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The impact of upland pasture improvement on solute outputs in surface waters

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1 Introduction

This paper outlines some of the major factors influencing solute outputs from sites following land improvement, and then considers data from improved catchments in mid-Wales.

Over the past 30 years, considerable areas of former rough grazings in the uplands of Britain have been converted to improved pasture. For example, Jones (1978) calculated that 100 000 ha of land were improved in the Welsh uplands in the 25 years prior to 1978, an area equivalent to 20% of the hills and uplands of the Principality. The replacement of natural vegetation of low productivity and low nutrient content with more productive, higher nutrient status, grass/clover swards can only be achieved if the inherent problems of soil acidity and nutrient deficiency are overcome. In most situations, this requires the addition of relatively large quantities of lime and fertilizers with, in many instances, some form of cultivation. A proportion of the readily soluble fertilizer compounds and lime, plus elements rendered more mobile as a result of cultivation, inevitably find their way into streams draining the improved ground. This added load of solutes may have impacts on water quality in areas which are important as water gathering grounds. The changes in water chemistry may also affect freshwater biota in otherwise unpolluted streams.

These impacts on surface water chemistry and freshwater biota are generally assumed to be insignificant (Baldwin 1978). These assumptions, however, are not based on actual case studies. A recent extensive review of the British literature on the influence of land use on water quality in upland Britain (Roberts in press) revealed a total absence of papers on the impact of land improvement. Data may exist in Water Authority records, but they are not readily available. Similarly, there has been little attempt to evaluate fertilizer losses to drainage waters or to consider possible loss from the soil capital of nutrients as a result of improvement.

2 Factors influencing solute outputs

The output of solutes in the stream draining any given improved area will be influenced by the interaction of many factors, important amongst which are:

i. method of improvement;
ii. chemical and physical properties of the soils;
iii. catchment hydrology;
iv. climate.

2.1 Methods of improvement

The method of improvement used is mainly determined by the soils and vegetation of the site (East of Scotland College of Agriculture 1980; Newbould 1983). On the more favourable brown soils with bent/fescue swards containing some white clover, significant sward improvement can be achieved simply through intensive controlled grazing (Floate 1972). This process produces the quicker and more efficient cycling of plant nutrients, especially nitrogen, phosphorus, and potassium, needed to maintain a relatively high productivity, high nutrient content sward. Floate (1972) suggests that this approach may result in small losses of phosphorus and nitrogen from the site. These losses are unlikely to have a significant impact on drainage water chemistry or on the capital of these nutrients held on the site.

In contrast, most pasture improvement schemes involve the addition of lime and fertilizers, and reseeding with a grass/white clover seed mix. The treatment may also include cultivation and, on wetter sites, drainage. The detailed prescription for the improvement will depend on the soil type, vegetation, and climate. The lime is added to reduce soil acidity and the levels of soluble aluminium in the rooting zone, although these 2 problems are inter-related (Floate 1977; Munro *et al.* 1973). The quantities used are usually based on the amount required to raise the pH to 5.5-5.8 or to produce 50% base saturation, and depend, therefore, on the initial soil chemistry. The lime is usually added as magnesium limestone and a typical treatment for a soil with a peaty surface horizon would be between 5-8 t/ha. The liming, therefore, provides a large potential source of calcium and magnesium for output to drainage waters.

Additions of phosphorus and nitrogen are also usually required for establishment of the sown grasses and the white clover. The quantities used are broadly determined by the demands of the white clover and will vary somewhat with soil type. Usually, some 60-80 kg P/ha are added. Phosphorus was formerly added as basic slag, which had the added bonus of its considerable acid neutralizing capacity, but, today, rock phosphate-super-phosphate mixtures are generally used. Recommendations on the quantities of nitrogen to be added vary widely, but 40-80 kg N/ha are probably the most common. It is usually added as ammonium nitrate. White clover also has a high potassium demand and additions of up to 100 kg K/ha may be needed on peats or peaty surfaced soils: it is usually added as potassium chloride. The timing and method of application of the lime and fertilizers vary regionally, and with the type of cultivation used, and may influence the loss in drainage waters.

