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Effects of plantation forest clearfelling on stream temperatures in the Plynlimon experimental catchments, mid-Wales

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Abstract

Hourly stream temperatures monitored over 28 months, which spanned a 3 month period of environmentally sensitive plot-scale harvesting of 20 ha. (20%) of the Nant Tanllwyth catchment (0.89 km^2) on the south side of the main stream in early 1996, resulted in a 0.58°C ($p < 0.001$) increase in monthly mean stream temperature. Over the same 28 month experimental period, there was no significant increase in the monthly mean air temperature recorded at a nearby automatic weather station. Monthly mean temperatures are highest in July and August in the year before and the year after the clearfelling, and one of the main effects of the clearfelling was to decrease the difference between the monthly mean stream and air temperatures. Despite the air temperatures being cooler in the post-clearfelling year, the stream temperatures still showed an increase in the summer months.

Monthly mean maximum stream temperatures, also highest in July and August in the year before and the year after the clearfelling, showed a marked increase of 7.0°C in July and 5.3°C in August from the pre- to the post-clearfelling years, while monthly mean minimum air temperatures actually showed a slight decrease for the same months. The likely effects on stream fauna are discussed, as are suggestions for, and likely effects of, buffer strips alongside the streams.

Keywords: stream temperature; air temperature; ground surface temperature; clearfelling; Plynlimon

Introduction

One of the most important factors determining stream water vitality is temperature (Smith, 1979). Several studies have reported on the temperatures of small streams in the UK (Macan, 1958; Eddington, 1966; Crisp and Le Cren, 1970; Roberts and James, 1972; Walling and Webb, 1981; Webb and Walling, 1986; Crisp, 1997). Various studies have isolated the important effect which stream temperature has on stream fauna. For example, the time of hatching of invertebrates (Elliot, 1972) and of eggs (Elliot, 1972; Humpesch and Elliot, 1980) and the incubation time for eggs of Chinook salmon (Alderdice and Velsen, 1978) are all affected by temperature. Macan (1961) has reviewed the importance of temperature as an environmental factor in the biology of aquatic animals while Zimmerman (1974) developed an early model for predicting the daily temperature cycle of natural streams.

Changes in upland land use such as afforestation and deforestation can affect stream temperature. Most previous studies of the effects of coniferous forest on stream temperatures come either from North America (Corbett *et al.*, 1978; Feller, 1981; Lynch *et al.*, 1984; Rishel *et al.*, 1982) or New Zealand (Rowe and Pearce, 1994) where the scale of rivers, and environmental conditions are usually very different from the UK. Clearfelling of plantation forests in the British uplands is now becoming widespread and it is important to assess the impact of clearfelling on stream temperatures. In Westland, New Zealand, Rowe and Pearce (1994) reported that streams in harvested native forest showed mean temperature increases in summer of 5.5°C and streams in a harvested area were up to 11°C warmer than in an adjacent control catchment. Clear-cut logging can increase the temperature of small streams significantly (Levno and Rothacher, 1967; Brown and Krygier, 1970; Swift and Messer, 1971). Ringler and Hall (1975) reported on the effects of logging on water temperature and dissolved oxygen in spawning beds and Holtby (1988) discussed the effects of logging on stream temperatures and the associated impacts on the coho salmon (*Oncorhynchus kisutch*). In a small tributary of the River Coquet at Rothbury in northern England, Gray and Edington (1969) also reported a marked increase of 6.5°C in summer temperatures in a stream after clearfelling deciduous woodland compared to the same stream further upstream where it flowed through fields.

Afforestation has been the largest single land-use change in Britain this century, and reached a peak rate of 40 000 ha yr^{-1} in the early 1970s (Robinson and Blyth 1982). The total area covered by forest and woodland has increased by 18% since 1980 though there has been a stabilisation in conifer forest cover in recent years and a decline in new planting since the peaks reached in the late 1980s (DETR, 1998). Historical patterns of afforestation in England, Scotland and Wales have differed slightly; respective peaks of planting occurred in England in the period 1955–59 (12,000 ha y^{-1}), in Scotland in 1970–74 (35 000 ha y^{-1}), and in Wales in 1960–64 (6 000 ha y^{-1}) (Ormerod and Edwards, 1985). These peaks have resulted in differences in age structures of forests between regions of Britain and thus harvesting times will differ. To date, only a relatively small proportion of the timber planted in this century has been harvested.

