ISSN 0308-3675

Merlewood Research and Development Paper
Number 68

THE EFFECTS OF LAND-USE AND MANAGEMENT ON UPLAND ECOSYSTEMS WITH PARTICULAR REFERENCE TO SOILS IN THE LAKE DISTRICT

K. L. BOCOCK and J. K. ADAMSON

R & D 76/68

Part of this paper was funded by the Department of the Environment under the Upland Land Use Contract (DGR 483/10) and is published with the permission of the Department.

Contents

Introduction

Many data are available on the effects of land-use and management on upland soils in general but few refer specifically to the Lake District in spite of increasing public interest in the use of the area during the past few decades. Pearsall (1950), and more recently, Pearsall & Pennington (1973) summarized available data on soils, vegetation and land-use and provided the relevant historical background. Both publications stressed the beneficial effects of trees in maintaining and restoring soil fertility and the harmful effect of leaching of nutrients from the soil by the high rainfall which occurs in upland areas in western Britain. Pearsall (1950) emphasized the long-term nutrient extractive effect of sheep-grazing whereas Pearsall & Pennington (1973) placed more emphasis on the harmful effects of deforestation and the need for soil conservation in the Lake District, particularly by re-afforestation.

Publication of Pearsall and Pennington's book stimulated the holding of a meeting of representatives of farmers, foresters, amenity organizations, conservationists, planners and research scientists in Kendal, Cumbria in October 1974 to identify and discuss local soil problems. The meeting, "Soils and Man in the Lake District", was sponsored by the Nature Conservancy Council. One of the papers presented, concerned with the effects of woodland and forest in a historical context, was published recently (Chard, 1975). The present paper is an expanded version of another of the papers and is presented here for discussion prior to final drafting of a summary for the Countryside Commission (Appendix below). It views soil as a resource and also as part of an ecological system of interacting parts. As a resource, soil must be conserved, that is, used wisely so that it is maintained in a suitable condition for a variety of land-uses in the long term as well as in the short term.

As part of an ecological system, such as woodland or grazed grassland, soil influences and is influenced by other parts of the system including the vegetation and the animals which feed on it and, therefore it cannot be viewed realistically in isolation. Interaction of soil characteristics and vegetation, topography, climate, land-use and management ultimately moulds the landscape of an area.

In practice, each ecological system changes continuously towards a condition in which the various parts and the rates of processes in the system are in an equilibrium determined by factors such as climate and management. When use or management is changed, adjustment of the system to a new set of factors, inputs and outputs, may take a considerable time and may involve losses and gains in certain parts of the system. The latter changes are not evidence of soil deterioration unless they impose major limitations on the future use of the soil for some defined purpose or unless they lead to soil erosion.

The areas of particular interest in this paper lie between the intensively managed arable land of the valley bottoms and the virtually soil-less and unmanageable high mountain tops. They fall into grades 4 and 5 of the Agricultural Land Classification (Ministry of Agriculture, Fisheries and Food, 1966) or classes 5 and 6 of the Soil Survey Land Use Capability Classification (Bibby & Mackney, 1969) and are classed mainly as woodland or heathland, moorland and rough land in the Second Land-Use Survey of Britain (Coleman & Maggs, 1968). Soils range from well-drained brown earths carrying Agrostis - Festuca grassland frequently invaded heavily by Pteririum on the lower fells to nutrient poor, often peaty but well-drained soils with Calluna and Vaccinium or poorly aerated gleys with Nardus grassland on the higher gentle slopes. Stagnant or non-stagnant bogs dominated by Molinia or Eriophorum respectively, occur on level areas at most altitudes in the zone of interest. These areas are used traditionally for rough grazing, forestry, water catchment and recreation, so their use concerns the general public as well as landowners and managers, particularly now as increased use of timber and high timber prices are encouraging the spread of commercial forestry, socio-economic factors are favouring changes in hill-farming and public pressure on hill land is increasing.

With the above background, this paper has three main aims. First, to summarise the effects on soil in general of the main types of land-use and management found or likely to be found in the future in the Lake District and to indicate their relevance to the soils of the area. Second, to compare the effects of the main land-uses, particularly hill-farming and forestry. Third, as a basis for future research, to identify those aspects for which relevant data are lacking.

Effects of grazing animals

Many authors, Coppock & Coleman (1970), Darling (1955), Hart (1968), McVean & Lockie (1969), Pearsall (1950), Pearsall & Pennington (1973), Tivy (1973), tend to regard free-grazing sheep as harmful to hill soils and vegetation and hold the view that, by their selective close grazing, sheep suppress all but the coarsest plants such as mat-grass, *Nardus stricta*, and heath-rush, *Juncus squarrosus*, and by their treading they destroy vegetation cover and thereby increase the likelihood of soil erosion. Sheep are also said to compact the soil thus reducing aeration, water absorption and circulation of nutrients. The culling of the flock is said to deplete areas of nutrients, particularly bases, and thus to accelerate the natural trend towards acidity in areas of high rainfall. Clearly, many of these ideas apply also to hill cattle so for convenience we will consider the effects of sheep and cattle together.

a) Effects of the animal hoof

The direct effect of treading varies with the hoof area, the pressure exerted, the number of times, and the way in which the hoof is applied to the ground per unit area and per unit time, the pattern of movement of the animal within an area and also the age, size and breed of animal. Available data on hoof measurements and pressures exerted suggest that cattle tread 2-4 times more heavily than sheep (Table 1) but such comparisons based on extrapolation from data for standing animals must be viewed with great caution bearing in mind results for standing and walking Man (Harper et al., 1961 and p. 16).

Most studies of treading effect or daily movement of animals have been carried out in lowland grassland areas and in enclosures where the animal may behave abnormally either because it is stimulated to move excessively or at a higher speed than normal (Edmond, 1958) or because movements are reduced when ample food is supplied (England, 1954). Data for individual sheep (Table 2) combined with observations on the daily movement of upland flocks in hefts or home ranges of known size (Hunter, 1962, for Cheviots on mainly Agrostis-Festuca, Nardus and Molinia grassland and Pteridium; Grubb & Jewell, 1974, for Soay Sheep on Nardus, Agrostis Festuca, Holcus and Poa grassland and Calluna) indicate a daily movement of 1.2-12.9 km with most values falling between 2 and 5 km. From such data, Welch & Cummins (pers. comm.) concluded that the daily movement of British hill sheep is about 2.5-5.0 km. Comparable data for cattle cover a range of 2.3-7.8 km day^{-1} (Table 2). Hancock (1953), quoting various published data, gives a range of 1.8-2.8 km day^{-1} for dairy cattle and he stresses that an old pasture or rough ground cattle travel twice as far as on new pastures. From all the above data one may conclude that cattle and sheep travel approximately the same distance per day.

Stride lengths in sheep and cattle are respectively about 15 cm and 45 cm (Frame, 1971). Using these data and approximate mean daily movements of animals, Welch & Cummins (pers. comm.) calculated that sheep and cattle perform respectively 100,000 and 4,000 leg movements $animal^{-1}$ day^{-1}. Assuming hoof areas of 15 cm^2 and

60 cm^2 respectively for hill sheep and cattle they calculated percentage of range trampled per year with different degrees of aggregation of trampling and stocking. Sheep averaged from 1.1 tramples year^{-1} evenly spread over the whole area with 0.2 animals ha^{-1} to 109.5 tramples year^{-1} on 10% of the area plus 12.2 tramples on the remaining 90% with a mean stocking rate for the whole area of 4.0 sheep ha^{-1}. Comparable data for cattle ranged from 88% of the area trampled per year with 0.1 animals ha^{-1} and evenly spread trampling to 100% trampled, 10% 21.9 times and 90% 2.4 times year^{-1}, where the mean stocking rate is 0.5 animal ha^{-1}. These calculations do not allow for repeated treading of the same area during each trample or for removal of stock from the hills during the more severe weather. In most hill areas, the stocking rates for cattle tend to approach 0.2 animals ha^{-1} and, for sheep, fall between 0.2-1 animal ha^{-1}.

Compaction by animals is concentrated in the top few cms of soil (Wind & Schothorst 1964; Edmond, 1958) although, occasionally, it extends to about 20 cms (Federer et al, 1961). Compaction may be greater at a few cms depth than at the soil surface if the top few cms is highly organic and resilient (Howard & Howard, 1976; Keen & Cashen, G. H., 1932). The overall degree of compaction varies with soil characteristics. Sandy soils low in organic matter or dry soils in general are little compacted, whereas soils rich in clay, peat and moisture are very susceptible to trampling damage (Wind & Schothorst, 1964).

Compaction involves not only an increase in bulk density but also a reduction of soil pore space, aeration, moisture storage capacity and infiltration rate, destruction of water-stable soil aggregates, and changes in thermal characteristics (Edmond, 1958; Federer et al, 1961; Gillard, 1969; Gradwell, 1960; Lull, 1959; Steinbrenner, 1951; Wind & Schothorst, 1964). Such changes may be expected to lead to soil biological and chemical changes but these are difficult to separate from changes associated with the effects of feeding and dung and urine deposition and seem to be small relative to the latter judging by the findings of Floate (1972). Moreover, as Welch & Cummins (pers. comm.) point out, the frequent occurrence of frost in British upland areas will tend to minimize any trend towards compaction.

Soil erosion associated with grazing does not appear to have been studied much in Britain although erosion gullies, which may be partly an effect of the grazing animal, are seen frequently on hill grazings. Thomas (1965) describes sheet erosion beginning from "burrows" or "bunkers" used by sheep as sheltering places in the Plynlimon and other moorland areas of Wales and we have observed fans of eroded soil below "bunkers" on grassland on the lower fells in the Southern Uplands of Scotland, the Pennines and the Lake District. Another aspect of erosion is the slow downhill movement of soil. Thomas (1959) mentions the movement of a particular sheep-path two feet downhill in four years, but in such examples disentanglement of the effects of Man, effects of the animal, and natural downhill soil movement is difficult. The effect of the hoof is more pronounced on wet soils, where the animal tends to slip and slide more than on dry soils. The sod which protects the soil surface is broken more easily by cattle than by sheep because the former exert the greater hoof pressure (Table 1).

In New Zealand, where soil erosion is recognised as a problem associated with grazed hill-soils, Gibbs (1964) has outlined the various types of erosion which occur and stressed the need for assessment of permissible stocking densities on particular soil types. These and other comments which he makes, appear to be relevant to soil conservation in the Lake District.

New Zealand work has also shown that vegetation, e.g. sown grassland with clover, may be considerably damaged by treading, particularly when the soil is wet and sheep densities are high (7-50 ha^{-1}) (Edmond 1958; 1962; 1963). Damage alone reduced herbage yield to as low as one eighth of the control value. In the Lake District, because of much lower overall sheep densities, such damage and also soil compaction are probably small except on or near sheep-paths and overnight resting sites and on areas of the most palatable vegetation, Agrostis - Festuca grassland (Hughes et al., 1964; Hughes et al., 1975; Rawes & Welch, 1969). In such places, changes in sward composition are likely to occur as a result of variation between herbage species in resistance to treading (Bates, 1935 for mixed grasslands on various soils; Edmond, 1958, 1962, 1963 for sown grasslands with clover). Grasses are more resistant to trampling than species such as Myrica gale, Pteridium aquilinum and Vaccinum myrtillus which are undesirable to livestock (Frame, 1971). Changes in the composition of the sward also occur when grazing pressure is insufficient to lead to severe treading damage (Welch, 1974; Welch & Cummins pers. comm.). Any changes in sward composition produce changes in the type and/or amount of plant remains returned to the soil and thus may lead to changes in soil chemical, biological and physical characteristics (pp.8 - 12).

