WATER SOLUBLE COLOUR IN UPLAND PEAT SOILS: THE EFFECT OF FORESTRY ON THE COLOUR STORE

Sean E. Reynolds, Pauline E. Kneale
and Adrian T. McDonald

WORKING PAPER 95/17

SCHOOL OF GEOGRAPHY • UNIVERSITY OF LEEDS

WATER SOLUBLE COLOUR IN UPLAND PEAT SOILS: THE EFFECT OF FORESTRY ON THE COLOUR STORE

Sean E. Reynolds[1], Pauline E. Kneale[2] & Adrian T. McDonald[3]
School of Geography, University of Leeds, Leeds LS2 9JT

ABSTRACT

The discoloration of upland runoff is a focus of concern to water authorities and consumers. In this paper it is hypothesised that peat covered gathering grounds under a dense coniferous canopy are likely to contain a larger accumulation of water discolouring humic substances than heath dominated moorland catchments. An experimental investigation is reported of the maximum soil-water colour yield from 117 peat samples taken from beneath stands of two coniferous species, forest ride, and moorland plots in the English Pennines and Southern Uplands of Scotland. The role of seasonal drying of the peat and the likely influence of forestry on colour generation and runoff is discussed.

---

1. Research Student
2. Senior Lecturer, Physical Geography
3. Professor of Environmental Management

INTRODUCTION.

The natural discoloration of raw water by dissolved organic matter is common in peat covered catchments throughout the United Kingdom. Following the severe summer droughts of 1975 and 1976 a marked upward trend in runoff colour levels has been observed in several upland catchments (McDonald *et al*, 1989; Kay *et al*, 1989). A notable example is the sharp rise in colour levels observed in raw waters arriving at Thornton Moor reservoir in West Yorkshire (Edwards, 1987), see Figure 1. Colour variability also increased and was associated with problematic high peaks which did not return to pre-1977 levels on the cessation of drought conditions. The drought of 1984 saw a return of high colour conditions and enhanced variability and indeed the maximum colour was recorded in 1985, one year after the 1984 drought.

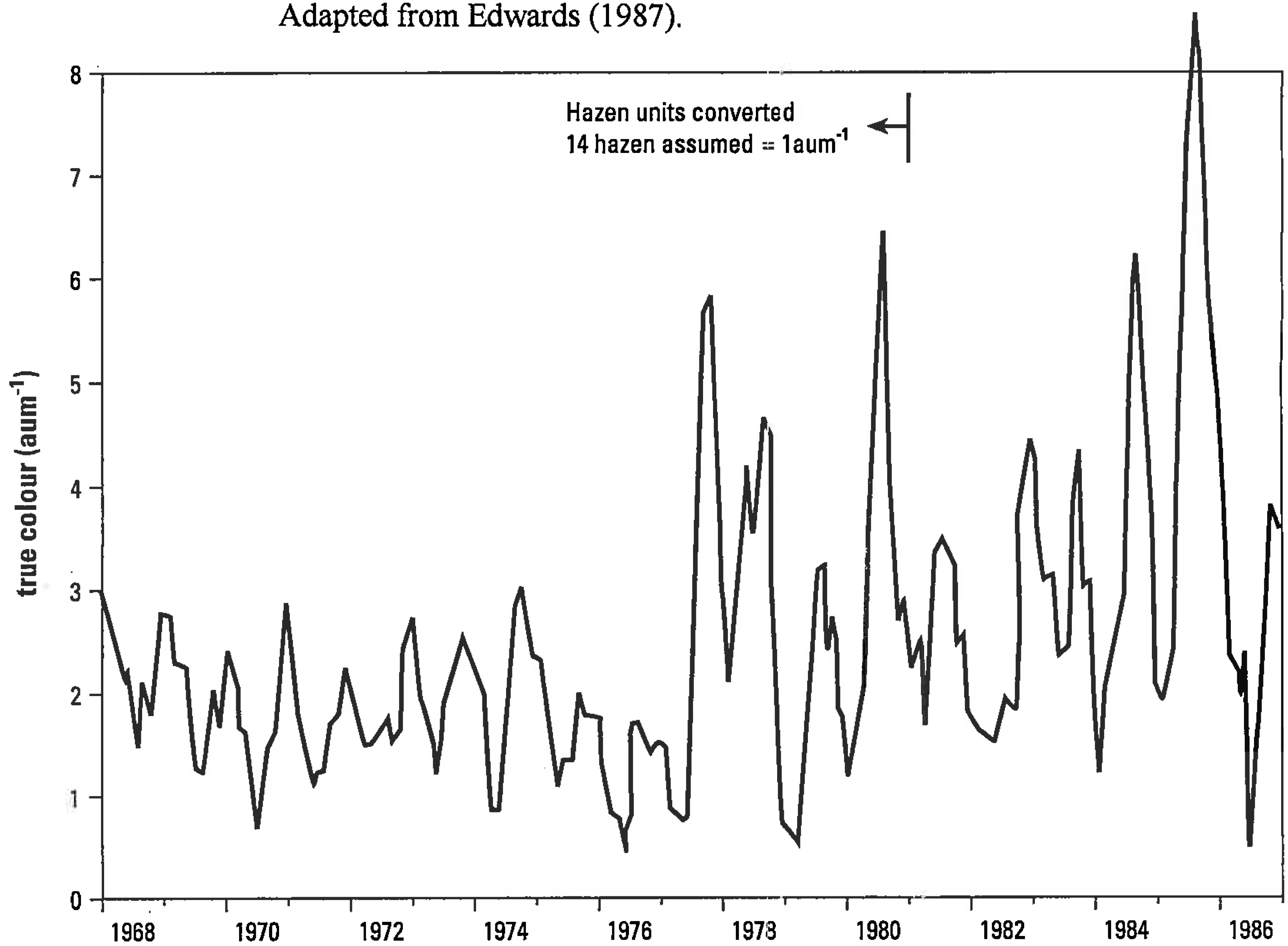
Problems associated with coloured runoff

Discoloured runoff is a problem for water resource managers who utilise the affected gathering grounds for supply. Potable water exceeding the EC maximum colour standard of 1.5aum^{-1} (determined at 400nm; equivalent to 20 Hazen) is readily visible, like weak tea in appearance. This peat-stained water is considered aesthetically undesirable, as indicated by the number of complaints received from dissatisfied consumers following its distribution (Lucas, 1986). Due to the presence of organic acids, humic rich water is often strongly acidic (Otto & Svensson, 1983) and is also associated with an enhanced mobilisation of organically complexed metal ions (Livens, 1991). These additional factors present their own particular problems in the water distribution network. Colour can be eradicated by treatment but this is a complex procedure that heightens operating costs (McDonald & Kay, 1987; McDonald *et al*, 1991). Coloured water poses no direct health risk. However, there is evidence to suggest that harmful mutagenic by-products are formed from the disinfection of raw waters which contain high concentrations of dissolved organic matter (Långvik & Holmbom, 1994).

The process of natural freshwater discoloration.

The soluble humic substances responsible for the discoloration of upland waters are mainly a by-product from the decomposition of soil organic matter under oxidising conditions (Mitchell 1990a, Kononova, 1961). Aerobic decomposition rates are more than twice the anaerobic rate in peaty soils, it is therefore in the near-surface peat horizons that most colour is produced (Mitchell, 1990b). This colour forming matter is quite resistant to further chemical, physical and, microbiological degradation (Cresser *et al*, 1993). However, over prolonged periods of soil moisture deficit the humic material becomes structurally unstable (Raveh & Avnimelech, 1978) but with a healthy turn-over of organic substrate, a store of water-soluble colour forming matter is accumulated (Mitchell & McDonald, 1992a).

Figure 1. Monthly mean raw water colour: Thornton Moor reservoir Adapted from Edwards (1987).



