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Land use and water issues in the uplands with reference to the Plynlimon study

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Abstract

This paper presents the background to the catchment studies at Plynlimon, through outlining the original water resource concerns which led to the establishment of the studies, the principal land use changes, land use impacts that were considered and the principal research findings. The 'scene' is also set for the new areas of research, presented in this special issue, which are focused less on strictly water resource issues, but more on holistic concerns about the management of land use to protect and conserve the natural environment.

Introduction

Small-scale exploitation of upland water resources was one of the catalysts of the Industrial Revolution in Britain. However, the large-scale exploitation of upland water resources for drinking water and industry did not begin until late in the Victorian era with the construction of major impoundments in Wales and the Lake District to supply water to the industrial conurbations of Birmingham, Liverpool and Manchester. The uplands, although comprising a third of the land surface of Britain, (Roberts *et al.*, 1994) now provide half of the country's water supply, most of its hydro-electric power, and, with reservoir regulation, controls on the flow regime. With increasing use being made of interbasin transfers, and fears over the quality of some lowland supplies, particularly from groundwater tainted by nutrients and organic leachates, exploitation of upland sources is almost certain to increase.

Use of the uplands for the traditional practices of agriculture, recreation and, increasingly over this century, plantation forestry, has inevitably led to conflicts between water resources and the alternative or coincident commercial exploitation of land. Originally, a harmonious relationship was built up between foresters and water engineers. The latter's perception of forests on the reservoir catchment was that the risk of pollution of upland water supplies could be reduced, and water treatment costs minimised, by limiting human access and preventing bacteriological problems associated with livestock. It was also commonly believed that forests helped to prevent erosion, provided improved regulation of streamflow through increased infiltration, and may even have been responsible for changes in local climates that increased rainfall.

By the mid-1950s, following results of basin studies overseas, water engineers, instigated by Law (1956), were starting to question whether planted (as opposed to indigenous) forests in British catchments were a universal blessing. The process of testing hypotheses regarding the effects of land use change to forestry, through well-structured field experimentation and research, began with a lysimeter experiment in the central Pennines. Attempts to extend the results to the catchment scale led to the Plynlimon experiment, and to the Coalburn experiment in the northern Pennines. The former was designed to enable assessment of a range of expected effects on water resources, including changes in annual streamflow volumes, the seasonal distribution of streamflow, changes in short term catchment response, and at the same time to provide answers to the question 'how?' as well as 'by how much?'. The Coalburn experiment was designed specifically to monitor changes in the flood response of land undergoing the change from pasture to plantation forest, but it has since proved to have more general application (Robinson *et al.*, 1994).

Two further catchment experiments were added at the beginning of the 1980s to the suite of studies being undertaken by the Institute of Hydrology and her sister organisations. Llanbrynmair, in mid-Wales, was set up to examine the effects of initial afforestation practices on nutrients, inorganic chemistry and fish populations

(Roberts *et al.*, 1986), with a longer term aim of studying canopy closure, the phase of forestry when it is generally believed the most striking hydrological and chemical changes occur. A further catchment experiment at Balquhidder, in central Scotland, was thought necessary to provide a better geographical spread of hydrological studies around Britain, and to complement the existing studies by addressing the specific problems posed by a quasi-continental climate, characterised by cold winters and frequent snow, and by land use change from a different vegetation type dominated by heather and other dwarf shrubs (Johnson, 1995).

Concerns about the water quality effects of upland land use—largely related to nutrients and potability in the mid-1970s, and to acidification and its ecological effects by the 1980s—soon became of equal importance to concern about the water yield. The effects of agricultural and forestry practices on sediment and nutrient supply to water courses were of interest, not only from the water engineer's point of view as affecting the resource, but also because of their impacts on aquatic life and fish stocks. The value of the uplands for amenity uses, the benefits of maintaining wilderness areas and wetlands, the need to promote biological diversity and flourishing yet ecologically-appropriate aquatic life are now high on the list of priorities of land-use planners. The advantages of renewable sources of energy, such as hydropower, are such that calls for expansion are receiving support, yet this will introduce further environmental and resource complications.

This paper precedes a collection of articles describing the most recent research in the Plynlimon catchments and surrounding area, and seeks to set the information baseline from which the latest research is evolving.

Land use and impacts

Land-use options for the uplands are limited by the adverse climate and the long-term decline in the nutrient status of the soils. Grassland productivity can be improved by liming, fertiliser and re-seeding, but conversion to coniferous forest is often a more economically attractive option. The environmental impacts of changing land use are due both to differences between the main vegetation types once established (plantation forest, grassland, moorland) and also to the transient effects of disturbances during ground preparation and management, such as ploughing, draining and felling.

MATURE CONIFEROUS FOREST AND INDIGENOUS GRASSLAND

Mature coniferous forests and indigenous grasslands are examples of semi-natural systems that have achieved a state of temporary environmental stability following a period of disturbance associated with the initial land-use change. Both land uses have been advocated at one time or another as a means of guaranteeing a high quality of water supply from rivers and man-made reservoirs. However this traditional and cosy view may not be accurate: the canopy of a mature coniferous forest is aerodynamically very different from the grassland or moorland it replaces. Feedback to atmospheric processes such as cloud formation, wind and rainfall patterns and energy balances results in different quantities and quality of water entering the soil and groundwater system.