From the above comments, the treading animal appears to be entirely harmful to the grazed sward-soil system however, Davies (1938) considered that a small amount of trampling helps to break up and aerate the soil surface and to earth up the bases of grassland plants. Some farmers use light trampling on a reseeded hill pasture in the belief that it has a firming effect similar to that achieved by using a roller (Newbould, 1974). Miles (1973), working on heather moor, birch and pine woodland and juniper scrub in Inverness-shire, found much higher densities of self-sown seedlings on soil bared by deer trampling than on vegetation-covered soil so perhaps trampling is important locally in creation of niches for new species in a closed community. Crocker (1953) considers that heavy grazing creates vacant niches which are occupied by less palatable species from within or outside the community and this applies also to low levels of trampling (Liddle & Greig-Smith, 1975b). However, Floate et al., (1973) and Jones (1967) find that grazed-out species are not necessarily replaced by unpalatable species (pp. 8 - 12). Published comments on the effect of trampling on vegetative reproduction of pasture species are conflicting. Davies (1938), Pearsall (1950), and Rawes & Welch (1969) state that treading plus grazing promotes the tillering of grasses whereas Edmond (1958) noted a progressive reduction in tillering of ryegrass and node formation by clover as stocking density increased from 0 to 8 sheep ha^{-1}.

b) Effects associated with the cycling of organic matter and nutrients within the animal-vegetation-soil system

On ungrazed hill-land, plant material produced above and below ground eventually dies and, as it decays under the influence of soil bacteria, fungi and animals, the nutrients which it contains are released and either held in the soil or re-absorbed by plants, or leached out of the soil. This leaching is most pronounced where rainfall is high, as in much of western Britain, and where the plant remains produce substances such as acids and polyphenols which promote movement of materials down the soil profile. Bases, are amongst the nutrients which are leached out, so the plant remains, tend to become progressively more acid. This acidity, combined with the lack of readily-available nutrients and the low temperatures prevalent in hill areas restricts the numbers and activities of decomposer organisms, so decomposition proceeds slowly and formation of a mat of plant remains and/or of peat occurs.

The imposition of regular grazing on the system described above involves defoliation, damage to the plant by trampling and soil compaction and hence usually lower herbage production (Bryant et al., 1972; Edmond, 1958; Floate, 1972; Rawes & Welch, 1969) and root growth (Schuster 1964). This, together with digestion and assimilation of some material by the animal, reduces the amount of organic matter returned to the soil. In a paired-plot fence-line study in Scotland, Floate (1972) found that imposition of grazing led to a reduction in the thickness and amount of surface organic matter. Howard & Howard (1974), working on Agrosto-Festucetum in the northern Pennines, found no change in the amount of surface organic remains with grazing but suggested that in the absence of grazing much of the dead grass is supported by the live vegetation and hence was not collected in their soil cores.

If overstocking occurs, herbage will be so reduced and damaged that bare soil will appear. The latter is highly susceptible to erosion and is also exposed to extremes of temperature which may, on balance, be unfavourable for microbiological activity although moderately high temperatures favour high activity if moisture does not become limiting.

Grazing involves channelling some vegetation through the animal and back to the soil in droppings and urine. The beneficial effects of dung and urine on soils and vegetation are well-known but quantitative evidence of their influence on nutrient cycling is less well documented. Floate (1972), in laboratory incubation studies, compared the release of nutrients from (A) plant material cut in October and (B) faeces produced by sheep fed the same materials cut at monthly intervals from May to October. He found that readily available nitrogen (N), including urine N, increased from 31.5 for A to 52.7 kg ha^{-1} for B for Agrostis-Festuca and 12.0 for A to 18.4 for B kg na^{-1} for Nardus in spite of herbage production decreases of 6% for A and 24% for B. Similar results were found for phosphorus (P). He also demonstrated increased uptake of N and P from dung and urine by the pasture plants. Clearly, grazing speeds up the nutrient circulation in the surface soil/vegetation system and this more rapid re-use of the small amounts of available nutrients present in hill soils can be interpreted as an indication of improved soil fertility.

In his fence-line study, Floate (1972) found that grazing led to:

i) Reductions in the ratios of carbon (C) to N and P for plant remains and of soil to 40 cm depth. Such ratios are often thought of as indicators of soil fertility.

ii) Increases in both total and organic P but no significant change in the concentration of available P in the top 40 cm of soil.

iii) An increase in soil pH but not in base saturation.

Howard & Howard (1976) recorded higher nitrogen contents and a lower C/N ratio in the top 3.5 cm of soil with grazing. Respiratory activity of the soils was higher on the ungrazed area, probably as a result of conversion of herbage to faeces with a lower respiratory activity (Floate, 1970). During & Radcliffe (1962) found that the top 4 cm of the dung-enriched soil of sheep-tracks on hills in New Zealand had a higher C content, a much higher N content and a lower C/N ratio than other soil on the hill.

The above comments refer to nutrient cycling in unimproved soils. If lime and/or basic slag are applied on a grazed area, marked increases in soil fertility occur from enhanced decomposition, reduction of mat formation and improved base status (Shaw, 1958). Liming and other soil amelioration treatments are usually coupled with increased stocking. This leads to a further increase in the proportion of the herbage production which is channelled through the animal and a further reduction in the amount of decomposing herbage on the soil surface (Floate, 1970, 1972). It also leads to increased utilisation of relatively unpalatable species and ultimately a change in sward composition towards dominance by more palatable graminaceous species. Floate et al. (1973), for example, showed that a <u>Nardus</u> sward could be changed to a palatable grass-dominated sward using controlled intensive grazing + lime + NP + Potassium (K) + surface seeding, but at a high cost. Jones (1967) obtained similar results in Wales.

From the soil conservation viewpoint, if sheep are to be kept in high rainfall areas, a management regime is required which:

i) maintains a continuous protective cover of palatable herbage plants and associated plant remains

ii) maintains the soil in as fertile condition and with as good structure as possible.

These requirements are at least partially met by the H.F.R.O.'s proposals for a two-pasture system involving:

i) improvement of the part of the available pasture which can be most economically improved, that is, that on the better soils already carrying some Agrostis-Festuca or bracken

ii) maximum use of the herbage production on this area by heavy intermittent cropping

iii) heavier use of the unimproved area especially during the summer (Eadie, Armstrong & Maxwell, 1973).

This approach allows much heavier overall stocking with sheep and some cattle. The latter are less selective in their grazing than sheep and they control and reduce the coarser herbage species (Fenton, 1937). In field trials, mixed grazing has led to a higher output of sheep flesh plus a bonus of some cattle flesh (Wannop, 1965) and may therefore be desirable on economic as well as ecological grounds.

In the Lake District, although the H.F.R.O.'s proposals have not been put into practice to any appreciable extent, improvement and more efficient use of the lower altitude grazings with better soils is favoured. In particular, the use of herbicides such as asulam for bracken is being tried. Soil changes resulting from such treatments and from associated practices, such as reseeding and stocking with cattle, are currently undescribed.

c) <u>Removal of nutrients from the system in the animal crop</u>

Several authors have calculated removal of nutrients in the hill sheep crop per unit area per year. Comparable data for hill cattle do not appear to be available although Dean et al., (1975) calculated removal of nitrogen from a short-grass prairie in northern Colorado by yearling Hereford heifers during June-August. The two grazing intensities used, 0.11 and 0.37 - 0.48 animals ha^{-1}, are of a similar order to those found on British hill grazings and they led to N removals over the three months of respectively 59.2 kg and 115.4 kg 100 ha^{-1}.

Crisp (1966) collected information on the nutrient budget for an 83 ha peat-covered catchment on the Moor House National Nature Reserve in the northern Pennines carrying about 18 sheep from April to October only (Table 3). Nutrient outputs in sheep were small in relation to a) outputs in water and eroding peat, b) nutrient reserves in the peat, c) and inputs in precipitation. Moreover, other studies indicate that precipitation contains only part of the total nutrient input (pp. 29 - 30). Alexander (1974) indicated that N fixation of the order of at least 10-20 kg 100 $ha^{-1} yr^{-1}$ occurs commonly on tundra/moorland type sites in the Northern Hemisphere. Two out of five values for Pennine moorland were excessively high, 3790 and 1059 kg 100 $ha^{-1} yr^{-1}$.

Rawes (1966) and Rawes & Welch (1969) calculated nutrient removal in sheep for the whole Moor House National Nature Reserve of 9850 ha stocked with a maximum of 8500 sheep from April to October (Table 4). Rawes (1966) also calculated comparable figures for the Lake District, assuming a stocking density of 2.5 ha^{-1} throughout the year (Table 4). In the absence of other comparable output data we have compared these losses with the nutrient inputs published in precipitation for the Lake District (Table 4). Data for both areas emphasize the nutrient removal in sheep in relation to nutrient input. Supporting data are also available for other areas. James (1971 and pers. comm.) and Roberts & James (1972) reporting work done on a R. Wye catchment of 1043 ha in the Plynlimon area of Wales, estimated that only 50-60 kg 100 $ha^{-1} yr^{-1}$ of calcium (Ca) was removed in the sheep crop of c. 2.5 sheep $ha^{-1} yr^{-1}$, whereas streamwater output was 2930 kg 100 ha^{-1} and input in precipitation was 500 kg 100 $ha^{-1} yr^{-1}$. Floate (pers.comm.) estimated that, taking a high estimate of 2.5 lambs (100 kg, 0.2% P) produced per acre of Scottish hill land, less than 20 kg 100 ha^{-1} of P are removed annually from a soil nutrient pool in excess of

200000 kg 100 ha^{-1}. Grant (pers. comm.) calculated that 1.6-12.8 kg potassium (K), 9-72 kg Ca, 5-40 kg P and 3 - 240 kg N 100 ha^{-1} was removed from the Scottish hill ecosystem by sale of lambs and cast ewes with respectively 0.5-0.66 ewes ha^{-1} and 70% lambing success and 1-2 ewes ha^{-1} and 100% lambing. King & Nicholson (1964) estimated that nutrient removal in sheep products in Scotland amounted to 22 kg Ca and 11 kg P 100 ha^{-1} with 0.625 sheep ha^{-1}.

Although the above calculations vary in analytical data used and in the ratio of weights of sheep carcase to wool, sheep consistently appear to remove small amounts of nutrients but this statement requires three qualifications.

1) As many authors have shown, sheep are highly selective grazers, so nutrient removal is concentrated on the most palatable parts of the sward particularly Agrostis-Festuca grassland. The latter may comprise less than 20% of a mixed moor in the Pennines (Rawes & Welch, 1969) with 2.2 sheep ha^{-1} but may support an average of up to about 9 sheep ha^{-1}. This is in the range of 5.6-18.2 ewe units ha^{-1} found for similar grassland in Wales (Hughes et al 1964). Assuming 9 sheep ha^{-1}, then the loss of P in sheep at Moor House is about 29 kg 100 ha^{-1}, c. 50% of the input in the rain, whereas for the Lake District the P loss would be about 30 kg 100 ha^{-1}, similar to that in precipitation. Wannop (1965) expressed some doubts about the ability of Scottish hill soils to replenish the P removed in sheep. Similar doubts may also apply for P and other nutrients in the Lake District for the areas of more palatable herbage.

2) A high percentage of soil nutrients is not readily available to plants, particularly in the wet, acid, leached organic soils of the Lake District, either because, nutrients are in resistant organic matter in peat, or in soil horizons below the rooting zone of herbage species. Perhaps the rate of removal of nutrients in sheep ought to be related to the rate at which nutrients can be supplied to herbage plants from the rooting zone rather than to the total soil nutrient pool. Although Rawes & Welch (1969) gathered a vast amount of data on the sheep and vegetation at Moor House they were forced to state that ...." as little is known about other factors such as uptake of nutrients by roots at Moor House, it is at present impossible to determine whether individual swards or vegetation types are declining in their stock of minerals and nutrients".

3) Although levels of removal are currently low in relation to nutrients in precipitation, this fact does not necessarily apply during the past few hundred years. In this period not only is the record of sheep densities incomplete, but also data on nutrient inputs are lacking. Composition of precipitation is known to vary with time because of factors such as changes in air pollution and wind direction. We cannot therefore assess accurately the importance of removal of nutrients by animals in the past.

