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Environmentally sensitive plot-scale timber harvesting: impacts on suspended sediment, bedload and bank erosion dynamics

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The impact on sediment pollution of environmentally sensitive harvesting of a 15 ha plot (20% of the catchment area) of mature coniferous plantation forest in the 0·89 km² Afon Tanllwyth catchment, Plynlimon, was investigated for 12 months before harvesting began and a further 18 months after. The results revealed: (a) a steepening of the suspended sediment concentration vs. discharge rating curve resulting in a 39% increase in suspended sediment yield (as compared to the adjacent forested Hafren catchment) during the year in which the harvesting operations took place; (b) a statistically significant increase in main channel bank erosion rates, as compared with the nearby Afon Cyff; main channel banks are estimated to have contributed around 80% of the total catchment suspended sediment yield during the two year period (1995–1996), and (c) no significant change in bedload yields over the duration of the study, though a longer post-harvesting time series of bedload data will be required to properly assess the impact of the harvesting operation upon bedload yields. Forest management implications of these findings are discussed in detail with respect to the existing Forest and Water guidelines.

Keywords: timber harvesting, suspended sediment, bank erosion, bedload transport, forest management, mid-Wales.

Introduction

Reviews by Moffat (1988), Soutar (1989) and Maitland *et al*. (1990) indicate that particulate inputs to fresh waters can be an important impact of forestry practice which has been widely recognised by forestry operators, conservationists and the water industry. Adverse impacts of afforestation on water resources was first demonstrated in the 1950s (Law, 1956) and gathered pace in the 1980s when investigations of the forest establishment stage reported increased suspended sediment concentrations (SSC) which in some instances have resulted in contamination of water supply reservoirs (Austin and Brown, 1981; Stretton, 1984). These impacts include increased suspended sediment concentrations (Robinson and Blyth, 1982; Burt *et al*., 1984; Stott *et al*., 1986; Francis and Taylor, 1989; Johnson, 1993), increased bedload transport (Stott, 1997b; Newson, 1980) and higher rates of channel bank erosion (Stott, 1997a, 1999). As well as the loss of soil and nutrients, increased sediment yields from forested headwater streams have been shown to be detrimental to fisheries (e.g. Milner *et al*., 1981; Ottaway *et al*., 1981; Carling, 1984) and stream ecology (Marks and Rutt, 1997) and have implications downstream for the infilling of lakes, lochs (Ledger *et al*., 1974; Battarbee *et al*., 1985) and reservoirs (Winter, 1950; Brune, 1953; Lovell *et al*., 1973; Ledger *et al*., 1980; Tallis, 1981; McManus and Duck, 1985; Duck and McManus,

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1987, 1994; Butcher *et al.*, 1993; Foster, 1995) thereby reducing their capacity to store drinking water as well as causing operational problems concerned with scour valve releases. Also, check dams installed to protect hydro-electricity intakes may fill up more rapidly (Richards and McCaig, 1985) and changes in coarse sediment production from headwater streams can lead to channel instability problems further downstream (Newson, 1986; Newson and Leeks, 1987; Tuckfield, 1980) which can result in costly erosion or deposition problems.

Most of the early British studies on fluvial sediment dynamics in forested catchments concentrated upon the afforestation (Robinson and Blyth, 1982) and mature forest stages (Newson, 1980; Moore and Newson, 1986), and research on these phases is relevant to sediment dynamics during felling as it provides baseline data from which to assess the impacts of felling. Today, many of the plantations established in the first half of last century are being harvested. Total wood production in Great Britain (conifer and broadleaf) was 8 630 000 m^3 in 1996, and is expected to almost double over the next two decades (Forestry Commission, 1997).

Elevated sediment yields associated with forest harvesting are well documented in the USA (Fredriksen, 1970; Brown and Krygier, 1971; Megahan and Kidd, 1971; Swanston and Swanson, 1976; Reid *et al.*, 1981; Sillsbee and Larson, 1983; Miller *et al.*, 1988), in New Zealand (O' Loughlin, 1974; O' Loughlin *et al.*, 1980; Derose *et al.*, 1993), in Japan (Fukushima, 1987), in Southeast Asia (Douglas, 1996; Greer *et al.*, 1996) and elsewhere. More recently a number of British studies have reported the impacts of harvesting upland plantations on fluvial sediment dynamics. However, previous UK harvesting studies (Stott *et al.*, 1986; Johnson, 1988, 1993; Ferguson *et al.*, 1991; Leeks, 1992) no longer represent typical government practice. To date three editions of Forests and Water Guidelines (Forestry Commission, 1988, 1991; Forestry Authority, 1993) have been published and Forest Enterprise, the current UK forestry body which manages the national forest estate, is obliged to follow the recommended environmentally sensitive plot-scale timber harvesting techniques outlined in these guidelines. Previous UK studies are therefore unsuitable for impact assessment associated with such contemporary plot-scale operations. For example, in the Loch Ard study (Ferguson *et al.*, 1991) 70% of the 0·84 km^2 experimental catchment was clear-felled and in the Afon Hore clear-fell experiment (Leeks, 1992) 91 ha, comprising 29% of the total catchment area, was harvested in one operation. In the Balquhidder experiment, clear-felling in the 6·85 km^2 Kirkton Glen catchment (40% mature forest) was phased over several years but even so, sub-catchments which were 65–80% mature forest with areas of 0·16 km^2 and 0·17 km^2 and average gradients of 30–40% were clear-felled in one phase, corresponding to felled areas equivalent to 104 and 145 ha respectively (Stott, 1997b). In contrast, current harvesting policy favours the phased felling of much smaller plots, normally in the region of 10–20 ha and hence there is now an opportunity and a need to evaluate the impact of this type of plot-scale timber harvesting on fluvial sediment dynamics.

Study aims

The study aims were as follows:

(a) To monitor suspended sediment loads (SSL) before, during and after harvesting in the Afon Tanllwyth experimental catchment and adjacent control streams in unforested and unfelled catchments;
(b) To monitor bedload dynamics by means of tracers and bedload traps in the experimental and control catchment;
(c) To monitor bank and forest ditch erosion rates before, during and after harvesting (compared with a control stream), and to compare bank erosion inputs of sediment with catchment outputs.

Location

Since records began in 1972, the sediment monitoring network within the Institute of Hydrology's Plynlimon experimental catchments (Figure 1(a)) has been intensified and combined with detailed bedload tracing and bank erosion monitoring to allow a detailed reach study associated with this specific phase in the forest rotation.

The harvesting plot selected for this study (Figure 1(b)) consisted of three separate areas, each felled using a specific technique appropriate to the site conditions. 13 ha (15%) of the 0·89 km^2 Afon Tanllwyth catchment was harvested. Felling took place during January–June 1996 and harvesting was carried out by a single harvester (Figure 2) which fells, cleans, processes and stacks timber ready for shipment.