Following the initial improvement, further additions of lime and fertilizers are required to maintain the new sward. Typically, 2-4 t/ha of lime are added every 4-5 years, 40 kg P/ha every 3-4 years, and, on peats, 60 kg K/ha every 3-4 years. The initial and maintenance inputs, therefore, provide a large readily soluble pool of phosphorus, nitrate and potassium, plus, depending on the form of the fertilizer, ammonium, chloride and sulphate which may be transferred to drainage waters.

In open swards, the seed mixture and fertilizer may be surface spread with surface scarification or trampling by stock to produce some penetration. Alternatively, surface applications may follow suppression of existing vegetation by burning, cutting or the use of herbicides. Most reclamation systems involving re-seeding and fertilization, however, also involve some form of cultivation. Deep ploughing, the standard technique in the early reclamations, is now used mainly on freely drained acid brown soils and brown podzolic soils. Rotavation of the surface is generally used on peats, stagnopodzols, stagnogleys, gleys and peats. On these soils, ploughing reduces the surface bearing strength, and can lead to germination of seeds of unwanted rush species, while the buried organic layers can cause drainage problems. Seed bed preparation will also involve disking and rolling, following the ploughing or rotavation. These various cultivations will change the patterns of water penetration and movement through soils. New surfaces will also be exposed to weathering, with possible release of elements to solution. The opening up of organic surface horizons may lead to an increased rate of decomposition and element release. The organic horizons may also dry out more readily, with consequent production of sulphate by oxidation of organic sulphides, and may result in raised sulphate levels in drainage waters and the leaching of balancing cations.

Drainage systems may also be installed on wetter sites. The type of drainage system used will depend on the cause of the problem, ie springs or seeps, surface water or groundwater. The aim of all systems, however, is to facilitate the removal of as much water as possible from the site by the shortest route, but such removal can lead to increased losses to drainage waters of fertilizers, lime, and supplies of available elements generated within the soil. Although open drains would rarely be used in agriculture, it is worth noting that, on a site fertilized with phosphorus and drained prior to afforestation, the main increase in P concentrations in drainage waters took place following the drainage (Robinson 1980).

2.2 The soil factor

The output of solutes derived from added lime or fertilizers, or released as a secondary effect of the improvement, is strongly influenced by the chemical and physical properties of the treated soils. As waters move through soils, they are influenced by many reactions and processes. These include cation exchange, anion adsorption, oxidation/reduction reactions, complexation, precipitation and fixation in clay lattices. Detailed consideration of these various reactions is outside the scope of this paper, but a few illustrations will be given of their impact. Hydrous iron and aluminium oxides are very efficient scavengers of phosphate anions from solution (Bohn *et al.* 1979). The phosphate is held on the oxides by anion adsorption or ligand exchange. The Bs horizons of podzolic soils, which are widespread in the uplands, have a high content of hydrous iron and aluminium oxides and can fix large quantities of phosphorus. Fertilizer phosphate not taken up by plants is, therefore, readily fixed by these soils, and one would predict that little will be lost from them in drainage waters. Similarly, phosphate can be immobilized as calcium phosphate in, for example, calcareous subsoils, thus limiting output from a site.

Potassium can be fixed in the lattices of some clay minerals and micas and is then not exchanged in cation exchange reactions with salt solutions. The loss of fertilizer potassium from mica and clay-rich soils will, therefore, be minimized by these fixation reactions. The ammonium ion is similarly fixed by vermiculite clays and weathering trioctahedral micas; like the other cations, it can also be held on clays and humic complexes in sites affected by cation exchange reactions. These processes will tend to reduce losses of potassium and ammonium from fertilizers. The nitrate anion, in contrast, is highly mobile, being little affected by anion adsorption reactions. Nitrate in solution at levels in excess of the demands of the surface vegetation will probably be lost in drainage waters. The nitrate ion lost, and the chloride derived from added potassium chloride, will also carry a balancing cation out of the system.

The sulphate added in some forms of phosphatic fertilizers, or produced by oxidation of sulphides in organic horizons, will certainly be present at levels in excess of the vegetation requirements. It is relatively mobile but is affected by anion adsorption on to the iron and aluminium oxides found in the podzolic B horizons. This adsorption is much less efficient than that of the phosphate anion, so that much of the sulphate will be lost. In addition, recent work has shown that added lime may result in the release of adsorbed sulphate from podzolic B horizons, and could lead to a further increase in sulphate levels in drainage waters.