Data on the effects of clearfelling on stream temperatures in the UK are now becoming available. Roberts and James (1972) compared unafforested streams of the upper Wye with afforested catchments in the upper Severn in mid-Wales. Weekly 'spot' temperature recordings concluded that summer temperatures were 2.4°C higher in the Wye than in the Severn, whereas in winter the Severn was up to 0.6°C warmer than the Wye though the statistical comparison of these findings should be taken with caution as they are based on relatively infrequent sampling. Smith (1980) working on the Kirk Burn, a tributary of the River Tweed, Scotland, concluded that shading by conifers reduced diurnal and seasonal fluctuations in stream temperature and that the water was relatively cooler in summer and warmer in winter. Weatherley and Ormerod (1990) monitored stream temperature on a number of afforested and unafforested sub-catchments of the River Tywi, Wales, and concluded that forests caused lower mean and maximum summer temperatures in the streams beneath them. Neal *et al.* (1992) made comparisons between the stream temperature of the Afon Hore and Afon Hafren on Plynlimon and found that deforestation caused stream temperatures to rise during the summer by 4–9°C and that this rise in temperature seems to increase progressively each summer for the first four years following harvesting. The overall change reported by Neal *et al.* (1992) shows almost identical patterns to those observed at Plynlimon between moorland and forest streams by Kirby *et al.* (1991). Crisp (1997) collected water temperature data from five stations in the upper Severn catchment: two on the Afon Hore (clearfelled) and three on the Afon Hafren (mature forest) and concluded that the effect of forest cover was to lower the annual mean water temperature by c. 0.4°C, mainly in summer and through depression of both daily maxima and daily minima, though mainly the former.

This paper reports the changes in stream temperature over a two year period during which modern plot-scale harvesting techniques were used to clearfell around one fifth of the 0.89 km^2 Nant Tanllwyth catchment in the head-waters of the River Severn on Plynlimon. The authors believe this is the first UK study of the effects of clearfelling on stream temperature that is based on data covering the before, during and after phases of clearfelling.

Location

The Plynlimon Catchments Experiment (Fig. 1 a) was established by the UK Institute of Hydrology (IH hereafter) in 1968 with the initial aim of investigating the effects of upland afforestation on water yields (Newson, 1979; Kirby *et al.*, 1991; Hudson and Gilman, 1993) but subsequently for research into the effects of forestry on water quality (Neal *et al.*, 1988, 1990) and sediment transport (Newson, 1980; Arkell *et al.*, 1983; Moore and Newson, 1986; Leeks and Roberts, 1987; Leeks, 1992; Marks, 1995; Stott and Marks, 1998). The physiography, deposits and vegetation of the catchments are described by Newson (1976). The Upper Severn, which is predominantly forested, is 8.7 km^2 in area and was 68% mature coniferous forest prior to the start of timber harvesting in the late 1980s. This study took place on the Nant Tanllwyth, a tributary of the River Severn with catchment area of 0.89 km^2 (Fig. 1). The altitude of the study site is approximately 350 m AOD and mean annual precipitation is of the order of 2400 mm.

Methods

Hourly air, ground surface and stream temperatures were recorded over a period of two and a half years from October 1994 to March 1997. The stream temperature of the Nant Tanllwyth was taken at a point in the middle of the channel where the flow entered a bedload trap (Fig. 1b). Hourly data were logged automatically and downloaded monthly. Hourly air temperatures were measured by the Moel Cynedd automatic weather station (AWS) situated in a clearing in the forest some 200 m east of the bedload trap where stream temperature was recorded (see Fig. 1 b). Ground surface temperatures were also logged by a thermistor fixed onto the bare soil surface of a stream bank above normal flood stages as part of a bank erosion study reported elsewhere (Stott, 1999). This was first located under the mature forest canopy (X on Fig. 1 b, from July 1995–March 1996), and later in a clearfelled area (Y on Fig. 1 b, from March 1996 onwards). Both sites were devoid of understory vegetation. Hourly temperatures which coincided with those taken in the stream and at the Moel Cynedd AWS were logged by a Grant's Squirrel datalogger which was downloaded every 3 months. It is believed that the logger-temperature probe combinations were accurate to within ± 0.1°C (Crisp, 1997).

