Some Effects of the First Rotation on Site Properties

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INTRODUCTION

The greater proportion of the land under forest plantations in the British Isles was not carrying forest when these stands were established. Most of this land had not been tree-covered for long periods before afforestation. During the treeless period changes in soil development took place primarily owing to the climatic changes which led to our present oceanic climate, characterised by strong winds, moderate to heavy precipitation and the generally low potential evaporation of the cool summers in the west and uplands. The influence of this cool humid climate on soil development obviously varied with combinations of topography, aspect and lithology, the last being the predominant factor as it influenced both the mineralogical and physical status of the profile. On many lithologies the inheritance of glaciation was a deep layer of till of low permeability (e.g. on Carboniferous rocks) sometimes with indurated layers (e.g. on Devonian rocks) which limited the capacity of the profile to absorb and conduct water. The resulting seasonal anaerobic conditions, cool climate and poor mineralogy led to accumulation of organic debris on the surface. The result of these conditions, no doubt assisted by centuries of grazing, muirburn and extensive use, was the development of the site characterised by poor internal drainage. The important soil types are peaty ironpans, surface water and peaty gleys and peats of varying depths and kinds (Pyatt 1970).

During the 19th century these soils, which now account for more than three quarters of the afforested land in Britain (Pyatt 1979), were considered unplantable. With the gradual development of afforestation techniques from the introduction of the planting turf to the intensive mechanised drainage and cultivation of today, these apparently intractable sites have become available to forestry.

Their utilisation has also been achieved by exploiting the adaptability of Sitka spruce (*Picea sitchensis* (Bong) Carr) and Lodgepole pine (*Pinus contorta* Dougl).

The intensity of site treatment has an effect on the performance of the established stand which, in turn, influences the site conditions available for subsequent rotations. This paper is concerned with these latter effects which, although difficult to separate, may be conveniently grouped into those resulting from the physical treatment of the site and those resulting from growth and management of the stand.

INITIAL SITE AMELIORATION

On the wet sites in the uplands, the minimum treatment required to establish a tree crop has been found to be a planting position raised above the surface and the provision of surface drainage to carry off surplus water. A small addition of phosphate fertiliser considerably improves the rate of establishment. These techniques were pioneered at Corrour in Invernesshire from 1909, with the introduction of the 'Belgian turf' and still form the basis of afforestation. The later developments have mainly resulted from mechanisation, an improved understanding of tree nutrition and a belief in the benefits to be obtained from greater drainage intensity. An ability to disrupt the iron-pan and sometimes underlying indurations in peaty iron-pan soils is perhaps the main advance in site amelioration practice in the last 30 years.

Most of the stands now approaching maturity were established in the 1920's with either hand-cut or primitively ploughed drains rarely exceeding 30cm depth and spaced at about 7m intervals. These shallow drains were able to remove surface water but did little to effect any drying of the organic horizons so that initial root extension of the turf-planted tree was confined to the surface of the soil as described by H. M. Steven in 1923 (Zehetmayr 1954). An important effect of this site treatment has been the radial orientation of the root systems and the ultimate crossing of the drains by roots, in marked contrast to the alignment of the roots with the plough ridge, when planting was later restricted to a continuous turf.

The main objective of these cultural treatments was the successful establishment of a tree stand, rather than a fundamental alteration of site conditions, and in this they were mainly successful. Once beyond the thicket stage the stand could be expected to continue to maturity at a growth rate appropriate to the site type. It is only recently that economic pressures and an improved appreciation of species requirements for optimal growth have led to attempts to permanently alter the physical conditions of the site.

These attempts appear to have been successful in, for example, peaty iron-pan soils of sand-loam textures, but appear to have had less success on soils of a higher clay content with poor pore size distribution (Pyatt 1973). One of the earliest studies in Britain of the effects of tree growth on a peaty iron-pan soil showed that the effect of ploughing was to increase air content of the upper profile from a very low volume percentage to 30-40 per cent throughout the year (Rennie 1962). Recently Pyatt (1978) has reported reductions in bulk density from about 2g cm^{-3} to 1g cm^{-3} in cultivated indurated soils on Old Red Sandstone in Morayshire.