The soil/water reactions will also be strongly influenced by the inter-related factors of the residence time and pathways followed by the waters. Short residence time, rapidly moving, waters in macropores will attain very different equilibria from the long residence time water in fine pores. Thus, although excess potassium or phosphate could, theoretically, be removed from solution and fixed in soils, this process may not take place from rapidly transmitted waters such as that moving through natural soil pipes. The proportion of infiltrating waters which move through the whole body of a profile will also vary. In stagnogleys and stagnopodzols, and other soils with an impermeable layer within the soils, much of the infiltrating water will move laterally through the upper horizons. It will not, therefore, be affected by reactions in the lower horizons. In freely drained brown soils, in contrast, a large proportion of the infiltrating water may move through the soil to the groundwater table.

2.3 Catchment hydrology

The considerations here are an extension of those outlined above when noting the influence of water pathways. The chemistry of any stream reflects the relative mix of water from a number of contributing sources within the stream catchment. Water may be input to the stream from, for example, groundwater sources, throughflow, soil pipes or overland flow. Each of these types of water may have a very different chemistry, as a result of their different residence times and contact with differing materials. Elements released from fertilizers, or as a result of cultivation, may persist in water from one source but not in that from another. For example, phosphate may remain in solution in overland flow but be removed by adsorption or precipitation reactions from throughflow or groundwater. Similarly, potassium may be present in overland flow, pipeflow, or throughflow from upper horizons, but be absent, due to fixation or cation exchange reactions, in throughflow from lower horizons or groundwater. Nitrate, once in solution, will tend to persist in all types of water, unless affected by biological processes. Liming will have a major effect on the pH of overland flow and upper soil throughflow, but may hardly alter lower soil throughflow or groundwater. The proportions of the streamwater derived from the different contributing sources will also vary with streamflow. At very low flows, groundwater may provide the only input, while at very high flows throughflow plus overland flow may dominate.

The derivation of the waters in the improved catchment will, therefore, be a major factor influencing the impact on the outflow chemistry. The most important factor, however, may be the proportion of the catchment affected by the improvement.

2.4 Climate

The major impact of climate is the amount and type of rainfall. Compared to the lowlands of Britain, all the areas likely to be affected by land improvement have a high rainfall. Within the hill and upland area, there is, however, enormous variation in rainfall from 800 mm in the North York Moors to over 2000 mm in mid-Wales and other western sites. The loss of lime and fertilizers is potentially higher in the high rainfall areas; allowance is usually made for this loss in calculating the rates of lime addition. The concentrations of the elements derived from solution of fertilizers may, however, be no higher in the streams of these areas because of the dilution effect.

Rainfall intensity will also influence losses of fertilizers to drainage waters. Losses will be greater as a result of high intensity rainfall, but, once again, may not produce high concentrations of fertilizer derived elements in the outflow streams because of dilution.

3 *An example from mid-Wales*

As part of a geochemical cycling study, we have monitored solute inputs and outputs of a number of first and second order stream catchments in mid-Wales. The following report covers the solute chemistry of one catchment (C2) draining unimproved upland grazing and 2 catchments (C7 and C17) which drain areas of improved pasture (Figure 1). The catchments are located in the headwaters of the River Wye at 450 m above sea level on the eastern slopes of the Plynlimon massif. The area is underlain by Ordovician and Silurian mudstones and the catchments are dominated by stagnopodzols. The unimproved area has a mat-grass/bent/fescue vegetation with smaller areas of a heather/cottongrass community. One im-