The soil itself is not immune from the long-term effects of forest planting. Drainage ditches and ploughlines alter flow pathways irrevocably, as does the development of tree rooting systems in the upper layers of the soil, affecting chemical cycling patterns at the same time. Ground vegetation is replaced by a thick, loose and largely sterile carpet of leaf (needle) debris, and the soil becomes vulnerable to the erosive power of raindrops and increased acidic inputs. Disruption of the stable surface layers of upland soils and deposits by ploughing and drainage can cause chronic and severe erosion from forest and agricultural drains.

Semi-natural grasslands and moorlands exist because of management of the grasslands by farmers who control the density of grazing animals according to profitability, and protection of the moorlands, particularly in the Pennines and Scotland, by landowners for grouse and deer hunting. Acidic grasslands are limited in productivity, and grant aid has been made available to sweeten the soil by liming and to apply fertiliser to encourage greatly increased productivity of indigenous and exotic grasses. This form of management, often supported by underdrainage, can pose a considerable threat to water quality in the uplands from nutrient pollution. Eutrophication, an existing problem in the warmer climate of lowland Britain, could also become a problem in the uplands with global warming, but currently its most significant effect is in reducing the diluting effect of previously high quality upland water when it enters the more polluted lowland reaches of major rivers. However, the long-term buffering effects of lime application to grasslands can also have an indirect benefit by limiting acidification and helping to reduce metal pollution in upland streams, particularly from aluminium which is toxic to fish.

AFFORESTATION

The management practices associated with afforestation in the uplands often have greater immediate impacts than those caused by the trees themselves. Cultivation and land drainage affects the hydraulic and hydrochemical regimes by lowering the water table, dewatering the soil profile, initiating soil erosion and allowing oxidising conditions to develop. The change to the hydraulic regime may have marked effects on flood and dry season flows in streams. Erosion of the drainage ditches may cause sediment problems downstream, while road construction may also have