Effects of agricultural vehicles

Damage to soil and vegetation by wheeled and tracked vehicles may be considerable on and around well-used tracks especially where the soil is wet. The effects include many of those already mentioned in association with trampling by animals.

Pressures exerted on soils and vegetation by agricultural tractors range from 0.21-0.63 kg cm^{-2} for crawlers to 1.41 kg cm^{-2} for four-wheeled machines (Lull, 1959). Wallace (1974) quotes pressures of 0.04-0.15 kg cm^{-2} for small cross-country vehicles with tracks or balloon tyres whereas small trucks with normal tyres exert about 2.54-4.58 kg cm^{-2} (Lull, 1959). Except for small trucks and larger vehicles which could exert pressures up to 7.90 kg cm^{-2} (Lull, 1959) vehicle pressures tend to be about the same or less than those exerted by grazing animals.

Effects of human recreation

The main effects of the recreating public on soil and vegetation in the Lake District are associated with walking, skiing, rock climbing, scree running and the use of wheeled vehicles. The effects are similar to and, in some specific locations, e.g. on much used tracks, are as severe as or more severe than the effects of the trampling grazing animal. However, in the area as a whole the effects are not considered by amenity bodies to be a major problem (see for example Friends of the Lake District, 1975).

From Lull (1959) pressures exerted on the soil by a human foot are 1.94 kg cm^{-2} for a 68 kg man with a bearing area of 35 cm^2 per foot (correction of Blair's 1937 data) and 0.84-0.92 kg cm^{-2} for man and 1.17-2.20 kg cm^{-2} for women (Lull's own data). Liddle & Greig-Smith (1975a) indicate a much lower value of 0.180 kg cm^{-2}. The above figures are calculated on the basis of body weight spread over the contact area of one foot and are the minimal pressures exerted during walking. They are of the same order as the pressure applied by a sheep foot (Table 1) however, recreating Man often wears walking boots the use of which could increase contact pressures several times. Moreover, Harper et al (1961 and 1967) showed that dynamic foot pressures can range from 1-59 kg cm^{-2} for humans in shoes.

Bayfield (1973) indicated pace lengths of 55-73 cm for walkers on Scottish hill paths. These values are considerably larger than those for sheep or cattle (15 and 45 cm p. 4). Further direct comparison between pressures exerted or areas compacted by grazing animals and Man is difficult because of differences in locomotion and in locomotory behaviour and currently impossible because of lack of suitable data for use of paths by sheep and cattle or average use of whole areas by Man.

The effect of trampling by Man on soil and vegetation has been much documented and discussed (Liddle, 1975, Lull 1959, Marren 1974; Speight, 1973; cf also pp. 3 - 8) so only an outline of the types of changes which occur will be given here. Chappell (1971) working on chalk grassland, found that as trampling increased the soil bulk density increased and water stability of soil aggregates, soil moisture content and numbers of soil animals all decreased. Chemical changes were not significant or could not be tested because of bulking of samples but tendencies existed for increases in percentage of iron in the reduced (ferrous) form, amount of ammonium N and percentage total N and decreases in amount of nitrate, percentage organic C and C/N ratio. Similar C and N trends were found on sheep-paths by During & Radcliffe (1962).

Composition of the sward changes considerably on heavily trampled areas (Bates 1935; Bayfield, 1971; Chappell, 1971; Davies, 1938; Liddle & Greig-Smith, 1975b). This has been attributed to differences in the resistance of different species to physical damage (e.g. Bates, 1935) and in the response of different species to changed soil conditions e.g. soil moisture status (Liddle & Greig-Smith, 1975b) or soil temperature (Liddle & Moore, 1974). Vegetation cover usually decreases with trampling (Bates, 1935) but vegetation diversity may decrease or increase depending on trampling intensity and initial condition of the vegetation (Liddle, 1975; Miles, 1973 and pp. 3 - 8).

Appreciable mechanical damage to vegetation leads to reduction in vegetation height (Liddle, 1975) and in the dry weights of aerial parts of plants (Duffey, 1972) although Liddle and Greig-Smith (1975b) indicate that low levels of trampling at, for example, path margins, may stimulate production. Any change in the type or amount of live or dead plant material in or on the soil is likely to lead to changes in the microclimate around the soil surface (Liddle & Moore, 1974) and in the soil biology (Chappell, 1971; Duffey, 1973).

Damage to soil and vegetation by skis and wheeled vehicles may be considerable and continual locally and include many of the effects associated with trampling by Man and animals (Bayfield, 1973a, 1973b; Lull, 1959). Pressures exerted by a family car amount to about 0.95 kg cm^{-2} on soft ground or 1.5 kg cm^{-2} on hard ground, that is about the same as pressures exerted by the sheep hoof (Table 1).

In the Lake District, commercially organized skiing, except for a small amount of grass-skiing, has not gained a foothold so the major effects of associated construction works (Bayfield, 1973a) are not seen. Wheeled vehicle damage, including that resulting from use of motor-cycles on the fells (Friends of the Lake District, 1975), appears to be slight.

Effects of trees and forestry

a) Effects of trees

Forest soils exhibit peculiar characteristics acquired under the influence of three soil-forming factors uncommon in other soils - tree roots, forest litter and specific organisms whose existence depends on the forest vegetation (Wilde, 1958).

We will consider the effects of trees under only two headings, i) roots ii) litter. Soil organisms are associated mainly with roots and plant remains and will therefore be discussed briefly under both headings.

i) Roots

The soil-stabilizing action of tree roots is well-known (Fournier, 1972). In many Lake District woodlands on steep slopes, an accumulation of soil and/or stones and most advanced soil profile development occurs on the upslope side of tree bases or of the main surface roots. This indicates that trees are inhibiting some downhill soil movement but that they are not preventing this movement entirely. Clearly, these observations do not indicate that tree roots are preventing soil erosion which would have occurred in the absence of trees.

The distribution of tree roots in the soil depends partly on tree species and partly on soil characteristics. It used to be thought that certain species, for example spruces, were typically shallow-rooting whereas others, for example pines and many deciduous trees, were deep-rooting. This view has now been largely discounted and it is becoming clear that many species can adapt their rooting form and depth when influenced by soil characteristics such as shallow depth, stoniness or a high water-table (Sutton, 1969).

Where roots come into contact with rock they appear to cause appreciable physical disintegration and chemical weathering. Klausing (1956), for example, suggested that in a beech wood granite and diorite weathered at rates of respectively 1.2 and 2.1 mm year^{-1}. Evidence of weathering in forests by the action of acids leached from organic materials, by carbon dioxide produced by the roots and by the action of soil micro-organisms is reviewed in Lutz & Chandler (1946). Voigt (1965) and Weed, Davey & Cook (1969) give further details.

One of the main functions of roots is absorption of water and nutrients from the soil. The mycorrhizal fungi growing in and around the root tissues helps the plant in the absorption of nutrients, particularly phosphorus. When a root dies or is killed by felling of the tree the organic matter it contains is slowly decomposed by the joint action of soil bacteria, fungi and soil animals and the contained nutrients are released slowly into the soil. The presence of root channels in soil renders the latter more permeable to air and water whereas organic matter from root decomposition helps to maintain the humus level throughout the soil profile. These effects are particularly important in an area such as the Lake District where the high rainfall tends to leach the soil of nutrients, and deep-burrowing earthworms are often absent because of high soil acidity.

ii) <u>Litter</u>

Litter, the fallen dead branches, leaves, flowers and fruits, acts as a blanket on the soil surface protecting the underlying soil and the roots and soil organisms it contains against extremes of temperature, direct insolation, and the direct impact of rain, and restricting evaporation from the soil. The nutrients in litter can only become available to plants by decomposition of the litter under the influence of numerous different types of soil organisms.

Litters differ in their composition. Some, such as many coniferous litters and beech, have a low lime and nitrogen content but contain relatively high amounts of acidic materials, fibre and polyphenolic compounds, whereas others, such as ash or elm, are rich in bases and nitrogen and low in acidic material and fibre. The polyphenolic compounds include the tannins found in large quantities in some tree barks. During senescence of the leaf or needle, the polyphenolic material in the cell sap interacts with the protein of the cell protoplasm by a process similar to the tanning of hides. The presence of tanned protein and of the other litter characteristics mentioned above helps to explain why certain litters are less digestible and more unpalatable to soil animals and more resistant to microbial attack than others (Handley, 1954).

Trees which produce slow-decomposing litters bring about a redistribution of nutrients in the soil profile with a concentration largely near the soil surface. Large amounts of nutrients may be immobilized in plant remains. Ovington (1959b, 1962), for example, showed that, in a 55-year old pine plantation, amounts of nutrients equivalent to 18% (Na) to 90% (N) of the nutrients in the standing trees were present in the plant remains on the soil surface. During percolation of rain-water, nutrients are leached from the remains and iron and aluminium are moved down the profile under the influence of acidic materials and polyphenols from the litter, the process of podzolization. The occurrence of podzolization and of obvious accumulations of acid nutrient-poor litter under conifer and some hardwood trees are perhaps the main reasons why some species have acquired the reputation as soil degraders, however, the justification for this reputation remains controversial (Page, 1968).

Although the effect of tree litter on soil is only partially understood certain points are now clear. The amounts of bases, polyphenols and other materials which affect soil profile development vary not only between species but also within species depending on the base status and type of soil on which the trees are growing (Mork, 1942; Coulson et al., 1960). This implies that it may be possible to alter the effect of the trees on the soil by altering the soil base status. Some species, for example birch, are often regarded as soil improvers (Dimbleby, 1952; Gardiner, 1968) but this view has been challenged and is still controversial (Rennie, 1956). One cause of such controversy is the tendency of some workers to focus their attention on the superficial soil layers, where some changes undoubtedly occur (Ovington, 1953), rather than considering nutrient content, nutrient availability and other characteristics of the whole soil profile in relation to the tree's requirements.

Podzolization appears to be unavoidable under conifers on some sites in Europe. It is rapid and complete under pine on poor sands or under spruce on fine-textured soils which previously carried deciduous forest whereas on other soils it is only partial with increases in the amount of superficial plant remains, acidity and C/N ratio for humus rich layers (Fournier, 1972). Pelisek (1974) indicated a similar picture for Czechoslavakia where 20-40% spruce mixed with broadleaved trees caused no adverse effects on moist alluvial soils at 100-200 m altitude and increasing percentages were tolerated as altitude and rainfall increased until, at 1100-1200 m pure spruce produced no significant deterioration of brown forest soils. Productivity was reduced significantly if a too high percentage of spruce was planted partly because of soil degradation physically and inadequate nutrient availability and also because of high interception of precipitation by spruce during the growing season. German workers, in general, also associate podzolization with decreased tree productivity but Genssler working in the Harz mountains and Holmsgaard et al., in Denmark found no reduction in timber volume production even over three generations of trees on the same sites with slightly podzolized soils of unspecified types (Fournier, 1972).

b) Effects of forestry

The main effects of forestry include soil compaction and disturbance associated with forestry operations, changes in amount and quality of run-off water, which has an obvious bearing on loss of soil nutrients and particulate matter, and removal of nutrients in the tree crop.

i) Soil compaction and disturbance

The maximum direct effect on the soil occurs during site preparation prior to planting when drainage operations, ploughing and roadmaking severely disturb and to some extent mix the soil, and during harvesting when heavy machinery moves into the forest. pp. 15-16 above indicate the new range of pressures exerted by vehicles likely to be used in forests however, as Lull (1959) points out, weight may not be very important as pronounced effects have been found with small pressures. Under wet conditions, macroscopic pore space was reduced by half and infiltration rate by 80% after one pass by a crawler tractor (cf pp. 15-16). 10-20% of total area may be compacted during tractor logging but areas affected can be much reduced by maximum use of roads and of log slides or overhead cable-ways.