Intensive drainage of gleyed sites has been shown to be of dubious value by Savill (1976) in Northern Ireland, where borehole studies demonstrated that drainage effects are limited to the drain edges on both surface water and peaty gleys developed on tills of low porosity. The development of semi-permanent fissures in lowland English clay soils (Fourt 1960) has not occurred in the drained upland of similar texture. The only way of improving aeration on these peaty gleys seems to be in reshaping the site into a 'rigg and furr' formation (Read, Armstrong and Weatherell 1973).

The almost total disruption of the existing profile and the distribution of the overlying organic horizon throughout the disturbed depth of soil can now be achieved by the rotary mould board plough (Thompson 1975). The effect of this treatment in trials on peaty iron-pan soils is dramatic, the profile remaining aerobic throughout the year to a depth of 60cm. On peaty gleys the outcome is still unclear.

Intensive cultivation clearly enhances early tree growth and root systems rapidly explore the disturbed material but are concentrated in pockets of the former surface organic material. Fears have been expressed that the improved growth rates may not persist due to the loss of the disturbed organic matter leading to either a reduced water capacity or nutrient deficiency. However, the evidence for reduction in growth rate from Europe (Van Goor 1977) and Britain (Thompson and Neustein 1973) is confined to freely drained sandy soils in areas of low rainfall.

On deep peats the effects of artificial drainage depend on the degree of humification, little effect being found on the amorphous and pseudo-fibrous types of peat, while even on the fibrous peats of raised bogs the winter water table remains at 30cm before canopy closure (Taylor and Everard 1969).

As the more intensive treatments of recent years have in general not yet shown major alterations in site properties on the wet soils, it can be concluded that the effects of the initial treatment of sites afforested 30-40 years ago were of short duration and had little influence on site development compared to the effects subsequently induced by the stand.

Stand Development and Silvicultural Treatment

The strongest influence on the site after a stand of trees is established is the modification of the microclimate following canopy closure. This process begins as soon as the trees are planted and accelerates as the thicket stage is reached, culminating in the attainment of maximum leaf area. The ground vegetation is progressively eliminated as the new canopy intercepts more of the incident radiation. Every aspect of the climate at the soil surface is altered, temperature flucuations diurnally and seasonally are reduced, windspeed is reduced, direct evaporation is reduced and, perhaps most importantly, incident precipitation is reduced.

The data that have been collected in recent years for the interception term in the site water balance are remarkably consistent at about one-third of the incident annual precipitation. This value varies of course with rainfall intensity, season and possibly species but for both Sitka spruce and lodgepole pine about 35% of the precipitation is evaporated annually from the canopy with a tendency for lodgepole pine to have a slightly higher value than the spruce. (Institute of Hydrology, pers comm). The greatest interception occurs once the leaf surface area attains its maximum at about a top height between 9-13m in Sitka spruce at a 0.9-2.4m initial spacing (Malcolm 1977). The reduced amount of water reaching the forest floor is also spatially redistributed as throughfall, drip and stemflow such that the areas around the stems have the highest input in young Sitka spruce stands (Ford and Deans 1977) although this may change later in the rotation.

The effective reduction in precipitation influences the soil water regime so that on many sites formerly saturated for most of the year there is at least a period in summer when the water table drops (Fig. 1). The development of aerobic conditions in the profile, however, still depends on the texture. On peaty gleys and surface water gleys on Carboniferous till in Newcastleton Forest, Smith (1976) has shown that oxygen levels remain low throughout the summer, despite the fall in the water table to below 70cm. On the other hand adequate oxygen levels are detectable below the pan in ironpan soils. The occurrence of these low oxygen tensions is thought to be due to an increased respiratory demand by roots as soil temperature increases in summer.

Polestage stands appear capable, through transpiration, of drying soil profiles at depths beyond those reached by the roots (Pyatt 1973, 1978). Water has been removed from depths of about 1m on peaty iron-pans on indurated till at Speymouth Forest and from similar depths on peaty gleys at Newcastleton. The clay till in this case does not crack but increases in bulk density suggesting that seasonal drying has a cumulative effect which will not improve later root penetrability.