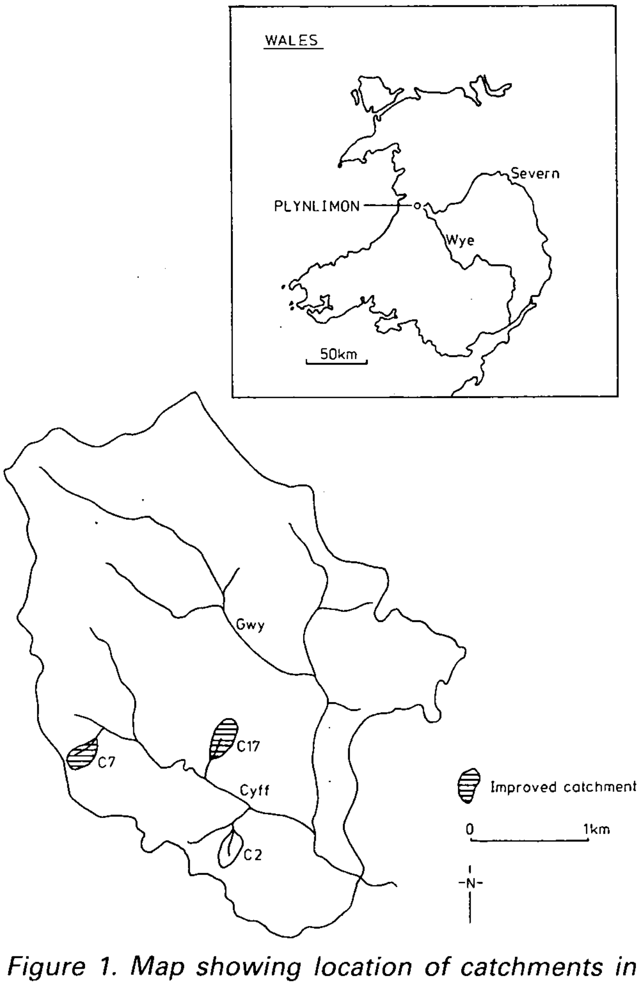

Figure 1. Map showing location of catchments in mid-Wales

proved catchment (C7) was ploughed some 40 years ago, magnesium limestone and basic slag added, and re-seeded. The vegetation has largely reverted, but some white clover remains. The other catchment (C17) was improved in the mid-1970s with surface cultivation, additions of limestone and compound fertilizers, and re-seeding; it has also received maintenance additions of lime and fertilizers.

The mean solute concentrations for the streams for a 2-year period are given in Table 1. The concentrations of most solutes were higher in the improved catchment drainage. Phosphorus concentrations, however, were below the detection limit of 0.005 mg/l throughout the 2 years in all 3 streams. Any excess phosphorus entering solution from fertilizers was probably immobilized in the stagnopodzols. Nitrate concentrations were raised in both streams draining improved catchments, and in catchment C17 could have been due to solution and loss of fertilizer. Nitrogen fertilizer was not added in catchment C7, and the higher concentrations here must have been due to a higher rate of nitrate production in the soils, perhaps as a result of the presence of white clover and the effects of liming and cultivation. These latter factors would also be operative in the C17 catchment.

Table 1. Summarized chemical data for streamwater in one unimproved (C2) and 2 improved (C17 and C7) catchments

	← mg/l							→	μeq/l		μeq/l
	Na	K	Ca	Mg	Si	NO_3-N	SO_4-S	Cl	HCO_3	pH	H
C2	3·1	0·10	1·1	0·7	0·8	0·07	1·6	5·0	53	5·27	5·4
C17	3·6	0·11	1·6	1·8	1·6	0·28	2·2	5·8	100	6·12	0·8
C7	3·1	0·13	1·6	1·6	1·4	0·18	3·2	4·9	45	4·83	14·8

Figures are arithmetic mean values for weekly samples over a 2-year period, 27 November 1979–24 November 1981

Potassium concentrations showed no significant difference between the 3 streams. The potassium added in fertilizers in catchment C17 must have been utilized very efficiently or any excess which entered solution was retained in the soil by cation exchange or fixation. The small, but significant, increase in chloride concentrations in C17 was probably due to solution of the potassium chloride fertilizer, but with little retention of chloride in the soil. The higher calcium and magnesium concentrations in the streams from the improved catchments will have been caused by solution of the added lime. It is surprising, however, that the magnesium concentrations increased more than the calcium. Differential retention within the soil system may have taken place or increased magnesium release from weathering, perhaps as a result of the cultivation. It is interesting that the effect of liming was still detectable in catchment C7 some 40 years after the initial treatment. The raised pH in stream C17 compared to C2 was also attributable to the effects of liming. Stream C7, however, had a lower pH, and it is thought that the more acid groundwater in this catchment masked the effect of the liming.