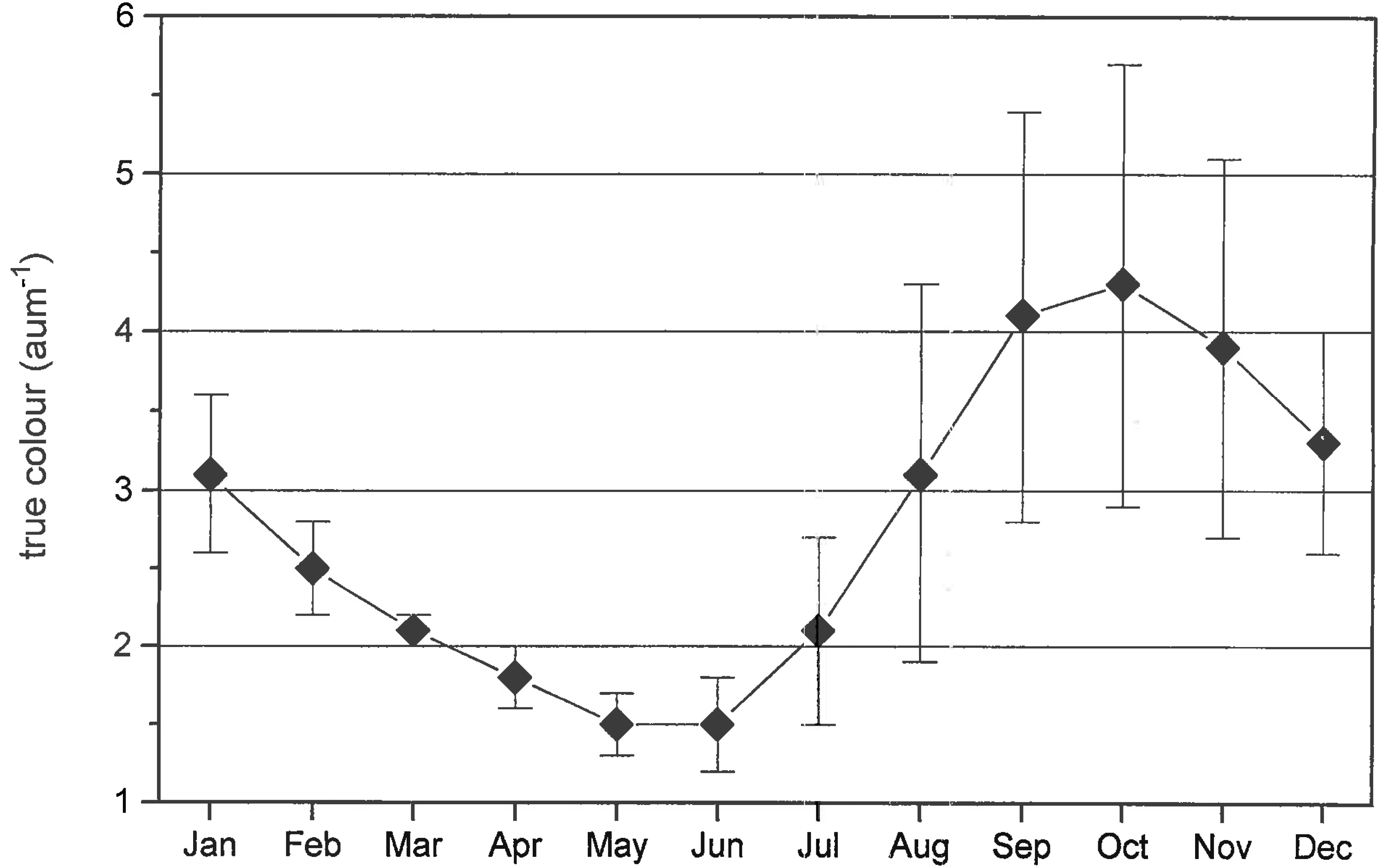
Drainage water is discoloured by the solubilisation and removal of the stored water-soluble humic substances following; moisture replenishment, residence, and movement through the colour containing matrix. Through a laboratory simulation of drying and wetting cycles in large intact peat cores, Mitchell & McDonald (1992a) found that the length of the drought period was positively related to the intensity of the colour flush during rainfall simulation, this was ascribed to the size of the colour store generated during peat drying. They also found that chemical and physical hydrophobicity, resulting from excessive soil-water loss (≥35%) during prolonged droughting, inhibits moisture replenishment and therefore produces a lagged colour flush response. In this state peat requires a prolonged wetting phase to allow saturation sufficient for solubilisation and subsequent runoff of the colour store. This lag increases the effective drought period and may even stimulate a sudden increase in microbiological activity upon rewetting (Birch 1958a, 1958b). This offers an explanation as to why maximum colour in Figure 1 was delayed until the autumn flush of 1985, one year after the 1984 summer drought. Naden & McDonald (1989) found that lagged soil moisture deficits of 3 and 14 months account for more than half the variation in the long-term colour trend for the Upper Nidd catchment, North Yorkshire.

The natural discoloration process is, therefore, governed by a period of soil moisture deficit when colour production is the dominant process and a wetting-phase when the stored colour is taken into solution and flushed from the soil. An infrequent switching between these two soil moisture states, induced by climatic conditions in British catchments, leads to a build up of colour throughout the summer months and a marked colour flush following the onset of high autumn rainfall when discharge through the upper soil layer occurs (Naden & McDonald, 1987; 1989). A lagged response may be involved depending on the antecedent soil-moisture status. This strong seasonal pattern is reflected by the annual cycle of runoff colour levels observed in many upland reservoirs, an example is given in Figure 2.

Effects of land management

Research in this field has concentrated on the processes, sources, and timing of coloured runoff in upland moorland catchments. By inducing an enhanced drying of the soil and by albedo induced temperature related increases in microbial activity, management practices such as gripping and burning have a considerable effect on the magnitude of peat colour stores and runoff colour levels (McDonald *et al*, 1991). Due to pre-afforestation ploughing and drainage ditching (McDonald, 1973), and an enhanced interception and evapotranspiration (Calder 1979; 1990), afforestation has a dramatic effect on the moisture status, hydrology and oxidation of peat soils (Hornung *et al*, 1986). These modified conditions act to lower the water-table thus deepening the aerobic zone and increasing the potential for rapid organic decomposition. Theory therefore suggests that colour production, and accumulations, in

Figure 2. Mean monthly raw water colour: Ogden Water reservoir, West Yorkshire (1986-1989). Error bars represent ± 1 standard deviation.



forest soils are likely to be high. This is an understudied area and this paper presents early results from a three year study which attempts to quantify and compare the production and release of colour from forest soils with that from moorland soils, for which the processes are now well understood.

Experimental aims

This paper presents preliminary results from experiments undertaken to compare the magnitude of stored colour in forest and adjacent moorland peat soils. The major experimental hypothesis was that soil under forest vegetation should contain a larger store of water-soluble colour forming matter than moorland peat due to factors which would tend to promote oxidation and colour production in forest soils. Sampling on the moorland was restricted to the dry, bare, and eroded sites since these areas have previously been found to contribute the most highly coloured waters upon rewetting (Mitchell & McDonald, 1992a; 1992b) and would therefore offer a useful comparison with the scale of stored colour in forest soils. On the basis of field and laboratory description, and soil survey evidence (1:10,000 scale), sampling was restricted to peat soils of the Winter Hill association at Langstrothdale and of the Ettrick association at Eskdalemuir. Coupled with the fact that sampling plots at each site were in close spatial proximity, detected colour store differences can be ascribed to colour production processes stimulated by the vegetation cover, rather than inherent variations in the soils prior to afforestation.

