Stream acidification resulting from afforestation in the UK: evaluation of causes and possible ameliorative measures

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ABSTRACT Recent studies have shown an increase in acidity and aluminum concentrations in streams draining plantation forests, compared with streams draining adjacent moorland or grassland, in some areas of the British uplands. These changes in streamwater chemistry have been linked to a parallel impoverishment of the freshwater invertebrate fauna, fish stocks and the populations of certain birds. Afforestation leads to a number of changes in the upland environment which, in turn, impact on the hydrology and hydrochemistry of drainage waters. Some of these changes are due to forest management practices while others result from crop-atmosphere and crop-soil interactions. The possible role of these changes, in the upland environment, in producing the increased streamwater acidity aluminum concentrations is considered. A range of proposed ameliorative measures, linked to management of drainage waters, is then assessed.

Acidification des cours d'eau suite au reboisement au R.U.: evaluation des causes et mesures amelioratrices possibles

RESUME Des études récentes ont montré un accroissement de l'acidité et des concentrations en aluminium dans des cours d'eau drainant des forêts plantées, comparativement à des cours d'eau drainant les landes et les prairies adjacentes. Ces changements chimiques de l'eau ont été liés à un appauvrissement parallèle de la faune aquatique invertébrée, et des populations de poisson et de certains oiseaux. Le reboisement entraîne certains changements dans l'environnement terrestre qui, en retour, impactent l'hydrologie et l'hydrochimie des eaux de drainage. Certains de ces changements sont dus aux pratiques d'aménagement forestier tandis que d'autres résultent d'interaction culture-atmosphère et culture-sol. Le rôle possible de ces changements de l'environnement terrestre dans l'accroissement de l'acidité et des concentrations en aluminium de l'eau est considéré. Des mesures amélioratrices proposées, liées à la gestion des eaux de drainage, sont évaluées.
BACKGROUND

Large-scale afforestation in the UK over the last 40 years has been concentrated in the uplands. The streams and rivers of the uplands are also important as plentiful supplies of pure water and as sports fisheries. Recently, a number of studies (e.g. Harriman & Morrison, 1982; Stoner et al., 1984), have reported increased acidity and aluminum concentrations in streams draining from plantations, compared with streams draining adjacent moorland and grassland. The mean annual stream pH can be up to 0.5 units lower in the forest streams while aluminum concentrations are two, to three times higher (Table 1). The differences in chemistry between the two types of stream are most pronounced at higher flows, at baseflow the differences may be very small or not existent (Whitehead et al., 1986) (Table 2). These changes in water chemistry have been linked to observed alterations in freshwater invertebrate populations and fish stocks (e.g. Stoner & Gee, 1985). A recent study has also suggested a decline in the populations of dippers (Cinclus cinclus) as a result of the changes in invertebrate populations (Ormerod et al., 1985).

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As a consequence of these reported changes there is considerable pressure to limit further afforestation in some areas. Any real expansion of forestry in these areas would seem to depend upon the development of modified techniques of forest management, and/or ameliorative measures, to limit or prevent the adverse impacts on water quality. The development of such measures is dependent upon an understanding of the processes and mechanisms producing the changes.
SOILS AND GEOLOGY

The changes in streamwater pH and aluminum concentrations referred to above are not found at all sites; they are most pronounced where acid soils overlie massive, base-poor bedrock.

**TABLE 2** Mean baseflow and stormflow concentrations of hydrogen ion and aluminum in selected streams draining semi-natural grassland and forest catchments at Plynlimon, mid-Wales

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<td>Baseflow</td>
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<tr>
<td>Baseflow</td>
<td>7.2</td>
<td>0.1</td>
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*Catchments have bedrock containing carbonate mineral veins

The most widespread acid soils in the British uplands are brown podzolic soils (Orthods), podzols (Orthods), stagnopodzols (Aquods), stagnogleys (Awuepts), and acid peats (Hemists or Fibrists) (Avery, 1980). The surface pH of these soils is usually between 3.5 and 4.5, rising to between 4.5 and 5.0 in the subsoil. In a few areas, where the soils are overdeveloped over base-rich material, the subsoil pH may reach 6.0. An impermeable E horizon in the stagnopodzols and stagnogleys can result in considerable lateral water movement (Bell, 1972; Gilman & Newson, 1980). Thin iron pans in the stagnopodzols and podzols, and fragipans, may also limit vertical water movement.

Acid rocks, in the present context, include most acid igneous rocks, mudstones, slates, most greywackes and grits, and some schists and gneisses. Within these rock types, however, small variations in mineralogy may have an overriding influence. Thus, in mid-Wales, carbonate veins within massive mudstones effectively buffer drainage waters except under stormflow conditions (Reynolds et al., 1986), Table 2. Similarly, some greywackes contain sufficient feldspars to provide significant buffering.
Site preparation

Most afforested upland areas are ploughed and drained prior to planting. Ploughing improves rooting conditions for the young trees (Thompson, 1984).