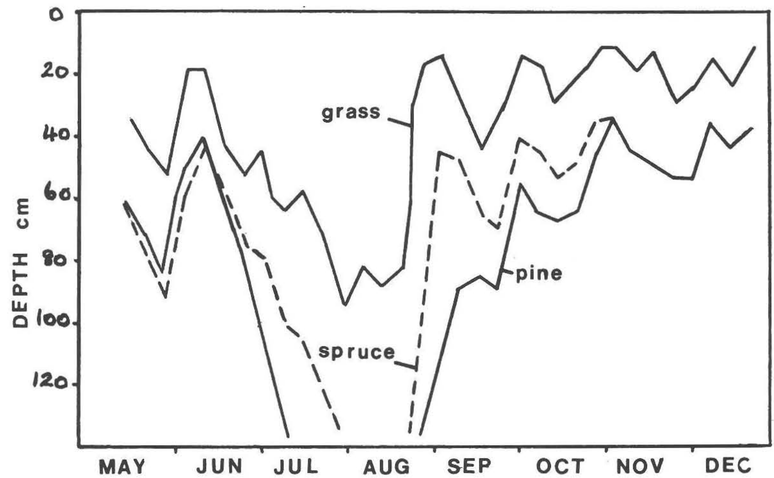

Fig. 1 — Water table levels under spruce, pine and grass, Falstone Northumberland, 1977.

(Forestry Commission Data)

The summer fall in water table levels appears to be of slightly longer duration under lodgepole pine than Sitka spruce (Fig. 1) but in any case the levels are rapidly restored in autumn, when anaerobic conditions are again present near to the surface (Armstrong et al 1976). Any roots which followed the water table down in spring are then killed giving the typical flat root plate with 'shaving brush' sinkers typical of unstable stands on gleys.

The penetration of the soil by the developing root systems forms the basis of soil drying by the transpiration of the trees and it is interesting that on nutritionally poor and wet peaty soils there is a higher proportion of the dry weight production devoted to roots than on better sites. Fraser (1966) showed for Sitka spruce that, for the structural root system, the root:shoot ratio increased from 0.39 on brown earths to 0.61 on deep peats with peaty iron-pan soils and gleys intermediate. There was also a rough negative correlation with rooting depth.

The drying effect of roots permeating the organic horizons is different to the seasonal changes in the water table. On deep peats large fissures develop due to shrinkage and irreversible drying, the effect being strongest on well humidified peat less than 2m deep (Pyatt 1979). These fissures provide lateral drainage through the peat and thus a permanent lowering of the water table. Most species appear capable of initiating this drying but lodgepole pine can induce cracking a few years after canopy closure. Large fissures have been observed at 1.5m depth on an intensively drained deep peat under a 60 year old Sitka spruce at Corrour, Invernesshire where differential species effects are also discernible on peats less than 1m depth. Drying due to the fibrous rooting of *Abies nobilis* Lindl., has led to the formation of separate hard lumps of peat, no longer rootable and completely altering the former organic horizon; the effect of spruces seems to be similar although the new structure in the former massive organic horizon is softer and less well defined. *Abies grandis* Lindl., usually confined to flushed peats, seems capable of inducing a type of peat 'mull' which is readily dispersed by drip from the canopy. Irreversible drying of the amorphous peats formerly associated with the *Molinia* dominated vegetation of gleys also occurs, becoming most obvious after windblow when the small 'gritty' fragments may be dispersed by wind from upturned root systems.

These phenomena are now being studied systematically but the full effect of the drying process is still unknown. What does seem important both to the rate of drying of the organic horizon and for subsequent rotations is the root penetrability of the underlying mineral soil. Where the roots can enter and exploit the mineral horizons as in some cut-over peats in Ireland (Carey and Barry 1975) the drying effect takes place faster and should lead to few problems for future stands. Where root penetration is restricted to the organic horizon because of high bulk density or poor pore size distribution on gleyed mineral soil, there must be serious doubts about the wind-throw stability of future rotations, as well as the ability of the site to supply water and nutrients in periods of low rainfall.

Practical aspects of the reduction in incident precipitation and the subsequent drying of peaty organic matter during the first rotation are that less maintenance of surface drains is required and the provision of a raised planting site in no longer necessary on many sites. It is, in any case, difficult to cut cohesive turves due to the old root systems.