Binns (personal communication) has pointed out that evidence of effects of compaction on forest production is scanty. Youngberg (1959) examined the growth of Douglas fir seedlings in soils compacted by tractors during logging. Growth was significantly less on compacted soils compared with that on the apparently undisturbed soils of clear-felled areas, probably because of poor aeration and low nitrogen in the former soils. Forest soils in general are light and easily compacted (Lull, 1959) but they are usually little disturbed for long periods and are therefore able to recover from severe compaction or disturbance with the aid of natural biological and physical processes.

ii) Changes in the run-off water

In British plantations, 10-54% of the incident precipitation fails to reach the ground because of interception by the tree canopy and only 0.04-0.32% of the total flows down the stems of trees (Ovington, 1954). Trees therefore reduce considerably the amount of water available for soil leaching and also the direct impact of rain on the soil.

Appreciable quantities of water which have been taken up by the roots are lost via the leaves as transpiration. As a result of interception plus transpiration, trees especially conifers, tend to dry out the soil. This is seen best in the shrinkage of peat soils after afforestation (Binns, 1968). Trees also reduce run-off water to only 28-58% of incident precipitation, conifers tending to give lower figures than hardwoods (Ovington, 1962).

Comparisons of total evaporation from forest and grassland or of water yield from forest and grassland catchments have given variable results (Rutter, 1968). This variability is associated with variability in the pattern of rainfall and in the evaporation of intercepted water (Rutter, 1972; Stewart & Oliver, 1972). Evaporation is likely to be fastest and hence possibly greater during the warmer months. In low-growing vegetation, transpiration and evaporation are of similar magnitude but evaporation of intercepted water from forest is greater than transpiration loss (Rutter, 1968), up to five times greater under windy conditions because of the aerodynamic roughness of the tree canopy (Rutter, 1972).

In watershed studies at Coweeta, USA (Hoover, 1944), clear-felling of mixed hardwoods increased run-off by nearly 53% and run-off as a percentage of incident rainfall from 34% to 59% (c. 41-62% according to Hibbert, 1967). Data from other sites summarized by Hibbert (1967) indicate increases in run-off of the same order or less after clear-felling forest. At Coweeta, establishment and growth of pines for 16-17 years on two catchments reduced streamflow to 20% below the value expected for a hardwood stand (Swank & Douglass, 1974).

Preparation of an area for planting of trees often involves drainage operations. From studies by Painter et al., (1974) on catchments with variable soils (peaty podzols, peat, boulder clay, sand) on Plynlimon in Wales and at Coalburn in north-west England these operations can lead to a 1000-fold increase in loss of particulate matter and presumably also in nutrients. A similar but smaller effect occurs when an area is clear-felled (Borman et al., 1974; Likens et al., 1970), although Packer (1967) concludes that clear-felling itself is virtually harmless and it is the subsequent logging operations which increase soil erosion and stream turbidity (Dyrness, 1967; Packer, 1967). Likens et al., (1970) studied effects of clear-felling an area of mixed hardwoods with some pine and fir in north-east USA. Their experimental area had a continental type of climate but in some respects resembled parts of the Lake District. Altitude ranged from 229-1006 m, rainfall was about 123 cm and the soil was acid podzolic glacial till overlying acid metamorphic rock. The main results were as follows:

1. Annual run-off of water increased by 39% in the first year and 28% in the second year after clear-felling over the values expected if the forest had not been cut.

2. Particulate matter in stream-water increased from about 25 kg to 100 kg ha^{-1}, with an increase in inorganic particulate matter from about a half to three-quarters of the total.

3. Concentrations of all major ions, except ammonium, sulphate and bicarbonate, in the stream-water increased five months after deforestation. Nitrate showed a 41-fold and 56-fold increase in the first and second years respectively after clear-felling.

4. The increase in cations was explained by a change in the nitrogen cycle in the forest system. In the undisturbed system, any nitrate produced during decomposition of plant remains was conserved by uptake by plants but when the vegetation was removed, nitrate plus associated cations were readily washed out of the soil. Hydrogen ions replaced the cations in both the decomposing organic matter and on inorganic materials.

5. Sulphate in stream-water decreased because of increased run-off and elimination of sulphate generation within the system.

6. Stream-water temperatures were higher after deforestation and varied 3^{o}-4^{o}C diurnally in summer compared with virtual constancy prior to felling.

The management practices used by Likens et al., prevention of regrowth of all vegetation after clear-felling by use of herbicide, no construction and use of forest roads and no removal of felled trees from their site, were very different from normal forestry operations in U.S.A. and in Europe so their results are likely to be of limited applicability generally. Sopper (1975) has placed them in the context of results from numerous other catchment studies in North America and concluded that sediment and turbidity problems can be minimized by careful siting and construction of logging roads, stream temperature changes can be avoided by leaving a narrow strip of trees or brush alongside streams: and nutrient losses following clear-cutting are small to negligible if rapid revegetation of the site occurs. The importance of a continuous vegetation cover and its associated litter layer in retaining nutrients on a site has been stressed by Thomas & Grigal (1976) for evergreen mountain laurel in Tennessee.

Tamm et al., (1974) also reviewed the effects of forest operations with particular relevance to Europe. They provide evidence that *nitrate* - *N* increases up to 8-fold in water from clear-cut areas particularly on the more fertile soils. Addition of N fertilizers, particularly ammonium nitrate, can lead to large increases in N content of stream-water and ground water. The fate of added nitrogen on clear-felling is debatable but the scanty available evidence suggests that the soil plus vegetation will be able to retain most of it on site. Sopper (1975) concluded that use of N fertilizers leads to only temporary increases in the N content of run-off water. Phosphorus and other elements are lost in drainage water from peatlands particularly after fertilization with soluble phosphates (Tamm et al., 1974). The latter authors also express concern that increased fertilizer use could lead to marked changes in soil and water acidity.

iii) Removal of nutrients in timber

During the past 80 years or so, and particularly during the past 20 years, numerous data have been collected on the amounts of organic matter and nutrients in the various parts of trees of a various species growing under a wide range of site conditions (Ovington, 1962; Rennie, 1956; Rodin & Bazilevich, 1967). Ovington's (1959a, 1959b) study of Scots pine is one example of this type of work (Table 5). He felled a series of sample trees of different ages all growing on virtually the same soil type and in the same area and measured the weights and chemical composition of their component parts. He also gathered data on roots, needle fall and on the soil. He was then able to estimate the rates of accumulation of nutrients in different parts of the tree and in plant remains as well as changes in the soil with time.

For comparison with the tree data, we have assembled data on inputs of nutrients in precipitation (Table 5). These are of the same order as values given in Table 3 for Moor House and published data for other parts of Britain, (Egner & Eriksson, 1958/1959; Madgwick & Ovington 1959).

Of the average annual uptake of nutrients over the 55 years, a high percentage passes into the leaves and ultimately returns to the soil surface in dead needles, branches and cones. Some nutrient uptake is retained in the tree crown and roots (not shown in Table 5). Only a small percentage, often less than 10%, is retained in the trunks. Clearly, average annual nutrient losses from the system in tree trunks alone, which can be regarded as losses from the soil, are very low and could be accounted for approximately by nutrient input in precipitation. However, precipitation supplies only part of the nutrient input. Droplets and fine dust particles (aerosols) originating from dusty roads, sea spray and other sources also contain nutrients and they enter the system even during dry weather. The size of this input at Thetford is unknown but White (1969) estimated annual aerosol inputs to a deciduous woodland near Grange-over-Sands to be 12520 kg 100 ha^{-1} Na, 630 kg 100 ha^{-1} K, 420 kg 100 ha^{-1} Ca and 12 kg 100 ha^{-1} P. The N input in Table 5 is also a minimum value as atmospheric N is fixed biologically by micro-organisms in soil and on leaves or as atmospheric ammonia-trapped in acidic plant residues. Ovington (1962) indicated that N fixation in forest may be about two-four times the amounts of N in precipitation quoted in Table 5, but Jones et al., (1974), basing their calculations on nitrogen fixation measurements in in Douglas fir canopy and soil in the southern Lake District and tree data from Ovington's studies in southern England plantation (summarized in Ovington, 1962), estimated total N fixation of 757-1974 kg 100 ha^{-1} yr^{-1} with 58-76% of the fixation occurring in the tree canopy. Alexander (1974) gives a range of 0-3500 kg N 100 ha^{-1} yr^{-1} fixed in Betula, Pinus and Picea forest soils on tundra-type sites in the Northern Hemisphere. Brouges et al., (1969) recorded up to 4900 kg N 100 ha^{-1} yr^{-1} fixed in various moderately acid forest soils in Quebec.

Weathering of mineral soil and rock provides some nutrients but relevant data on rates of weathering per unit area under field conditions are unavailable. Differences between inputs and outputs of nutrients for a site may be taken only as a rough guide to weathering rates because of the complexity of each system, the usually low precision in measurement of system components and the existence of long-term trends in some components. None of the most relevant available input and output data for afforested catchments, four quoted in Likens et al., (1967) and one in James (1971), include estimates of all possible nutrient inputs and outputs.

Although production of complete nutrient balance sheets for forests is difficult, consideration of available data above as a whole leads to the conclusion that managed forest systems tend to accumulate nutrients and do not deplete the soil of nutrients excessively as suggested by Rennie (1956) who under-rated the importance of the various nutrient inputs to the forest.

Rennie produced some useful data on average nutrient uptakes by trees and parts of trees over 50 and 100 years and we have used these on a modified basis to estimate removal of nutrients in tree stems during forestry operations (Table 6). Rennie used published data on yield, nutrient composition and dry weights of trees in European forests as a basis for his calculations, the data coming from 42 original studies including trees in growth classes I - V on predominantly acid sandy soils and some base-rich soils. Data were grouped into pines (two species), other conifers (three species) and hardwoods (eight species). Rennie did not explain fully why he separated off pine data from other data, but he implied that this was because low nutrient demand was expected for this group.

Our estimates of nutrient removal (Table 6) exclude brush timber of less than 7 cm in diameter. If brush timber was removed from the site, the values given would have to be increased by about 37-59% (Ca), 54-61% (K) and 69-88% (P). Figures produced by other authors for individual nutrients for other sites (Ovington, 1962) often differ numerically from those given in Tables 5 and 6 but all agree in stressing the low percentage of nutrient uptake removed in timber. Rennie did not provide data on N removal so rough estimates of loss in trunk timber were obtained from K or Ca loss and the ratios of N/K or N/Ca for trunks including bark assembled by Ovington (1962) (Table 6). Other published data, for example in Duvigneand & Denaeyer-de Smet (1970) and Rodin & Bazilevich (1967), indicate that the ratios used in Table 6 are adequate in the limited context of this paper.

The applicability of Rennie's data to Lake District conditions may be questioned. In answer, one may say that the figures refer to trees growing predominantly on nutrient-poor sites, Rennie himself considered that the results were applicable to moor soils in Yorkshire, and his nutrient retention data are of the same order as data obtained and assembled for various tree species on poor soils by Duvigneaud & Denaeyer-de Smet (1970). Our estimates (Table 6) are lower than the values quoted by Fournier (1972) who suggested that nutrient removals for a class I spruce plantation yielding 1500 m^2 of timber 100 ha^{-1} were 663 kg (K), 1143 kg (Ca), 131 kg (P) and 1500 kg (N) 100 $ha^{-1} yr^{-1}$.

The data in Table 6 confirm the conclusion drawn from Table 5 that nutrient removal in tree trunks is of the same order as total nutrient input in precipitation over the life of the tree and indicate that conifers, especially pines, are less nutrient-demanding than hardwoods. However, as Rennie (1956) stressed, nutrients are removed from circulation for many years in the woody parts of trees and this immobilization may have a major effect on the nutrient status of the site. Rennie's (1956) data for total uptake exclude nutrients in foliage and roots of thinnings and in litter but support our statements above.