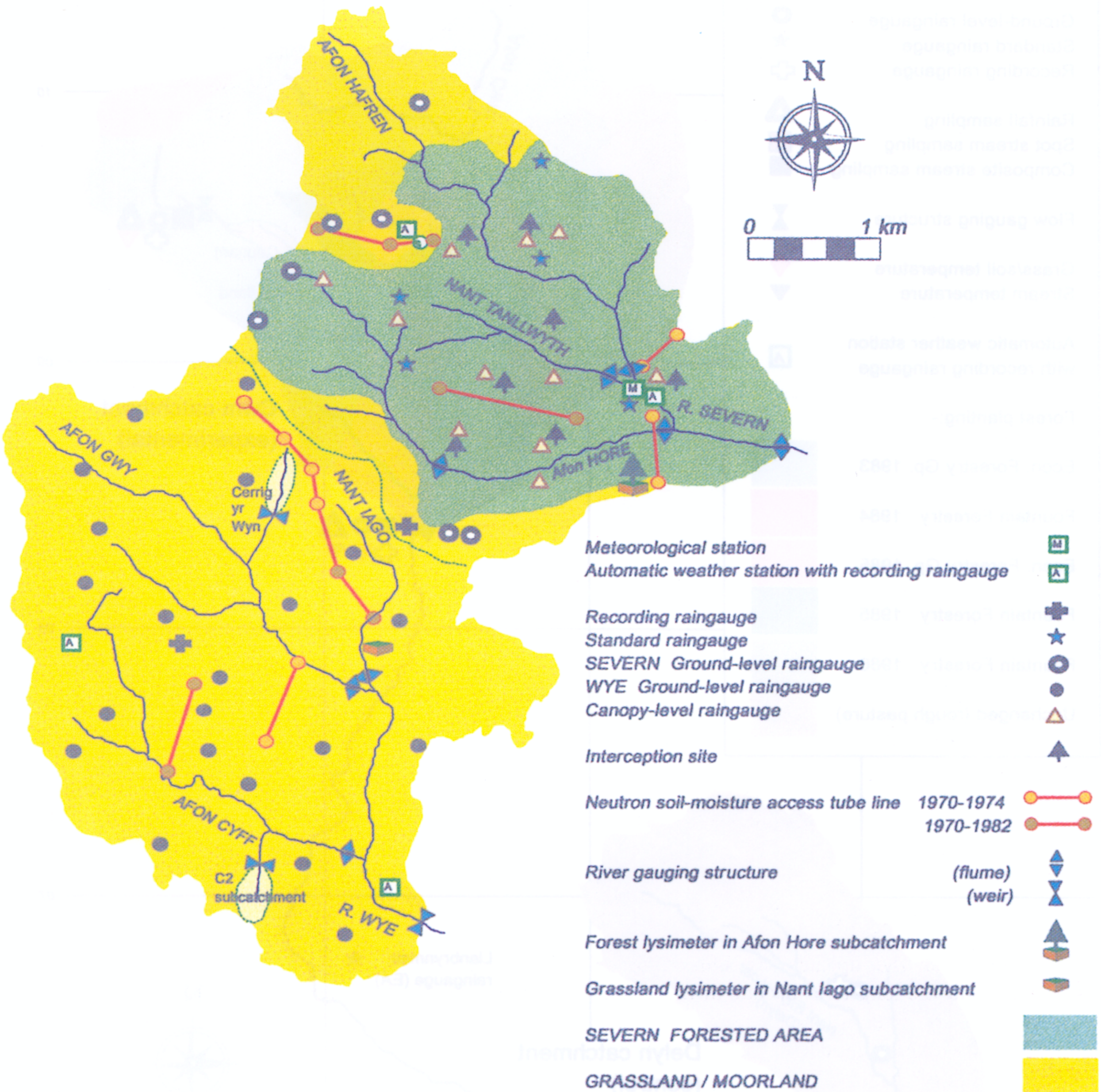

Plate 7 *Instrumentation of the Severn and Wye catchments, Plynlimon, mid-Wales*

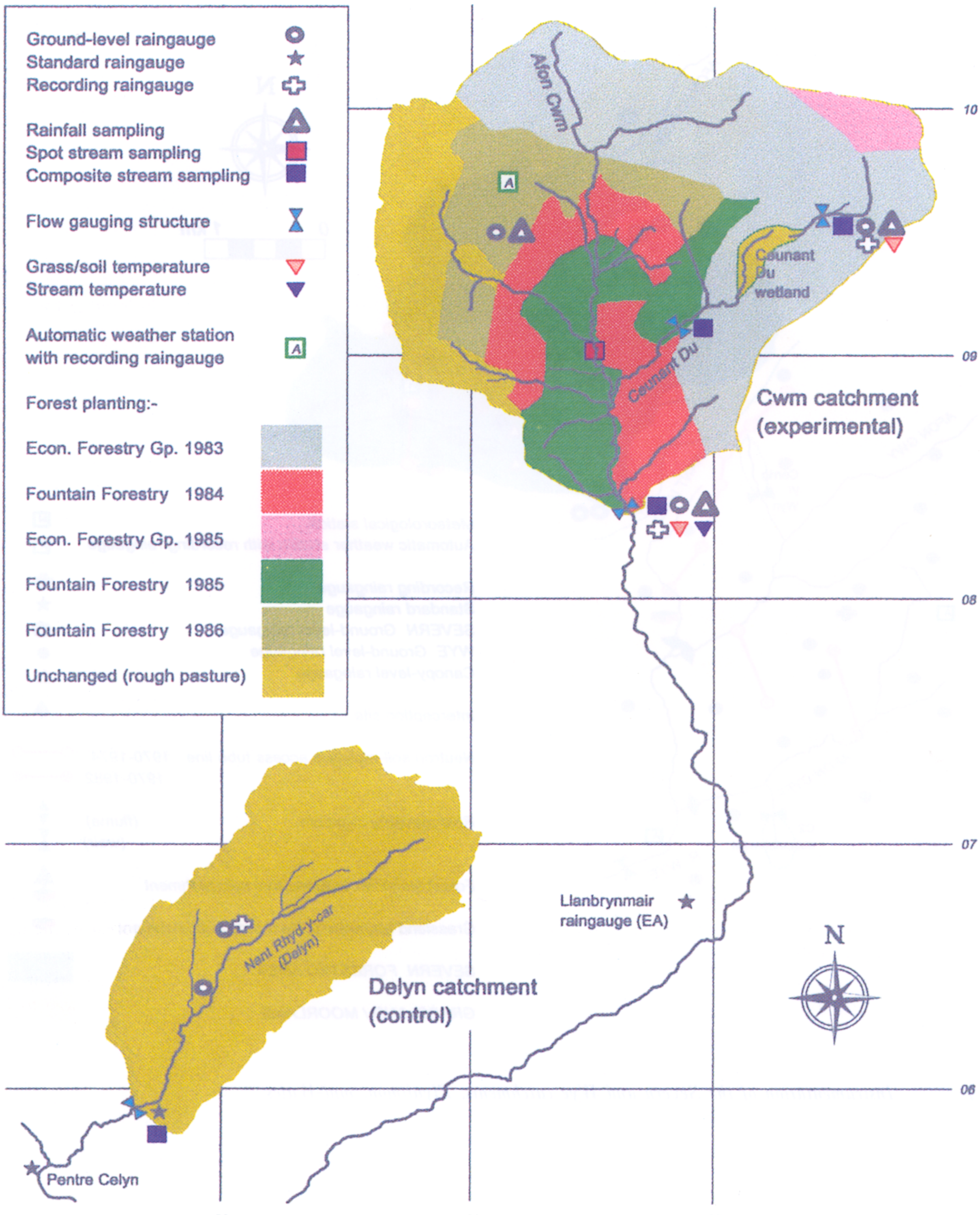

Plate 8 *Instrumentation and forest history of the Llanbrynmair catchments, mid-Wales (see page 391)*

adverse affects on erosion processes (Leeks & Roberts, 1987). Perhaps the biggest effects are chemical, with increased nutrient levels in streams derived from mineralisation of part of the huge nutrient pool in organic matter, and the release of phosphorus in association with particulate matter.