The third main effect on the site of stand development is the initiation of a nutrient cycle within the stand, through the litterfall. The quantity of litter deposited each year on the forest floor seems to be an expression of the vigour of the stand but must reach an asymptotic level when canopy density results in continuing tree mortality. There is some inconsistency in the reported quantities of litter accumulating on the surface of soils with a peaty covering, which may reflect difficulties in the separation of the tree litter from that of the previous vegetation. Rennie (1962) gives a litter value of 37 t ha^{-1} for a 70 year old pine stand on a peaty iron-pan soil. In a recent paper Carey and Farrell (1978) found values of 45-55 t ha^{-1} for the forest floor of three middle-aged Sitka spruce stands while a mean value of 23 t ha^{-1} was given by Adams (1974) for a study of 119 plots ranging in age from 7-41 years on surface water and peaty gleys. The former authors consider there is accumulation of organic matter whereas Adams (1974) showed only a 2 t ha^{-1} y^{-1} increase on average, although there was a considerably greater depth of material on the peaty gley soils. What is important in terms of the effect on the site is the rate of decomposition of this organic matter and whether a balance is reached between decomposition and litterfall. This topic has recently been reviewed by Miller (1979) and for base-poor sites it seems clear that accumulations of mor humus may immobilise greater quantities of N and P than are contained in the stand, leading to ultimate deficiencies of uptake. To the extent that trees depend on nutrients from the soil. the supply available from the rootable organic horizons of peaty iron-pan, peaty gley and deep peat soils is inadequate and has to be made good by fertilisation. Parker (1962) suggested that even on moderately fertile peats depletion would result in eventual deficiency and a lodgepole pine stand at Inchnacardoch was shown by Binns (1968) to have removed most of the K in the upper peat. However, Williams, Cooper and Pyatt (1978) were unable to show depletion of nitrogen, phosphorus or potassium content in the upper 30cm of a range of afforested peats although decreases in exchangeable calcium, magnesium and potasium were noted, together with increased acidity related to improved aeration and decomposition. Increasing acidity with stand age has also been noted for the litter layers of Sitka spruce (Carey and Farrell 1978, Adams 1974).

Adverse effects on soil productivity, through the development of mor humus layers, have often been suggested but the evidence is usually circumstantial and difficult to substantiate because of inherent soil variability (Stone 1975). The biological decomposition of litter certainly follows different pathways under different species but podsolisation is a process depending on internal soil drainage and thus unlikely to be a problem on the soil types considered here. Surface water gleys may be an exception, where deposition of acid, unpalatable litter could reduce the populations of soil fauna, particularly earhworms, that maintain some aeration in the upper horizon. This, together with the rocking of flat root plates may lead to some physical deterioration of the soil for subsequent rotations.

The effects of stand development discussed above do not take into account silvicultural treatments. The most obvious of these is the manipulation of stand density by thinning which, by reducing the interception and evaporative surfaces, increases the amount of precipitation reaching the soil. Not surprisingly it has been shown that there is a concomitant rise in water table levels (Heikurainen and Paivanen 1970). There is some evidence that dense, unthinned stands root more deeply into wet soils (Fraser 1966) and it may be that part of the increased windblow, experienced following thinning, is due to the death of roots under the higher water table.

Reduction in canopy density allows a greater proportion of the incident radiation to reach the forest floor which is important for the rate of decomposition of the litter and recycling of nutrients (Wright 1957) so that thinning has opposing effects on these sites.

Perhaps the main change in silvicultural practice in recent years has been the introduction of large scale fertilisation of peaty sites. Much of this has been remedial in nature, acknowledging inadequate earlier treatment and resulting in marked responses in thicket stage stands. The nutrient universally used has been phosphorus but in Britain potassium has also been required on the poorer peats. It has become clear that spruce stands on these sites will also require repeated applications of nitrogen (Dickson and Savill 1974). Polestage fertilisation has produced more equivocal results, about half the Forestry Commission experiments with Sitka spruce showing little response in terms of basal area increment (R. McIntosh, pers comm). We know far too little about the mechanisms of increasing yield through fertilisation. The effects on the site are complex and depend on the materials used, the condition of the site and stand.