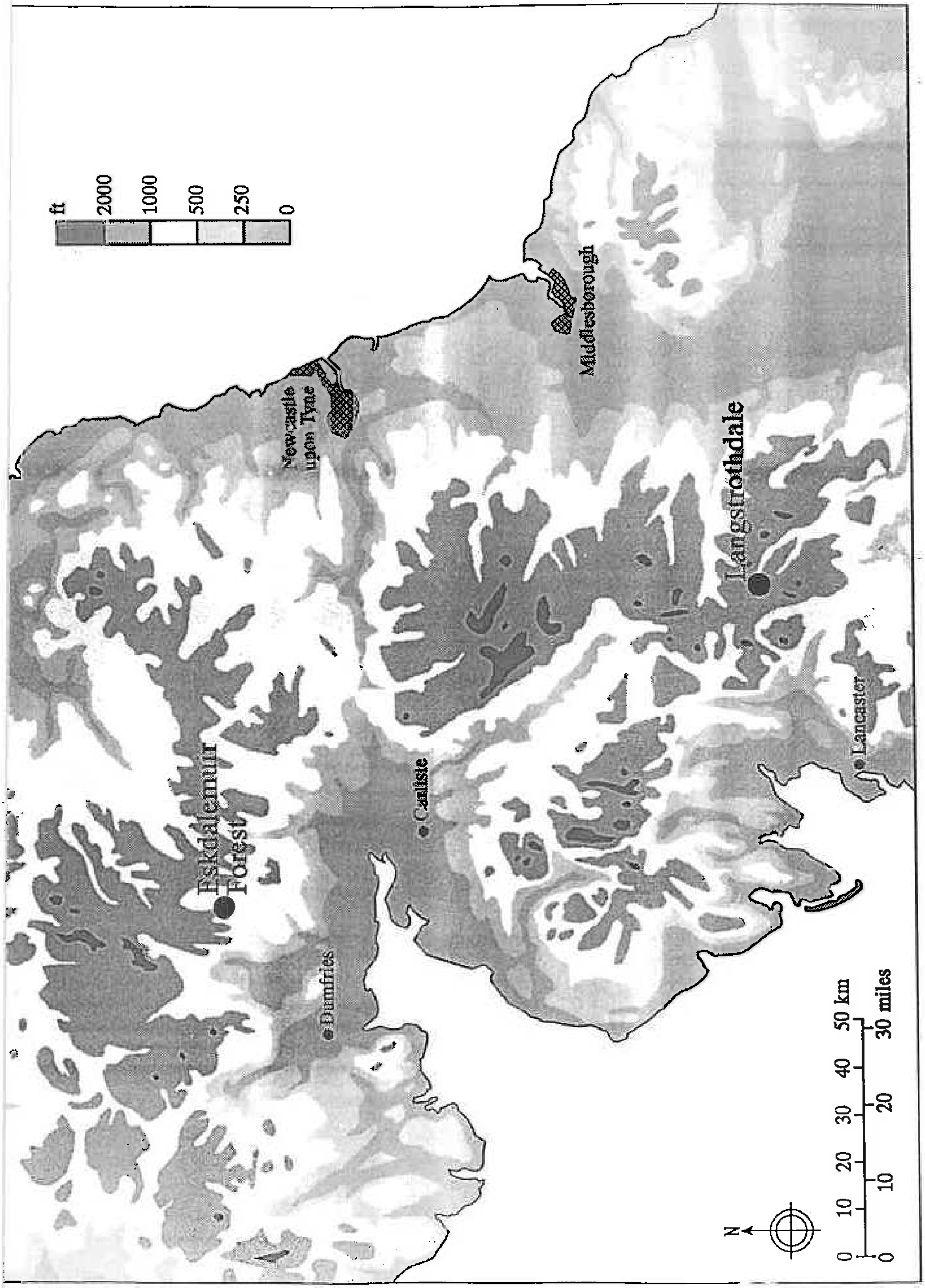
METHODS

Field sites

Soil sampling was carried out at two field sites; Greenfield in Langstrothdale Chase, North Yorkshire (SD8177), and the Eskdalemuir Forest in Dumfries & Galloway (NY2299), see Figure 3a. The forest plantations at both of these sites are first rotation crops planted on previous open moorland.

The Langstrothdale site is underlain by carboniferous limestone and millstone grit covered with a boulder clay drift. The soils are acid peat of the Winter Hill association to a depth of approximately 50cm. Afforestation in the catchment was carried out between 1970 and 1976. Sitka Spruce and Lodgepole Pine are the dominant species occupying 72% and 9% of the total planted area respectively. The valley has an altitudinal range of around 380-600m, the sampling plots are at an elevation of 405m. The average annual rainfall is approximately 1750mm.

Figure 3a. Location of field sites: Langstrothdale (Yorkshire Pennines) and Eskdalemuir (Southern Uplands, Scotland)



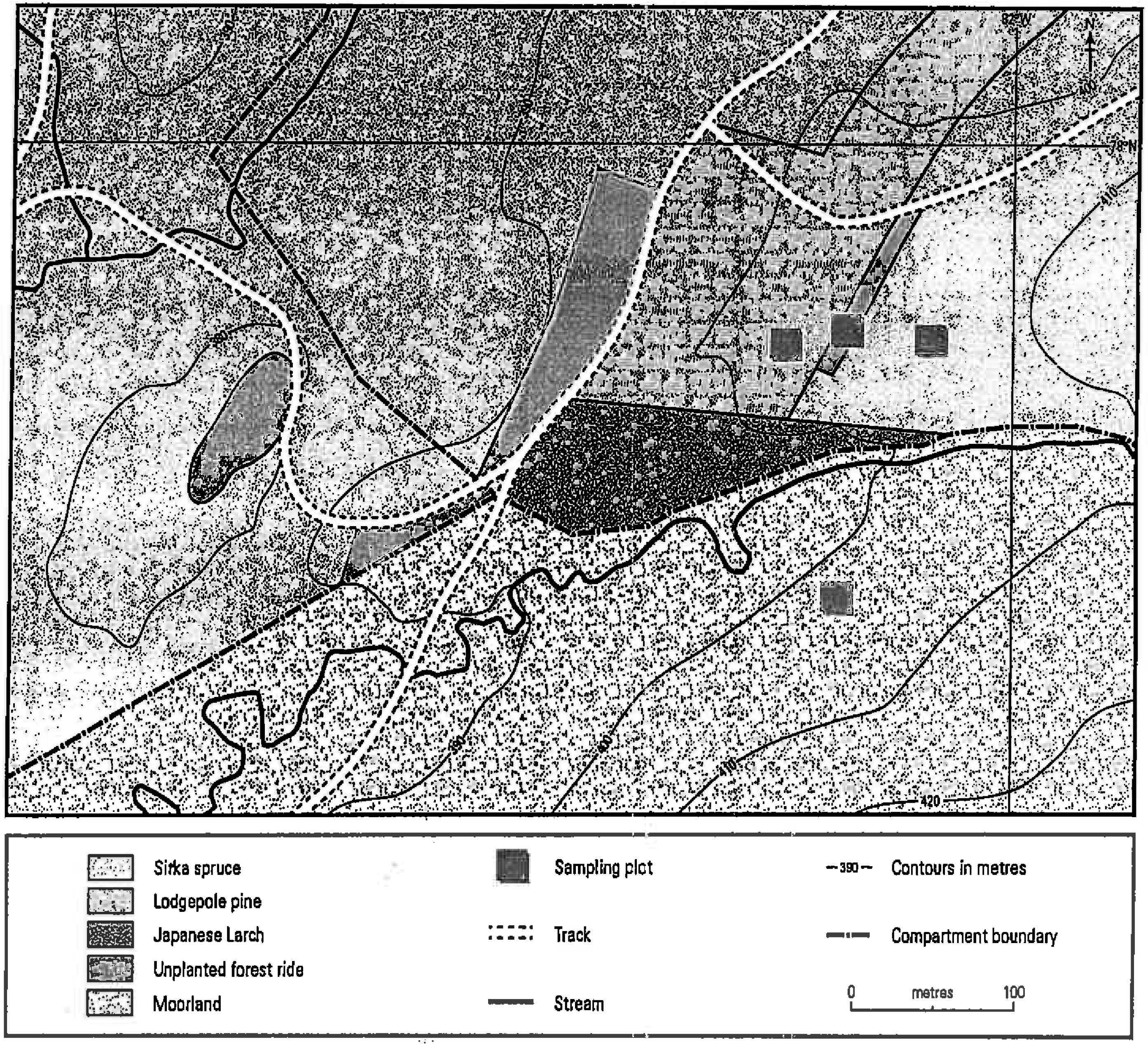
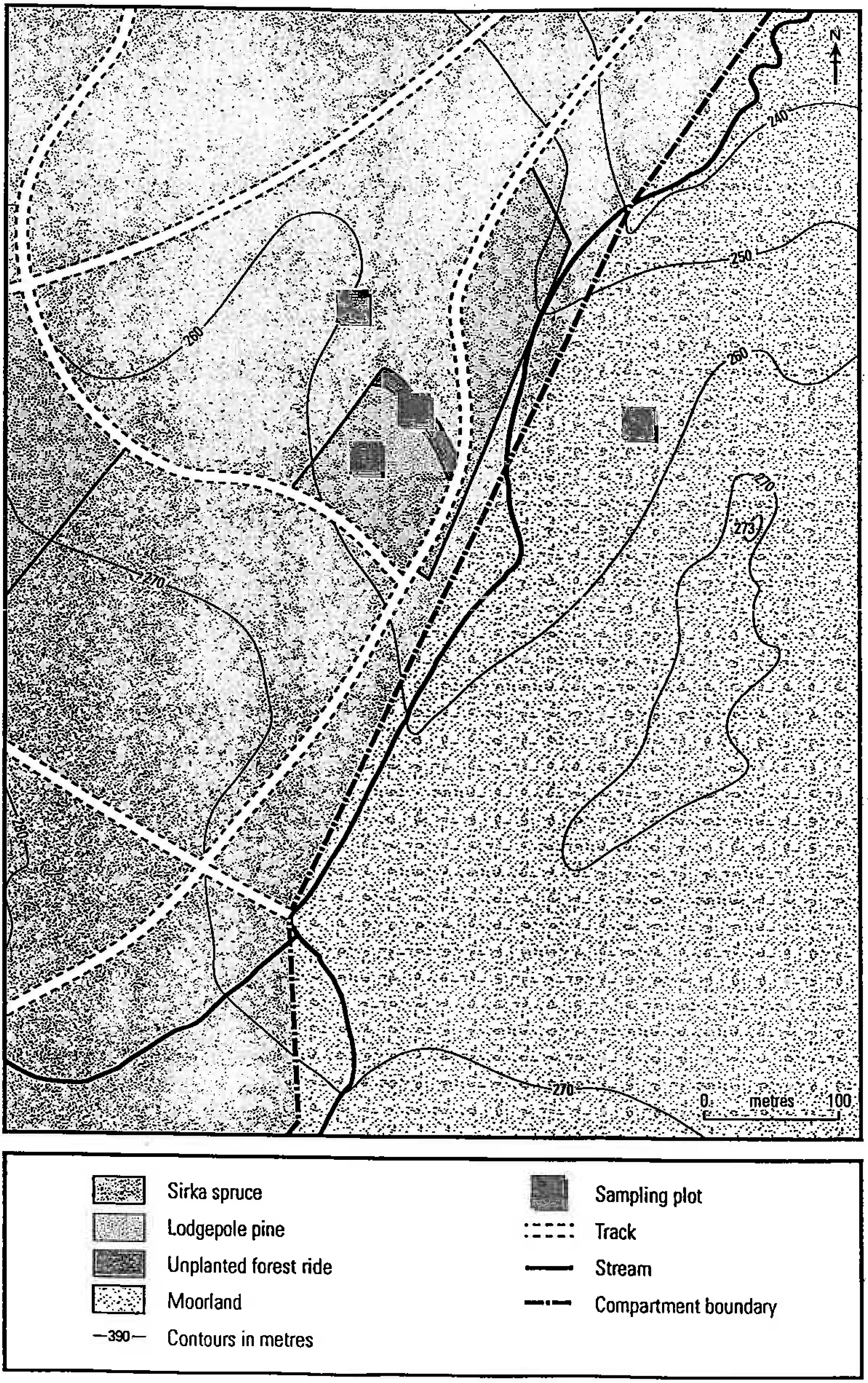