CLEAR FELLING

The life cycles of natural and plantation forests differ in the abruptness of the changes that occur between growth phases. In a typical headwater catchment, tree harvesting takes only a few years to cause a change from mature forest to a jumble of roots, disturbed soil, brash and weeds. This widespread devastation is made necessary by the block monoculture method of planting and harvesting employed in the uplands, where even-aged stands all tend to mature at the same 45–50 year intervals, and where selective harvesting leaves the rest of the block susceptible to windblow.

Harvesting is accompanied by changes in the hydrological response of the catchment. Ground disturbance also makes the soils and subsoil vulnerable to mechanical and chemical weathering and erosion. As the arterial drainage system is largely still in place, and the established cycles of water and nutrients have been severely disrupted, the potential for rapid movement of sediment and solutes to water courses increases dramatically.

Research findings

The Plynlimon catchment experiment uses the largely forested headwaters of the River Severn and the moorland/grassland headwaters of the Wye. The complementary study at Llanbrynmair is set in the Afon Cwm and Delyn feeder catchments to the Afon Dyfi. From its beginnings as a water yield experiment, the Plynlimon study has expanded to include environmental impacts on flow regimes (the extremes of flood and drought), and on water quality and its implications to freshwater ecosystems, as well as touching on the impact of climate change on water resources. The Llanbrynmair study has similarly broadened, from a water quality study assessing the chemical effects of afforestation to a hydrological study of the management practices associated with afforestation through to the canopy closure phase.

WATER YIELD

Mature coniferous forest and indigenous grassland

Results from Plynlimon have confirmed that, contrary to many expectations, afforestation increases evaporation and hence reduces river flow from upland areas (Kirby *et al.*, 1991). Detailed process studies (Calder, 1976; 1977) show that advected heat extracted from the air mass as it moves over the forest, in addition to the energy available from direct solar radiation, is used to evaporate water lying on the forest canopy (interception); in these wet conditions, evaporation rates from wet forest can exceed those from wet grassland by a factor of ten.

In conditions when vegetation canopies are dry, but soils are sufficiently wet not to impose limitations on water extraction by roots, coniferous forest transpiration is found to be approximately 10% less than that from grassland. The high quantity of low intensity rainfall at Plynlimon leads to vegetation surfaces being wet for a significant proportion of the year, and this duration of wet conditions, together with the high rates of evaporation from wet forests, are the principle reasons why closed canopy forest evaporation, on an annual basis, can be double that from grassland (Calder, 1990).

Afforestation

During the early stages of afforestation, large changes can occur in catchment subsurface water storage because of disturbance of soils and deposits. It is difficult to interpret the water balance at such times as the change in storage for any individual year can be similar to the annual evaporation. After a fluctuating start the water balance from the Llanbrynmair afforestation study is starting to show an increase in evaporative losses from the young forest relative to moorland. Similar results have been recorded at Coalburn in Northern England (Robinson *et al.*, 1994), although at this colder site tree growth is slower and it has taken longer for the increase in evaporation to show. These provisional findings go some way towards validating the largely circumstantial evidence from Plynlimon that the differences between catchments under mature forest and grassland are entirely due to vegetation type.

Effects of clear felling on upland streamflow

In the Severn catchment at Plynlimon 100 hectares of trees in the lower half of the Hore sub-catchment were clear-felled over a five-year period, while the forest in the upper half was left untouched to act as a climate and land use control. Changes in evaporation, and hence in river flow, were not immediately apparent, and it took three to four years for the effects to show (Roberts *et al.*, 1994). Evaporation rates from the Upper and Lower Hore are now diverging, with the Lower Hore reverting to rates lower even than those characteristic of moorland in mid-Wales. An increase in streamflow of 150 mm y^{-1} in the Hore relative to the less-affected Hafren sub-catchment would suggest that an increase of 475 mm y^{-1} has occurred in the clear felled area.

This represents a larger drop in evaporation than the difference between mature forest and grassland, and must be due not only to declining interception rates but also low transpiration from the sparse herbaceous vegetation left after felling. The slowness of the increase in streamflow is thought to be partly due to the gradual removal of the trees over a period of five years, and partly due to interception occurring from the tree debris before this rotted down.

FLOW REGIMES

Flood peak magnitudes at Plynlimon are similar in both the forested Severn and the grassland Wye catchments (Kirby *et al.*, 1991). This is thought to be because the lower volume of effective rainfall (rainfall reaching the ground surface) in the Severn is offset by the lower flow resistance of the forest drainage system, which allows a more rapid concentration of the flood peak. The times-to-peak remain similar, possibly because the increased flow resistance afforded by the forest canopy is balanced by the decreasing resistance in the drainage system.

Comparison of low flows between catchments is more difficult, as geological influences tend to dominate. Even in mid-Wales, where the regional bedrock is acknowledged to be low in permeability and storage is low, low-flow yields are controlled more by the existence of water-bearing rocks, flow through fracture zones in otherwise impermeable rocks, drift deposits, and the depth of the soil, than by the vegetation cover. At Plynlimon, tributary streams rising at higher altitudes, on the Ordovician rocks of the core of the Plynlimon anticline, have higher low-flow yields than those from lower altitude sources on the flanking Silurian rocks. This is reflected in higher drought flows from the Severn than the Wye (Newson, 1980a; Clarke & Newson, 1978).