Coarse rock phosphate contains about 20 per cent citric acid-soluble phosphorus, which is readily dissolved at the low pH of peat soils. In distinction to mineral soils phosphorus is not strongly held by organic material so that there is some loss to drainage water. Our work, on a raised bog at Leadburn near Edinburgh, suggests an annual rate of loss of 2 kg ha^{-1} y^{-1} or about 20 per cent of the readily soluble fraction. Harriman (1979) recently published equivalent results on a watershed basis and like us, also found that most of the release is in the winter. Potassium is well known to leach freely and at Leadburn 20 per cent of that applied has been lost from the peat in two years. Canopy closure effects a change and the network of fine roots and mycorrhizal hyphae in the litter layer seems able to absorb or retain the bulk of applied fertiliser within the stand.

The effect of nitrogen fertilisation on the site is still unclear. Urea hydrolyses to ammonium which results in an increased pH and mineral nitrogen content of fibrous peat (Malcolm 1972) but the extent to which the organic nitrogen, already present in the peat, can be mineralised appears limited (Dickson and Savill 1974). It has been suggested that pretreatment of peats by heavy liming application may alter favourably the nitrogen status of peat for tree growth (Dickson 1977) but liming experiments have not usually resulted in tree responses on peaty soils. Thus the beneficial biological effects may take some time to develop and might have some influence on nutrient cycling in later rotations (Adams et al 1978). It should be noted, however, that rock phosphate is generally insoluble at pH values above 4.5 so that another form of fertiliser is required on heavily limed sites.

The long term effects of fertilisation on the physico-chemical properties of the organic-horizons of afforested peat soils is largely unknown. As at least a proportion of the added nutrient is retained on site, even if not immediately accessible to trees, it is unlikely that the effects can be other than beneficial.

HARVESTING

Removal of the tree stand attains the original objective of afforestation and presages the start of the next rotation. Economic forces and mechanisation, together with the risk of windthrow, has meant the adoption of a clearfelling system as the standard technique for harvesting on peaty soils. This process has dramatic effects on the site and the conditions available to regenerated or replanted trees.

The felling of the old stand removes in one operation the buffering influence of the canopy. Without its interception the soil is again subject to all the precipitation with an inevitable rise in the water table. On peaty iron-pans it is probable that sufficient penetration of the pan will have occurred to avoid near surface waterlogging while fissured peats are unlikely to again become saturated to the surface. The condition of peaty gleys and surface water gleys after clearfelling is somewhat different as even under full canopy the winter water table lay close to the surface. In some years clearfelled sites may have a continuously high water table as in Kielder Forest (Fig. 2). This creates problems for replanting as new turves cannot be produced by ploughing or even by hand. Planting must therefore be restricted to the better aerated areas close to residual stumps for adequate survival of Sitka spruce.

Clearfelled sites with an insulating layer of litter can be subject to extremes of surface temperature either scorching or frosting newly planted trees. Frost damage is related to the size of the felling coupe and its topographic situation.

Stand removal and the changed climate results in a rapid increase in nutrient mobilisation through biological acticity (e.g. Popovic 1975) and release of nutrients from the site. This 'flush' of nutrients does not appear to last long, disappearing again after revegetation (Likens et al 1977), although no work appears yet to have been done on this in clearfelled plantations on peat. The activation of accumulated mor humus is a strong ecological argument for the clearfelling technique in climates leading to slow organic matter decomposition. The removal of nutrients in the felled trees is unlikely to be important, unless the branchwood is taken as well as the stem. On infertile sites fertilisation is then necessary (Miller 1979). An interesting feature of current clearfelling techniques on peaty soils is the piling of brash in broad bands to improve the