Differences between nutrient cycling in coniferous and deciduous forests include nutrient return in litter. Litter-fall on a dry weight basis is 15-16% greater in coniferous forests than in deciduous forests and mineral content of conifer litter is about 35-36% of that in deciduous litter excluding Fagaceae (Bray & Gorham, 1964). Nutrients in conifer litter-fall per unit area, excluding N, are therefore about 41% of those for deciduous trees. For sites growing conifers, the advantage of low nutrient demand is offset by production of large quantities of nutrient-poor and slowly decomposing litter which may affect soil characteristics in undesirable ways(p.21) but which, nevertheless, may help to retain nutrients on a site (Thomas & Grigal, 1976). The reverse is true for many deciduous trees with other litters occupying an intermediate position.

Comparison of the effects of grazing animals and trees on the soil

The main differences and similarities in the ecological effects of grazing and forestry fall into two main classes, a) effects on the soil and b) removal or loss of nutrients from the system in animals or timber, in solution and as particulate material.

a) Effects on the soil

Soil compaction and/or disturbance by animals, Man and vehicles occur very locally on paths and roads with both hill farming and forestry but this does not appear to be a major problem over large areas largely because of the low intensity or frequency of use and because affected areas tend to recover naturally (pp. 3 - 8 & 23 - 24). Both uses also lead to changes in vegetation which reflect back on the soil (pp. 8 - 12 & 19 - 23). Data are not available which allow a comparison of changes in soils and vegetation for the two uses in the Lake District.

Evapotranspiration is higher for forest than for non-forest areas (Douglass, 1967; Ovington, 1968; Rutter, 1968), largely because of the higher evaporation in forests, transpiration tending to be the same in forests and grassland in the British climate (Rutter, 1968). This leads to a drier soil and lower run-off for forests than for non-forest. The tree canopy together with the layer of plant remains on the soil surface, help to protect the soil from the direct impact of rainfall and from climatic extremes thus favouring root growth and activity. In contrast, on grazed non-forest areas, management tends to reduce the protective influence of vegetation and plant remains by encouraging grazing of the sward and reducing the amount of plant remains on the soil surface.

Tree roots undoubtedly bind the soil on slopes better than the roots of herbage species. It is well-known for example, that gullying can be halted if trees can be planted around the rim of the gully. Whether it is necessary to plant trees in a particular area to protect the soil against erosive influences must ultimately depend on the rates of erosion and soil formation under normal climate and the frequency, severity and erosive influence of climatic extremes. In commercial forests, the times of planting and timber extraction are likely to be the critical periods for soil erosion whereas on a grazed area erosion potential changes gradually reaching a critical point only when high potential coincides with extreme climate.

In general, tree roots extend to a greater soil depth than do roots of herbage species (Douglass, 1967; Rutter, 1968). This implies that more water and nutrients are potentially available to trees than to herbage species. In addition, trees appear to be able to exploit nutrients in the underlying rock by actively encouraging physical break up and chemical weathering in the rooting zone (pp. 19 - 20).

Grazed upland pastures, unlike forest systems, do not accumulate a large store of nutrients in the standing vegetation so their nutrient cycling tends to be faster than that in woodlands, particularly where most of their primary production is diverted into the grazing animal (pp. 8 - 12). Both forests and grasslands return large quantities of organic matter and nutrients to the soil surface annually and this return tends to counteract the leaching effect of high rainfall particularly in forests where nutrients tend to be brought up from the deeper soil or rock. Data given in Bray & Gorham (1964) and Rodin & Bazilevich (1967) together suggest that amounts of litter-fall may be similar for both land-uses in a given climatic zone. The rates of decomposition of leafy plant remains and of release of the contained nutrients appear to be highly variable but of the same order in forest and grassland (Latter & Cragg, 1967; Mikola, 1954). Liming, fertilizer additions and increased stocking on hill pastures encourage faster nutrient cycling whereas the very slow decomposition of woody material in forests tends to retard cycling.

Both hill-farming and forestry can produce changes in the soil, such as decreases in the organic matter or nutrient content and in available nutrients, which may be interpreted as deterioration. However, unless these changes lead to rates of erosion greater than the rate of soil formation they are not necessarily of major importance.

b) Removal or loss of nutrients from the system in animals or timber, in solution and as particulate material

From Table 6, sheep production involves far less removal of nutrients from the hill than forestry, even for N which is much more abundant in animal tissues than in plant material. Data given by King & Nicholson (1964) for Ca and P removal in pines (after Rennie, 1956) and in a sheep crop (their own estimates, p. 14 above) supports this conclusion. The same conclusion would be reached from our estimates, even if the stocking density was increased to 10 ha^{-1}, which might be found under very intensive farming or on small favoured grazing areas with much lower overall stocking densities.

Any major disturbance to both systems such as ploughing, burning, road-making, fertilizing, tends to result in a change in loss of soil or nutrients in the run-off water. This change is particularly marked during site preparation and at felling time in forests (pp. 24-28), an aspect which may exaggerate the difference in nutrient loss/removal between forests and grazed areas.

We conclude from the evidence assembled above that the vegetation, and to some extent the soil characteristics of an upland area, may be changed to meet the requirements of a chosen land-use, but any change must be made smoothly and a continuous vegetation cover must be maintained as far as possible to avoid soil and nutrient loss.

Some evidence suggests that natural inputs to the forest are greater than those to the grazed system (Davies, 1969; Minderman & Leeflang, 1968) but outputs, other than the crop, are similar for both land-uses (pp. 12 - 15 & 23 - 32, Roberts & James, 1972) when the ecosystems are undisturbed. This is reflected in the greater accumulation of nutrients in the forest than in the grazed system (pp. 28 - 32).

Acknowledgements

We gratefully acknowledge the advice and information readily given by Dr. W. O. Binns of the Forestry Commission, Dr. M. J. Floate of the Hill Farming Research Organization and our colleagues in the Institute of Terrestrial Ecology in particular, Dr. D. F. Ball, Mrs. C. Cummins, Mr. A. J. P. Gore, Dr. O. W. Heal, Professor F. T. Last, Miss P. M. Latter, Dr. J. E. Satchell, and Mr. D. Welch.

Appendix: The effects of land use and management on upland ecosystems, with particular reference to soils in the Lake District. Merlewood Research and Development Paper No. 68.

K. L. Bocock and J. K. Adamson

Summary and conclusions

These notes, based on a paper by Bocock and Adamson, summarize the main effects of land-use and management on upland ecosystems in the Lake District, with particular reference to soils. Most of the relevant data used were collected outside the Lake District. Unless we have indicated reservations about the applicability of data to Lake District conditions, the reader may assume that we have considered and accepted its applicability.

Particular emphasis is placed on the effects of hill-farming, forestry and recreation. Any or all of these may occur on a water catchment and the latter use has few special features, so it will be covered in discussion of the other uses.

The altitudinal zone, which is of particular interest here, lies between the intensively managed coastal plains and valley bottoms with deep, predominantly fertile soils and the virtually soil-less and unmanageable high mountain tops. Soils range from well-drained, brown earths carrying *Agrostis-Festuca* grassland, frequently invaded by *Pteridium*, on the lower fells, to nutrient-poor, often peaty, but well-drained soils with *Calluna* and *Vaccinium*, or poorly aerated gleys with *Nardus* grassland, on the higher gentle slopes. Stagnant, or non-stagnant bogs, dominated respectively by *Eriophorum* and *Molinia*, occur on level areas at most altitudes in the zone of interest.

The main effects of the grazing animal include treading of the soil and vegetation, defoliation of the vegetation, and removal of nutrients from the ecological system in the animal crop.

The effect of treading varies with age, size, and breed of animal involved, more specifically with hoof area, the pressure exerted on each hoof, the number of times, and the way in which the hoof is applied to the ground per unit area and per unit time, and the pattern of movement of the animal within an area.

The few data available for hill breeds and conditions and extrapolation from data for lowlands, indicate that cattle tread two-four times more heavily than sheep, and their stride and hoof contact area are respectively three and four times greater. Sheep and cattle travel about the same distance per day, around 2-5 km. Such data suggest that, with the level of stocking commonly found in hill areas, 0.2-1.0 sheep ha^{-1} or 0.2 cattle ha^{-1}, much of the pasture is trampled several times per year. Because of vegetation variation, food selection, and the characteristics of diurnal and seasonal movement of animals, trampling is concentrated on areas of more palatable vegetation, e.g. Agrostis-Festuca, or on much-used paths.

Trampling causes soil compaction and disturbance and damage to the vegetation but may also be beneficial by creating new sites for establishment of seedlings, by firming seeds in the soil and by promoting tillering.

Soil compaction is concentrated in the top few cms. of soil and is greatest on soils rich in clay, organic matter and moisture and least on the well-drained sandy and stony soils. It leads to changes in soil characteristics such as aeration, root penetrability, infiltration rate, and thermal characteristics, all of which can affect soil fertility and vegetation composition or performance.

Small agricultural vehicles exert similar pressures to those calculated for animals and their passage has similar effects to those of animal trampling, but is concentrated more on established tracks.

Soil compaction does not appear to be a major problem in grazed hill and upland areas because of low stocking rates, infrequent use of agricultural vehicles, recovery of compacted soil under the influence of the frequent winter frosts and, in the case of animals, by the swamping of trampling effects by the beneficial effects of dung and urine deposition.

Soil disturbance occurs on much-used tracks, particularly on soils rich in clay, organic matter and moisture, on steep slopes where animals tend to slip and slide and for cattle rather than for the lighter-stepping sheep. Any disturbed soil is susceptible to erosion as can be seen on hill paths in wet weather. Hollows created on hill-sides by sheep action are focal points for sheet erosion. However, the extent to which the varying rates of erosion in the Lake District in the past and present can be attributed to the effect of animals is unclear.

Trampling and defoliation by grazing may result in damage to, and hence in reduced production by, plants. As plants differ in their sensitivity to damage and to changed soil conditions resulting from trampling, grazing animals can encourage changes in the vegetation composition which may lead ultimately to soil changes associated with changes in the type and amount of plant remains reaching the soil surface.

On hill-land ungrazed by domesticated animals, plant material eventually dies and forms part of the surface mat of plant remains. The type of decomposition which this mat undergoes under the influence of the high rainfall and low temperatures of upland areas, encourages high acidity *and low nutrient availability in the upper soil. Grazing channels* an increased proportion of the herbage through the animal and so reduces the supply to the mat. The effects of a reduced mat and of deposited dung and urine change the chemical characteristics of the upper soil, increasing nutrient availability and turnover. This, together with selective feeding by animals, particularly by sheep, encourages changes in the vegetation.

Assessment of the importance of the various practices and factors associated with grazing and which influence vegetation and ultimately the soil has not been carried out in the Lake District, but evidence from other upland areas suggests that intensity, timing, and location of grazing and use of fertilizers and herbicides are of prime importance.

A complete assessment of the importance of removal of nutrients in the animal crop cannot be made for the Lake District because of lack of data on inputs of nitrogen from various types of fixation, inputs of all nutrients in aerosols and from rock weathering, and outputs of all nutrients in run-off. However, available data, coupled with data from other areas, suggests that removal in animals is likely to be very small in relation to the total nutrient reserve in the soil and to input in precipitation. Phosphorus input in precipitation and output in animals are approximately equal, so, for this element, removal in animals may lead to an overall loss from the system when all inputs and outputs are accounted for.

Trampling of soil and vegetation is the main effect on soil associated with recreation. Detailed changes are likely to be similar to those caused by animal trampling, although few data have been collected in the Lake District, and data are not available generally which allow detailed comparisons of the effects of trampling by Man and by animals. Trampling damage is not considered to be a major problem except on well-used footpaths, particularly on steep slopes, on wet peaty areas, and on the higher altitude ridges. Use of vehicles on unsurfaced tracks and paths has similar effects to those produced by Man's trampling and, currently, rarely produces significant damage in the Lake District.