The Llanbrynmair and Coalburn studies have the advantage that they follow the progress of an actual change in land use. Modifications to the response of the catchment caused by pre-afforestation cultivation and drainage, and changes in evaporation caused initially by vegetation disruption and later by the growth of the new canopy, have caused observed changes in both flood flows and low flows. Because of the water resource implications, low flows are of particular interest to the water and forestry industries, sometimes ranking alongside the acidification issue as the major control on further forest planting.

The initial drainage of the Cwm catchment at Llanbrynmair was seen to increase flood peaks by some 46% in the first year, but with no reduction in time-to-peak. At Coalburn there was a similar increase of 45% in the flood peaks, but a reduction in the time to peak was evident as most of the catchment was ploughed at the same time (Robinson, 1993). Subsequent planting at Llanbrynmair in the second and third years did not lead to further increases in peak flows, but did result in reduced times to peak because later drainage was closer to the catchment outlet.

The effects of afforestation on low flows are more complex. In the Cwm catchment low flows initially increased, as the catchment dewatered in response to the loss of soil volume and the steeper hydraulic gradients set up around the drains A similar response was seen in the Coalburn catchment, but, in contrast to Coalburn, the low flows from the Cwm have subsequently rapidly declined. The difference in response between the two catchments may be due to differences in ploughing practices: the pre-afforestation ploughing at Coalburn involved deep ditching, which is not a common procedure, and has resulted in the long term persistence of Q_{95} flows some 50% above pre-afforestation levels. The ploughing of the Cwm was shallower and more representative of traditional and contemporary practice.

WATER QUALITY

Catchment Acidification

There have been numerous studies around Britain, for instance the Llyn Brianne study (Edwards *et al.*, 1990), that have indicated that streams draining forested catchments in upland Britain, when underlain by soils and rocks with low buffering capacity, will have lower pH, lower alkalinity and higher concentrations of potentially toxic metals (particularly aluminium) in solution than streams draining grassland areas. Few of these studies have taken the holistic integrated approach adopted at Plynlimon and Llanbrynmair, and it is still largely circumstantial evidence that suggests that acidification is solely responsible for important modifications of stream ecology, primarily the loss of salmon and trout, and not also for other changes associated with afforestation.

The feature of forest streams implicated in these severe ecological impacts is thought to be the persistence of acidic conditions following high flow events, compared to the relatively rapid recovery of pH in grassland catchments (Hornung & Newson, 1986). Comparative soil studies under grassland and forest have shown that soil waters are more acid and aluminium rich under the trees, providing an immediate source of acidity in storm runoff (Reynolds *et al.*, 1989).

At Llanbrynmair, although chemical changes associated with ploughing, drainage, and fertiliser application have been identified, there is little evidence of changes in acidity during afforestation. There is some evidence from spatial surveys of stream chemistry that contour ploughing has forced greater contact between infiltrating water and the highly buffered mineral subsoil beneath the acid peat, which has offset the increases in acidic anions, NO_3 and SO_4, resulting from mineralisation and oxidation processes in the disturbed catchment (Emmett *et al.*, 1994). Within the Afon Hore, clearfelling of plantation forestry has led to increased nutrient releases for about 5 years with a subsequent decline to baseline levels (Neal *et al.*, 1992a,b,c, 1998). Despite this, there is little evidence of an acidification process other than, surprisingly, a small decrease in alkalinity at baseflow conditions. Indeed, one of the characteristics of the hydrochemical studies at Plynlimon has been the absence of acidification patterns that current environmental impacts models suggest (Neal, 1996).

Despite the further, short-lived, increase in acidity under baseflow conditions, some invertebrate populations, foremost being the mayfly, appear to have benefited from the deforestation. The return of the mayfly to these waters indicates that the impact of coniferous forests on biology may not be solely chemical but may also involve factors such as shading, stream temperatures, food chain disruption and changes in the bed sediment.

The impacts on the ecology of the streams at Plynlimon and Llanbrynmair have also been monitored. As yet no overall changes in fish populations have been noticed at Llanbrynmair (Crisp & Beaumont, 1995), although recently a small but significant decline in alkalinity has been noted as the canopy starts to close on some areas of the Cwm catchment. By contrast, the upper Severn catchment at Plynlimon, under mature forest, has long been devoid of migratory species such as salmon or sea trout, but, perhaps surprisingly, supports a remnant population of brown trout, restricted to one short reach of the Hafren (Crisp & Beaumont, 1996).

Nutrients and Eutrophication

Mature forest and grassland Stream nutrient levels under mature forest and grassland are generally similar and, on a national scale, very low (Roberts *et al*., 1984). Typically, nitrogen concentrations in soils and freshwaters vary seasonally, with winter maxima and summer minima, reflecting the seasonal variation in nutrient uptake. In grassland ecosystems, extremes of drought can disrupt this regular cycle. In summer, soil water solutes become concentrated by evaporative water losses; in addition drought stress can reduce nitrogen uptake by plants leading to an accumulation of nitrogen in soil waters. During re-wetting, flushes of the products of mineralisation and nitrification also occur, so that runoff water becomes greatly enriched with nitrate in the immediate post-drought period. In subsequent years, damage to roots caused by the drought may delay uptake of nitrogen in the spring; additionally these damaged fine roots and lysed microbial biomass provide a readily available substrate to stimulate further mineralisation and nitrification. The net effect is to elevate summer streamwater nitrate concentrations above the negligible amounts normally observed.