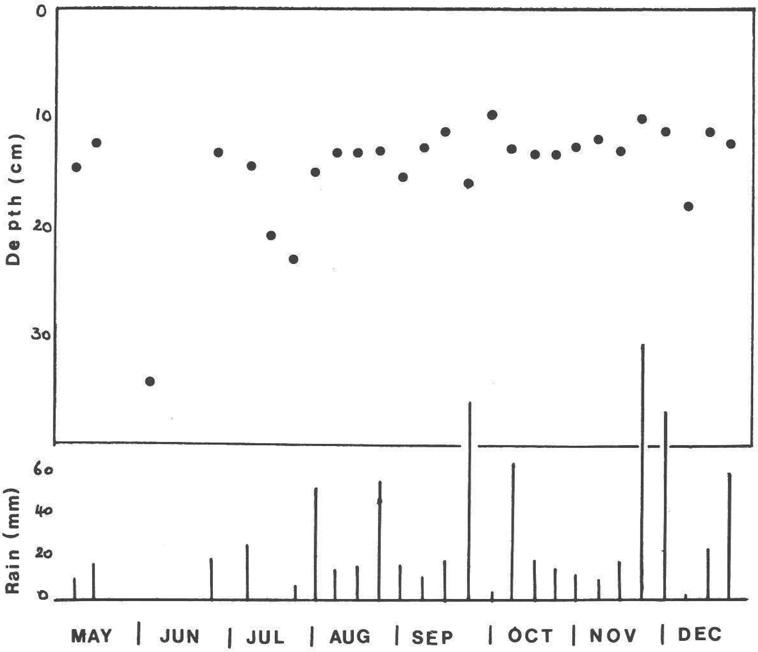

Fig. 2 — Clearfelled site, peaty gley, Kielder Forest. Depth to water table and rainfall, 1978.

traction of extraction machinery which could result in some nutrient redistribution within the site.

Currently some concern is being expressed about the use of heavy machinery to increase extraction payloads on felling sites. There is no doubt that these machines can disrupt the surface horizons on wet soils with serious consequences for the aeration and drainage of affected areas. Perhaps a longer term economic viewpoint would restrict their use to firm mineral sites.

The final effect of harvesting is to allow the reinvasion of the site by ground vegetation. On surface water gleys grassy vegetation rapidly reappears and may be more vigorous than at the time of afforestation. The inability to provide a weed-free planting position is awkward but suitable herbicides are available. On peaty iron-pan, peaty gley and deep peat soils reinvasion is slower but interestingly includes the return of ericaceous species, seeds of which may have lain dormant for up to 50 years (Hill 1979).

CONCLUSIONS

Afforestation of previously bare hill land sets in train a series of changes that reverse the processes that have been taking place on these sites, often for centuries. The major change on peaty sites is the development of an aerobic soil environment, at least in the upper horizons. This induces a more rapid cycling of nutrients and, with the stand itself assisting, leads to fundamental changes in the physical conditions which will be available for subsequent rotations. Some of these changes are irreversible and can only improve the sites for tree growth. This seems particularly so for peaty iron-pan soils where roots can explore the aerobic horizons below the pan level. Deep peats, suitably fissured, will present a rather different rooting medium to second and later rotations which may or may not offer greater stability and it will be interesting to see whether they can be occupied effectively by more exacting species than lodgepole pine. Peaty gleys however may present greater problems than at afforestation depending on the permeability of the underlying mineral horizons, on the poorer tills the drying and dispersion of the peat could lead to less regular stands as dominant trees exploit the pockets of better aerated soil. If roots can penetrate the mineral horizons the site will have been improved.

There remain some serious gaps in our knowledge of changing site conditions, in particular we do not know enough of the nutritional status of peat soils after a rotation of trees and whether we will be committed to continuing inputs of fertiliser nutrients. During the next half century fertiliser costs will increase and their availability may decrease, a possibility which should encourage greater investment in understanding nutritional processes and the utilisation of nitrogen fixation on these sites. Van Goor (1977) addressing this Society presented evidence of improved growth of second rotation Douglas Fir *(Pseudotsuga menziesii* Mirb. Franco) on a heathland soil, which had an increased nitrogen status and no longer needed additions of phosphate. Will a similar state of affairs arise on the peats? The majority of the stands about to be harvested did not benefit from the site preparation now considered desirable and, because of the stumps, no effective method is available to remedy this. If nothing is done are they then committed to low growth rates for the second rotation? Or, if this is not the case are current afforestation methods fully justified? The peaty gleys remain the major problem in this respect and demand fresh thinking about the structure and specific composition of the new stands.

The standard technique for afforesting peaty sites depended on a suitable planting position and removal of surface water with sometimes a small addition of phosphate. After a rotation these sites may not appear so uniform as they did before planting, thus second rotation stands may display greater variation than the first. The challenge for the forester is how best to exploit this variation.

ACKNOWLEDGEMENT

I am grateful to D. G. Pyatt for permission to use his unpublished data for Fig. 1.

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