The main effects of trees and forestry on the soil include those associated with tree roots, plant remains, soil disturbance during forestry operations, influences on run-off water quality and, removal of nutrients from the system in timber.

The soil stabilizing effect of tree roots is of particular importance on steep slopes. The zone of soil around tree roots is a site of active mineral weathering. The importance of the latter effect for forest in the Lake District is unclear. The presence of root channels in soil renders the latter more permeable to water, whereas root decomposition adds humus and nutrients slowly throughout the soil profile.

Plant remains on the soil surface buffer the soil against the effects of climate, particularly direct insolation and extremes of air temperature and rainfall. The rate and type of decomposition of plant remains influences the chemical and physical properties of the underlying soil. Conifer litter, like *Calluna* and *Erica* on moorland, has the reputation of causing physical, chemical and biological deterioration of soil. Whilst these effects remain somewhat controversial, and incompletely understood it is clear that they vary with soil type, site characteristics and tree species. Relevant local data are few and indicate tendencies towards acidity, low nutrient availability and podzolization in many upland soils but no clearly developed podzol profiles. Evidence from elsewhere indicates that trees, even conifers, will grow well on similar soils to those found in the Lake District without causing serious soil degradation, although they may cause the tendencies indicated above.

The maximum direct effect of forestry operations on the soil occurs during site preparation and harvesting, both of which involve use of heavy machinery which compacts and disturbs soil, partly because of its own weight, and partly because of its use in ploughing, draining or logging. Except for light cross-country vehicles and heavy trucks, such as timber lorries which can exert pressures on the soil of up to about 8 kg cm^{-2}, vehicle pressures fall in the range 0.2–4.6 kg cm^{-2}, about the same as the static pressures exerted by animals. One application of about 0.2 kg cm^{-2} can reduce soil pore space by 80% and 10–20% of an area can be affected by vehicles during tractor logging. Data from other areas suggests that soil compaction by forestry is not a major problem, but that marked vegetation changes occur after ploughing, draining and roadmaking. These changes will ultimately reflect back on the soil.

Forests have an appreciable influence on the hydrology of a site, including soil moisture status and run-off. Transpiration rates in forest and grassland are of approximately the same order but forests intercept up to half, but more commonly around 20-40% of precipitation, often several times the interception for grassland. Intercepted water is evaporated so the soil tends to be drier and less leached under forest than under dense grassland.

Site preparation leads to a loss of particulate matter and nutrients in run-off, which may continue for several years after planting of the forest. Roadmaking also increases soil and nutrient loss from the site temporarily.

Felling, especially clear-felling, leads to increases in soil leaching, in run-off, and in the amounts of particulate material and nutrients in run-off. Soil and nutrient loss is only slight if logging is carried out carefully, and if rapid regrowth of herbaceous vegetation occurs. Felling leads to increases of several ^{o}C in mean soil and stream temperature and in the diurnal temperature range. Temperature changes will have an appreciable effect on the numbers and activities of fauna, flora and microflora of these habitats.

Fertilizers and herbicides used in forestry, affect the quality of the run-off water only slightly and temporarily, if they are applied carefully. However, they will have some effect on the soil by altering biological activity or the type and amount of plant remains reaching the soil surface.

Forest systems, in contrast with non-forest systems, accumulate a large nutrient capital in the trees themselves and in the plant remains on, and in, the soil. Factors which favour this build up include evergreen condition of many forest trees, resistance to decomposition of litter, exploitation of a greater soil volume by tree roots than by roots of grassland and moorland plants, except perhaps Pteridium, greater trapping of aerosols and possibly greater mineral weathering under forest than under non-forest.

Only a few percent of the nutrient uptake of trees, often less than 10%, is retained in the trunk, and this is approximately the same as nutrient amounts in precipitation. Brush timber contains nutrients equivalent to 40-90% of those in trunks of the main trees. Timber extraction therefore removes only a small fraction of the annual nutrient income to a site, but, nevertheless, removes much more - for some nutrients more than ten times more - than that removed in the animal crop.

To summarize the above, the characteristics of soils under different land uses and managements often differ markedly as a result of the use or management. When use and management are altered, soil changes occur as natural adjustments of the ecosystem to the factors applied. These changes rarely lead to severe deterioration in soil quality, or to soil erosion, unless changes have been made suddenly and without careful planning.

Table 1 Hoof area and pressure for sheep and cattle

Available details on country of study, animal breed, sex and live weight.	Area of one hoof (cm^2)	Mean pressure exerted (kg/cm^{-2})[1]	Author
Sheep (adult female)	19	0.71-1.05[2]	Taylor Page (1957)
Sheep (unspecified)	19	0.71-1.05[2]	Lawrence & Brown (1973)
Sheep (Kerry Hill, 59.0-73.5 kg)	23.1	1.47-1.84	Spedding (1971)
Sheep (Kerry Hill, 74.3-87.5 kg)	19.9	1.61-1.89	Spedding (1971)
Sheep (New Zealand, 27.2 kg)	12.9	1.05	Sears (1956)
Sheep (unspecified)	10-16	0.71-2.00[2]	Frame (1971)
Sheep (USA, 54.5 kg)	21	1.30	Lull (1959)
Cattle (adult female)	58	2.57-4.32[3]	Taylor Page (1957)
Cattle (S. Africa, steer 452 kg[4])	40[5]	5.64	Gillard (1969)
Cattle (unspecified)	69	2.17-3.63[3]	Lawrence & Brown (1973)
Cattle (New Zealand, Jersey cows (817 kg[4])	64.5	3.18	Sears (1956)
Cattle (Scotland)	65-90	2.80-4.20	Frame (1971)
Cattle (USA, 613 kg)	91	3.37	Lull (1959)
Cattle (Netherlands, Friesian, 600 kg)	75	4.0	Wind & Schothorst (1964)
Cattle (Netherlands, Friesian, young or small cows)	?	3.0	Wind & Schothorst (1964)
Cattle (South Devon, 500-560 kg)	87.8	2.86-3.20	Spedding (1971)
Cattle (Jersey, 320-365 kg)	62.5	2.56-2.92	Spedding (1971)

1. All values calculated on the basis that the live weight is distributed between two legs during walking.
2. Estimated from hoof area and live weights of 27-40 kg quoted by Rawes & Welch (1969) for Pennine sheep of more than one breed.
3. Estimated from hoof area and a live weight range of 300-500 kg for hill cattle (Welch & Cummins, pers. comm.).
4. Estimated from hoof contact area and mean hoof pressure.
5. Contact area.

Table 2 Daily movement of sheep and cattle (modified and extended version of table by Welch & Cummins, pers. comm.)

Animal	Vegetation	Conditions	Distance travelled (km)	Authors
SHEEP				
Rambouillet ewes Targhee ewes Columbia ewes	Wooded mountain grasslands, Utah	Free range	4.7 3.9 3.1	Bowns (1971)
Rambouillet ewes	Very rough, scrubby grassland on level areas to steep slopes, Texas	5 enclosures of from 155 - 363 ha	6.1	Cory (1927)
Mature Romneys and Cheviots	Flat grassland, New Zealand	2.4 ha paddock	1.8 (1.7-2.1) (Romneys) 1.9 (1.1-2.4) (Cheviots)	Cresswell (1957)
	Steep, very rough grassland, New Zealand	6.4 ha paddock	1.0 (0.4-1.1) (Romneys) 1.6 (0.9-2.0) (Cheviots)	Cresswell (1957)
Rambouillet, Hampshire, and Columbia ewes	Flat grassland, New Zealand	1 and 2 ha paddocks	1.8-2.9 (Rambouillets) 1.0-2.6 (Hampshires) 1.8-2.4 (Columbias)	Cresswell & Harris (1959)
Mature Romneys and Cheviot ewes throughout one year	Flat grassland, New Zealand	0.4-2.4 ha paddocks	1.9 (1.5-2.3) (Romneys) 2.2 (1.1-2.6) (Cheviots)	Cresswell (1960)
	Steep, rough grassland New Zealand	7.2-32.4 ha paddocks	1.2 (0.4-1.8) (Romneys) 1.9 (0.8-2.7) (Cheviots)	Cresswell (1960)

Table 2 (Continued)

Animal	Vegetation	Conditions	Distance travelled (km)	Authors
Spanish ewes			2.2 (lush) 3.5 (short)	
Clun ewes			2.1 (lush) 3.5 (short)	
Suffolk ewes	lush and very short grasslands, Wales	0.8 ha paddocks	1.8 (lush) 3.9 (short)	England (1954)
Scottish Black-face ewes			1.4 (lush) 2.6 (short)	
Oxford Down cross and Clun Forest	Sown grassland, England	0.2–1.0 ha paddocks	2.3	Hughes & Reid (1951)
Cheviots	Sown grassland, Scotland	0.4 ha paddock	4.2	Tribe (1949)
Scottish Black-face ewes	Heather moors and adjacent sown pastures, Scotland	Free range	3.0–4.5	Welch & Cummins (pers. comm.)
CATTLE				
Hereford cows	Very rough, scrubby grassland on level areas to steep slopes Texas	5 enclosures from 155-363 ha	5.3	Cory (1927)
Steers	Transvaal highveld	7 ha paddocks	3.2	Gillard (1969)

Table 2 (Continued)

Animal	Vegetation	Conditions	Distance travelled (km)	Authors
Hereford bullocks	Sown grassland, England	0.2–1.0 ha paddocks	2.3	Hughes & Reid
Yearling steers	Prairie grassland, Colorado	20 ha paddocks with 0.2 anim./ha	3.9	Quinn & Harvey (1970)
		with 0.4 anim./ha	5.1	
Hereford yearling steers	Sagebrush-bunchgrass semi-arid range, Oregon	free range	7.5	Sneva (1970)
Crossbred yearling steers			7.8	

Table 3. Part of the nutrient budget for the 83 ha Rough Sike catchment at Moor House, modified after Crisp (1966). (kg 100ha^{-1} year^{-1}).

	Na	K	Ca	P	N
Precipitation	2554	307	896	57	820
Soil reserve *	51000	375360	379240	81600	2660160
Stream water	4524	896	5375	40	294
Peat erosion	28	206	483	45	1463
Stream fauna	0.14	0.47	0.09	0.53	5.68
Sheep (0.22 ha^{-1})	0.19	0.53	1.90	1.18	5.30
Total output	4552	1103	5860	87	1768

* Estimated from Crisp's peat nutrient content data and an average peat depth of 1.5 m (Rawes & Welch, 1969).

Table 4 Input of nutrients in precipitation and output of nutrients in sheep and wool in the Lake District and on the whole Moor House N.N.R. (kg 100 $ha^{-1} yr^{-1}$)

Lake District

Precipitation[1]	190-540	650-1200	23-100	577-1500
Sheep[2]	13.8	27.8	8.4	57.9

Moor House

Precipitation[3]	307	896	57	820
Sheep[4]	11.1	23.8	7.2	49.0

1. Range of available data, after Allen et al (1968), Sutcliffe & Carrick (1973), White (1969), White et al (1971).

2. After Rawes (1966). Stocking density 2.5 ha^{-1}.

3. After Crisp (1966).

4. After Rawes & Welch (1969). Stocking density 2.2 ha^{-1}.

Table 5 Part of the nutrient budget for a plantation of 55-year old Scots pine at Thetford (kg 100 $ha^{-1} yr^{-1}$).

	Na	K	Ca	P	N
Precipitation[1]	1970-5100	190-540	650-1200	23-100	577-1500
Uptake by trees[2]	240	3514	4130	751	8758
Litter fall[2]	78	2556	2552	514	6362
Loss in stems (thinnings up to 55 years)	9	178	382	25	292
Loss in stems (thinnings up to 55 years and clear felled stems at 55 years)	18	262	604	38	453

1. Range of available data for the Lake District, after Allen et al (1968), Sutcliffe & Carrick (1973), White (1969) and White et al (1971).