Nitrate leaching from plantation conifers also varies over a much longer timescale. Nitrogen deposition to mature (>35 years) stands of Sitka Spruce in mid-Wales is in excess of ecosystem requirements, resulting in elevated nitrate leaching losses (Stevens *et al*., 1994). In mature stands, the magnitude of the leaching losses are determined by atmospheric inputs and soil nitrogen status. At sites with more nitrogen-rich soils, nitrification is stimulated by incoming ammonium which increases nitrate production and leaching.

Afforestation Afforestation at Llanbrynmair has resulted in increased yields of nutrients from disturbed or fertilised areas. Having doubled initially, owing to mineralisation and oxidisation of organic soils, concentrations of nitrogen in the Cwm have gradually declined, as ploughlines have recolonised with vegetation and the young trees and heather understorey have become hungry for nutrients (Hudson & Blackie, 1993). Phosphorus and potassium levels are more variable. The latter is rapidly assimilated and tightly cycled by the vegetation. Phosphorus is also readily taken up by plants and microbes, and also adsorbed onto the surfaces of iron and aluminium oxides in the soil.

Clear felling The disturbance associated with clear felling—removal of the trees as a nutrient sink, soil disruption by machinery, increased effectiveness of raindrop impacts on bare ground and the breakdown of tree debris—results in increases in streamflow concentrations of nutrients. In the clear-felled Hore subcatchment, nitrate levels quadrupled, due to the combined effects of removal of the trees as a nutrient sink, increased rates of organic matter mineralisation and nitrification, and the decomposition of fine tree roots. Regrowth of grasses and herbs, and subsequent replanting of trees in the felled areas, was responsible for the decline in nitrate leaching some 3–5 years after felling, probably almost back to background levels (Neal *et al*., 1992a,b,c). Evidence from studies at Plynlimon and at Beddgelert (Stevens *et al*., 1988) suggests that phosphorus, often the limiting nutrient in the uplands, is released from disturbed ground during felling. Although this can spark major but short-lived concentration increases in streamwater during extreme high flow conditions, in most cases the phosphorus released is rapidly taken up within the catchment, reflecting the tendency to combine with mineral soil, particulate matter, and ditch and channel deposits. Increases in stream nutrient concentrations have implications for potability and ecology, but concentrations remain low compared to lowland rivers and groundwater sources.

Grassland improvement In the mid 1970s a paired lysimeter experiment was established to look at problems associated with enhanced nutrient losses under grassland improvement schemes and the associated practices of underdraining, ploughing, reseeding and heavy applications of lime and fertiliser (Roberts *et al*., 1986). The ability of grassland to take up applied nitrogen can be counteracted by the release of nitrogen from dewatered organic soils, or from ploughed land before the grass crop has established. Although serious water quality problems could ensue at the local scale, on a larger catchment scale the effects would be mitigated by the staggering of improvement schemes and the uptake of nitrate in unimproved riparian zones. Alternative methods of improvement, using sward burning, spike rotavation and low nitrogen inputs, have also been researched at the catchment scale and found to be successful in reducing nutrient pollution to streams while maintaining traditional levels of grass productivity (Roberts *et al.*, 1989).

The lysimeter study also revealed the existence of shallow groundwater, sometimes under artesian pressure, and gave one of the first indications of the significance of groundwater as a means of maintaining baseflow and streamwater quality in upland areas. The existence of groundwater (or at least non-soil storage) inferred from water balance studies (Hudson, 1988) and hydrochemical hydrograph splitting studies (Neal *et al.*, 1990) has been confirmed by a major hydrogeological survey (Neal *et al.*, 1997a,b).

IMPACTS OF RIPARIAN WETLANDS ON STREAMWATER CHEMISTRY AND GREENHOUSE GAS FLUXES

Riparian wetland areas at both Plynlimon and Llanbrynmair have been shown to have some effect in removing nutrients mobilised upslope and thereby improving downstream water quality (Roberts *et al.*, 1984; Emmett *et al.*, 1994). Streamwater samples from the recently afforested Cwm catchment at Llanbrynmair showed an apparent reduction of various solutes, in particular phosphate, total-phosphorus, ammonium-nitrogen, organic-nitrogen and potassium, and an increase in nitrate, pH, hardness, calcium and magnesium, on passage through part of the catchment containing a riparian wetland. Although year-to-year variations in climate appear to affect the ability of riparian wetlands to strip dissolved nutrients, there is considerable potential in such wetlands, natural and man-made, to reduce pollution problems if properly managed. This has important implications for downstream water quality and stream biota, as fisheries are particularly susceptible to high metal concentrations, and is starting to guide forestry operations towards the sensitive future use of riparian wetlands (Forestry Commission, 1992).