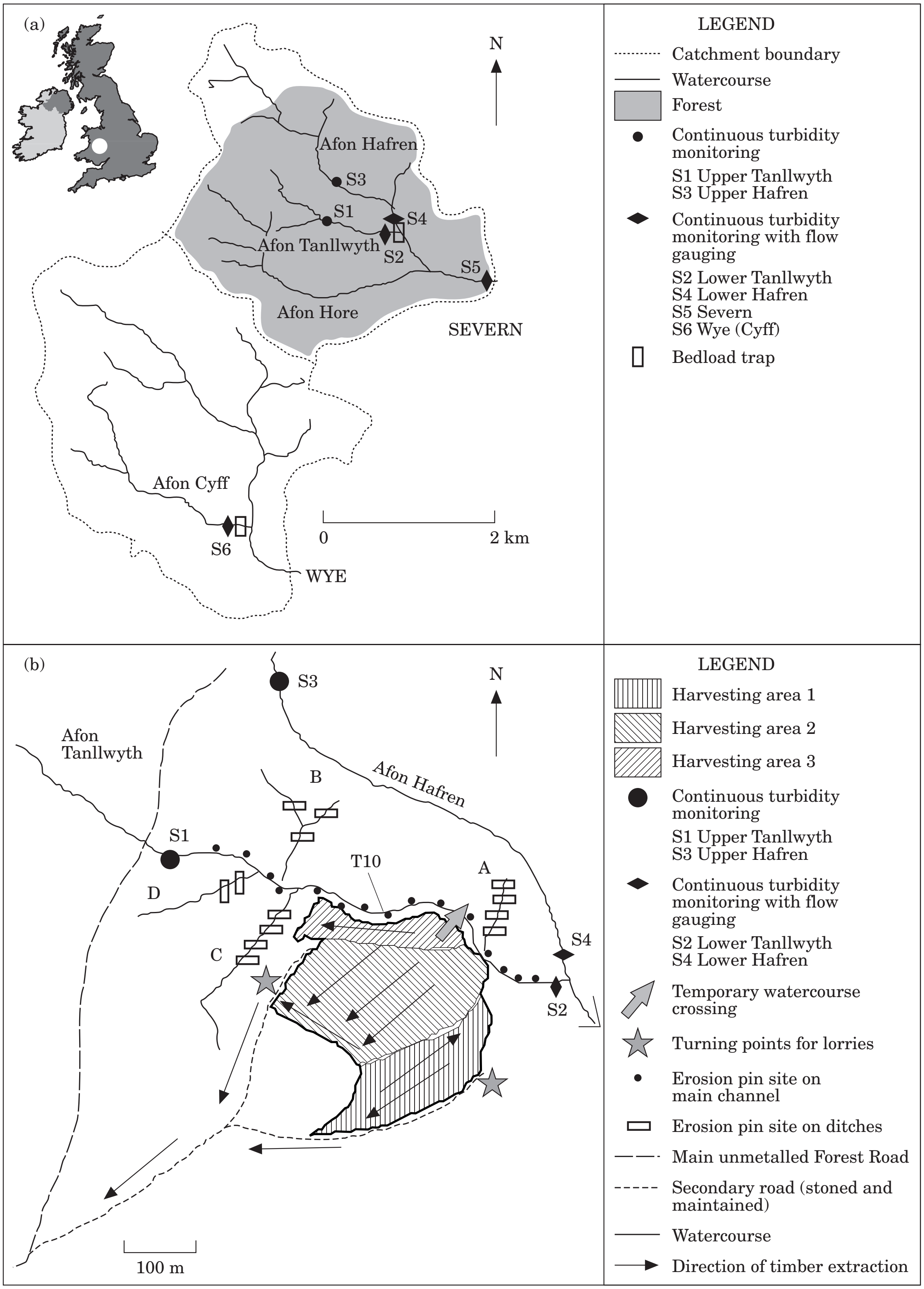

Figure 1. (a) Location of Plynlimon catchments showing sediment monitoring network. (b) Details of harvesting operations in Afon Tanllwyth with bank erosion and sediment monitoring sites located.

Figure 2. One machine timber harvester processing felled tree, Plynlimon.

All efforts were made to ensure that the machine drove only on brashings and never on bare, unprotected ground. The number of stream crossing points was minimised and timber was extracted away from the main Tanllwyth watercourse (Figure 1(b)). Timber next to the main channel was hand felled and removed away from the channel.

Methods

Stream discharges were monitored using purpose-built flumes installed, calibrated and maintained by the UK Institute of Hydrology as part of the Plynlimon Experimental catchments established in the late1960s (Hudson and Gilman, 1993) and 15-minute streamflow records from the Lower Tanllwyth, Lower Hafren and Cyff were available for the experimental study period (Figure 1(a)). Continuous SSC data were collected (Wass *et al*., 1997) at all turbidity monitoring sites (Figure 1(a)). Simultaneous SSC data during 1996 and January–June 1997 were collected at both the Upper and Lower Tanllwyth sites.

Bedload traps comprising concrete pits $4\,m \times 4\,m \times 1{\cdot}5\,m$ deep were installed at the Lower Tanllwyth and Cyff sites in the early 1970s (Painter *et al*., 1974) and long-term bedload transport data from these traps have been reported by Moore and Newson (1986). However, since this publication, bedload records have been intermittent and so the bedload traps were upgraded and records started again in 1995 in preparation for this study (Sawyer, 1999).

Bank erosion monitoring of the main channel banks, tributary banks and forest ditches was carried out in two ways and the details are reported elsewhere (Stott and Marks, 1998; Stott, 1999). On the main Tanllwyth channel, erosion pins were located at 16 sites (on Figure 1(b)) where 105 erosion pins ($300\,mm \times 3\,mm$ welding rod) were installed in vertical lines (100 mm spacing) at 30 m intervals along the main channel, on either the right or left bank, at a point on the channel where the cohesive bank sediment was exposed and not vegetated. On tributary streams C and D pins were installed in the same way at four and two sites respectively (a total of 42 pins). On forest ditches A and B pins were installed at seven sites (a total of 90 pins). All pins were resurveyed on 14 occasions between 22 October 1994 and 20 May 1997 which represents ~3100 individual pin readings, measurements being taken with callipers which read to 0·1 mm accuracy. A further 30 pins were installed in the same way on five sites on Afon Cyff (Figure 1(a)) and these were resurveyed on four occasions between 24 April 1995 and 15 February 1997 (~120 individual pin readings). In order to assess the possibility of pins being heaved out of the banks by frost a further 32 pins were installed at 11 of the Tanllwyth sites on 13 January 1997. These pins were pushed into the bank until they hit a wooden stake installed vertically some 250 mm from the bank face. Resurveys of these pins after 36, 86 and 127 days respectively showed that none had been heaved out by frost.

Results

Suspended sediment yields

The detailed results for1995, 1996 and 1997 for the main turbidity monitoring/flow gauging sites (Marks, 1998) along with continuous SSC data for the upper and lower Tanllywth sites are presented by Leeks and Marks (1997). SSC for equivalent discharge follow the pattern Lower Tanllwyth > Lower Hafren > Severn > Wye, with increases in SSC at Lower Hafren and Lower Tanllwyth sites during 1996 as compared to 1995. During January–June 1997, although the increase above the 1995 values was maintained, both sites showed a slight decrease from the 1996 levels. Rating curves for the Severn remained comparatively stable during all three years (Table 1).

The monthly pattern of SSL at the lower Tanllwyth site (Figure 3) seems to indicate a delay in the increase in suspended sediment yields until late 1996 and early 1997. This is in marked contrast to the immediate enhancement of SSC (by an order of magnitude) observed during the Hore clear-felling experiment (Leeks, 1992) where 29% of the catchment (91 ha) was clear-felled using less environmentally sensitive harvesting techniques. Since monthly SSL and total flow are closely correlated ($r^2=0{\cdot}79$, $P<0{\cdot}001$) this delay could be due to a lack of competent flows (in terms of magnitude and duration) until December 1996, though this does not appear to be the case (see Figure 6). Alternatively, and more likely, it could be due to brashings which protected the catchment surface during and immediately after the harvesting operation, breaking down and exposing more soil to erosion. Consequently, in this study, post-harvesting soil erosion appears to be more significant than the immediate disruption of the catchment surface during the felling operations. Another possibility is that the lagged increase in SSY during the post-harvesting phase may be due to the spatial patterns and scale of the felled plots, which are much smaller and more remote from streams than was the case in the Hore catchment felling experiment.

Main channel banks, tributary and ditch erosion: temporal and spatial patterns

Table 2A summarises the bank erosion monitoring results and indicates that for the whole study period the mean erosion rate (± standard error) of the Tanllwyth main channel was $64{\cdot}3\pm1{\cdot}1$ mm yr^{-1}, which was about twice the rate on the tributaries ($30{\cdot}3\pm0{\cdot}5$ mm yr^{-1}), which

Table 1. Summary of suspended sediment monitoring results from Plynlimon Experimental Catchments

Monitoring Location (see Figure 1)	Year	Mean SSC (mg l^{-1})	Max SSC (mg l^{-1})	Total SSL (tonnes)	SSY (t km^{-2}yr^{-1})
*Upper Tanllwyth S1	1996	4·3	280·3		
	Jan–Jun 1997	4·3	305·0		
Lower Tanllwyth S2	1995	7·0	319·1	21·6	24·2
(0·89 km^2)	1996	8·9	417·1	38·9	43·8
	Jan–Jun 1997	13·0	843·0	25·4	
*Upper Hafren S3	1996	5·2	280·5		
	Jan–Jun 1997	4·9	120·9		
Lower Hafren S4	1995	4·9	97·1	59·1	16·1
(3·67 km^2)	1996	6·7	184·0	84·7	23·1
	Jan–Jun 1997	10·0	37·8	32·9	
Severn S5	1995	4·0	137·9	138·4	15·9
(8·7 km^2)	1996	5·1	261·9	127·0	14·6
	Jan–Jun 1997	5·0	125·0	92·4	
Wye (Cyff) S6	1996	1·8	145·8	16·7	5·3
(3·1 km^2)	Jan–Jun 1997	1·7	73·4	7·6	

SSC=suspended sediment concentration (means based on log 10 data); SSL=suspended sediment load; SSY=suspended sediment yield; *Flow data not available, SSL estimated using S2 flow records. 1997 monitoring is for Jan–Jun only so annual yields cannot be calculated.

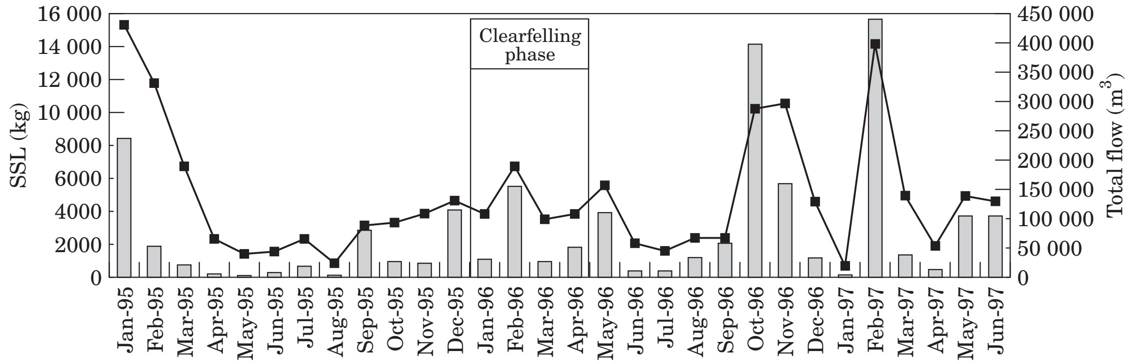

Figure 3. Monthly total SSL (□) and flow (m3 ■) for Lower Tanllwyth.

