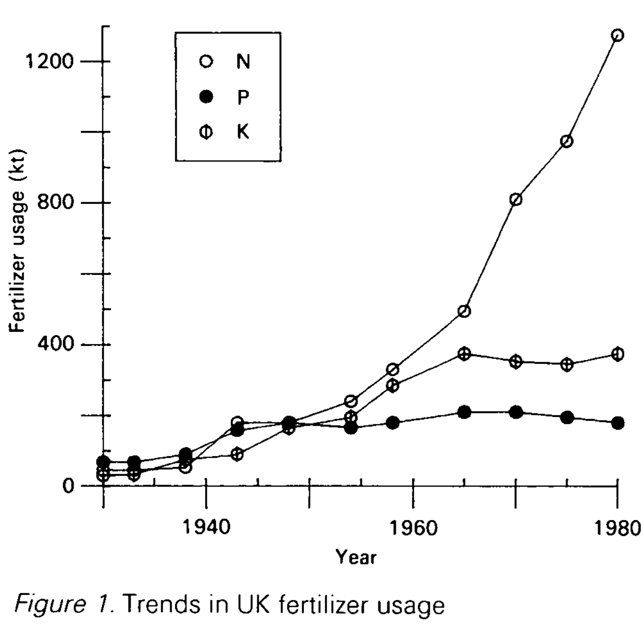

Figure 1. Trends in UK fertilizer usage

2 *Understanding nitrogen*

The movement of N through the environment is cyclic and any atom of N can move between gaseous, liquid or solid phase. The main components of the N cycle can be seen in Figure 2, which shows the principal forms of N and the pathways between them.

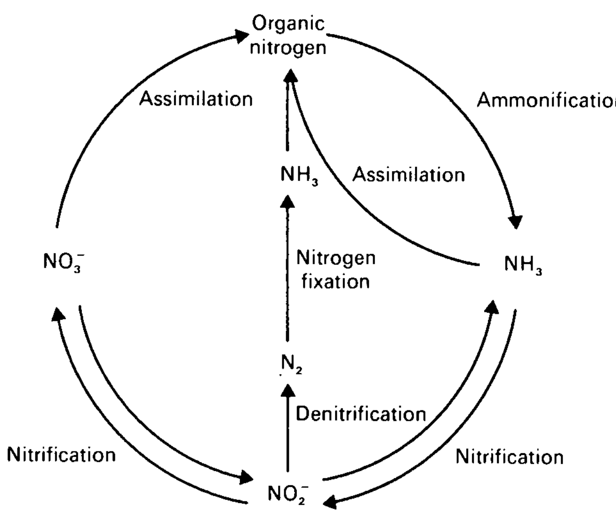

Figure 2. The nitrogen cycle

2.1 N fixation

It has been emphasized above that one major feature of the N cycle is the fact that the largest pool of N is in the atmosphere, in the form of dinitrogen gas (N_2). N can move from this pool into organisms *via* the route of N fixation. The vast supply of N gas in the atmosphere, coupled with the relative scarcity of combined N on the earth's surface, suggests that the process of N fixation is the major rate-limiting step in the N cycle. N fixation is the conversion of dinitrogen from the air to ammonium, a process which can be achieved biologically at normal ambient temperatures and air pressures, or artificially by chemical processes requiring high temperatures and pressures. Additionally, N can be converted from gaseous to liquid forms as a consequence of lightening, and by dry deposition of oxides of N to surfaces.

Only a small number of bacteria are capable of fixing N biologically, and the organisms involved can be divided into 2 groups: free-living bacteria which carry out non-symbiotic N fixation and symbiotic bacteria which exist in a mutualistic partnership with plants. Quantitatively, the most important N fixers belong to the genus *Rhizobium*, and members of this genus live symbiotically in the roots of leguminous plants, where they form characteristic nodules. The fixation of N is accomplished by enzymes produced by the bacterium, and the host plant provides carbohydrates and an environment suitable for the bacterium to carry out this fixation.

The most important agents of non-symbiotic N fixation are certain members of the blue-green bacteria, which are capable of fixing both carbon and N from the atmosphere. Although their role in N fixation in temperate agriculture is often assumed to be negligible, there is still some evidence that they may make a significant contribution to the N economy of certain arable lands (Powlson & Jenkinson 1988). Evidence is also accumulating that free-living N-fixing bacteria may exist in close association with plant roots, and fix significant quantities of N in the rhizosphere.

2.2 Assimilation

Nitrogen is essential for life, being a necessary component of amino acids, which are the fundamental building blocks of structural and enzymatic proteins. Plants are able to assimilate N in inorganic forms, mainly from the soil, and incorporate them into organic N compounds, with the principal nitrogenous compounds taken up by plants being ammonium and nitrate.