Figure 3b. Langstrothdale field site (NGR: NY2299), showing location of sampling plots

Figure 3c. Eskdalemuir field site (NGR: NY2299), showing location of sampling plots



In the Eskdalemuir catchment, the soils are predominantly peaty-podzols and gleys with areas of flushed bog peat. The afforested area has a diverse planting age with first rotation stand ages ranging from 18 to 46 years, several compartments planted with Sitka and Norway Spruce are up to 10 years into the second rotation. The dominant tree species are Sitka Spruce, Lodgepole Pine and Norway Spruce. The catchment has an altitudinal range of around 220-600m. The long-term annual average rainfall is 1700mm.

Sampling procedure

Humified near-surface peat samples were collected from adjoining single stands of Sitka Spruce (*Picea sitchensis*), Lodgepole Pine (*Pinus contorta*), grassed forest rides, and adjacent dry moorland plots, at each of the field sites. In each stand replicates of 15, or 12, samples were taken from within 10m by 10m sampling plots, a total of 117 samples were collected. The forest sampling plots were at least 50m inside the forest boundary. Moorland samples were collected from plots approximately 80m outside the forest boundary (Figures 3b and 3c).

The samples were $1000cm^3$ monoliths of well-humified peat (Oh) excavated at depths of 5-10cm, below the Ol and Of horizons. In order to ensure that experimental results would reflect field soil conditions it was necessary to take the following precautions. To inhibit microbial activity and moisture loss in the peat between collection and laboratory analysis, each sample was immediately sealed inside an impermeable polythene bag, with the air expelled from the container, and stored in refrigeration at $5^{o}C$ within 8 hours of collection. All samples were collected within a 30 hour period and laboratory treatment was initiated within 48 hours following the start of cold storage.

Laboratory procedure

There are several techniques for extracting humic substances from soils, the various methods have been reviewed by Hayes (1985) and Parsons (1988). In the work reported here acidified distilled water was used as a solvent since the objective was to determine the maximum yield (size of store) of water soluble colour and not to speciate the colour store into its humic fractions. A similar approach to this was adopted by Mitchell (1990b) to investigate colour dissolution processes in peat and by Martin (1992) in experiments simulating the effects of land management (burning and lime application) on colour store levels and solubility in moorland peat soils.

Each peat sample was thoroughly broken up and passed wet through a 2mm aperture sieve, a sub-sample of $50.0 \pm 0.1g$ was taken. The sub-samples were each put into solution with 500ml of distilled water (1:10 w/v) which had been adjusted to pH 5.0 ± 0.1 with 0.1M

Table 1. **Average gravimetric soil moisture content (%) for the sampling plots at Langstrothdale and Eskdalemuir.**

Site	Spruce	Pine	Moor	Ride
Langstrothdale	74.4 ± 1.5*	76.4 ± 0.9	79.5 ± 2.9	78.8 ± 2.0
Eskdalemuir	73.0 ± 2.0	75.9 ± 2.2	79.4 ± 2.3	78.5 ± 1.7

Each value is the arithmetic mean ± 1 standard deviation for replicate samples at each plot.
For each sample plot n=15, except * where n=12.

Table 2. **Average day 49 colour levels ($aum^{-1}g^{-1}$) for the sampling plots at Langstrothdale and Eskdalemuir.**

Site	Spruce	Pine	Moor	Ride
Langstrothdale	12.4 ± 2.0*	9.7 ± 1.1	8.9 ± 0.8	9.2 ± 0.9
Eskdalemuir	10.7 ± 0.7	9.8 ± 1.3	9.0 ± 0.9	9.1 ± 0.8

Each value is the arithmetic mean ± 1 standard deviation for replicate samples at each plot.
For each sample plot n=15, except * where n=12.

H_2SO_4. Once a week the solution bottles were placed on an orbital shaking table at 200 rpm for 15 minutes to ensure that the solutions became fully mixed.

Change in solution colour was monitored on a once weekly basis over a seven week period. Solution true colour (DOE, 1984; Mitchell & McDonald, 1992c) was measured by drawing off a 15ml aliquot and recording the optical density at 400nm on a Pye-Unicam u/v Visible Spectrophotometer, after 0.45µm membrane filtration. Results were expressed in units of absorbance per metre (aum^{-1}), where $1aum^{-1}$ is equivalent to $15mgl^{-1}$ on the Hazen scale (Mitchell & McDonald, 1992c). The filtered samples were returned to the solution after colour determination so as to minimise any disturbance to the soil: water ratio.