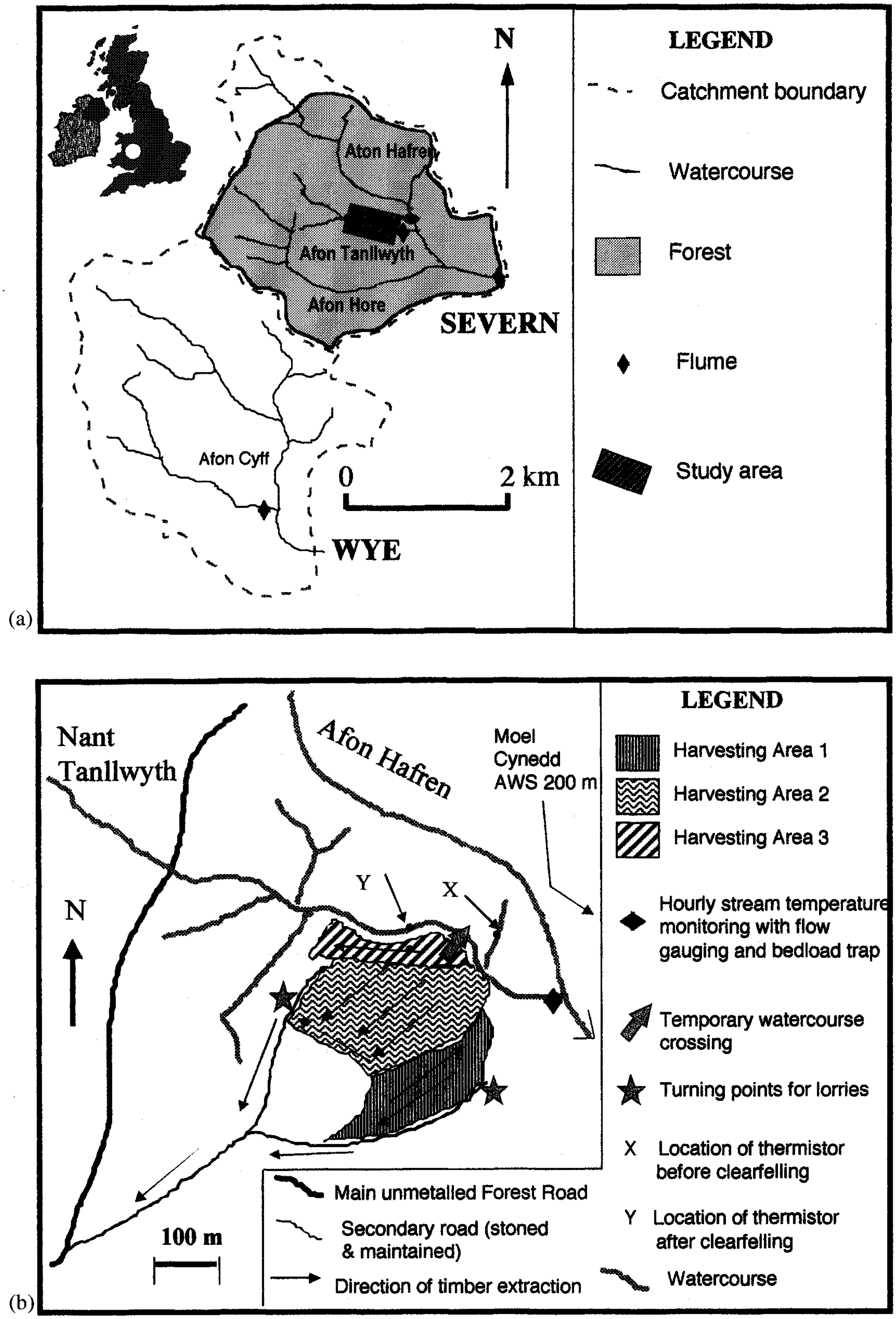

Fig. 1. *(a) Location of the Plynlimon Experimental Catchments. (b) Plan of instrumentation and clearfelling in the Nant Tanllwyth study area.*

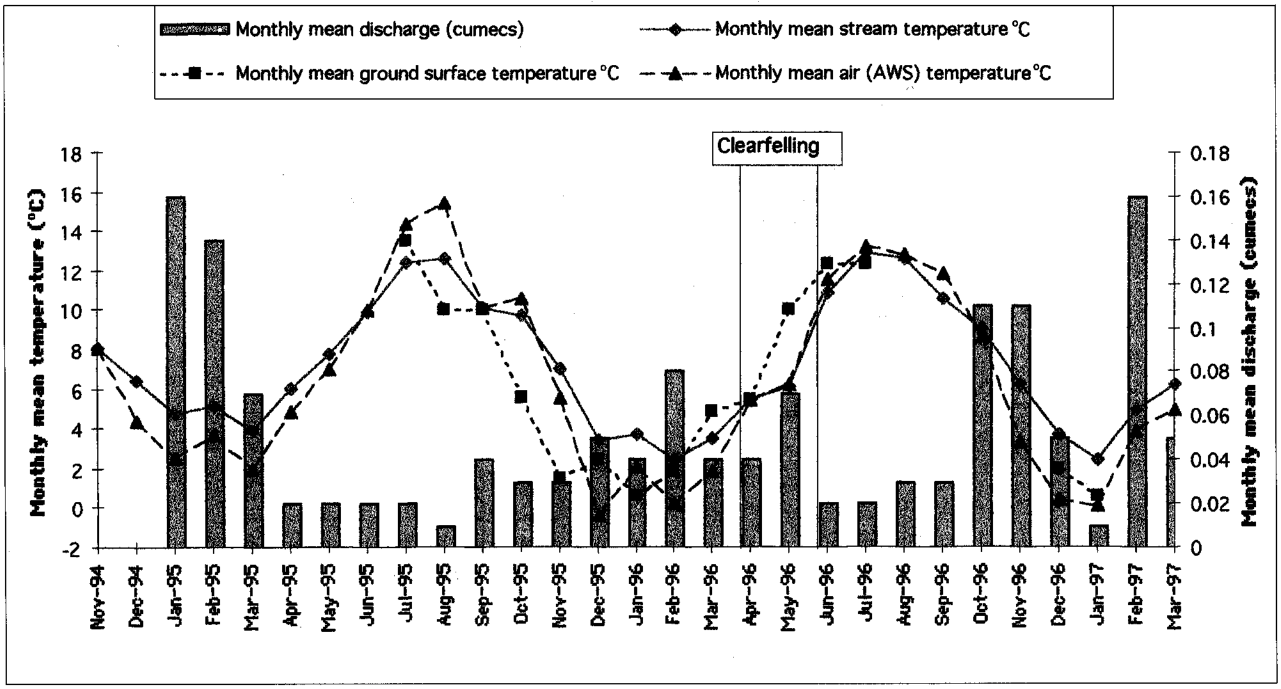

Fig. 2. *Monthly mean stream, ground surface and air temperatures throughout the study period (calculated from hourly records).*