2. After Ovington (1959a, 1959b).

Table 6 Nutrient input in precipitation and probable nutrient losses in tree trunks, the sheep crop and dissolved nutrients for the Lake District (kg 100 $ha^{-1} yr^{-1}$).

	K	Ca	P	N
Precipitation[1]	190-540	650-1200	23-100	577-1500
Pines 50/100 year[2]	94/104	242/279	20/20	(161/178)[6] or (262/302)[7]
Other conifers[2] 50/100 year	193/277	376/566	30/40	(405/581)[6] or (433/651)[7]
Hardwoods[2] 50/100 year	277/326	1191/1433	53/69	(686/808)[6] or (1083/1303)[7]
Sheep[3] (2.5 per ha)	13.8	27.8	8.4	57.9
Dissolved nutrients in stream water[4]	520/580	3830/7400	-	110[5]

1. Range of available data for the Lake District, after Allen et al (1968), Sutcliffe & Carrick (1973), White (1969) and White et al (1971).
2. After Rennie (1956)
3. After Rawes (1966)
4. After Sutcliffe & Carrick (1973) and White et al (1971).
5. Nitrate-N only
6. K values x 1.708, x 2.098 or x 2.478 after data given by Ovington (1962)
7. Ca values x 1.081, x 1.151 or x 0.909 after data given by Ovington (1962)

REFERENCES

Alexander, V. (1974). A synthesis of the IBP Tundra Biome circumpolar study of nitrogen fixation. In Soil Organisms and Decomposition in Tundra. (Holding, A. J., Heal, O. W., Maclean, S. F. Jr., & Flanagan, P. W., Eds.), 109-121. Stockholm: Tundra Biome Steering Committee.

Allen, S. E., Carlisle, A. & White, E. J. (1968). The plant nutrient content of rainwater. J. Ecol. 56, 497-504.

Bates, G. H. (1935). The vegetation of footpaths, sidewalks, cart tracks and gateways. J. Ecol. 23, 470-487.

Bayfield, N. G. (1971). Some effects of walking and skiing on vegetation at Cairngorm. In The Scientific Management of Animal and Plant Communities for Conservation (Duffey, E., & Watt, A. S., Eds.). Symp. Br. ecol. Soc. 11, 469-485. Oxford-London-Edinburgh: Blackwell Scientific Publications.

Bayfield, N. G. (1973a). Human pressures on soils in mountain areas. Rep. Welsh Soils Discuss. Grp. No. 14, 36-49.

Bayfield, N. G. (1973b). Use and deterioration of some Scottish hill paths. J. appl. Ecol. 10, 635-644.

Bibby, J. S. & Mackney, D. (1969). Land use capability classification. Agric. Res. Coun. Soil Surv., Tech. Monogr. No. 1.

Binns, W. O. (1968). Some effects of tree growth on peat. Proc. 3rd int. Peat Congr., 358-365.

Blair, S. G. W. (1937). Compressibility curves as a quantitative measure of soil tilth. J. agric. Sci. 27, 541-556.

Bormann, F. H., Likens, G. E., Siccama, T. G., Pierce, R. S. & Eaton, J. S. (1974). The export of nutrients and recovery of stable conditions following deforestation at Hubbard Brook. Ecol. Monog. 44, 255-277..

Bowns, J. E. (1971). Sheep behaviour under unherded conditions on mountain summer ranges. J. Rge. Mgmt. 24, 105-109.

Bray, J. R. & Gorham, E. (1964). Litter production in forests of the world. Adv. ecol. Res. 2, 101-157.

Brouzes, R., Lasik, J. & Knowles, R. (1969). The effect of organic amendment, water content, and oxygen on the incorporation of $^{15}N_2$ by some agricultural and forest soils. Can. J. Microbiol. 15, 899-905.

Bryant, H. T., Blaser, R. E. & Peterson, J. R. (1972). Effect of trampling by cattle on bluegrass yield and soil compaction of a Meadowville loam. Agron. J. 64, 331-334.

Chappell, H. G., Ainsworth, J. F., Cameron, R. A. D. & Redfern, M. (1971). The effect of trampling on a chalk grassland ecosystem. J. appl. Ecol. 8, 869-882.

Chard, J. S. R. (1975). Soils and Man in the Lake District: the woodland scene. Q. Jl. For., 69, 67-74.

Coleman, A. & Maggs, K. R. A. (1968). Land Use Survey Handbook. London: Land Use Survey.

Coppock, J. T. & Coleman, A. M. (1970). Land use and conservation. II. The conservation of wildscape: a quest for facts. Geogrl J. 136, 191-205.

Cory, V. L. (1927). Activities of livestock on the range. Bull. Tex. agric. Exp. Stn. No. 367.

Coulson, C. B., Davies, R. I. & Lewis, D. A. (1960). Polyphenols in plant, humus, and soil. I. Polyphenols of leaves, litter and superficial humus from mull and mor sites. J. Soil Sci. 11, 20-29.

Cresswell, E. (1957). A new technique for ranging behaviour studies. Br. J. Anim. Behav. 5, 119-120.

Cresswell, E. (1960). Ranging behaviour studies with Romney Marsh and Cheviot sheep in New Zealand. Anim. Behav. 8, 32-38.

Cresswell, E. & Harris, L. E. (1959). An improved rangemeter for sheep. J. anim. Sci. 18, 1447-1451.

Crisp, D. T. (1966). Input and output of minerals for an area of Pennine moorland: the importance of precipitation, drainage, peat erosion and animals. J. appl. Ecol. 3, 327-348.

Crocker, R. L. (1953). Soil and ecological problems related to chronic overgrazing. Int. Grassld. Congr. 1, 770-775.

Darling, F. F. (1955). West Highland Survey: An Essay in Human Ecology. London: Oxford University Press.

Davies, A. J. (1969). The distribution of wind-borne marine salts and their impingement on vegetation. Ph.D. Thesis, University of Wales.

Davies, W. (1938). Vegetation of grass verges and other excessively trodden habitats. J. Ecol. 26, 38-49.

Dean, R., Ellis, J. E., Rice, R. W. and Bement, R. E. (1975). Nutrient removal by cattle from a shortgrass prairie. J. appl. Ecol. 12, 25-29.

Dimbleby, G. W. (1952). Soil regeneration on the north-east Yorkshire moors. J. Ecol. 40, 331-341.

Douglass, J. E. (1967). Effects of species and arrangement of forests on evapotranspiration. In Forest Hydrology (Sopper, W. E., & Lull, H. W., Eds.), 451-461. Oxford: Pergamon Press.

Duffey, E. (1972). Effects of trampling on the fauna of grassland litter. In Monks Wood Experimental Station, Report for 1969-1971, 64-65. Abbots Ripton, Huntingdon: Natural Environment Research Council.

During, C. & Radcliffe, J. E. (1962). Observations on the effect of grazing animals on steepland soils. Trans. Jt. Mtg. Comm. IV and V Int. Soc. Soil Sci., New Zealand, pp. 685-690. Lower Hutt, New Zealand: Soil Bureau.

Duvigneaud, P. & Denaeyer-De Smet, S. (1970). Biological cycling of minerals in temperate deciduous forests. In Analysis of Temperate Forest Ecosystems (Reichle D. E., Ed.), 199-225. London: Chapman & Hall.

Dyrness, C. T. (1967). Erodibility and erosion potential of forest watersheds. In Forest Hydrology (Sopper, W. E., & Lull, H. W., Eds.), 599-610. Oxford: Pergamon Press.

Edmond, D. B. (1958). The influence of treading on pasture. A preliminary study. N.Z. Jl. agric. Res. 1, 319-328.

Edmond, D. B. (1962). Effects of treading pasture in summer under different soil moisture levels. N. Z. Jl. agric. Res. 5, 389-395.

Edmond, D. B. (1963). Effects of treading perennial ryegrass (Lolium perenne L.) and white clover (Trifolium repens L.) pastures in winter and summer at two moisture levels. N. Z. Jl. agric. Res. 6, 265-376.

Egner, H. & Eriksson, E. (1955-1960). Current data on the composition of air and precipitation. Tellus 7-12 (20 papers).

England, G. J. (1954). Observations on the grazing behaviour of different breeds of sheep at Pontyrhuad Farm, Carmarthenshire. Brit. J. Anim. Behav. 2, 55-60.

Federer, C. A., Tenpas, G. H., Schmidt, D. R. & Tanner, C. B. (1961). Pasture soil compaction by animal traffic. Agron. J. 53, 53-54.

Fenton, E. W. (1937). The influence of sheep on the vegetation of hill grazings in Scotland. J. Ecol. 25, 424-430.

Floate, M. J. S. (1970). Decomposition of organic materials from hill soils and pastures. II. Comparative studies on the mineralization of carbon, nitrogen, and phosphorus from plant materials and sheep faeces. Soil Biol. Biochem. 2, 173-185.

Floate, M. J. S. (1972). Plant nutrient cycling in hill land. Proc. N. England Soils Discuss. Grp. No. 7, 11-27.

Floate, M. J. S., Eadie, J., Black, J. S. & Nicholson, I. A. (1973). The improvement of Nardus dominant hill pasture by grazing control and fertilizer treatment and its economic assessment. In Hill Pasture Improvement (Gething, P., Ed.). Proc. Colloqu. 3, 33-39. Henley-on-Thames: Potassium Institute Ltd.

Fournier, F. (1972). Aspects of soil conservation in the different climatic and pedologic regions of Europe. Nature and Environment Series, No. 5. Council of Europe.

Frame, J. (1971). Fundamentals of grassland management. Part 10: the grazing animal. Scott. Agric. 50, 28-44.

Friends of the Lake District (1975). Report and Newsletter.

Gardiner, A. S. (1968). The reputation of birch for soil improvement. A literature review. Res. Dev. Pap. For. Commn, Lond. No. 67.

Gething, P., Newbould, P. & Patterson, J. B. E. (Eds.) (1973). Hill pasture improvement. Proc. Colloqu. 3 Henley-on-Thames: Potassium Institute Ltd.

Gibbs, H. S. (1964). Stability of hill country under heavy stocking. I. Soil stability. N. Z. Inst. agric. Sci. Proc. 10, 61-67.

Gillard, P. (1969). The effect of stocking rate on botanical composition and soils in natural grassland in South Africa. J. appl. Ecol. 6, 489-497.

Gradwell, M. W. (1960). Changes in pore-space of a pasture top soil under animal treading. N. Z. Jl. agric. Res. 3, 663-674.

Grubb, P. & Jewell, P. A. (1974). Movement, daily activity and home range of Soay sheep. In Island Survivors; the Ecology of the Soay Sheep of St. Kilda (Jewell, P. A., Milner, C., & Boyd, J. M., Eds.), 160-194. London: Athlone Press.

Hancock, J. (1953). Grazing behaviour of cattle. Anim. Breed. Abstr. 21, 1-13.

Handley, W. R. C. (1954). Mull and mor formation in relation to forest soils. Bull. For. Commn. Lond. No. 23.

Harper, F. C., Warlow, W. J. & Clarke, B. L. (1961). The forces applied to the floor by the foot in walking. I. Walking on a level surface. Res. Pap. natn. Bldg. Stud. No. 32.

Harper, F. C., Warlow, W. J. & Clarke, B. L. (1967). The forces applied to the floor by the foot in walking. II. Walking on a slope. III. Walking on stairs. Res. Pap. natn. Bldg. Stud. No. 32.

Hart, R. A. de J. (1968). The Inviolable Hills. London: Stuart & Watkins.

Hibbert, A. R. (1967). Forest treatment effects on water yield. In Forest Hydrology (Sopper, W. E., & Lull, H. W., Eds.), 527-543. Oxford: Pergamon Press.

Hoover, M. D. (1944). Effect of removal of forest vegetation upon water yields. Trans. Am. geophys. Un. 25, 969-975.