Table 2. (A) Summary of Tanllwyth bank erosion results. (B) Comparison of temperature indices before and after timber harvesting

Stream	Mean erosion rate mm yr^{-1}	N	Stream	Mean erosion rate mm yr^{-1}	N	*P*-value
(A)						
Pre-clear-felling (27/4/95 to 2/4/96)						
Tanllwyth mainstream	34·6±0·5	376	Cyff mainstream	31·2±0·8	70	ns
Post clear-felling (2/4/96 to 15/2/97)						
Tanllwyth sites T1-12 (in clear-felled area)	95·8±0·8	348	Cyff mainstream	65·5±1·1	72	$P<0{\cdot}05$
Tanllwyth sites T13-17 (not clear-felled)	70·5±1·1	139	Cyff mainstream	65·5±1·1	72	ns
Tanllwyth (forested) catchment (all periods)						
Tanllwyth mainstream (all sites, whole study period)	64·3±0·4	962	Tanllwyth tributaries	30·3±0·5	357	$P<0{\cdot}001$
Tanllwyth mainstream (all sites, whole study period)	64·3±0·4	962	Tanllwyth forest ditches	17·0±0·2	831	$P<0{\cdot}001$
Tanllwyth tributaries (all sites, whole study period)	30·3±0·5	357	Tanllwyth forest ditches	17·0±0·2	831	$P<0{\cdot}01$

	Before harvesting			After harvesting		
	AWS	Bank	Bank as % of AWS	AWS	Bank	Bank as % of AWS
(B)						
Maximum (°C)	7·7	3·8	49	9·2	7·5	81
Minimum (°C)	−11·0	−0·6	6	−13·3	−1	8
Range (°C)	18·7	4·4	24	22·4	8·5	38
Mean (°C)	−1·0	0·8	80	−0·5	1·4	280
No. Frost cycles	13	7	54	8	4	50
No. hours <0°C	376	63	17	434	198	46

ns=not significant at the $P<0{\cdot}05$ level

in turn was almost twice that on the ditches ($17{\cdot}0\pm0{\cdot}2$ mm yr^{-1}).

These differences are statistically significant as shown by the *t*-test. In the pre-harvesting phase of the study, mean erosion rates on the Tanllwyth ($34{\cdot}6\pm0{\cdot}5$ mm yr^{-1}) and Cyff ($31{\cdot}2\pm0{\cdot}8$ mm yr^{-1}) main channels showed no significant difference. In the post-harvesting phase, however, mean erosion rates generally doubled on both the Tanllwyth and Cyff main channels. The mean erosion rate on the Cyff increased from $31{\cdot}2\pm0{\cdot}8$ to $65{\cdot}5\pm1{\cdot}1$ mm yr^{-1} in the post-harvesting phase. The mean erosion rate on the unclear-felled section of the Tanllwyth channel (sites T13–T17) showed an increase from 34·6±0·8 to 70·5±1·1 mm yr^{-1}, while the mean erosion rate at those Tanllwyth sites in the clear-felled area (T1–T12) increased to 95·8±0·8 mm yr^{-1}. Period 9 in Figure 4(a) had high flow and SSL but a low bank erosion rate. The high flow in this period seems to have transported suspended sediment from the previous winter and/or as a result of the harvesting. Period 10 had the highest bank erosion rate in December 1996–January 1997 and during a field visit on 13 January 1997 layers of bank material some 20–40 mm thick were being frost-heaved from the banks and slumped onto the bank toe. The very high SSL, despite the lower flow in period 11, suggest that this material was transported in periods 11 and 12.

Since bank erosion measurements were undertaken only every 1–3 months, erosion rates for 13 time periods during the clear-felling study have been combined with total flow and suspended sediment load in each period to allow comparison of their temporal distribution and to assess the effects of the timber harvesting (Figure 4(a)).

Figure 4(b) shows the temporal changes in mean erosion rates in the Nant Tanllwyth throughout the study (22 October 1994–17 July 1997) with sites grouped according to the effects of clear-felling on them.

The higher erosion rates in the winter of 1997, even at the unclear-felled sites (T13–T17) and particularly in the period 13 January 1997 to 15 February 1997 are thought to be due to local climatic factors (i.e. a greater amount of frost activity). Nevertheless, following harvesting, the

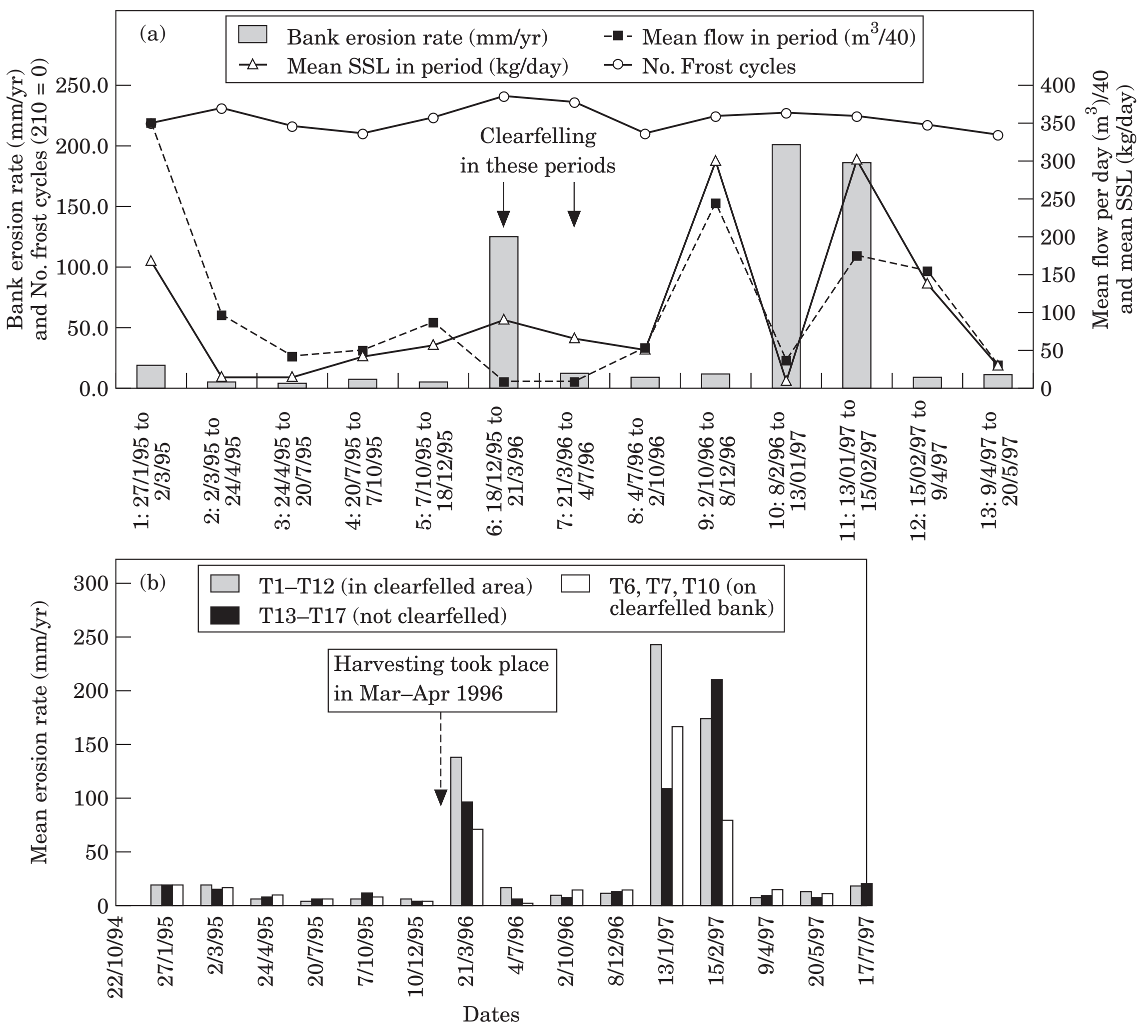

Figure 4. (a) Bank erosion rate, frost cycles, suspended sediment load and flow in Afon Tanllwyth (January 1995–May 1997). (b) Temporal changes in mean bank erosion rates in the Nant Tanllwyth throughout the study (22 October 1994–17 July 1997) with sites grouped according to the effects of clear-felling on them.

difference between the erosion rate on those Tanllwyth sites in the clear-felled area (T1–T12, mean is $95{\cdot}8 \pm 0{\cdot}8$ mm yr^{-1}) and the unaffected 'control' sites in the Cyff ($65{\cdot}5 \pm 1{\cdot}1$ mm yr^{-1}) was significant at the 0·05 level (see Table 2A). This suggests that the increased erosion rates measured at harvested sites on the Tanllwyth channel are real. Mean erosion rates of up to 600 mm yr^{-1} occur at the downstream sites in the winter following timber harvesting. The maximum erosion rate measured at one individual pin was 961 mm yr^{-1} recorded at site T3 during the last survey (13 January 1997–15 February 1997). The higher erosion rates seen in the winter periods in particular are associated with the greatest variability.