Results and discussion

Figure 2 shows the temporal variation in stream, ground surface and air monthly mean temperatures, calculated from hourly data, with monthly mean stream discharge added for information. A clear seasonal pattern is evident with stream temperatures being higher than air temperatures in winter and lower in summer 1995 before clearfelling. This may be attributed to the insulating effect of the forest in winter, though this is not proven. In summer 1996, following the spring clearfelling (April-May 1996) however, the differences between stream and air temperatures became smaller. This could be a consequence of the partial loss of the aforementioned insulating effect following the environmentally sensitive plot-scale harvesting by Forest Enterprise of around 20 ha. (20%) of the catchment along the south bank of the stream. Table 1 shows that pre-clearfelling ground surface mean temperature under the forest (calculated using only months with complete data: August, September, December, January, February, March—the logger failed in October and November 1996) were significantly lower than for the same months in the post-clearfelling period. This is most likely due to the fact that the ground surface thermistor was moved (Fig. 1 b) from position X (on a drainage ditch beneath the forest canopy) to position Y on a stream bank in the clearfelled area soon after clearfelling was complete. The change in location is likely to have affected the receipt of solar radiation resulting in higher temperatures being recorded. Based on the findings of previous studies, we would have expected the ground surface temperatures in the clearfelled area to have been lower,

Table 1. Pre- and post-clearfelling temperature differences: *t*-test results.

	Pre-clearfelling (Jun '95 to Mar '96) mean	Post-clearfelling (Jun '96–Mar '97) mean	n	*t*-statistic	critical *t*-value	Significance
Air temperature (AWS) °C	7.09	7.04	6892	0.41	1.64	not significant
Stream temperature °C	7.55	8.13	6892	−8.27	1.64	$p < 0.001$
*Ground surface temperature °C	5.70	6.74	3191	−7.34	1.64	$p < 0.001$

NB All means calculated using hourly data
*Ground surface mean temperature calculated using only months with complete data: August, September, December, January, February, March. Means before and after clearfelling can be compared meaningfully but should not be compared with means calculated for air and stream temperature.