Howard, P. J. A. & Howard, D. M. (1976). Studies on grazed and ungrazed high level limestone grassland. I. Quantities of organic matter and nutrients in litter, and of organic matter in soil. Merlewood Research and Development Paper (In press).

Hughes, G. P. & Reid, D. (1951). Studies on the behaviour of cattle and sheep in relation to the utilization of grass. J. agric. Sci. 41, 350-366.

Hughes, R. E., Dale, J., Mountford, M. D. & Williams, I. E. (1975). Studies in sheep populations and environment in the mountains of north-west Wales. II. Contemporary distribution of sheep populations and environment. J. appl. Ecol. 12, 165-178.

Hughes, R. E., Milner, C. & Dale, J. (1964). Selectivity in grazing. In Grazing in Terrestrial and Marine Environments (Crisp, D. J., Ed.), 189-202. London: Blackwell Scientific Publications.

Hunter, R. F. (1962). Hill sheep and their pasture: a study of sheep-grazing in south-east Scotland. J. Ecol, 50, 651-680.

James, D. B. (1971). Quality of water as affected by land-use. Welsh Soils Discuss. Grp. Rep. No. 12, 30-37.

Jones, K., King, E., Eastlick, M. (1974). Nitrogen fixation by free-living bacteria in the soil and in the canopy of Douglas fir. Ann. Bot. 38, 765-772.

Jones, L. I. (1967). Studies on hill land in Wales. Tech. Bull. No. 2, Welsh Pl. Breed. Stn.

Keen, B. A. & Cashen, G. H. (1932). Studies in soil cultivation. VI. The physical effect of sheep folding on the soil. J. agric. Sci. 22, 126-134.

Klausing, O. (1956). Untersuchungen über den Mineralumsatz in Buchenwäldern auf Granit and Diorit. Forstwiss. Zbl. 75, 18-32.

Latter, P. M. & Cragg, J. B. (1967). The decomposition of Juncus squarrosus leaves and microbiological changes in the profile of Juncus moor. J. Ecol. 55, 445-464.

Lawrence, M. J. & Brown, R. W. (1973). Mammals of Britain. Their tracks, trails and signs. London: Blandford Press.

Liddle, M. J. (1975). A selective review of the ecological effects of human trampling on natural ecosystems. Biol. Conserv. 7, 17-36.

Liddle, M. J. & Greig-Smith, P. (1975a). A survey of tracks and paths in a sand dune ecosystem. I. Soils. J. appl. Ecol. 12, 893-908.

Liddle, M. J. & Greig-Smith, P. (1975b). A survey of tracks and paths in a sand dune ecosystem. II Vegetation. J. appl. Ecol. 12, 909-930.

Liddle, M. J. & Moore, K. G. (1974). The microclimate of sand dune tracks: the relative contribution of vegetation removal and soil compression. J. appl. Ecol. 11, 1057-1068.

Likens, G. E., Bormann, F. H., Johnson, N. M. & Pierce, R. S. (1967). The calcium, magnesium, potassium, and sodium budgets for a small forested ecosystem. Ecology, 48, 772-785.

Likens, G. E., Bormann, F. H., Johnson, N. M., Fisher, D. W. & Pierce, R. S. (1970). Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Monogr. 40, 23-47.

Lull, W. H. (1959). Soil compaction on forest and range lands. Misc. Publs. U. S. Dep. Agric., No. 768.

Lutz, H. J. & Chandler, R. F. Jr. (1946). Forest Soils. New York: John Wiley & Sons.

Madgwick, H. A. I. & Ovington, J. D. (1959). The chemical composition of precipitation in adjacent forest and open plots. Forestry, 32, 14-22.

Marren, P. R. (1974). Ecology and Recreation. A Review of European Literature. London: University College.

McVean, D. N. & Lockie, J. D. (1969). Ecology and Land Use in Upland Scotland. Edinburgh: University Press.

Mikola, P. (1954). Experiments on the decomposition of forest litter. Comm. Inst. For. Fenn. 43, 1-50.

Miles, J. (1973). Early mortality and survival of self-sown seedlings in Glenfeshie, Inverness-shire. J. Ecol. 61, 93-98.

Minderman, G. & Leeflang, K. W. F. (1968). The amounts of drainage water and solutes from lysimeters planted with either oak, pine or natural dune vegetation, or without vegetation cover. Pl. Soil 28, 61-80.

Ministry of Agriculture, Fisheries and Food (1966). Agricultural land classification. Tech. Rep. agric. Ld. Serv. No. 11.

Mork, E. (1942). Om strøfallet i våre skoger. Medd. norske Skogforsøksv. 29, 297-365.

Northern Pennines Rural Development Board (1970). The Changing Uplands. London: Country Landowners Association.

Ovington, J. D. (1953). Studies of the development of woodland conditions under different trees. I. Soil pH. J. Ecol. 41, 13-34.

Ovington, J. D. (1954). A comparison of rainfall in different woodlands. Forestry, 27, 41-53.

Ovington, J. D. (1959a). Mineral content of plantations of Pinus sylvestris L. Ann Bot. 23, 75-88.

Ovington, J. D. (1959b). The circulation of minerals in plantations of Pinus sylvestris L. Ann. Bot. 23, 229-239.

Ovington, J. D. (1962). Quantitative ecology and the woodland ecosystem concept. Adv. ecol. Res. 103-192.

Packer, P. E. (1967). Forest treatment effects on water quality. In Forest Hydrology (Sopper, W. E., & Lull, H. W., Eds.), 687-699. Oxford: Pergamon Press.

Page, G. (1968). Some effects of conifer crops on soil properties. Commnw. For. Rev. 47, 52-62.

Pearsall, W. H. (1950). Mountains and Moorlands. London: Collins.

Pearsall, W. H. & Pennington, W. (1973). The Lake District. London: Collins.

Pelisek, J. (1974). Changes in the forest stands and soils in Europe. Nature in focus. No. 19, 3-7.

Quinn, J. A. & Hervey, D. F. (1970). Trampling losses and travel by cattle on sandhills range. J. Rge. Mgmt. 23, 50-55.

Rawes, M. (1966). Productivity of upland grazings. Proc. N. England Soils Discuss. Grp. No. 2, 34-40.

Rawes, M. & Welch, D. (1969). Upland productivity of vegetation at Moor House National Nature Reserve, Westmorland, England. Oikos Suppl. 11.

Rennie, P. J. (1956). The uptake of nutrients by mature forest growth. Pl. Soil 7, 49-95.

Roberts, M. E. & James, D. B. (1972). Some effects of forest cover on nutrient cycling and river temperature. In Research Papers in Forest Meteorology. An Abersystwyth Symposium, March 1970, (Taylor, J. A., Ed.), 100-108. Aberystwyth: The Cambrian News.

Richards, B. N. & Voigt, G. K. (1965). Nitrogen accretion in coniferous forest ecosystems. In Forest Soil Relationships in North America (Youngberg, C. T., Ed.), 105-116. Corvallis: Oregon State University Press.

Rodin, L. E. & Bazilevich, N. I. (1967). Production and Mineral Cycling in Terrestrial Vegetation. Edinburgh-London: Oliver & Boyd.

Rutter, A. J. (1968). Water consumption by forests. In Water Deficits and Plant Growth, 2, (Kozlowski, T. T., Ed.), 23-84. London New York: Academic Press.

Rutter, A. J. (1972). Evaporation from forests. In Research Papers in Forest Meteorology. An Aberystwyth Symposium, 1970 (Taylor, J. A., Ed.), 75-90. Aberystwyth: The Cambrian News.

Schuster, J. L. (1964). Root development of native plants under three grazing intensities. Ecology, 45, 63-70.

Sears, P. D. (1956). The effect of the grazing animal on pasture. Proc. Int. Grassl. Congr. 7, 92-103.

Shaw, K. (1958). Studies on nitrogen and carbon transformations in soil. Ph.D. Thesis, University of London.

Sneva, F. A. (1970). Behaviour of yearling cattle on Eastern Oregon range. J. Rge. Mgmt. 23, 155-158.

Spedding, C. R. W. (1971). Grassland Ecology. Oxford: Clarendon Press.

Speight, M. C. D. (1973). Outdoor recreation and its ecological effects. Discussion papers in Conservation. No. 4. London: University College.

Steinbrenner, E. C. (1951). Effect of grazing on floristic composition and soil properties of farm woodlands in South Wisconsin. J. For. 49, 906-910.

Stewart, J. B. & Oliver, S. A. (1972). Evaporation studies at Thetford, Norfolk. In Research Papers in Forest Meteorology. An Aberystwyth Symposium, 1970, (Taylor, J. A., Ed.), 91-99. Aberystwyth: The Cambrian News.

Sutcliffe, D. W. & Carrick, T. R. (1973). Studies on mountain streams in the English Lake District. II. Aspects of water chemistry in the River Duddon. Freshwat. Biol. 3, 543-560.

Sutton, R. F. (1969). Form and development of conifer root systems. Common. Agric. Bur. Tech. Commun. No. 7.

Swank, W. T. & Douglass, J. E. (1974). Streamflow greatly reduced by converting deciduous hardwood stands to pine. Science, 185, 857-859.

Tamm, C. O., Holmen, H., Popovic, B., & Wiklander, G. (1974). Leaching of plant nutrients from soils as a consequence of forest operations. Ambio, 3, 211-221.

Taylor Page, F. J. (1957). Field Guide to British Mammals. No. 1. Birmingham: Mammal Society of the British Isles.

Thomas, A. S. (1959). Sheep paths. Observations on the variability of chalk pastures. J. Br. Grassld. Soc. 14, 157-164.

Thomas, T. M. (1965). Sheet erosion induced by sheep in the Pumlumon (Plynlimon) area, mid-Wales. Brit. Geomorph. Res. Gp. Occ. Publ. 2, 11-14.

Thomas, W. A. & Grigal, D. F. (1976). Phosphorus conservation by evergreenness of mountain laurel. Oikos, 27, 19-26.

Tivy, J. (1973). The organic resources of Scotland. Edinburgh: Oliver & Boyd.

Tribe, D. F. (1949). Some seasonal observations on the grazing habits of sheep. Emp. J. Expt. Agric. 17, 105-115.

Voigt, G. K. (1965). Biological mobilization of potassium from primary minerals. In Forest Soil Relationships in North America (Youngberg, C. T. Ed.), 33-46. Corvallis: Oregon State University Press.

Wallace, D. H. (1974). Cross country vehicles in forestry. Forest Rec., London No. 93.

Wannop, A. R. (1965). Using Scotland's hills. The problem of fertility. Scott. Landowner, No. 119, 311-313.

Weed, S. B., Davey, C. B. & Cook, M. G. (1969). Weathering of mica by fungi. Prco. Soil Sci. Soc. Amer. 33, 702-706.

Welch, D. (1974). The floristic composition of British upland vegetation in relation to grazing. Land, 1, 59-68.

White, E. J. (1969). Aspects of nutrient income to the forest ecosystem and of the nutrient cycle within the forest. M.Sc. Thesis, University of Wales.

White, E. J. & Turner, F. (1970). A method of estimating income of nutrients in catch of airborne particles by a woodland canopy. J. appl. Ecol. 7, 441-461.

White, E., Starkey, R. S. & Saunder, M. J. (1971). An assessment of the relative importance of several chemical sources to the waters of a small upland catchment. J. appl. Ecol. 8, 743-749.

Wilde, S. A. (1958). Forest Soils, their Properties and Relation to Silviculture. New York: The Ronald Press.

Wind, G. P. & Schothorst, C. J. (1964). The influence of soil properties on suitability for grazing and of grazing on soil properties. Trans. 8th int. Congr. Soil Sci. II, 571-580.

Youngberg, C. T. (1959). The influence of soil conditions, following tractor logging, on the growth of planted Douglas fir seedlings. Proc. Soil Sci. Soc. Amer. 23, 76-78.