Gravimetric moisture content analysis was performed on all samples. Average moisture contents for each plot is given in Table 1. The colour data was subsequently corrected for moisture content and the results are expressed in units of colour yield per gram of dry soil ($aum^{-1}g^{-1}$). This correction eliminates bias introduced by differential soil water contents when the samples were weighed out and put into solution. Tipping & Hurley (1988) adopted a similar approach to this except they suspended field moist samples as 1g dry weight equivalents based upon the gravimetric moisture content of their samples.

RESULTS AND DISCUSSION

Colour dissolution

Colour dissolution rates over the experimental period are depicted in Figures 4 and 5 for the Langstrothdale and Eskdalemuir samples respectively. Solution colour for all samples increased during the experimental period. Dissolution rates were fastest during the initial part of the experiment after which dissolved colour levels attained near constant levels. These maximum values were assumed to represent chemical equilibrium with regard to colour dissolution within the solution. Therefore, the final colour measurement (day 49) represents the maximum potential for the peat sample to discolour water and is an indication of the magnitude of the store of water discolouring humics within the peat sample, *ie*: size of colour store.

Colour dissolution is pH dependent. Increasingly alkaline solvents promote increasing total colour release into solution (Tipping, 1987). Conversely, highly coloured waters are often acidic due to the release of humic acids into solution. Experimental conditions were such that initial solvent pH was a constant (pH 5.0). Therefore, it is not thought that the colour differentials in this experiment are a result of pH dependent solubility since mean solution pH's of all samples were in a narrow range (3.63 - 4.13) at the end of the experiment and the most

Figure 4. Pattern of colour dissolution, Langstrothdale samples.

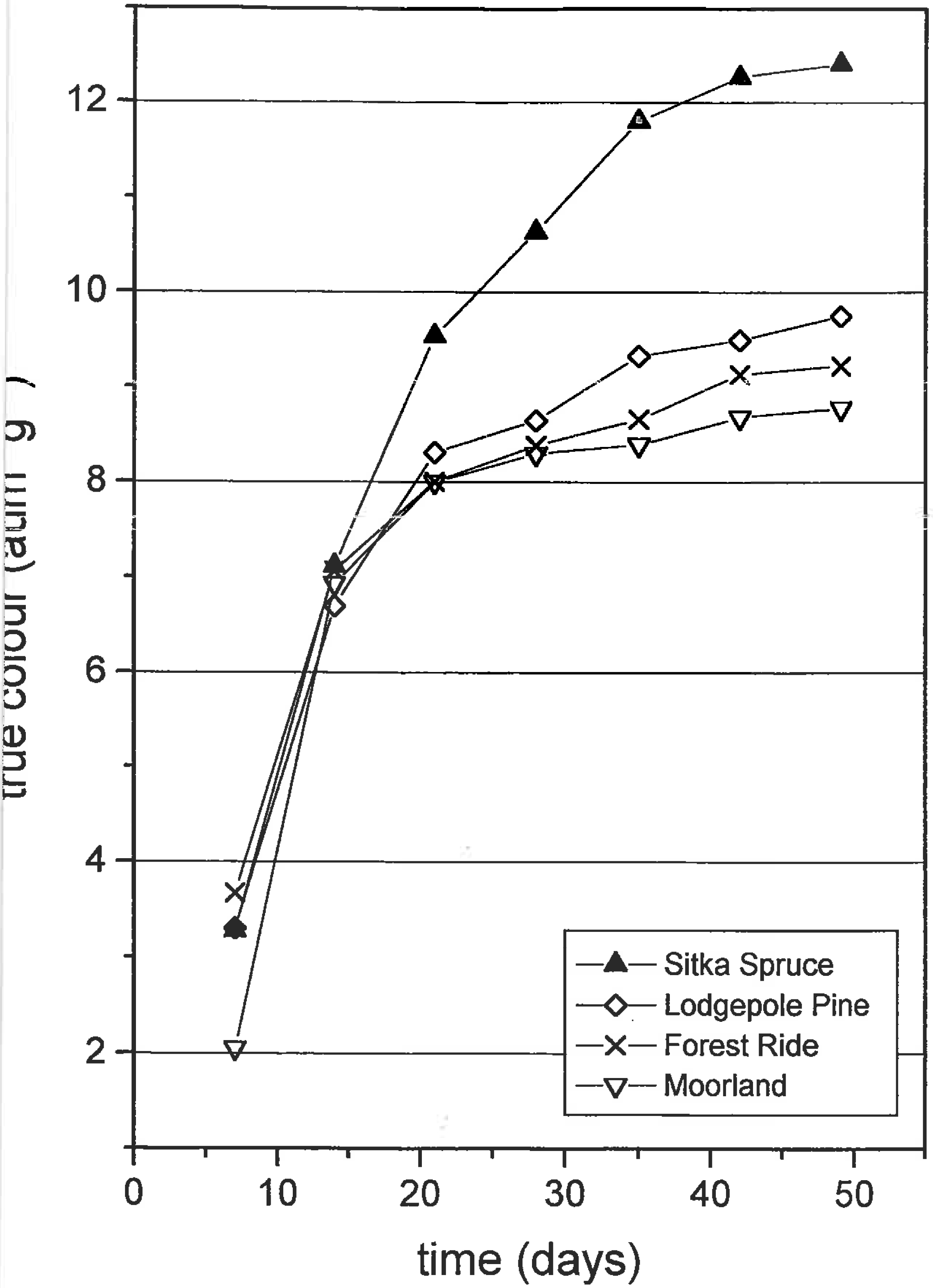
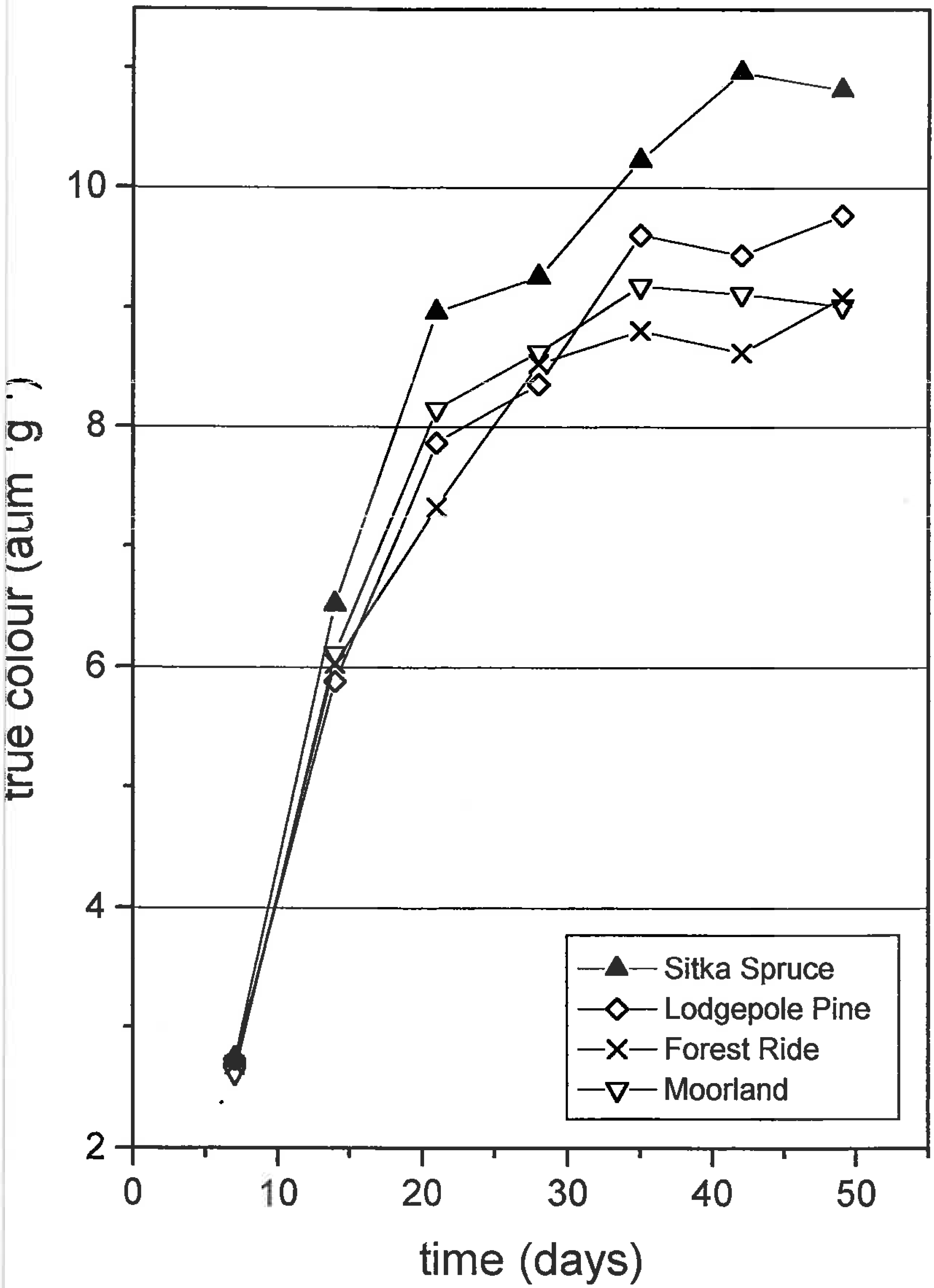