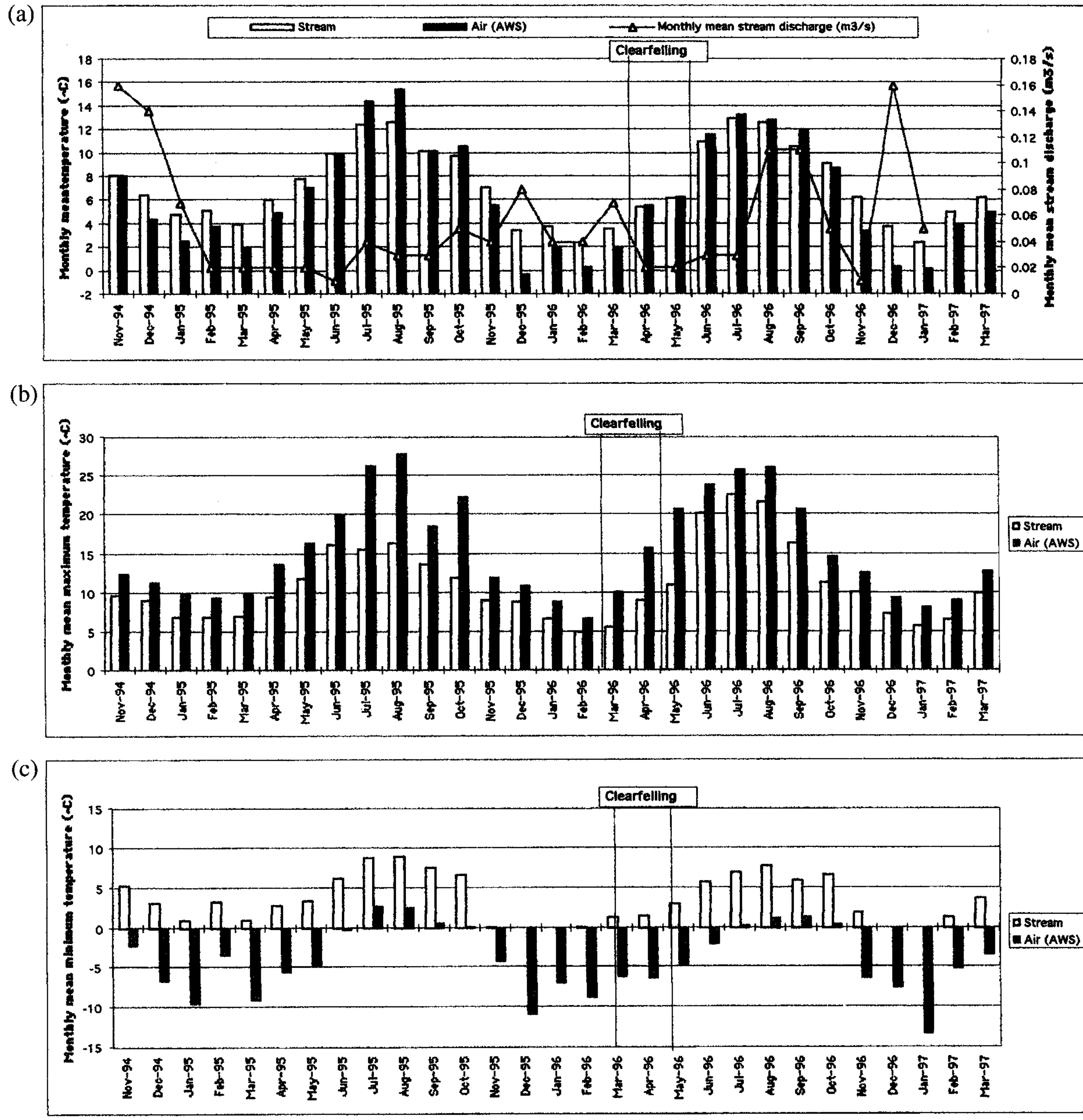

Fig. 3. *(a) Monthly mean stream and air (AWS) temperatures with monthly mean stream discharge plotted, (b) monthly mean maximum stream and air (AWS) temperatures, (c) monthly mean minimum stream and air (AWS) temperatures.*

especially in winter, due to the removal of the tree cover and exposure of the ground to night-time radiation losses.

Figure 3 shows the temporal variation in (a) monthly mean, (b) monthly mean maximum and (c) monthly mean minimum temperatures for both stream and air (AWS). The timing of the clearfelling is indicated; following clearfelling, a closer association between air and stream temperatures develops as shown by both monthly means (Fig. 3a) and monthly mean maximum temperatures (Fig. 3b). Stream monthly mean minimum temperatures are lower in the summer following clearfelling (Fig. 3c). Figure 4 highlights the differences between air and stream temperatures. Figure 4a clearly shows how the stream is warmer than the air outside the forest during each of the three winters in the study period. Conversely, the air is warmer during both summers, most likely caused by shading of the stream by the forest canopy (Boon and Shires, 1976) in summer when cloud cover is at a minimum. Whereas the monthly mean temperature difference between the air and stream in summer 1995 was between 2–3°C, in summer 1996 following clearfelling of only 20% of the stream catchment, the difference is less than 1°C during the months of June–September. In Fig. 4b, the difference between the monthly mean maximum air temperature and the monthly mean maximum stream temperature is reduced by 5–6°C in the summer following clearfelling. However, the difference