In turn, animals, including man, obtain N by consuming plants and other animals. During incorporation into animal tissue, the complex nitrogenous compounds of plants are hydrolyzed by varying degrees, with the N remaining largely in reduced organic form. Animals, unlike plants, excrete a significant quantity of metabolically produced nitrogenous compounds, and the form of excretory N differs markedly between animal species. Principal excretory products include ammonia, urea, uric acid and some organic nitrogenous compounds.

2.3 Ammonification

Much of the N assimilated by plants and animals remains in plant and animal tissues until the death of the organism, at which stage decomposition occurs and N is released. The process of decomposition is carried out mainly by micro-organisms, which attack proteins and nucleic acids liberating ammonium (ammonification). Part of the N is assimilated by the micro-organisms themselves (immobilization) and converted into microbial constituents, which will in due course be released when the microbe dies. The process results in a net release of N and is referred to as N mineralization, so called because organic N is converted to mineral, inorganic, form. Under anaerobic conditions, some of the amino acids are converted to amines (with their characteristic odour) and this process is referred to as putrefaction.

2.4 Nitrification

Although very small amounts of nitrate may be liberated on decomposition of organic matter, the principal inorganic N form released during decomposition is ammonium, as outlined above. However, there are groups of bacteria in the soil, collectively known as nitrifiers, which are able to convert ammonium to nitrate. These organisms are unusual in that they use the process of nitrification to provide energy for growth and reproduction, instead of the oxidation of organic matter. Their activity is very important, because certain plants preferentially assimilate nitrate, and nitrate is far more readily leached from soils than ammonium.

2.5 Denitrification

Denitrification is the biological conversion of nitrate to gaseous N products, such as dinitrogen and nitrous oxide. It is the major route by which fixed N is returned to the atmosphere. Again, it is a microbiological process achieved by a wide variety of organisms, but only occurs under certain environmental conditions. The process uses nitrate as a substrate, and requires anaerobic conditions and a source of energy for the organisms.

Although recent research has demonstrated that denitrification may be a major route for fertilizer losses in agricultural systems, it must be remembered that this process is also responsible for helping to shed excess nitrate from waters, and has an important function in preventing nitrate accumulation in aquatic systems.

3 The nitrogen cycle in the uplands

Figure 3 shows the overall inputs and outputs of N to agricultural land in the UK, with estimated total inputs and outputs being balanced at around 3 M t N yr^{-1}. This figure represents the overall situation for agricultural land in the UK, and the relative amounts have to be modified when considering upland areas alone. The specific use made of a particular area in the uplands also modifies this picture.

Unfortunately, the information we have about the N cycle in upland soils is limited to a few studies, yet we do know that there are certain important differences between these sites. The overall picture is presented in Figure 3 (Batey 1982). The unfavourable climate in the upland areas has important consequences for N cycling. Because of high rainfall rates and low temperatures, the soils are heavily leached, and organic matter accumulates, which leads to acid soils with low levels of available nutrients. The low levels of productivity also preclude expensive management options.

The results of one intensive study performed on a montane grassland ecosystem dominated by common bent-grass (*Agrostis capillaris*) and sheep's fescue (*Festuca ovina*) are considered here as an example of an upland N cycle. The study was performed at Llyn Llydaw and is described in detail by Perkins (1978). A summary diagram of the N cycle for this sheep-grazed grassland is illustrated in Figure 4, which shows the various pools and the fluxes between them.