Effects of clear-felling on channel erosion, bank temperatures and frost incidence

The influence of forest on air temperatures (Fritts, 1961; Kittredge, 1962; Smith, 1970) and stream temperatures (Greene, 1950; Crisp, 1997; Stott and Marks, 2000) is well recognised. Gray and Eddington (1969) reported a marked rise in summer temperature of a woodland stream which was clear-felled. Hurst (1966) reported that shading in the forest of Thetford Chase gave considerable protection from frost. Given the now well established link between frost action (freeze-thaw) and stream bank erosion (e.g. Wolman, 1959; Hill, 1973; Blacknell, 1981; Gardiner, 1983; Curr, 1984; Lawler, 1986, 1987, 1993; Ashbridge, 1995; Stott, 1997a, 1999) the impact of clear-felling upland forest plantations on stream bank temperatures is beginning to be understood. Having identified a statistically significant difference in mainstream bank erosion rates before and after harvesting an area of the Afon Tanllwyth, as compared with the Afon Cyff over the same period, the changes in the temperature regime of the stream banks which have occurred through the clear-felling phase are now investigated further.

Figure 5 shows the temporal variation in both stream bank temperature (measured by a thermistor fixed on the bank) and air temperature (measured by an automatic weather station (AWS) in a nearby forest clearing) over 28 day periods in early winter (a) before clear-felling (8 December 1995–5 January 1996) and (b) after clear-felling (8 December 1996–5 January 1997).

The complex nature of the relationship is apparent and the greater variability in the AWS air temperature is clear. An analysis of these data is presented in Table 2B and it is the relationship between bank and AWS temperatures which can be used to assess the impact of clear-felling on bank temperatures since the AWS records remained unaffected by the clear-felling.

Bank temperature indices expressed as a percentage of the AWS temperature indices are used to assess the changes which have occurred following clear-felling. Five of the six bank temperature indices chosen show an increase as compared to the AWS indices. Rating relationships between bank and air temperature for (i) pre-harvesting (20 July 1995–8 September 1995) and (ii) post-harvesting (20 July 1996–8 September 1996) phases are presented in Figure 5(c).

Although rating relationships have been established for each season, the relationships in Figure 5(c) compare the summer ratings for (i) before and (ii) after harvesting. There is an obvious steepening of the relationship in the post-harvesting phase suggesting than banks have become more sensitive to changes in air temperature as measured by the AWS. This may well have implications for bank 'preparation (freeze thaw) processes' as well as for stream temperatures as reported by Gray and Eddington (1969).

Bedload transport

Bedload trapping results (Table 3A) show considerable variations in yields for the surveyed periods and more than a nine-fold difference in sediment yields between the forested and unforested streams.

It should be noted that the period dates for the Tanllwyth and Cyff do not always coincide: for logistical reasons it was not always possible to measure bedload accumulation in both traps on the same field visit. Figure 6 shows the survey periods and illustrate the mean weekly bedload yield for both the Nant Tanllwyth and Afon Cyff.

The maximum weekly value of 0·61 t wk^{-1} in the Nant Tanllwyth occurs between 1 October 1996 and 19 November 1996. During several other study periods, notably at the start of the fieldwork, and during the two winter periods of 1995–1996 and 1996–1997, bedload totals are high and clearly relate to flood magnitudes in the Nant Tanllwyth. In contrast, Figure 6(b) shows that the Afon Cyff has yielded significantly lower totals, despite a catchment area three times larger and flows of

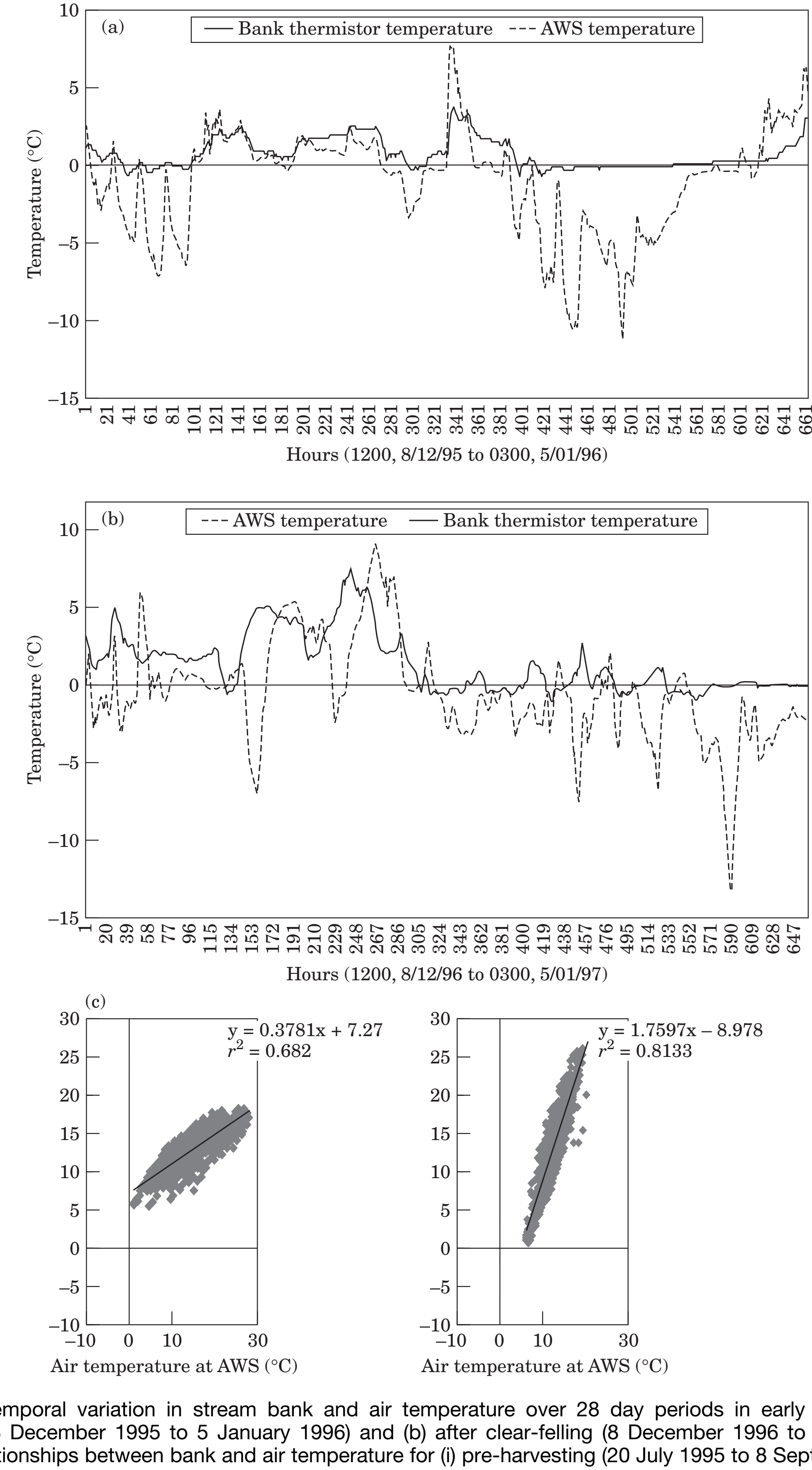

Figure 5. Temporal variation in stream bank and air temperature over 28 day periods in early winter (a) before clear-felling (8 December 1995 to 5 January 1996) and (b) after clear-felling (8 December 1996 to 5 January 1997). (c) Rating relationships between bank and air temperature for (i) pre-harvesting (20 July 1995 to 8 September 1995) and (ii) post-harvesting (20 July 1996 to 8 September 1996) phases.

Table 3. (A) Total bedload outputs of the Nant Tanllwyth and Afon Cyff measured using bedload traps. Dashes in cells below indicate no reading was made, thus cells with values indicate bedload accumulation since the previous reading. The grey hatched area shows the post-harvest phase of the Nant Tanllwyth. (B) Comparison of pre- and post-harvesting bedload outputs in the Nant Tanllwyth

(A) Survey periods	Nant Tanllwyth		Afon Cyff	
	Bedload output t	Weekly yield t wk^{-1}	Bedload output t	Weekly yield t wk^{-1}
03-Feb-95 to 07-Jul-95	5·34	0·243	—	—
07-Jul-95 to 27-Jul-95	0·25	0·089	—	—
27-Jul-95 to 5-Oct-95	0·24	0·024	—	—
07-Jul-95 to 15-Oct-95			0·76	0·053
05-Oct-95 to 15-Dec-95	0·03	0·003	—	—
15-Oct-95 to 11-Jan-96	—	—	0·10	0·008
15-Dec-95 to 11-Jan-96	1·12	0·289	—	—
11-Jan-96 to 20-Feb-96	0·76	0·133	0·29	0·050
20-Feb-96 to 02-Apr-96	—	—	0·23	0·039
20-Feb-96 to 03-May-96	0·07	0·006	—	—
02-Apr-96 to 02-Jul-96	—	—	0·40	0·031
03-May-96 to 02-Jul-96	0·88	0·103	—	—
02-Jul-96 to 01-Oct-96	0·37	0·029	0·13	0·010
01-Oct-96 to 19-Nov-96	4·28	0·611	2·28	0·326
19-Nov-96 to 10-Dec-96	0·32	0·107	0·35	0·117
10-Dec-96 to 14-Mar-97	4·30	0·320	0·81	0·060
14-Mar-97 to 9-Apr-97	0·04	0·010	0·05	0·015
09-Apr-97 to 02-Jun-97	0·10	0·013	0·07	0·009
03-Feb-95 to 02-Jun-97	18·09	0·149	—	—
07-Jul-95 to 02-Jun-97	—	—	5·40	0·054
Catchment area (km^2)	0.89		3.13	
Study length (yr)	2.3		1.9	
Yield (t $km^{-2}yr^{-1}$)	8.68		0.91	

(B)	Pre-harvesting (03-Feb-95 to 02-Apr-96) 454 days	Post-harvesting (03-May-96 to 02-Jun-97) 395 days	Percentage change
Total bedload (tonnes)	7·81	10·29	+32
Bedload yield per million m^3	4·21	5·12	+22
Bedload yield per million m^3 over threshold ($0.3\,m^3s^{-1}$)	16·75	17·54	+5
Bedload yield per million m^3 over threshold ($0.5\,m^3s^{-1}$)	30·84	31·26	+1

matching and greater magnitude. From a visual examination of the Afon Cyff data, it is possible to see from the bar charts a response to flood peaks, but the relationship is significantly less well defined than in the Nant Tanllwyth.