Figure 5. Pattern of colour dissolution, Eskdalemuir samples.



highly coloured solutions were the most acidic (Figure 6). This indicates that solution colour variations are a result of the amount of stored colour forming matter (fulvic acid fractions) released into solution.

Comparisons between the average colour store in each plot

Mean and standard deviation colour yield for each site is given in Table 2 and in Figure 7. The research hypothesis was tested by assessing the statistical significance of the differences between each plot using independent sample comparison tests. Following an assessment of the sample distributions and variance, the non-pooled Student's t-test was applied to the data set. Tables 3 and 4 give the test results for Langstrothdale and Eskdalemuir respectively.

At the Langstrothdale site, the largest colour store was found underneath the dense Sitka Spruce canopy. This proved to be a significantly greater amount than under each of the other plots ($p<0.001$ for each test). Lodgepole Pine held the second largest store of colour forming matter, a significantly greater amount than the dry moorland plot, but although it can be seen that mean stored colour was slightly higher than that for the grassed ride this was not proven to be a significant difference at the 95% level. The level of stored colour in the forest ride plot was not proven to be greater (or different) from that in the dry moorland plot.

A similar pattern, in terms of the relative level of the colour stored under the different vegetations, was observed at the Eskdalemuir site. The Sitka Spruce plot had a significantly higher store of colour than under Lodgepole Pine ($p=0.01$), forest ride ($p<0.001$), and moorland ($p<0.001$). The Pine plot contained a significantly greater store of colour than both the forest ride ($p=0.043$) and moorland ($p=0.036$) plots. As with the Langstrothdale site, there was no observed difference between colour yield from the forest ride and moorland samples.

The results show a consistent pattern at both field sites. The afforested peat soils contain a larger store of colour than the soils under the grassed forest ride and the dry moorland sites. It is thought that these results are a reflection on the greater degree of peat decomposition in the more aerobic conditions found under the forest canopy.

The comparison of colour stores under the two tree species yielded results showing that peat planted with Sitka Spruce contains a larger store of colour forming substances than Lodgepole Pine soils. Several authors have noted that due to deeper rooting, Lodgepole Pine produces a greater drying effect in peat to a greater depth than Sitka Spruce (Pyatt, 1976; Ray & Schweizer, 1994). This might suggest that on the basis of the relative soil drying intensities, there should have been no observable difference in the amount of stored colour under the two species, or perhaps a greater store of the decomposition products under Lodgepole Pine.

Figure 6. Relationship between mean solution colour and pH. Error bars represent ± 1 standard deviation.

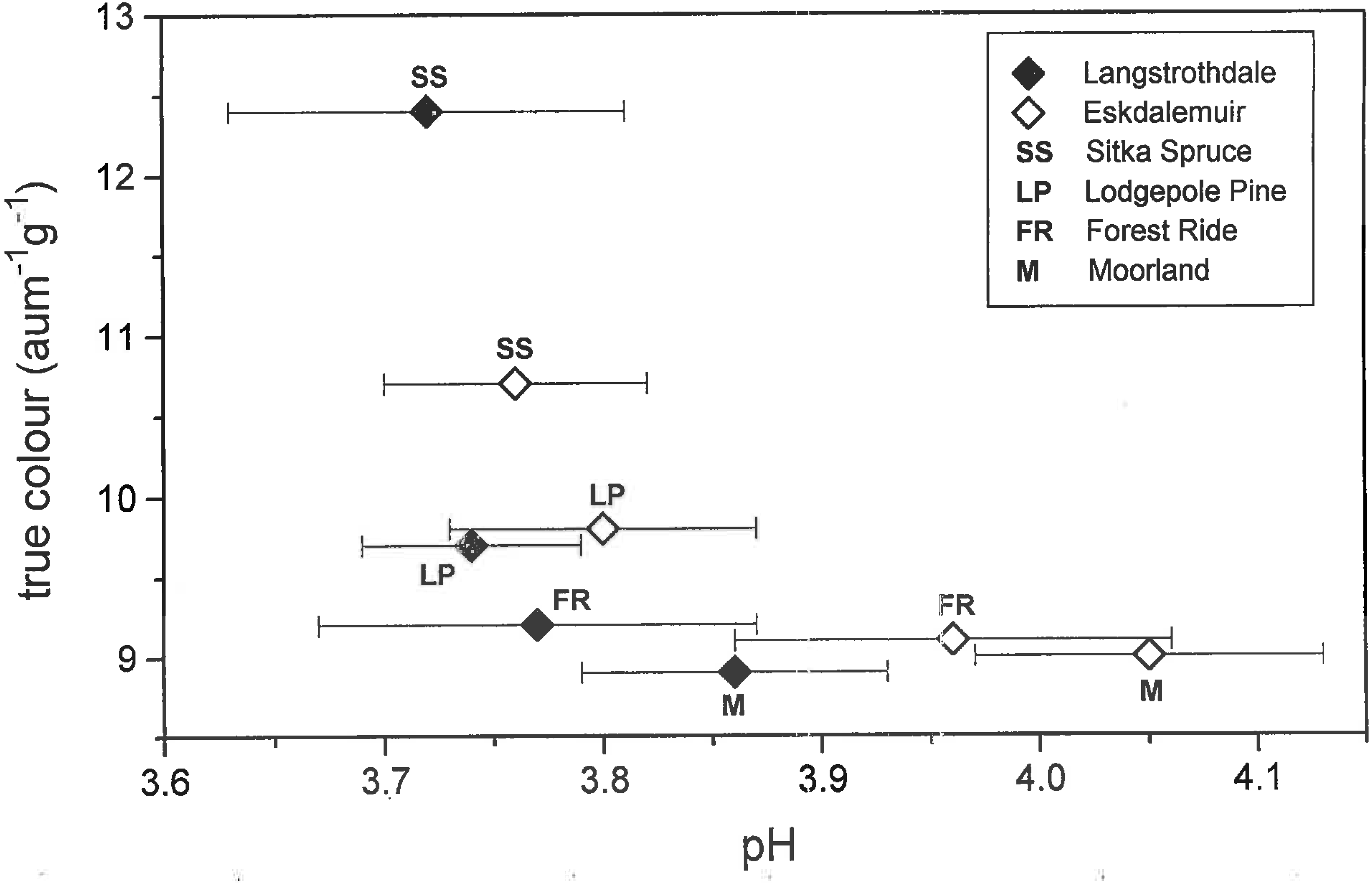


Figure 7. Maximum colour yield (day 49) from Langstrothdale and Eskdalemuir peat samples. Error bars represent ± 1 standard deviation.