The higher sulphate concentration in catchment C17 was probably due to solution of fertilizers, but superphosphate was not added in C7. Sulphate displacement from the Bs horizon as a result of liming (Korentajer *et al.* 1983) might also have been operative, but sulphate input from groundwater sources probably explained the higher concentration in C7. The increased silica concentrations in the improved catchment streams were probably due to increased solution from soil mineral sources.

Solute budgets for the 3 catchments (Table 2) give an indication of possible loss of lime, fertilizers or the soil capital of nutrients. The additional calcium output from the improved catchments is small compared with lime inputs. If outputs of magnesium from C7 had continued at the rates measured here since improvement, the added magnesium would have been exhausted. This observation provides some support for the suggested increased rate of release of magnesium from mineral weathering. The increased potassium deficit in catchment C17 was also small compared with fertilizer addition, but the higher output from C7, compared with C2, must represent a real loss from the soil capital. Losses at this rate, however, are probably insignificant in terms of the nutrient demand of the natural vegetation.

It is not possible to calculate a full nitrogen budget from the data presented here, as only inorganic solutes were measured. There would also be a nitrogen input through fixation by the white clover, an organic nitrogen output, and possible gaseous losses. The inorganic solute budget indicated a change from

Table 2. Solute budgets (kg/ha/yr) for the 3 study streams (C2, unimproved; C17 and C7, improved)

	Na	K	Ca	Mg	Si	NO_3-N	SO_4-S	Cl	HCO_3	H
C2	−28	−0·5	−20	−10	−24	+1·4	−15	−41	−64	+0·6
C17	−47	−2·0	−37	−39	−53	−8·7	−37	−78	−127	+0·9
C7	−28	−1·2	−37	−33	−35	−0·2	−62	−37	−72	+0·6

net accumulation in the unimproved catchment to a net deficit in the improved catchments. The deficit in catchment C17 was very small, and even the small remaining amount of white clover probably fixed enough nitrogen to balance the loss. The larger apparent deficit in C17 is probably still balanced by fixation inputs as clover is an important component of this sward.

There were apparent chloride deficits in all 3 catchments because of an under-estimate of particulate inputs such as sea salts. There was an increase in the net output of chloride and sodium from catchment C17 compared with the other 2 catchments; this increase was due to fertilizer solution and would not produce stress in the vegetation. Similarly, the apparent increases in sulphate and silica output were small compared to the site capital and would not produce significant changes in the soil/plant system.

The data showed differences in streamwater chemistry which apparently resulted from pasture improvement, some of which persisted long after improvement. The changes in chemistry were, however, unlikely adversely to affect freshwater communities or water quality and would soon be masked in a larger catchment. Nitrate concentrations were well below the 11 mg/l maximum recommended by the World Health Authority, with peak concentrations around 3 mg/l. Phosphorus concentrations, the other major concern for water quality, remained at concentrations below 0.005 mg/l. The systems examined here had returned to an equilibrium, and data are needed for the actual period of cultivation. Preliminary results from a lysimeter study by Institute of Hydrology staff showed nitrate concentrations of 6 mg/l nitrate during drainage operations prior to fertilizer additions. The element budgets for the catchments also indicated that losses would not lead to significant depletion of the site capital of nutrients.

4 Future research needs

There is a clear need for further data on the impact of upland pasture improvement on streamwater chemistry and on the export of elements from catchments. As shown above, the solute outputs following improvement are the result of the interaction of a number of factors, including method of improvement, soil type, catchment hydrology and climate. The one small study reported here, however, was restricted to one soil type and one modern method of improvement, and did not cover the period of cultivation and fertilizer addition. Another study just completed in mid-Wales by Institute of Hydrology staff, and work in progress by Ministry of Agriculture staff at Pwll Peiran experimental farm will increase the available information but will still only cover a limited range of upland sites. Further studies are needed, particularly in other regions and with contrasting methods of improvement, before broadly applicable predictive models can be developed. It is also important that some of these studies use an integrated approach with inputs from agronomists, soil scientists, hydrologists and freshwater biologists. Such an approach would enable us to examine processes, as well as monitoring effects, and thus strengthen any interpretation and application of the results.