Analysis of bedload trap data

Relationships between discharge and total bedload output were established by selecting discharge thresholds (Werritty, 1984; Moore and Newson, 1986) over which bedload transport is initiated. Stott (1997b) computed the total time certain discharge thresholds were exceeded and related these to total bedload trapped. Field observations at Plynlimon suggested that floods of magnitudes between $0{\cdot}3\,m^3s^{-1}$ and $0{\cdot}5\,m^3s^{-1}$ were capable of initiating bedload movement. The analysis first related total bedload output to a function of time, but the *total flow over the discharge* threshold gave consistently better results and r^2 values than a *time over threshold* function.

Relationships with both time between trap measurements and a range of discharge thresholds (0·3, 0·5, 1·0 and $1{\cdot}5\,m^3s^{-1}$) were investigated. The best relationships found were for the amount of bedload trapped and the $0{\cdot}3\,m^3s^{-1}$ and $0{\cdot}5\,m^3s^{-1}$ thresholds. Figure 7(a) shows the relationship between bedload trap output and total discharge and Figure 7(b) shows the relationship between bedload trap output and discharge over the $0{\cdot}3\,m^3s^{-1}$ threshold.

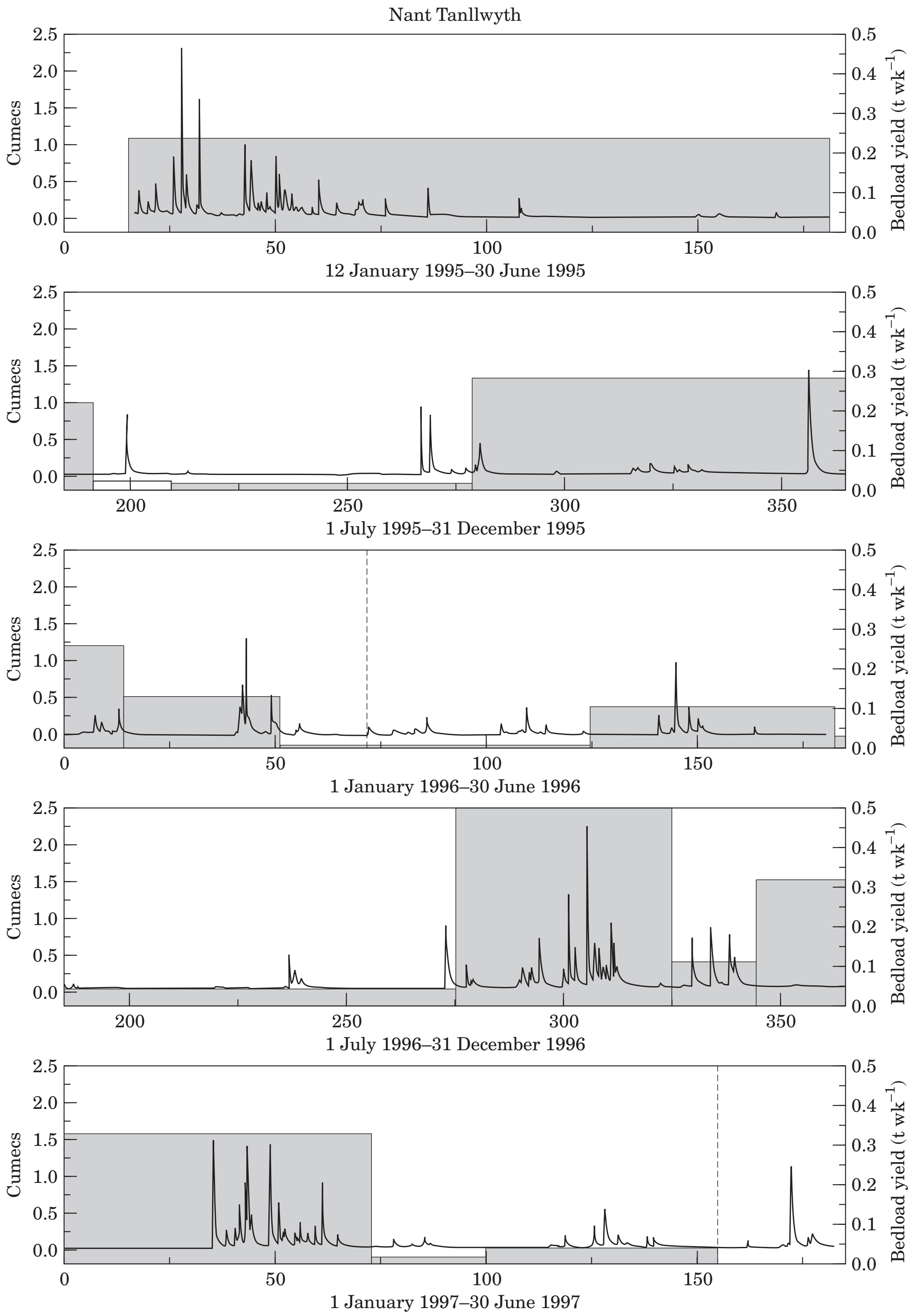

Figure 6(a). Bar charts showing mean weekly bedload yield and stream discharge in Nant Tanllwyth 1995–1997.

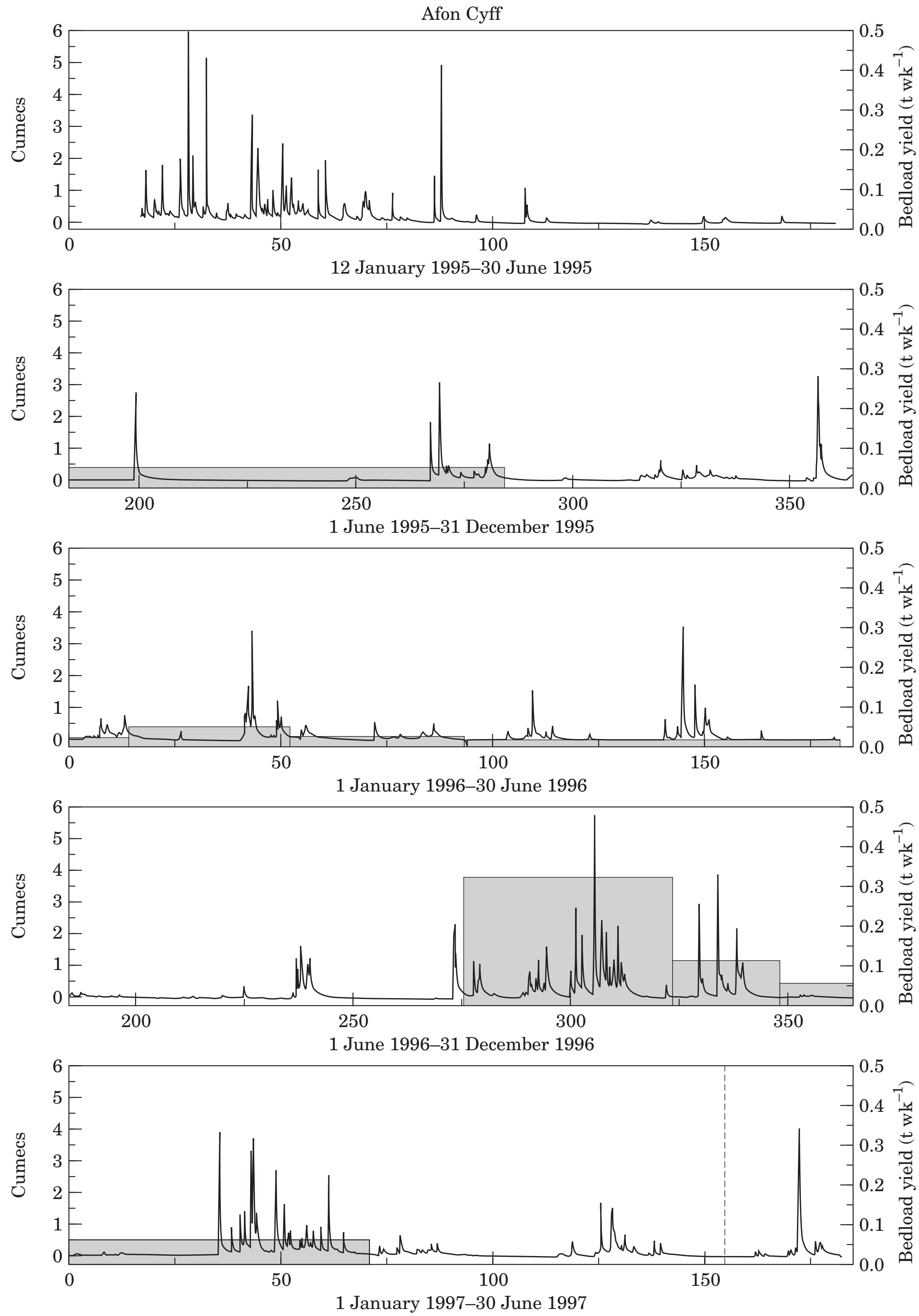

Figure 6(b). Bar charts showing mean weekly bedload yield and stream discharge in Afon Cyff 1995–1997.