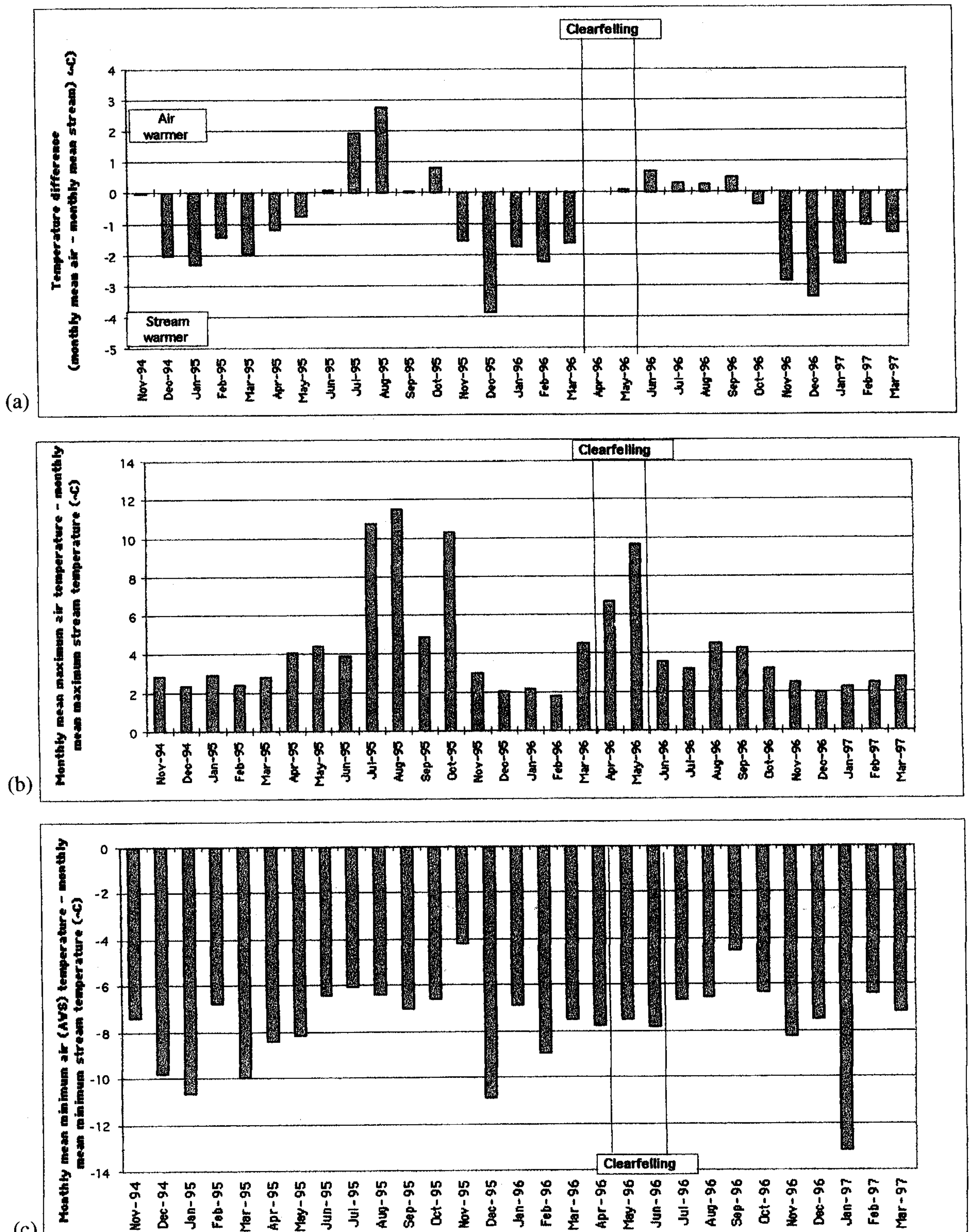

Fig. 4. *Differences between air and stream temperatures: (a) monthly means, (b) monthly mean maxima and (c) monthly mean minima.*

between the monthly mean minimum air temperature and monthly mean minimum stream temperature, plotted in Fig. 4c, appears less affected by the clearfelling operations than the monthly mean maximum and monthly mean, though the greatest difference between monthly mean minimum air temperature and monthly mean minimum stream temperature does occur in January 1997 in the post-clearfelling period.