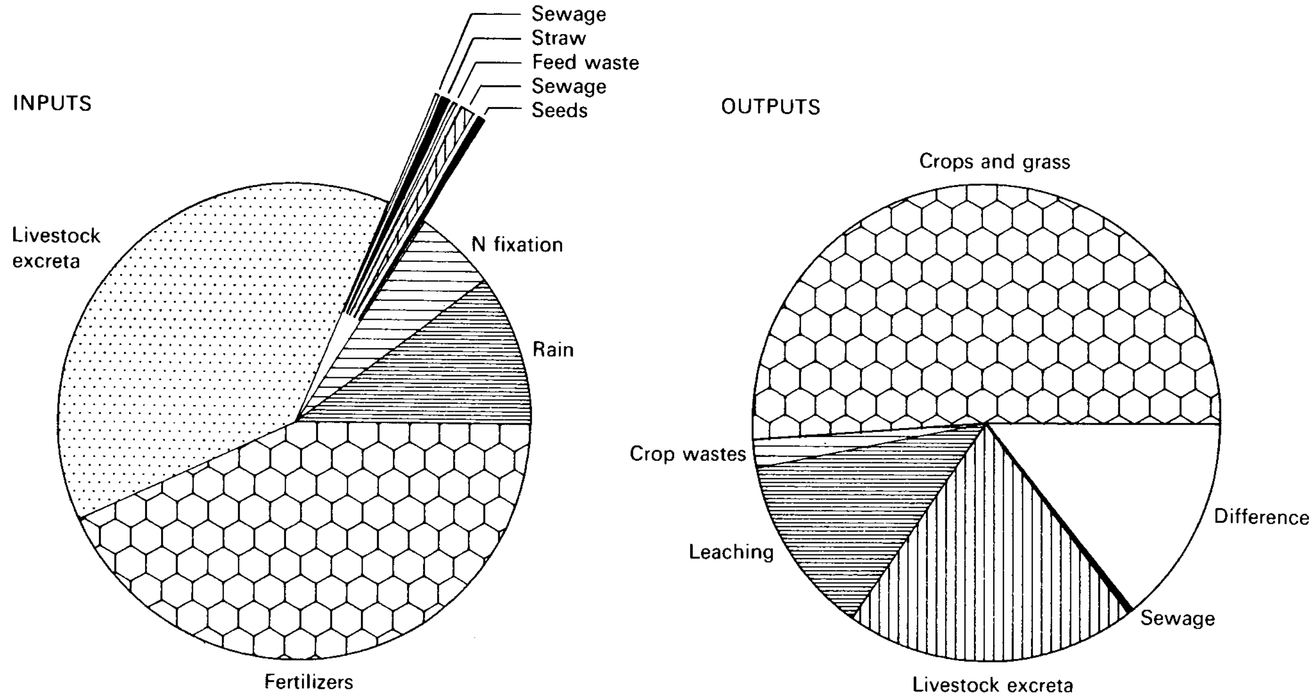

Figure 3. Overall nitrogen inputs and outputs for UK agriculture

3.1 Inputs

The relative overall inputs of N to agriculture in the UK are presented in Figure 3, with an estimated total input of around 3 M t N yr^{-1}. The major inputs are from fertilizers and animal excreta, which far exceed those from rainfall, N fixation and other sources.

The situation in the upland grassland ecosystem is very different, with no inputs from fertilizer or external sources other than rain, which contributed an estimated 18.4 kg ha^{-1} in the Llyn Llydaw study. The low occurrence of N-fixing plants in the sward gave rise to a negligible input from this source. Thus, this upland system represents one which is dependent on rainfall N, and which could be changed by different deposition rates. The suggestion that the concentration of nitrate in rainfall is increasing as a consequence of anthropogenic sources could have important effects in an area such as this, and it has indeed been seen as an important factor in affecting the floral composition of upland areas (Woodin & Lee 1987).

It has been estimated that a clover (*Trifolium* spp.) sward without added fertilizer can fix nearly 200 kg N ha yr^{-1} (Cowling 1982), which compares with an average fertilizer input to UK agricultural crops and grasslands of around 130 kg N per hectare and year (Church 1982). A review of N fixation in upland and marginal areas of the UK by Newbould (1982) emphasized the commercial advantages of adding to the nitrogen income by the use of clovers, especially white clover (*Trifolium repens*).

The contribution of wild white clovers and other N fixers to rough grazings is low because of their low density on acid soils. However, by the addition of lime, phosphorus (P) and potassium (K), it is possible to improve the percentage of white clover in upland soils, and the N they contribute. The pH of the soil must be increased above 5.2 before the wild clover will grow well, and a correct balance of added nutrients is necessary to achieve the establishment of a significant clover component (Floate *et al.* 1981). These workers demonstrated a large increase in rye-grass (*Lolium perenne*) herbage production on deep peat in response to a combined application of lime, P and K, which was mainly due to extra N transferred from the clover to the grass by urine from grazing animals. Figure 4 shows the importance of the excretory route in cycling N at Llyn Llydaw.

Using the above improvement techniques, clovers may become established on soils which either lack or have inefficient strains of *Rhizobia*, and experiments have shown that inoculation with effective strains can increase fixation levels. However, these experiments show a strong interaction with soil type, deep peats showing a positive response to inoculation and mineral soils showing a lack of response (Newbould 1982). The reason for these interactions is not clearly understood, but may be due to the interaction between lime and N mineralization. Addition of lime to acid, organic soils often results in increased mineralization of nitrogen, and it is known that increasing the inorganic N concentration in soils frequently results in an inhibition of nodule formation in leguminous plants. Also, for this reason, it is difficult to determine the extent to which improvements in the fixation of nitrogen by clover lead to increased nitrogen availability to swards, or the extent to which this increase is due to improved N mineralization caused by the addition of lime. However, despite these uncertainties, it has been suggested that fixation in the order of 125 kg N ha^{-1} yr^{-1} can be achieved through the establishment of white clover in upland systems (Newbould 1982).