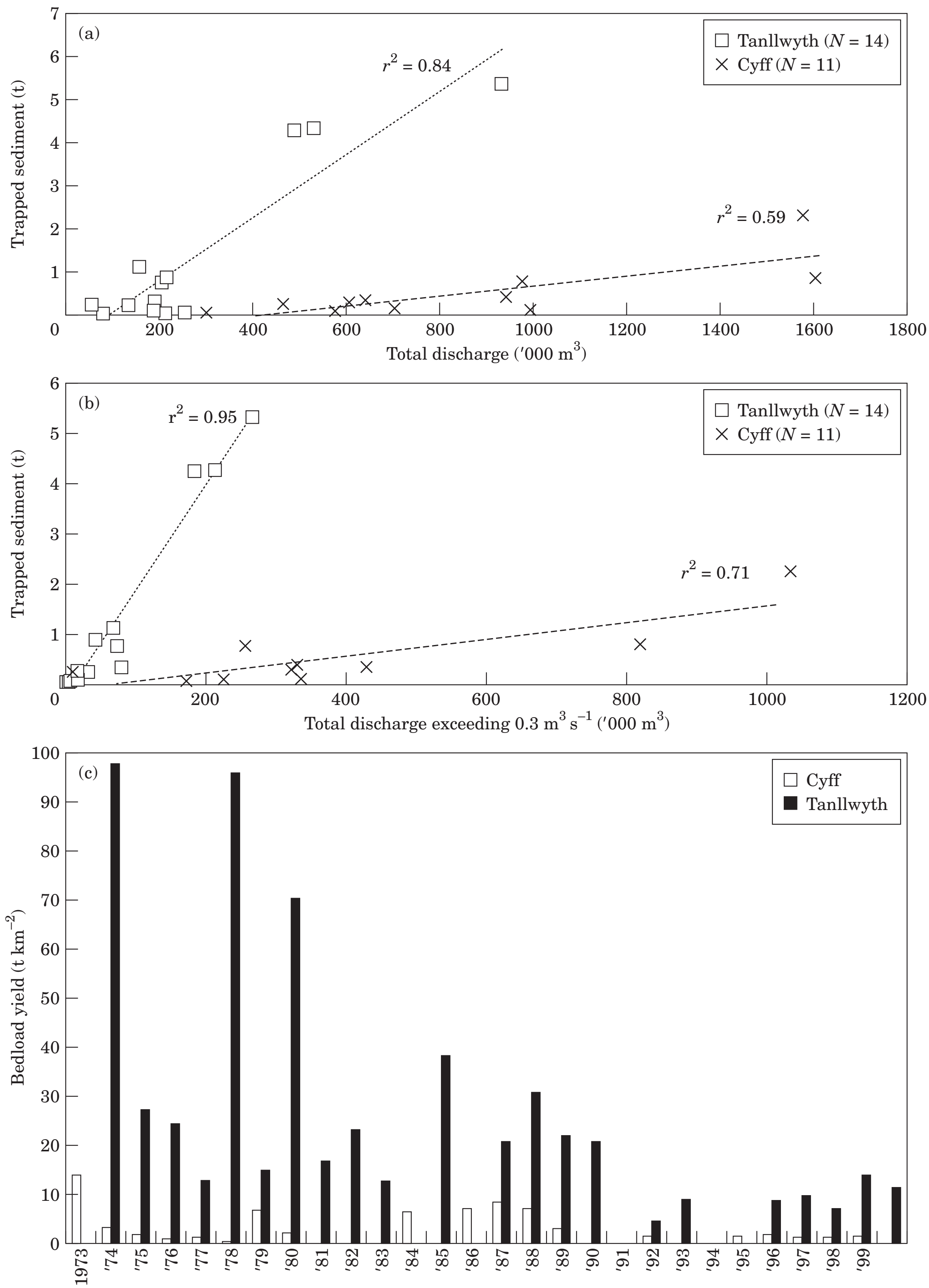

Figure 7. Relationships for the Nant Tanllwyth and Afon Cyff between trapped bedload and, (a) total stream discharge and (b) total discharge above $0{\cdot}3\,m^3 s^{-1}$ threshold. (c) Long term bedload data for the Afon Cyff and Nant Tanllwyth, Plynlimon.

The r^2 values are improved from 0·84 to 0·95 ($N = 13$, $P < 0{\cdot}001$) and from 0·59 to 0·71 in the Tanllwyth and Cyff respectively, by considering only discharge in excess of $0{\cdot}3\,m^3s^{-1}$, but despite the higher discharges, the Afon Cyff gives significantly lower bedload outputs. The Nant Tanllwyth exhibits flow-limited bedload transport characteristics: where floods capable of entraining bedload occur, the bedload available is transported through the system efficiently. In the Afon Cyff, however, the relationship suggests a bedload supply limited situation, which was similarly reported by Moore and Newson (1986).

Discussion

When suspended sediment monitoring results after 1995 are compared with previous results (Leeks and Roberts, 1987; Kirby *et al*., 1991; Leeks, 1992; Neal *et al*., 1992) suspended sediment yield (SSY) from the Tanllwyth has been lower than from the adjacent Afon Hafren, $12{\cdot}7\,t\,km^{-2}\,yr^{-1}$ and $35{\cdot}3\,t\,km^{-2}\,yr^{-1}$, respectively (Kirby *et al*., 1991). The 1995 data, however, show that SSY from the Tanllwyth catchment was 51% higher than from the Hafren, $24{\cdot}3\,t\,km^{-2}\,yr^{-1}$ and $16{\cdot}1\,t\,km^{-2}\,yr^{-1}$, respectively. When timber harvesting was undertaken in the Nant Tanllwyth catchment during 1996, the SSY of $43{\cdot}8\,t\,km^{-2}\,yr^{-1}$ increased this difference to 81%, an increase of a factor of 1·8 between 1995 and 1996. In the adjacent Afon Hafren the increase in SSY was by a factor of 1·4. If the 1995 results are used to represent the background difference in the suspended sediment yield between the two catchments, and assuming all other variables are equal, it could be argued that the timber harvesting operation appears to have led to a 39% increase in SSY from the Tanllwyth, corresponding to an additional $9\,t\,km^{-2}\,yr^{-1}$. Although no felling took place in the Afon Hafren catchment in 1996, there was nevertheless a 43% increase in the SSY. One possibility is that this could be due to increased traffic on forest roads which pass through the catchment en route to the adjacent Nant Tanllwyth felling area. This has been identified as one of the major causes of forest road erosion, resulting in particulate inputs to watercourses (Reid and Dunne, 1984; Ferguson and Stott, 1987; Fukushima, 1987; Robichaud *et al*., 1993; Johnson and Bronsdon, 1995).

The mean SSC figures for the Upper and Lower Tanllwyth sites for the complete 1996 and 1997 datasets (Table 1) show an increase in both mean and maximum SSC between the sites in the post-harvesting phase. The mean SSC remains stable at the Upper Tanllwyth site during 1996 and 1997 while there is a marked increase at the Lower Tanllwyth site. This increase at the lower site is not caused by different weather or flow conditions between the two phases, as this would affect both sites.

Mainstream bank erosion rates in the Nant Tanllwyth vary over almost two orders of magnitude and a clear seasonal pattern is apparent, with peaks in erosion rates occurring in the winter periods, particularly after timber harvesting. Erosion rate is more closely related to frost frequency and intensity than to discharge (Stott, 1999). 89% of the total erosion in the study period occurred in the winter periods (January–March).

Mean bank erosion rates on the Tanllwyth and Cyff broadly compare with those reported for other similar sized British catchments (e.g. Hill, 1973; Lewin *et al*., 1974; Lawler, 1986, 1987; Stott, 1997a). Tributary and forest ditch erosion rates are significantly lower than mainstream channel banks and this may be attributable to infrequent and lower magnitude fluvial entrainment events. The forest ditches show low steady erosion over this study period although this was not the case over the whole of the forest cycle. Newson (1980) reported increases in ditch cross-sectional areas of up to 75% in some Tanllwyth ditches 26 years after they were first established.