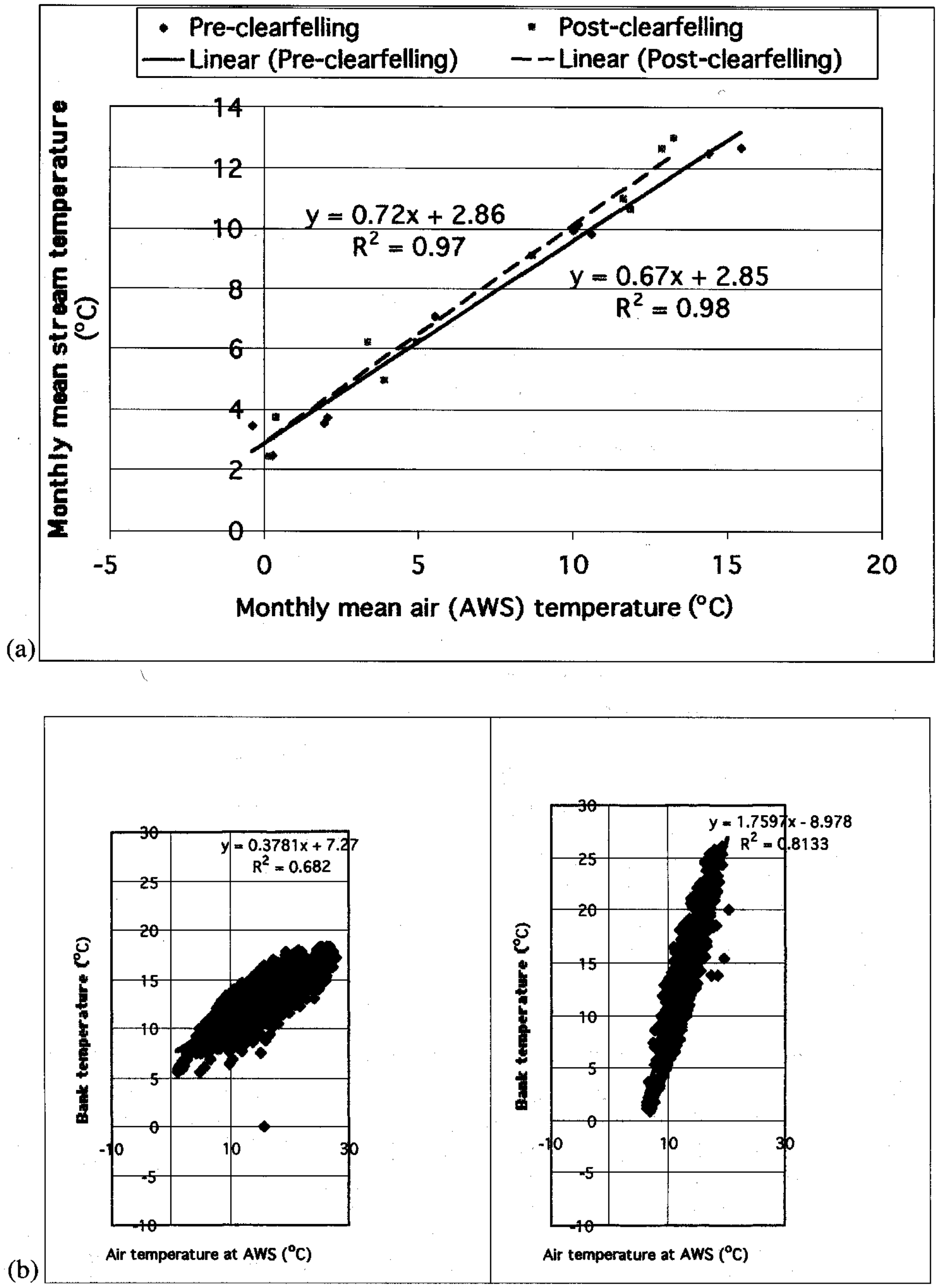

Fig. 5. *(a) Stream temperature vs air temperature relationship for June August 1995 (pre-clearfelling) and June–August 1996 (post-clearfelling). (b) Pre- (left) and post- (right) clearfelling ground surface (stream bank) vs. air temperature relationship.*

Figure 5a shows the approximately linear relationships between monthly mean air temperature and monthly mean stream temperature which is consistent with previous findings in upland streams of the north Pennines and English Lake District (Crisp and Howson, 1982). Clearfelling has reduced the gradient of the stream versus air temperature relationship, so that for air temperatures in the 10–15°C range (i.e. those likely to be experienced in the summer months), the post clearfelling relationship will predict a stream temperature of approximately 1°C higher than that using the pre-clearfelling relationship. However, at lower temperatures, such as those which may be experienced in winter, the difference between the relationships is negligible. This is likely to be a function of the fact that water, because of its higher thermal capacity and the latent heat effects of ice formation, cannot, unlike air, have a temperature significantly below 0°C. Figure 5 b shows that the effect of clearfelling has been to increase the gradient of the ground (bank surface) temperature vs air temperature relationship, due to the removal of the tree cover but the relationship remains approximately linear.

Table 1 shows *t*-test results for the pre- and post clearfelling phases of the study. The post-clearfelling period of the study (June 1996–March 1997 inclusive) is balanced with the equivalent time period in the pre-clearfelling phase (June 1995–March 1996 inclusive) so that the number of data points is equalised and a fair comparison can be made which is not seasonally biased. There is no significant difference in air (AWS) temperatures between pre- and post-clearfelling phases, whereas an increase in monthly mean stream temperature of 0.6°C from 7.6°C in the pre-clearfell phase to 8.1°C in the post-clearfell phase is statistically significant ($p < 0.001$). Crisp (1997) compared stream temperatures on the Afon Hore (a 335 ha clearfelled catchment to the south of the Nant Tanllwyth, Fig. 1) where the stream had flowed for c. 1.5 km through clear felled land with the Afon Hafren (a 347 ha catchment to the north of the Nant Tanllwyth, Fig. 1) where the stream had flowed for c. 2.5 km through mature coniferous forest. He concluded that the effect of forest cover was to lower the annual mean water temperature by c. 0.4°C, mainly in summer, and largely through depression of daily maxima but to a lesser extent through depression of daily minima, but found no clear evidence of temperature elevation in the afforested stream in winter. As one of his conclusions Crisp (1997) commented that there was "some evidence that water temperatures in some parts of the upper Severn system may be influenced by groundwater inputs" and that his conclusions, depend on several assumptions that cannot be substantiated objectively, as do those for this study therefore. If groundwater inputs are important in the Nant Tanllwyth, as Crisp (1997) suggests, one advantage of a study such as this, which monitored water, ground surface and air temperature on one stream throughout the clearfelling operations, is that any influence which groundwater inputs might have on stream temperature, will more likely affect both pre- and post-clearfelling phases equally. The changes observed can therefore be assumed to be real.