Forest drains, linked to the plough furrows, are designed to remove excess soil water (Thompson, 1979). They are usually c. 0.9 m deep and 1 to 4 m deep. They may be sited to cut-off natural springs or seeps, for example, or to collect water from plough furrows and then to carry this water to a natural watercourse. Run-off to streams takes place much quicker via the furrows and drains than as soil seepage or throughflow; this may limit soil water interactions and any related buffering. The drainage and ploughing will aid drying of surface soil horizons, with consequent changes in chemical reactions and solute outputs. Mineral material may also be exposed in the sides of the ditches; this may lead to increased mineral weathering.

Growth of the crop

Increased evapotranspiration  The development of the forest canopy in the moist, windy uplands increases the evaporation of moisture through interception; this reduces the amount of any incoming precipitation which reaches the ground (Calder & Newson, 1979). Any solutes contained within the evaporated precipitation will, however, remain on the canopy to be washed off by the remaining water as it passes to the ground as stemflow or throughflow. Trees also transpire much greater quantities of water than the moorland vegetation they replace. Thus, losses due to evapotranspiration increase from c. 15% on moorland to c. 30% in closed canopy forest; resulting in a c. 15% increase in the concentration of solutes in throughfall and stemflow.

The canopy as a filter  The tree canopy is also an efficient filter of the atmosphere, "capturing" aerosols, mist and cloud droplets (occult precipitation) considerably more efficient than the pre-existing moorland vegetation. Occult precipitation has higher concentrations of solutes, both pollutant and non-pollutant, than rainfall (Unsworth, 1984; Lovett et al., 1982). The inputs from aerosols and occult precipitation will be added to the concentration effect due to the increased evapotranspiration of rainfall. Dry deposition of gas molecules onto and into leaves will also take place but this is unlikely to be greater than for the pre-existing moorland vegetation.

Development of the forest floor  During the growth of the coniferous plantation a "forest floor" develops. This builds up rapidly following canopy closure but attains an equilibrium during the later stages of the rotation. The forest floor is commonly more acid than the surface horizons of the underlying, pre-existing soil.
The forest floor also appears to be an important zone of water movement in many forests and this water is generally very acid, pH 4 (Reynolds et al., 1986).

**Changes in soil hydrology**  The soils below forest plantations change physically as a result of tree growth. The combined results of the increased interception losses and increased transpiration lead to a drying of the soils with the development of drying cracks. This is most pronounced in peats and peaty surface horizons. The development of tree roots also forms new, large pores in some soils. The drying cracks and the root channels both act as pathways for the rapid movement of water through soils.

The drying may itself lead to chemical changes. Thus drying of organic horizons, or peats, can lead to oxidation of organic sulphur and nitrogen compounds with the production of sulphate and nitrate. These oxidation products can increase drainage water acidity (Bache, 1984).

**CONTROLLING PROCESSES**

The changes consequent upon afforestation, and discussed above, lead to modifications in soil processes and site hydrology. The impact of ploughing and drainage is to increase the input to streams of water derived from acid, near surface soil horizons. This will tend to increase stream acidity especially at high flows. The importance of changes in the balance between soil-derived water and groundwater in streams has been demonstrated by modelling (Whitehead et al., 1986). The precise chemistry of the soil derived waters will vary with soil type and the detailed pathway from soil surface to stream. Where plough furrows and ditches are entirely within peat, the waters are very acid but will contain relatively little aluminum. In podzolic and gley soils, the water is drawn partly from mineral horizons and moves down furrows and ditches floored and walled by mineral material; these waters are less acid than the organic horizon waters, but contain more aluminum.

The increased concentration of solutes, due to evapotranspiration, plus the increased ion input resulting from atmospheric scavenging by the tree canopy, result in an increased anion loading to the soils (Table 4). The effect of this increased anion loading on the acid soils is to release aluminum and hydrogen ions to solution through ion exchange (Reynolds et al., in press). Results from two study sites in Wales, Plynlimon and Llyn Brianne, show that a doubling of anion loading has led to a slight increase in the acidity of soil waters but a tripling of aluminum concentrations, compared with waters from adjacent moorland soils, see e.g. Table 3. Modelling exercises have also demonstrated the importance of dry and occult deposition onto forests in determining streamwater acidity (Neal et al., 1986). Dissociation of organic acids derived from the forest floor may make a significant contribution to the anion sum; however present results suggest a dominant role for inorganic anions (Table 3).
Both the changes in site hydrology and soil solution chemistry will influence streamwater chemistry. At present we are unable to quantify their relative importance in producing the increased acidity and aluminum concentrations of the streams. Our Beddgelert Forest study site in north Wales was not, however, ploughed or drained prior to planting. The streams draining from the site are still more acid and contain more aluminum than adjacent moorland streams (Table 1). At this site therefore, the changes in streamwater chemistry cannot be attributed to the affects of ploughing and drainage on site hydrology.
MANAGEMENT OPTIONS

The design of any ameliorative, management strategy will depend on the mechanisms producing the increased acidity and aluminum concentrations, the characteristics of the soils, drift and bedrock of the particular site, and the atmospheric pollutant levels.