During visits to the study sites, freeze-thaw processes, the growth of needle ice (Lawler, 1993) and, at a larger scale, ice lenses which heave apart soil peds and blocks destroying inter-ped cohesion (Thorne, 1990) have been observed. Freezing of soil moisture can reduce erosion resistance in the cohesive banks in this study by heaving material from the bank surface in layers. This reduces cohesion when the ice melts, which allows sediment to slump and be entrained by the next rise in stage. Thorne (1990: 127) states that, "The processes responsible for loosening aggregates are mostly driven by the dynamics and physical state of soil moisture close to the bank face". If the bank is poorly drained, positive pore water pressure acts to reduce the effective cohesion and weaken the soil. High pore pressures occur in saturated banks after heavy/prolonged precipitation, snowmelt or rapid drawdown in the channel. Although bank drainage was outside the scope of this study, it must form a focus for future research in upland afforested areas. Vegetated and forested banks are drier because: (i) the tree canopy prevents 15–30% of precipitation from ever reaching the soil (Johnson, 1990), (ii) plants draw water from the soil and transpire it to the atmosphere, and, (iii) suction pressures in the soil are increased by water abstraction at the roots. Thus, the height of the capillary fringe is increased and water is drawn towards the surface from greater depths than in an unvegetated bank which results in increased evaporative loss (Thorne, 1990). This accepted, the effect of clear-felling on the bank moisture regime should be to increase the amount of precipitation which reaches the bank and reduces evaporative losses until vegetation regenerates and raises the height of the capillary fringe. Results from this study show a steepening of the bank versus air temperature relationship, a greater diurnal temperature range which results in a greater duration of sub-zero temperatures in winter, probably more freeze-thaw cycles in winter and higher maximum bank temperatures. Such higher maxima should increase evaporative losses and result in more extreme wetting and drying cycles. According to Thorne (1990) this generates a ped fabric with desiccation cracks between peds and a crumb structure to the soil. Cohesion between peds and crumbs is much weaker than within them, so a heavily desiccated soil may have little erosion resistance. Soil and bank stability may be further reduced by the decay of root systems from the first crop.

An estimate of the total area of main channel bank undergoing active bank erosion on the Afon Tanllwyth was made by dividing the 800 m channel reach between the upper and lower Tanllwyth monitoring sites into 10 m sections. Each section was visited in the field and assigned a value (m^2) of area of eroding bank for both left and right banks. The mean erosion rate for 1995 and 1996 ($64{\cdot}3 \pm 0{\cdot}6$ mm yr^{-1}) was then applied to this area to estimate a volume of material removed. Using bulk density figures for bank material estimated by Stott *et al*. (1986) of 1100 kg m^{-3}, the mean mass of sediment produced from the banks per year for 1995 and 1996 would be 25 200 t which, expressed as SSY is 28·3 t km^{-2} yr^{-1}. The SSY (see Table 1) for the Lower Tanllwyth was 24·3 and 43·7 (mean=34) t km^{-2} yr^{-1} for 1995 and 1996 respectively. The main channel banks are thus estimated to have contributed in the region of 80% of the mean SSY during the two year period.

In order to disentangle the effect of harvesting on total bedload outputs, analysis of yields before and after harvesting operations was undertaken. Table 3B shows the total bedload output for the pre- and post-harvesting phases (note the unequal lengths) and gives the bedload yields which take account of the unequal length phases and thus make the figures comparable.

There appears to be an increase in bedload yield for equivalent time periods in the post-harvesting phase (51%), but when account is taken of the differences in flow regime between the two phases, by computing the yield of bedload per unit flow for the two phases, the difference in bedload yield per million m^3 decreases to 22%. If the total volume of flow above the entrainment thresholds is taken into account, the difference in bedload yield per million m^3 over $0{\cdot}3\,m^3s^{-1}$ decreases to 5%, while the difference in bedload yield per million m^3over $0{\cdot}5\,m^3s^{-1}$ is only 1%. None of these differences was statistically significant when tested by the *t*-test and so it can be concluded that the timber harvesting resulted in no significant change in bedload yield over the timescale of this study.

Figure 7(c) shows the longer term bedload yield records for the Nant Tanllwyth and Afon Cyff and compares the findings of this study with those. Both catchments show significantly lower yields of bedload than the data show for the 1973–1980 period and some possible explanations for the current lower yields are offered by Sawyer (1999).

Summary of findings and management implications for future timber harvesting

The adoption of the Forests and Water Guidelines (Forestry Authority, 1993) by the UK forest industry over the past decade has reflected earlier concerns regarding sediment pollution in upland rivers and reservoirs. Research from the Plynlimon experimental catchments has contributed to the development of this guidance and this latest study adds further recent and relevant information. The environmentally sensitive plot-scale harvesting of 15% of the Nant Tanllwyth catchment was predicted to bring changes to the character of the channel, elevating both suspended sediment and bedload outputs. Evidence from previous studies worldwide had shown the likelihood of loose brashings from harvesting operations entering channels and forming debris jams resulting in severe bank erosion (Megahan, 1972; Murphy *et al*., 1986; O' Connor, 1986; Whitaker, 1992). The proximity of heavy machinery to streams has also been shown to cause bank collapse and accelerated erosion. These changes might have manifested themselves as instant and dramatic increases on the sediment regime of the Nant Tanllwyth, but in practice the harvesting of 15% of the catchment directly adjacent to the study reach, did not result in the predicted dramatic increase in the sediment flux and yield as reported in the other UK studies shown in Table 4.

Although the 1995 background suspended sediment yield increased by 81% in 1996, when the equivalent increase of 43% in the neighbouring Afon Hore catchment is considered, the real increase in the Tanllwyth is only 39%. The delayed response in SSYs in the Tanllwyth suggests that either post-harvesting soil erosion appears to be more significant than the immediate disruption of the catchment surface seen during the felling in the Hore and other UK studies shown in Table 4, or, the smaller scale of the harvesting plot (only 15% of the catchment), the specific harvesting techniques employed and the time of year the operations were carried out, have all had a role to play in reducing and delaying the suspended sediment response.

Bedload yields (Table 3A) remained stable throughout the study period, most notably responding similarly to the flood peaks coming in the post-harvesting phase as to those peaks pre-harvesting. There was little evidence of sediment building up behind timber debris within the main channel as observed by Leeks (1992) in the neighbouring Hore clear-fell experiment, and as seen at Balquhidder (Stott, 1997b; Whitaker, 1992), although there was considerable build-up of brashings and resulting reduction in sediment transport in first order tributaries of the main channel and existing drains (Figure 8(a)).

Preliminary results from an experiment which traced the movements of 20 tagged bedload clasts carried out between 1998–2000 in the harvested first order tributary seen in Figure 8(a), and a similar sized tributary in a nearby unclear-felled tributary, showed marked contrasts in travel distances of individual tracers (Table 5). These contrasts are a direct consequence of the build up of brashings in the clear-felled tributary channel. The implications of this are that a longer post-harvesting time series of bedload data will be required to properly assess the impact of the harvesting operation upon bedload yields. The Tanllwyth main channel was monitored closely throughout and after the harvesting operations for three years to look for the possible formation of coarse woody debris jams. Although most studies concentrate mainly on the removal of naturally occurring debris jams in non-plantation catchments (e.g. Smith *et al.*, 1993), some work (e.g. Bryant, 1980; Leeks, 1992) has shown how harvesting can promote these features with brashings and excess logs. Smith *et al.* (1993) showed that after development and experimental removal of debris jams, sediment transport increased along with increased transport energy and bank erosion. The effect was that the stability of the sediment regime was affected in the medium term with continuous adjustments made to bedforms in the channel. None of these major dams formed in the Nant Tanllwyth, indeed during the study period, on only a few occasions were logs found anywhere in the channel. Keller and Swanson (1979) observed a decrease in bank stability as flow is deflected against channel banks and greater sediment inputs resulted due to debris jams. Keller and Swanson (1979) also note that, at peak discharges, floating debris itself may batter the bank sides and cause erosion. The attempts made by the forestry operators in the Nant Tanllwyth to ensure that the channel banks were undisturbed proved to be successful, with little or no direct effects on either the main channel or its banks. There is little doubt that the care taken by forest workers, the felling techniques employed and the harvesting machinery used (Figure 2) had an enormous influence on the low impacts of the partial felling in the Nant Tanllwyth catchment. However, examination of Figure 6(a), where

Table 4. Sediment yields associated with timber harvesting in upland Britain

Catchment	Reports	Area km^2	Land use	Years of data	SSY t km^{-2}	% change
Kirkton, Balquhidder, central Scotland	Stott *et al.*, 1986 Johnson, 1993	6·85	Mature forest	4	56·6	
			progressive felling to 50% of catchment	4	462·8	+718
Loch Ard, central Scotland (Catchment 10)	Ferguson *et al.*, 1991	0·84	Mature forest	1	55·2	
			clear-felling	2	89·6	+62
			post-clear-felling	0·25	98·4	+78
Plynlimon, mid-Wales	Leeks, 1992	3·08	Mature forest	2	24·4	
Hore			felling	1	57·1	+134
Tanllwyth	This study, 1995–7	0·89	mature forest	1	24·2	
			clear-felling of 20%	1	43·8	+81 (39%)

(a)

(b)

Figure 8. (a) Tree brashings and lops in a small ephemeral sub channel of the Nant Tanllwyth, October 1997. (b) Wind-blown trees on the Nant Tanllwyth in July 1999.

the dashed vertical line shows the felling date, highlights the significant period of low flows during and immediately following the felling period. The methods used in this case might still have caused increased erosion under wet conditions where surface soils are more susceptible to erosion from machinery and overland flow sources. These methods differed from the work undertaken on the steeper terrain of the Balquhidder catchments (Johnson, 1993; Johnson and Bronsdon, 1995; Stott, 1997b) where aerial skylines, drags and forwarders were used, all potentially more erosive methods.