In terms of the biological status of the stream, the effect of deforestation is unclear. Kirby *et al.* (1991) reported a return of mayflies within two years of harvesting. Such a return must be associated with temperature and light changes as all the other water quality parameters show deterioration (Neal *et al.*, 1992). On the other hand, Gee and Smith (1997) working on the Afon Hore at Plynlimon found no change in the invertebrate assemblage between 1974 and 1994 even though clearfelling was seen to result in changes in stream chemical and physical conditions (including temperature). Roberts and James (1972) compared the forested headwaters of the River Severn with the adjacent headwaters of the River Wye draining an area of open sheep pasture and reported that monthly mean temperatures in the Severn were generally 2°C cooler in summer and up to 1°C warmer in winter. The increase in monthly mean temperature of 0.58°C due to plot-scale clearfelling of less than 20% of the catchment of the Nant Tanllwyth reported in this study, suggests that these differences reported by Roberts and James (1972) may be reduced or even eliminated once whole catchments are clearfelled. Weatherley and Ormerod (1990) conducted experimental bank-side forest clearance in the River Tywi catchment and reported 0.7–1.2°C decreases in temperature in January/February following treatment, with increases of up to 1°C in May-June, and around 0.5°C in September/October. In this study, the equivalent figures for comparative purposes, when pre- and post-treatment air temperature differences are taken into account are: a 0.3°C increase in January/February, 0.7°C increase in May/June and no difference in September/October. So, the winter decrease in stream temperature reported by Weatherley and Ormerod (1990) was not found in this study, though the summer increases are similar. This may be due to the relatively small amount of the catchment and stream length clearfelled in this study.

Brazier and Brown (1973) reported on the use of buffer strips for stream temperature control and showed how increases in temperature of small streams can be prevented during and after logging by leaving a protective strip of vegetation alongside the stream to provide shade. However, in this part of mid-Wales this would almost certainly encounter problems of wind blow. Leaving a buffer area of uncultivated land (Forestry Authority, 1993), or planting of broadleaf species such as alder and willow along the stream banks may: buffer stream temperature changes; act as a sediment trap; benefit the general ecology of the streams, and overcome the problem of wind blow. However, as these streams discharge into streams with flows one or two orders of magnitude larger, the increase in summer stream temperatures is likely to be dissipated rapidly. The cumulative effect of harvesting many such small headwater catchments that discharge into a larger stream could influence noticeably stream temperature and ecology unless riparian buffer strips are retained or planted.

As with all studies of this kind there is always the problem of being able to extrapolate these findings to other streams and catchments. This study has presented a simple linear regression model relating air temperatures (from an AWS only 400 m from the stream) to stream temperature before and after clearfelling. Crisp and Howson (1982) reported good correlations between air and water temperatures, even when the air and water temperature recording stations are several tens of km apart. Crisp (1988) calculated regressions for streams and rivers in northern England and Crisp (1997) calculated regressions of the form $y = bx + a$, relating monthly mean water temperature at the Hore and Hafren stations to monthly mean air temperature at the Clywedog reservoir. The a and b values of 2.85 and 0.67 before clearfelling and 2.86 and 0.72 after clearfelling calculated in this study compare well with those calculated by Crisp (1997) for the neighbouring sub-catchments of the Hore to the south and Hafren to the north (Fig. 1a). Testing the applicability of these relationships in other streams is beyond the scope of this paper but will form a productive avenue for further research.

Conclusions

1. Sensitive plot-scale harvesting of 20 ha. (20%) of the Nant Tanllwyth catchment on the south side of the main stream in Spring 1996 has resulted in a 0.58°C increase in monthly mean stream temperature, while there was no significant increase in the monthly mean air temperature recorded at a nearby automatic weather station over the same experimental period.

2. Monthly mean temperatures are highest in July and August in the year before and the year after the clearfelling. One of the main effects of clearfelling has been to decrease the difference between the monthly mean stream and air temperatures–the difference between monthly mean air and stream temperature in July decreased from 1.9°C pre-clearfelling to 0.3°C post-clearfelling and in August from 2.8°C pre-clearfelling to 0.2°C post-clearfelling. In other words, despite the air temperatures being cooler in the post-clearfelling year, the stream temperatures still increased in the summer months.

3. Monthly mean maximum stream temperatures, also highest in July and August in the year before and the year after the clearfelling, showed a marked increase of 7.0°C in July and 5.3°C in August from the pre- to the post-clearfelling years, while monthly mean maximum air temperatures actually showed a slight decrease for the same months.

4. If groundwater inputs are important in the Nant Tanllwyth, as Crisp (1997) suggests they might be important in the upper Severn catchment, one advantage of a study such as this, which monitored water, ground surface and air temperature on one stream throughout the clearfelling operations, is that any influence which groundwater inputs might have on stream temperature, will more likely affect both pre- and post-clearfelling phases equally. The changes observed can therefore be assumed to be real.

5. Crisp (1997) calculated regressions of the form $y = bx + a$, relating monthly mean water temperature at the Hore and Hafren stations to monthly mean air temperature at the Clywedog reservoir. The a and b values of 2.85 and 0.67 before clearfelling and 2.86 and 0.72 after clearfelling calculated in this study compare well with those calculated by Crisp (1997) for the neighbouring subcatchments. Testing the applicability of these relationships in other streams is beyond the scope of this paper but will form a productive avenue for further research.

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