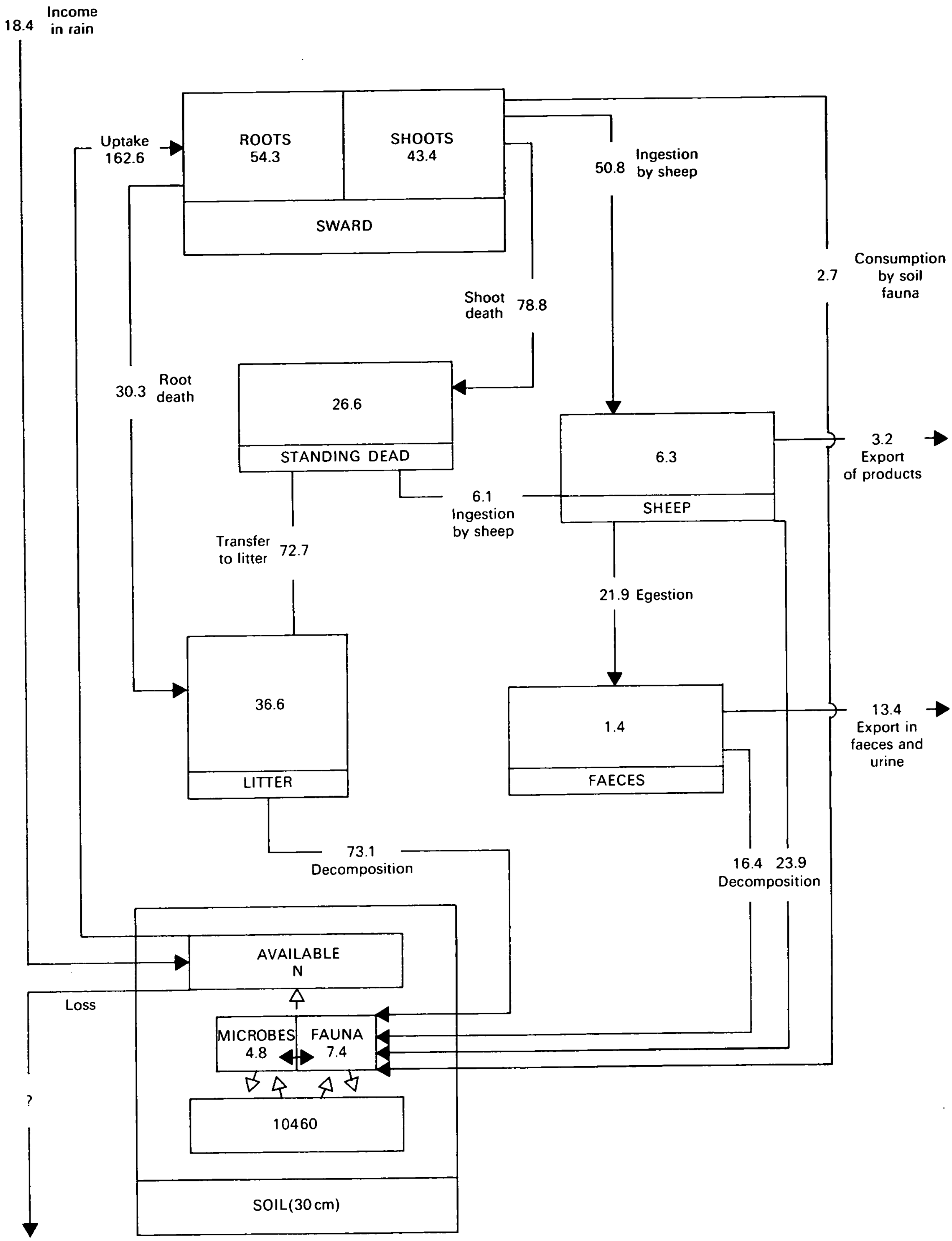

Figure 4. The nitrogen cycle at Llyn Llydaw. Pools are represented by boxes, and are given in kg ha^{-1}. Fluxes are shown as lines, with the quantities in kg ha^{-1}

3.2 N turnover

Perhaps the most surprising feature in Figure 4 is the discrepancy between the size of the pool of organic nitrogen in the soil and the relatively small quantities of nitrogen in circulation. The rate of ammonification of the organic matter in these soils is very low, dictated by the low temperatures and soil acidity at upland sites. Thus, despite the high nitrogen capital held in the soil (to 30 cm), less than 2% is mineralized per annum.