The Forests & Water Guidelines (Forestry Authority, 1993) were well adhered to in the felling of the Nant Tanllwyth for both timber harvesting and extraction. It seems that the acknowledgement of the importance of small headwater streams on the sediment regimes of larger rivers, is manifested in practical operations, though the smallest first-order streams in this study did not receive the same consideration as the main channel.

Forest operators in this study harvested the area immediately next to the channel by hand and removed brashings back from the channel. This good practice minimises the impact of heavy machinery on or near channel banks which can cause bank collapse. Undertaking a hand felling policy near the channel is in the interest of a forester who wishes to maintain the channel in its current state. The removal of brashings and careful felling avoids the interference with the medium to long-term sediment dynamics by continuous formation and destruction of debris jams. Specific care also needs to be taken in the removal of logs in the vicinity of the channel banks. A consequence of the partial felling of the catchment combined with the hand felling adjacent to the channel was observed approximately 200 m above the experimental section. The harvesting area was delimited using the main channel and several of its small tributaries as borders for each section. This led to a neat but exposed 'wall' of trees, which was susceptible to wind action. With the shallow root systems of the plantation (particularly around the channel where furrows and drains did not appear to have been as deeply ploughed), the trees were unable to support themselves and became windblown (Figure 8(b)).

The effect of this wind exposure both damaged and uprooted trees in the winters of 1998 and further windblow occurred over the winter of 1999–2000. In addition, because the interface between the harvested and standing areas was the channel, the bare roots of the trees broke up the banks of the main channel. Some of the bases of these uprooted trees were in excess of 3 m in diameter and loosened significant volumes of non-cohesive sediment that might be entrained and transported into the channel, particularly during high and over-bank flow events. The problem (which did not manifest itself immediately) could be solved by ensuring watercourses were not used to delimit the partial clear-felling areas. If, for management reasons, this was impossible, it would be appropriate to leave a small standing (but significant) buffer of trees on both sides of the channel so that the entire stream area was protected from wind blown trees. Alternatively, protection could be built into the harvesting programme by felling a buffer on both sides of the channel, so that the wind blow would occur some distance from the watercourse so that exposed roots would not damage the channel and banks. Early replanting of such a harvested buffer strip with appropriate broadleaf species such as birch, willow, rowan, alder or maybe even common ash and aspen might produce several benefits for the streams. These benefits could include: stabilising the banks and reducing bank erosion (Vansplunder *et al*., 1994); shading the stream from direct sunlight so alleviating observed stream temperature increases in summer (Stott and Marks, 2000); ameliorating frost activity on banks in winter (Stott, 1997a, 1999); providing protective cover and encouraging insect life on which fish feed; protecting banks and surrounding riparian land from the impacts of precipitation; intercepting sediments and solutes (e.g. toxic material from spraying) carried in overland flow and generally benefiting the health and ecology of the stream (Mills, 1980).

Undertaking techniques for minimising the impacts of harvesting, such as hand felling next to watercourses and laying down matting for heavy machinery has significantly reduced erosion to both the channel itself and the surrounding slopes. The advent of the one machine harvester (Figure 2), used for economic rather than environmental reasons, has in itself brought benefit to the environment of the catchment. Work is undertaken at a much faster rate than before and fewer heavy machine hours are required in the catchment. Machinery to transport the logs can move easily over the felled area of the catchment, as brashings are well ordered and sorted into matting and the tops of stumps are cut low and evenly. This means that fewer new forest roads are required, roads that have proven to be significant sediment sources in previous studies (e.g. Painter *et al*., 1974; Johnson and Bronsdon, 1985; Ferguson and Stott, 1987; Fukushima, 1987).

The importance of the timing of harvesting work should not be underestimated The Forest and Water guidelines recommend that any essential in-stream work be carried out in the period May–September. Perhaps the guidelines should also include direction on the hydrological and meteorological conditions under which work can be undertaken near watercourses. While it would be impractical to expect foresters to discontinue work at the advent of a rain shower, guidelines for working around watercourses during intense periods of rainfall or snowmelt, or in highly saturated conditions, would be a useful addition. The recommendations would apply only in close proximity to watercourses (including forest ditches), where stream and ditch banks are susceptible to damage, particularly when wet. This recommendation could be built into the current document.

The net effect of undertaking ecological harvesting has been that enormous efforts have been made to prevent damage to the small second order watercourses such as the Nant Tanllwyth. The focus on these larger watercourses has possibly been to the detriment of the network of small ditches and first order tributaries, some of which exhibit ephemeral discharge patterns, but which nevertheless make an important contribution to peak flows and sediment loads in the main channel. A large amount of organic material (including branches and brashings up to 70 mm in diameter and 2 m in length) have either clogged the channel, or have completely covered over the first-order channel shown in Figure 8(a). The results of the bedload tracing experiments, reported in Table 5, show that the harvested first-order tributary shown in Figure 8(a) had mean bedload travel distances an order of magnitude lower than those in a similar nearby mature forest tributary over a two year period.

The limitations of transport in the harvested tributary are physical dams rather than stream power. These findings suggest that bedload is being held back in these first order streams while the brashings remain in the channel. Two years after harvesting, much of the smaller brashing material in the first-order streams has started to decompose and the tributary banks are becoming well vegetated with mosses and grasses, further stabilising these channels. It is too early yet to assess any downstream impacts this deprivation of bedload might have. The cumulative effects of such retention of bedload over a large harvested catchment such as the whole of the upper Severn, could be of significance to the stability of channels downstream of the harvested areas and, if so, future guidance might include the removal of such brashings from tributaries and drainage ditches once harvesting operations are complete (e.g. Smith *et al*., 1993).

Table 5. Results of tributary tracer experiment in first order stream on Nant Tanllwyth, 1997–2000

	1998–1999	1999–2000
Harvested tributary		
Mean distance moved (m yr^{-1})	0·16	0·46
Maximum distance moved (m yr^{-1})	0·75	0·85
N	19	18
Mature forest tributary		
Mean distance moved (m yr^{-1})	5·31	2·34
Maximum distance moved (m yr^{-1})	14·50	6·90
N	19	19
t-test significance	$P<0{\cdot}001$	$P<0{\cdot}001$

We suggest that during periods of high precipitation, or rapid run off after snowmelt, the inability of these ditches to provide stable water courses could lead to the development of erosive overland flow and soil erosion in the main catchment of the Nant Tanllwyth. The possible benefits of log jams are discussed in Maitland *et al*. (1990) and seem to be with reference to when large volumes of sediment are liberated in poor working conditions. With the use of new guidelines seemingly halting the seriously destructive practices seen in the past, it might be appropriate in future for forest managers and operators to take more care to avoid the formation of log jams in small first-order tributaries.

The findings of this study add further support to forest management proposals and guidelines which advocate the inclusion of 'buffer strips' in the management plan (e.g. Brazier and Brown, 1973; Mills, 1980; Forestry Commission, 1988; Maitland *et al*., 1990). Mills (1980) stipulated reserve areas 10 times the width of the stream, up to a maximum of 30 m, to protect stream channels from excessive shade (temperature stability) and the inflow of sediments and toxins. Some vegetation (e.g. birch, alder, willow, rowan) is seen as desirable to give shade for fish and provide nutrients via leaf-fall and to control and prevent bank erosion (e.g. Vansplunder *et al*., 1994). In the Kielder Forest, for example, extensive riparian corridors of broadleaf trees feature in the second planting and in some areas riparian plantation forest is even being prematurely felled in order to carry out such replanting, partly in the interest of landscape aesthetics, but also in the hope that the stream ecology will benefit. Newson (in Maitland *et al*., 1990) points out that the whole policy is proceeding without research confirmation. This study confirms the preliminary impacts of plot-scale harvesting at Plynlimon on stream bank temperatures, and tentatively links this to increased bank erosion rates observed over the timescale of this study. Stott and Marks (2000) have reported on the increase in stream temperature of the Nant Tanllwyth during this same clear-felling experiment and Crisp (1997) has demonstrated that the mean annual water temperature of a Plynlimon stream flowing through mature coniferous plantation was c. 0·4°C lower than a nearby stream which flowed for 1·5 km through clear-felled land. The guidance relating to leaving an unfelled buffer strip on either side of the main stream, or replanting with broadleaf trees, might reduce the impact on stream temperatures and sediment pollution at the same time as benefiting stream ecology (Gee and Smith, 1997).

Further research needs include: investigation of the effects of broadleaf planting in riparian buffer strips on bank erosion processes; monitoring the effects of clear-felling and replanting on bank moisture regimes and frost activity; re-vegetation rates of bare surfaces and banks and the gathering of longer term data to confirm these preliminary effects of clear-felling on suspended sediment yields and recovery times, bedload yields and bank and forest ditch erosion rates.

Conclusions

Environmentally sensitive harvesting of a 13 ha plot of mature coniferous plantation forest in the Afon Tanllwyth catchment (15% of the catchment area) on Plynlimon has resulted in the following:

(a) A steepening of the SSC vs. discharge rating curve resulting in a 39% increase in SSY (as compared to the adjacent forested Hafren catchment) during the year in which the harvesting operations took place;
(b) A statistically significant increase in main channel bank erosion rates, as compared with the nearby Afon Cyff; main channel banks are estimated to have contributed around of 80% of the total catchment SSY during the two year period (1995–1996);
(c) No significant change in bedload yields over the duration of this study, though a longer post-harvesting time series of bed-load data will be required to properly assess the impact of the harvesting operation upon bedload yields.

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