Some of the changes in soils and sites which result from afforestation seem unavoidable consequences of plantation forestry in the British uplands. Others are a consequence of management practices which could be modified or replaced. Increased evapotranspiration, increased 'capture' of aerosols and occult deposition, the creation of macropores by tree roots and the development of a forest floor seem inevitable consequences of afforestation. Those changes resulting from ploughing and drainage could perhaps be limited or avoided by the use of alternative techniques of site preparation or by modifications to drainage networks. The manipulation of site drainage networks may, however, provide a means for ameliorating the acidity and aluminum concentrations in runoff whatever the causative mechanisms.

It has been suggested that deepening of drainage ditches would ensure contact between drainage waters and more base rich mineral materials, and that the water-mineral reactions would lead to increased buffering (Miller, 1985). The impact of such reactions will depend on the chemistry and mineralogy of the lower soil horizons or underlying drift. In deep peat terrain, deepening ditches to beneath the peat layer may have detrimental effects, if the underlying mineral material is acid, as aluminum may be mobilized. At out Beddgelert Forest site, north Wales, UK, water draining from the lower soil horizons, underlying drift and bedrock is acid and contains 19 μM l⁻¹ aluminum; the bedrock is slate, which does not contain carbonates or reactive aluminosilicates. Forcing drainage waters into contact with bedrock would not increase buffering significantly at this site. In Hafren Forest mid-Wales, the subsoil and drift layers are acid and drainage waters from them are acid with high aluminum concentrations, up to 74 μM l⁻¹. The underlying bedrock, however, contains calcite veins and solution of the carbonates results in groundwater with a pH above 6.0 and insignificant levels of aluminum. To achieve buffering of drainage waters in this instance would necessitate forcing the waters into bedrock; surface contact with bedrock, e.g. in a ditch or stream bed is not sufficient. In Kershope Forest site in northern England, large areas of acid peats and stagnohumic gleys overlie calcareous material - this has been decalcified to between 75 and 150 cm. If ditches were dug into the calcareous material, i.e. through the decalcified zone, buffering may result from reactions with the carbonates. Groundwater pH at this site is c. 6.5 and aluminum concentrations are less than 1 μM l⁻¹.

The potential benefit of deep drainage ditches will depend, therefore, on the nature of the soils, drift and bedrock of a given site. If the lower mineral soil horizons, or underlying drift are calcareous, or contain large quantities of readily weathered silicate minerals, then there may be benefits in deepening drainage ditches to penetrate these materials. The impact on the drainage water chemistry will depend on the speed of the mineral-water reactions as con-
tact time will be short. In the case of carbonate rich tills reactions may be rapid enough. It is, however, difficult to predict how long the effect would last. In deep peat terrain it may actually be preferable to keep the plough furrows and ditches within the peat layer. This would produce acid, but relatively low aluminum runoff.

The system of plough furrows and drainage ditches act together to feed acid, surface waters directly into natural water courses (Miller, 1985). Proposals have been made to prevent these ditch waters flowing directly into streams. Dams could be constructed short of the stream, or a combination of a sump behind a dam, such that water seeped slowly through to the stream. It is hoped that some buffering would take place during this seepage. The amount of any buffering would depend upon the chemistry and mineralogy of the materials through which the water drained. In areas with acid soils, drifts and bedrock the effect would be slight. If, however, more base rich drift were present at depth, some benefit could be envisaged from a sump-dam combination. In areas of acid soils and rocks, the dam could be built of imported calcareous or basic/ultrabasic rocks; similar materials could be used to floor any sumps. The major problem here may be contact time and area. Liming of forest soils and, clearance and lining of a riparian strip are also being explored and results should be available during the next few years.

Some valleys in mid-Wales have Molinia bogs developed on streamside benches. Preliminary data from such sites suggests that pH is increased and concentrations of aluminum, sulphate and nitrate decreased as waters move through these bogs (cf. Urban & Bayley, 1986). In these situations the bog should be used as a sink for these materials. Drainage ditches could be stopped at the edge of the bog, allowing the water to drain through the bog to the stream; the bogs should be left unploughed and unplanted.

CONCLUSIONS

It is clear that on certain "sensitive" site types afforestation results in increased acidity and aluminum concentrations in drainage waters. More data, or data analysis, is required, however, to enable us to define the 'sensitive' sites more precisely. Even within sensitive areas small variations in bedrock chemistry may largely offset the impact of afforestation on streamwater chemistry.

We are still unable to identify with certainty the mechanisms and processes leading to the increased acidity and aluminum concentrations in runoff. Some are probably linked to changes in hydrology resulting from ploughing and drainage. Others seem to be due to a combination of changes which inevitably take place as the trees grow, i.e., increased evapotranspiration, increased occult deposition, development of a forest floor and of the tree root system. It is clearly important to separate the roles of site management and tree growth. This separation is crucial in the development of ameliorative measures; available evidence suggests that such measures may be site specific and will require detailed information on the soils, bedrock and hydrology of afforested catchments. One ameliorative measure which would not be site specific, is the reduction of emissions of SO$_2$ and NO$_x$. This would have a significant impact on at-
mospheric inputs at c. 80% of the deposited SO₄ is of non-marine origin. The impact of any reductions in emissions should be taken into account when developing on site ameliorative measures.

REFERENCES