In upland regions, the nitrogen assimilated by the sward is mainly obtained as ammonium, derived from the decomposition of soil organic matter. Low soil temperature is probably the main factor controlling mineralization of N (Floate *et al.* 1981), but soil acidity will inhibit both decomposition and nitrification. Nitrification in acid soils such as these is usually negligible, unless the soil is limed, fertilized or disturbed by ploughing.

The majority of N taken up by the sward enters the detrital pathway *via* root and shoot death, with only a small fraction being ingested by the sheep. As mentioned above, the return of N to the soil as urine and faeces is an important source of available N for the sward, but there is often a transfer of N to the dry or sheltered areas used as resting places by the sheep, resulting in patches of higher fertility (O'Connor 1981).

Surprisingly, more N is contained in the soil fauna than in the sheep, and the amount of N held in microbial tissues also approaches this level.

3.3 Outputs

The N-deficient nature of upland pastures causes the cycling of nitrogen to be very tight, in that little nitrogen leaves the site. One of the principal reasons is the low concentration of nitrate in soil solution, the inorganic soil N pool being dominated by ammonium. Ammonium is less readily leached than nitrate, being retained on soil cationic exchange sites. Because the concentrations of ammonium in the soil will also remain relatively low, due to poor mineralization rates and uptake by the vegetation, the opportunity for nitrification is limited.

Few estimates of nitrogen leaching from upland areas have been made, yet catchment studies suggest losses in the order of 3–6 kg ha^{-1} yr^{-1} (Batey 1982). This aspect of the N cycle was not studied at Llyn Llydaw, and estimates are difficult to make. The main known source of N loss in this study was its export in faeces, which is largely the result of high transference to night camping sites, by the sheep. Strictly speaking, this does not represent a loss to the grassland site as a whole, but simply emphasizes the heterogeneous nature of the study site.

Livestock and wool represent the most obvious export route for N from upland pastures, but at Llyn Llydaw the total N loss was only 17% of the income in rain. This export represents less than 5% of the N ingested, the remainder being recycled in faeces and urine. Other livestock losses include grouse and deer removal, which may be important for certain specific areas, yet generally represent insignificant components of the cycle.

Losses of N from upland sites to the atmosphere are very difficult to quantify. The process of denitrification, recently identified to be a major N route in fertilized lowland systems, probably has little significance in the uplands. Upland soils do not receive fertilizer N inputs and, consequently, soil concentrations of nitrate will never be sufficiently high to support denitrification. However, this situation may not apply at points where faeces are deposited and where anaerobic conditions and nitrification may provide conditions for denitrification to occur. Again, this export is likely to be small, due to the limited occurrence of suitable microsites.

The other principal route by which N may be released to the atmosphere is through burning, which may represent a considerable loss, according to the frequency of burning, vegetation and soil type, and severity of burn. In very severe fires, not only is the standing vegetation combusted, but also large quantities of organic matter in the upper soil horizons.

Allen (1964) showed that losses of N in a single burn could amount to 45 kg ha^{-1}, yet he suggested that the stimulation of mineralization of organic soil N as a consequence of the burn could compensate for these losses. Comparable field measurements of N losses through straw-burning suggest that a single burn may release around 10 kg ha^{-1} (Fowler *et al.* 1985). Batey (1982) gives a range of 4–6 kg ha^{-1} yr^{-1} for burning losses on upland pastures, but emphasizes that, for any particular site, losses may be substantially greater or less. In the Llyn Llydaw situation, for example, the level of sheep grazing is so great that burning is not practised.

4 *Conclusions*

Upland soils are strongly influenced by climate, with high leaching and weathering leading to losses of bases and increasing acidity. Together with low temperatures, this situation leads to low rates of nutrient return through decomposition, and an accumulation of organic nitrogen in unavailable forms in the soil. Typically, only a few per cent of the total soil pool N is mineralized every year and, of this amount, only a fraction ends up in the grazers. The vegetation on these soils is usually strongly N limited.

Herbage production of upland rough grazings can be markedly improved by liming and fertilization, and there is substantial scope for increasing the use of legumes as sources of fixed N. Usually, the only other inputs of N in these areas are from rainfall, yet losses tend to be small. Leaching losses and losses through denitrification are reduced because of the absence of nitrate in the soils. However, losses of N through burning may be substantial.

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