As well as improving water quality, wetlands are also important on a global scale in controlling the greenhouse effect: they are carbon sinks on the one hand and sources of the important 'greenhouse' gases, methane and N_2O, on the other. The hydrology of wetlands is vulnerable to dramatic changes, as a result of both artificial drainage and possible changes in rainfall and evaporation rates as a consequence of global warming itself. Hydrological manipulation of a gully flush at Cerrig yr Wyn, in the Wye catchment at Plynlimon, involving artificial drying out of the flush over two summers, resulted in increased release of carbon dioxide and nitrogen oxides, but suppression of the release of methane, owing to lowered water tables, increasingly aerobic conditions, and the inhibiting presence of free sulphate in soil waters (Hughes *et al.*, 1995; Hudson *et al.*, 1996).

SEDIMENTS AND EROSION

The traditional view of new forest as a land cover in water supply catchments was one of increased soil stability and improvements in water quality. Little account was taken by those responsible for the early planting of conifers in the British uplands of the inevitable land disturbance associated with afforestation and felling, and the potential for chronic erosion problems under mature forest when afforestation practices were less than ideal.

Ploughing of moorland for forestry, and the installation of artificial drainage, has been seen at Coalburn (Robinson & Blyth, 1982) and Llanbrynmair (Leeks & Roberts, 1987; Francis & Taylor, 1989) to result initially in increased losses of suspended sediment, including peat particles, in drainage water. Drainage inevitably exposes mineral soils and underlying erodible deposits at the base of the drains. Provided that drains are well engineered, with contributing areas minimised and gradients kept below about 2°, they will gradually recolonise with vegetation, the banks will restabilise, and suspended sediment levels will decline to pre-afforestation levels.

More often, however, particularly with forests planted in the 1920s and 30s, inadequate engineering has left some drains susceptible to continued erosion from banks and bed, providing a persistently heavy supply of suspended sediment and bedload to upland streams. The effects are geographically variable but, on average, there is a long-term 3–5 times enhancement of bedload yields from forested catchments compared to similar areas with moorland cover (Newson, 1980b).

At Plynlimon, sequential drain surveys, sediment tracing using radionuclide (Bonnett *et al.*, 1989) and magnetic methods (Arkell *et al.*, 1983), and particle size analyses indicate that the base of the drains are the main source of sediment, but in some forests where inappropriate installation techniques and raw materials have been employed there is a major contribution of suspended and bed-load from forest roads. This is particularly true of the early years, before vegetation recolonises the roadsides, and before remedial work, such as gabion protection for the toes of road embankments near streams, is carried out.

After clear felling, dams formed from tree debris in some feeder streams offer some respite from the high levels of bedload movement, as these hold back sediment for a short period until storage thresholds are reached. Disturbances associated with crude harvesting techniques more than compensate for this, with order-of-magnitude increases in suspended sediment concentrations resulting from erosion caused initially by soil loosening, channel formation in wheel ruts, drain bank collapse and increases in heavy harvesting traffic on forest roads.

The experience gained from strategic sediment work has enabled vital contributions to be made to forestry guidelines (Forestry Commission, 1992), and for advice to be given on amelioration techniques in catchments suffering erosion and sediment pollution problems. In the Cray Reservoir catchment in the Brecon Beacons, south Wales, erosion of drains supercharged with runoff following alterations to drainage patterns led to thousands of tonnes of coloured sediment to be discharged to the reservoir (Stretton, 1984), and caused major and expensive difficulties in water treatment. Drainage patterns were altered in collaboration between the Institute of Hydrology, Welsh Water and private foresters, a measure which succeeded in preventing further pollution.

CLIMATE CHANGE IMPACTS

Future climate change can only be identified if it occurs as a statistically significant step outside the envelope of known historical variations, yet such changes may be small compared to the overall year to year variability in climate. Plynlimon represents the type of study that gives the best chance of identifying any changes and developing predictiven models, particularly in relation to water yield and water quality. Data from the grassland Wye catchment, as well as acting as a control for the land use comparison with the Severn, has been a climate change study in its own right. Over the study period there has been considerable year to year variation in annual rainfall and annual streamflow, but there is also a discernable underlying trend towards increased rainfall and streamflow that follows observed nationwide trends (Green *et al.*,1996).

This new appreciation of the sensitivity of the hydrological system to climate variability and change is leading to better predictions of changes in other environmental parameters, such as stream chemistry, sediment losses and biology, that are dependent on flow along particular water pathways. Hydrochemical models are being developed using a framework of sophisticated, spatially-distributed, hydrological models, within which the changes in flow pathways due to land use or climatic change can be made explicit. Initial evidence is that the chemical system is even better buffered against change than the hydrological system, there being no evidence of a change in chemistry at Plynlimon that can be attributed to changes in climate (Robson & Neal, 1994).

Conclusions

Forests are the natural climax vegetation of the uplands, albeit indigenous broadleaves rather than exotic conifers, however upland aquatic communities and the water industry have taken advantage of the plentiful and clean water emanating from areas dominated for centuries by short-grazed pasture or moorland. Research at Plynlimon and related studies over the last 40 years indicates that plantation forestry has had a mainly adverse effect on the environment and the quantity and quality of water resources, although with sensitive and appropriate management this does not always have to be the case.