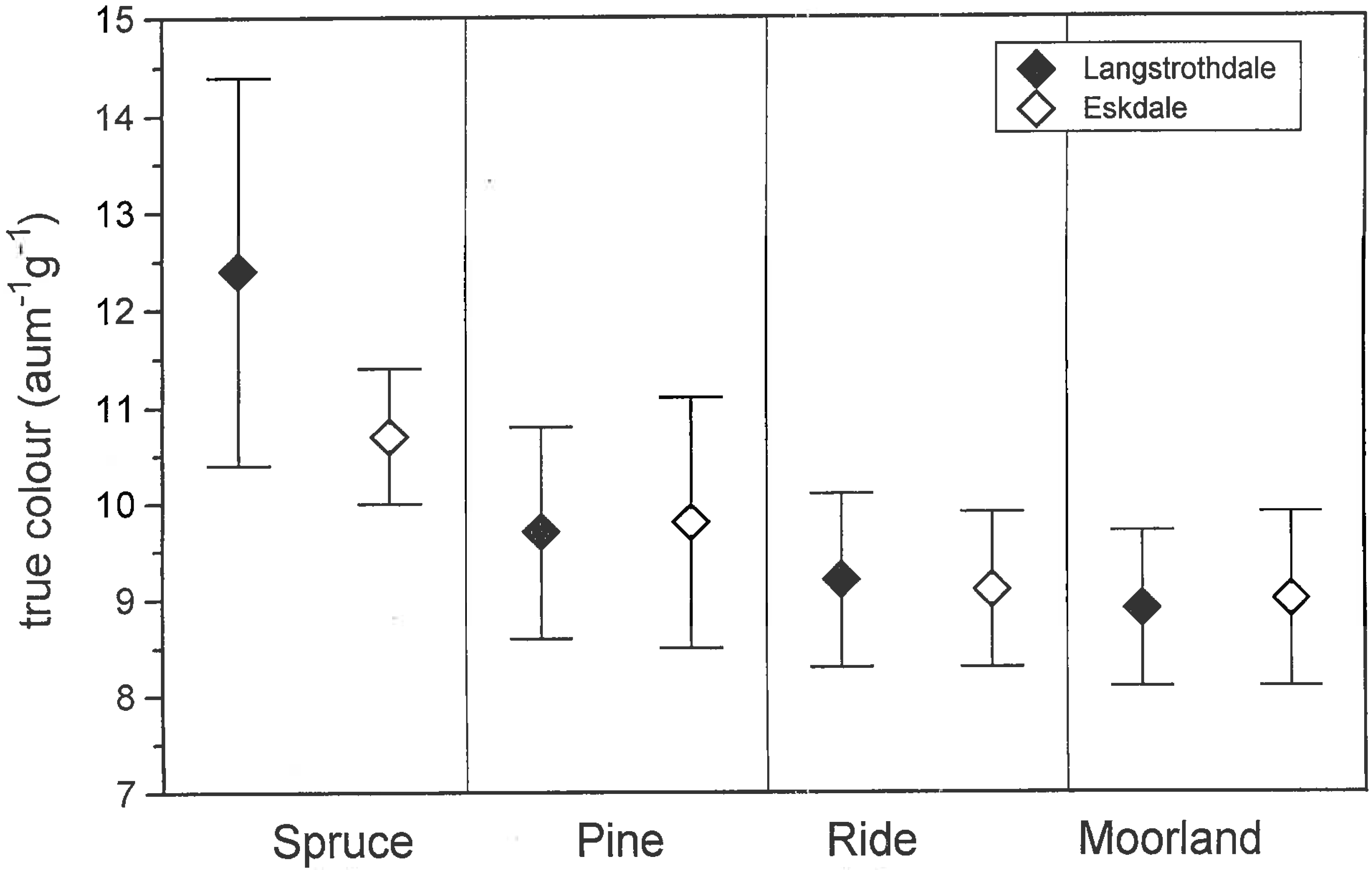


Table 3. **Results of non-pooled Student's t-tests for the difference in mean day 49 colour levels from the sampling plots at Langstrothdale.**

	Spruce*	Pine	Moor
Pine	Spruce > Pine t=4.22, p<0.001, df=16	———	———
Moor	Spruce > Moor t=5.75, p<0.001, df=13	Pine > Moor t=2.29, p=0.015, df=25	———
Ride	Spruce > Ride t=5.95, p<0.001, df=16	Pine = Ride t=1.42, p=0.083, df=27	Moor = Ride t=-0.94, p=0.180, df=27

For each sample plot, n=15, except * where n=12
Logical operators: significantly greater than (>), not significantly different from (=)

Table 4. **Results of non-pooled Student's t-tests for the difference in mean day 49 colour levels from the sampling plots at Eskdalemuir.**

	Spruce	Pine	Moor
Pine	Spruce > Pine t=2.50,p=0.010,df=21	———	———
Moor	Spruce > Moor t=5.99,p<0.001,df=26	Pine > Moor t=1.88,p=0.036,df=24	———
Ride	Spruce > Ride t=5.99,p<0.001,df=27	Pine > Ride t=1.79,p=0.043,df=23	Moor = Ride t=-0.15, p=0.880, df=27

For each sample plot, n=15
Logical operators: significantly greater than (>), not significantly different from (=)

Results from this experiment show that moisture contents were higher in Lodgepole Pine and that stored colour was lower. At both sites a fuller canopy coverage was observed in the Sitka Spruce stands, with a lower light intensity and a total absence of the ground flora which was observed in places under Lodgepole Pine. This allows a more efficient interception and evaporation of precipitation at the Spruce canopy and due to a denser distribution of roots in the near-surface horizons, a more efficient drying through greater evapotranspiration losses. It is therefore to be expected that the soils beneath Sitka Spruce are dryer than elsewhere and consequently microbiological activity and colour production processes are more active. Mitchell (1990b) found that peat decomposition rates are greater in the more aerobic peat conditions and that optimum colour production process rates are achieved at an intermediate moisture content of 70%, similar to those observed for Sitka Spruce in this experiment (Table 1). The details of these relationships are the subject of current further laboratory studies.

It was originally hypothesised that forest ride colour stores would be greater than moorland colour stores. The rationale behind this was based on the assumption that the lower water-table under the forest canopy would be carried over for some distance in the adjacent non-forest vegetation. Although mean stored colour was found to be slightly higher in the forest ride plots than in the moorland plots, statistical tests show that the magnitude of stored colour is not significantly different. These results indicate that forest stands do not have as significant an effect on the surrounding soil moisture conditions as was originally hypothesised. Forest-ride soil moisture contents and colour store levels, sampled at approximately 15m from the tree stands, are close to those of the moorland plots which were sampled at a distance of approximately 80m from outside of the forest boundary.

CONCLUSION

Results from these experiments show that the production of soluble colour forming matter is significantly greater under coniferous forest vegetation than under adjacent grass moorland at the sites in this study. This conclusion is consistent with theories suggesting that forest vegetation promote a greater degree of drying and oxidation in peat soils than under moorland.

Although it would seem that there is a greater potential for water discoloration by forest soils, the realisation of this potential problem is also a function of solubilisation and runoff processes. Afforested peat soils have a water-table level well below the surface for much of the year (Pyatt & Craven, 1979). It is only during the most extreme storm events, or during periods of prolonged rainfall or snow-melt that the water-table might remain at the surface for a time sufficient to solubilise a large part of the colour store. In this experiment it was shown that, at 100% saturation, a period of 49 days was required for a complete release of water available colour from the soil. In the near surface horizons of upland coniferous stands it is common to find that rooting and drying, leads to cracking and macropore development, which might favour the bypass of flow away from the colour containing matrix. This results in a further reduction in the potential for colour solution and runoff. The chemistry of the planted soil might also act to lower the potential for colour runoff. For example, the more acidic soil-waters found in coniferous stands (Hornung, 1985) inhibit the dissolution of the soil humic substances (Tipping, 1987).