5 Summary

Pasture improvement in the uplands generally involves addition of lime and fertilizers, plus cultivation. Loss of lime and fertilizers to drainage waters, plus increased solute outputs due to the changed soil conditions, may produce changes in the chemistry of otherwise unpolluted streams. There are virtually no published data on the magnitude of these changes or their impact on freshwater communities or water quality. A study in mid-Wales detected increases in the concentrations of a wide range of solutes in drainage waters, apparently as a result of improvement, but these were not large enough to have significant effects on freshwater communities or water quality. Element budgets also suggested that increased outputs would have little impact on the site capital of nutrients and, for those elements added as fertilizers, were small compared to inputs. Solute outputs following improvement will be a function of method of improvement, soil type, catchment hydrology and climate. The reported study only concerned one soil type and one modern method of improvement, and did not cover the actual period of cultivation and fertilizer addition. Further studies are needed, covering a range of upland site types and methods of improvement. These studies should be multidisciplinary, involving agronomists, soil scientists, hydrologists and freshwater biologists.

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Studies by ITE on the impact of agriculture on wildlife and semi-natural habitats in the uplands

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This paper considers the following 3 questions.

1. What are the major impacts of agriculture on upland habitats and wildlife?

2. What work relevant to these impacts has been done or is currently in progress in ITE?

3. What are the main needs for research in this field, and how should ITE contribute?

1 Factors influencing upland agriculture

Economic factors arising from EEC and UK agricultural support policies are dominant, but are discussed elsewhere in this volume (eg Marsh 1984). Climatic, geological and physiographic variety, and the consequent diversity in soil types and fertility give contrasting natural environmental characteristics that affect the regional applicability of the economic spurs to, and constraints on, agricultural methods and their potential for profitable change. Historical and social aspects of land ownership, farm tenure and structure, and of regional non-agricultural activities, also create conditions locally which can modify the rate or direction of responses to economic stimuli in similar physical environments. Where climate, land form, soils and farm structure in the uplands combine to give conditions marginally suitable for mixed or even arable farming, current economic policies tilt the balance away from pastoral systems. Changes in land use then involve the conversion of ley grassland to arable cultivation, the decay or removal of superfluous hedgerow or wall boundaries, more use of fertilizers, herbicides and pesticides, increased land drainage, and the removal of unwanted small copses and decline of farm woods. Stock that are retained are transferred to cultivated and re-seeded former rough pastures, and seasonally to remaining fragments of rough grazing and moorland, the latter's vegetation having changed from heather to grass by intensified grazing and burning.

More widely, in areas environmentally only suitable for pastoral farming, the certainty of financial returns from grants and subsidies increases stock numbers within farming systems unchanged in principle. Beyond an expanded zone of improved pastures, this increased grazing intensity again results in heather moorland being transformed into grass moors, with consequent changes in wildlife.

Extensive changes in the uplands also result from taxation policies. It becomes worthwhile to alter current upland farm/moor mosaics by linking agricultural change with zones of forestry planting on rough pastures and moorland. The possibility of agricultural intensification in parts of an upland area may thus be an essential trigger to the more wide-ranging effects on semi-natural habitats caused by associated extensive forestry enterprises.

In summary, these trends, if current support and taxation policies continue, will create uniformity in the more climatically amenable, lower altitude, sectors of the British uplands, through the disappearance of a high proportion of their characteristically varied semi-natural habitats (Plate 7). In the middle altitude ground, surviving semi-natural moorlands will be broken up into separated and declining fragments. The present typical upland landscape contrast, between diverse vegetation on an agricultural fringe, and expanses of uniform open moorland and hill, will persist only where the wishes of local landowners or administrative constraints check the tide of change in temporary museum pieces. Ultimately, only the highest hills, environmentally unsuitable for intensified agriculture or economic forestry, will remain visually rather as they are today, as open mountain and moor. In this fragile environment, even wildlife must compete with increasingly concentrated recreational pressures and now, apparently, also with development demands arising from the compensation principle of the Wildlife and Countryside Act.

2 Relevant research by ITE staff

2.1 Evaluation of upland land and biological resources

In the assessment of national land resources and their use, computer-stored data inventories co-ordinated from a wide range of data are an essential tool. Although the national land data bases set up in ITE were not directly aimed at relating habitats and wild species to agriculture, their availability can assist