In the wet, windy climate of the British uplands some 15–20% of rainfall is lost by transpiration from grassland while 30–40% is lost from areas with full forest cover. There is little that can be done about these losses, save reducing forest cover, particularly in reservoir catchments. Research into the second rotation forests that are currently being established in a more environmentally-friendly way indicates that mixed age forests with high proportions of their areas under younger trees may help to maintain higher streamflow.

Analysis of data with regard to the time distribution of evaporation and streamflow, is not so conclusive. Low flows are adversely affected once the canopy has closed, but short term benefits accrue after the initial ploughing due to lowered transpiration, dewatering and deeper mining of the water table. The case of Coalburn suggests that in certain circumstances the benefits may be longer term. Peak flows for a given rainfall are not significantly affected after canopy closure because the effects of ditch hydraulics and increased flow resistance through forest canopies effectively balance. However the moorland ploughing that is an integral part of initial afforestation invariably tends to decrease times-to-peak and increase peak flows. Basin-wide the effects are unclear as flow lower down the system depends on the coincidence (or lack of it) of flood waves from individual subcatchments. Drainage in the uplands for forestry or agriculture could actually improve the situation by phasing response and hence attenuating flood peaks.

Forestry has little effect on nutrient levels in the long term, especially after the initial disturbance has worn off. In its initial stages, mineralisation of organic nitrogen in the ploughlines and the disruption of cycling in the vegetation causes an increase in stream nitrogen, and phosphorus is mobilised intermittently when erosion occurs during high flow events. The disturbance associated with clear felling also causes a four-fold increase in NO_3–N, due to brash decay, reduced take-up by recolonising vegetation compared to the trees, and continued filtering of atmospheric acidic oxides by the brash canopy and rank vegetation. Soil disruption accounts for some phosphorus losses from plots, however upland catchments tend to have a series of soil, riparian and in-channel safety valves which prevent wholesale phosphorus pollution of the main water courses.

Increased acidity and metal pollution is a problem associated with upland forests on soils with low buffering capacity due to higher acidic anion inputs to rough forest canopies. More sensitive anti-emission regulations and improved technology means that atmospheric SO_2 continues to decline, however NO_x emissions are increasing to compensate. Research is continuing into whether the other acidic anions (including marine-derived Cl) have the same deleterious impact as SO_4. Clear felling, rather than decreasing acidity when the canopy is removed, appears to have the opposite effect due to the aforementioned increase in NO_3. Work is in hand on the potential beneficial effects of a more varied canopy stucture during the second forest rotation.

Migratory fish, and especially their young offspring, tend to be virtually absent from most forested streams. Brown trout can be found in small numbers, and these tend to have good growth performance probably due to limited competition for food. It is still not clear whether the overall decline in fish numbers in upland streams is due to acidification alone or to a combination of this and other physical factors such as shading, food chain effects, and spawning ground modifications caused by changes in sediment types and delivery rates. The Llanbrynmair afforestation study, now approaching canopy closure, should be able to provide over the next few years conclusive evidence on the reasons for general population declines in the uplands. Limited biological recovery has taken place in clear felled areas, particularly among invertebrate populations, however the suitability of such streams to support fish has yet to be proven. This may only be established by active restocking of fish populations to check on survival rates.

Sediment discharges from mature forest areas vary from 3–5 times the losses from equivalent grassland areas, and this is mainly in the form of bedload. There is evidence that the clear felling of forests can reduce bedload losses in the short term because of the formation of debris dams, which can be manipulated to stagger the delivery of bedload to the streams. However, suspended sediment loads increase significantly during both the afforestation and clear felling phases due to the increased supply of fines from banks, ditches, roadsides and the land surface disrupted by ploughing and harvesting machinery, a feature that is potentially more damaging to stream ecology and water treatment costs than bedload yields.

The impact of many of the individual land uses that make up the diverse patchwork of the uplands has been the subject of intensive research over the last 40 years. The most recent work carried out at Plynlimon and in related studies, in Wales and elsewhere in the uplands, is described in this issue. New work is already in progress to fill in the gaps, to assess new forestry and water resource management techniques and to look at other long term impacts such as climatic variability and change.

Plantation forestry remains a potential hazard to the health of upland environment when compared to the semi-natural grassland and moorland it is replacing. However it also has considerable environmental benefits when compared to land uses such as intensive farming. In the current financial and development climate, it may be outside the capacity of the forestry industry alone to find solutions to many of these problems, particularly in the cases of increased water use, the impact on low flows and acidification from atmospheric pollution. In such circumstances foresters must rely on reductions in atmospheric pollution, and changes in land use planning that encourage planting away from areas that are sensitive to increased evaporation, increased nutrient losses, higher sediment yields and potential acidification. Most of all they will rely on good quality scientific information of the type emanating from long term environmental impact studies such as those described in this issue. Well-informed forestry and agricultural guidelines promise to improve the situation, with sensitive utilisation, management and even manipulation of riparian areas showing the greatest potential benefits. Above all the information now available from upland catchments must inform and guide a holistic approach to large basin management.

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