In moorland areas, colour runoff is a more consistent and regular event, colour hydrochemistry is more responsive to summer and winter wetting and drying cycles, the highest colour flushes result from the most intense and prolonged peat drying events (Figure 1). Following felling of afforested catchments, the water table rises, the colour store can then be more readily solubilised and flushed in response to the seasonal wetting and drying patterns. This work shows that it is the magnitude of the store of water-soluble colour forming substances that might be a cause for concern. It is appropriate for forest managers involved in large scale felling operations on peat soils to consider the effects on water chemistry that might result from the modified hydrology.

ACKNOWLEDGEMENTS

The authors would like to thank the Forest Enterprise, Ae Forest District, Dumfries & Galloway, and Tilhill Economic Forestry, Kirkby Lonsdale, Lancashire for permitting field work and for supplying stock and soil maps for the two field sites.

REFERENCES

BIRCH, H.F. (1958a). Effect of Soil Drying on Humus Decomposition and Nitrogen Availability. *Plant and Soil*, **10**, 9-31

BIRCH, H.F. (1958b). Further Aspects of Humus Decomposition. *Nature*, **182**, 9-31

CALDER, I.R. (1979). Do Trees Use More Water Than Grass? *Water Services*, **83**, 11-14

CALDER, I.R. (1990). *Evaporation in the Uplands*. Wiley : Chichester. 148pp

CRESSER, M.; KILLHAM, K. & EDWARDS, A. (1993). Soil Chemistry and its Applications. *Cambridge Environmental Chemistry Series*, **5**. Cambridge University Press : Cambridge. 192pp

DEPARTMENT OF THE ENVIRONMENT (1984). *Methods for the Examination of Waters and Associated Materials - Colour and Turbidity of Waters 1981 Tentative Methods*. HMSO : London. 25pp

EDWARDS, A.M.C. (1987). Coloured Runoff in the Yorkshire Pennines and its Consequences for Water Supply. In: *Colour in Upland Waters*. Edwards, A.M.C.; Martin, D.S.J. & Mitchell, G.N. (Eds.). Proceedings of YWA and WRc Workshop, Leeds, 29th September 1987. pp1-8

HAYES, M.H.B. (1985). Extraction of Humic Substances from Soils. In: *Humic Substances in Soil, Sediment, and Water - Geochemistry, Isolation, and Characterization*. Aitken, G.R.; McKnight, D.M.; Wershaw, R.L.; & MacCarthy, P. (Eds.). Wiley : New York. pp329-362.

HORNUNG, M. (1985). Acidification of Soils by Trees and Forests. *Soil Use and Management*, **1(1)**, 24-28

HORNUNG, M.; STEVENS, P.A. & REYNOLDS, B. (1986). The Effects on Soils, Soil Water and Surface Water Chemistry. In: *Environmental Aspects of Plantation Forestry in Wales*. Good, J.E.G. (Ed.). Proceedings of ITE symposium No.22, Snowdonia, November 1986. pp25-36

KAY, D.; BOON, R. & CROWTHER, J. (1989). Coloured Waters in Wales: Spatial and Temporal Trends. In: *Proceedings of the BHS Second National Hydrology Symposium*, University of Sheffield, 4-6th September 1989. pp49-57.

KONONOVA, M.M. (1961). Soil Organic Matter: Its Nature, Its Role in Soil Formation and in Soil Fertility. Pergamon Press. 450pp

LÅNGVIK, V. & HOLMBOM, B. (1994). Formation of Mutagenic Organic By-Products and AOX by Chlorination of Fractions of Humic Water. *Water Research*. **28(3)**, 553-557

LIVENS, F.R. (1991). Chemical Reactions of Metals with Humic Material. *Environmental Pollution*, **70**, 183-208

LUCAS, S. (1986). Beating Brown Water. *Water Bulletin*, **19**, 19th September 1986, pp8-9

MARTIN, D.S.J. (1992). *The Influence of Land Management on Upland Water Quality Notably the Production of Soluble Colour in Supply*. Unpublished PhD Thesis, School of Geography, University of Leeds. 400pp

McDONALD, A.T. (1973). Some Views on the Effects of Peat Drainage. *Scottish Forestry*, **27(4)**, 315-327

McDONALD, A.T.; EDWARDS, A.M.C.; NADEN, P.S.; MARTIN, D.S.J. & MITCHELL, G.N. (1989). Discoloured Runoff in the Yorkshire Pennines. In: *Proceedings of the BHS Second National Hydrology Symposium*, University of Sheffield, 4-6th September 1989. pp59-64.

McDONALD & KAY (1987). The Strategic Implications of United Kingdom Catchment Research: Problems and Solutions. *Working Paper*, **490**, School of Geography, University of Leeds. 17pp

McDONALD, A.T.; MITCHELL, G.N.; NADEN, P.S. & MARTIN, D.S.J. (1991). *Discoloured Water Investigations*. Final report to Yorkshire Water plc. 432pp

MITCHELL, G.N. (1990a). Natural Discoloration of Freshwater: Chemical Composition and Environmental Genesis. *Progress in Physical Geography*, **14(3)**, 317-334

MITCHELL, G.N. (1990b). *Aspects of Solute Movement in the British Uplands*. Unpublished PhD Thesis, School of Geography, University of Leeds. 321pp

MITCHELL, G.N. & McDONALD, A.T. (1992a). Discoloration of Water by Peat Following Induced Drought and Rainfall Simulation. *Water Research*, **26(3)**, 321-326

MITCHELL, G.N. & McDONALD, A.T. (1992b). Characterisation of Non-Point Colour Sources in North Yorkshire, UK. *Working Paper*, **92/8**, School of Geography, University of Leeds. 22pp

MITCHELL, G.N. & McDONALD, A.T. (1992c). Relationship Between Different Methods of Colour Measurement in Potable Water. *Measurement and Control*, **24(10)**, 306-309

NADEN, P.S. & McDONALD, A.T. (1987). Statistical Modelling of Water Colour in the Uplands: The Upper Nidd Catchment 1979-1985. *Working Paper*, **478**, School of Geography, University of Leeds. 19pp

NADEN, P.S. & McDONALD, A.T. (1989). Statistical Modelling of Water Colour in the Uplands: The Upper Nidd Catchment 1979-1987. *Environmental Pollution*, **60**, 141-163

OTTO, C. & SVENSSON, B.S. (1983). Properties of acid brown water in streams in South Sweden. *Archiv Fur Hydrobiologie*. **99**. 15-36

PARSONS, J.W. (1988). Isolation of humic substances from soil and sediments. In: *Humic Substances and Their Role in the Environment*. Frimmel, F.H. & Christman, R.F. (Eds.). Wiley : Chichester. pp3-14

PYATT, D.G. (1976). Classification and improvement of upland soils - deep peats. *Report on Forest. Research*. Forestry Commission. pp24-25.

PYATT, D.G. & CRAVEN, M.M. (1979). Soil Changes Under Even-Aged Plantations. In: *The Ecology of Even-Aged Forest Plantations*. Ford, E.D., Malcolm, D.C. & Atterson, J (Eds.). ITE : Cambridge, UK. pp369-386

RAVEH, A. & AVNIMELECH, Y. (1978). The Effect of Drying on the Colloidal Properties and Stability of Humic Compounds. *Plant and Soil*, **50**, 545-552

RAY, D. & SCHWEIZER, S. (1994). A Study of the Oxygen Regime and Rooting Depth in Deep Peat under Plantations of Sitka Spruce and Lodgepole Pine. *Soil Use and Management*, **10**, 129-136

TIPPING, E. (1987). Solid Solution Interactions in Acid Organic Soils and their Effect on Colour of the Soil Solution. In: *Colour in upland waters*. Edwards, A.M.C.; Martin, D.S.J. & Mitchell, G.N.(Eds.). Proceedings of YWA and WRc workshop, Leeds, 29th September 1987, pp43-46

TIPPING E. & HURLEY, M.A. (1988). A Model of Solid-Solution Interactions in Acid Organic Soils, based on the Complexation Properties of Humic Substances. *Journal of Soil Science*, **39**, 505-519