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Changes to headwater stream morphology, habitats and riparian vegetation recorded 15 years after pre-Forest Practices Code forest clearfelling in upland granite terrain, Tasmania, Australia

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Abstract

The effects of clearfelling on headwater wet sclerophyll eucalypt forest streams and their riparian zones were examined in upland granite terrain in north-east Tasmania, Australia. Five first-order, headwater stream catchments, clearfelled and regenerated to native forest in 1985 (REGEN streams) were selected for comparison with five similar 'control' stream catchments (CONTROL streams). Channel morphology and stream habitat features were measured in 50 m representative study reaches along each stream. Stream sediments and riparian soils were analysed for particle size, loss on ignition, and carbon and nitrogen content. Vegetation composition and structure were assessed in plots within the riparian (0–10 m) and adjacent near-riparian (10–20 m) forest, adjacent to the study reaches. All catchments were assigned a historical disturbance rating based on aerial photograph and field observations.

There were significant differences between the composition and structure of the riparian and near-riparian vegetation of REGEN and CONTROL streams. Differences were less pronounced in the more homogenous riparian vegetation than in the more heterogenous near-riparian vegetation. Species richness was higher in the REGEN near-riparian vegetation, but not in the riparian vegetation. As expected, structural differences between the vegetation of the REGEN and CONTROL streams were still evident within both the riparian and near-riparian zones, 15 years after clearfelling.

REGEN streams were overlain by more logs, were more entrenched, and less complex morphologically, with a lower proportion of pools and bars, than CONTROL streams. REGEN streams contained less organic debris, and more variable bankfull widths, exposed boulders and locally variable slopes than CONTROL streams. REGEN streams had coarser sediments with a lower C/N ratio than CONTROL streams. REGEN stream riparian soils contained more total nitrogen than those of CONTROL streams.

Impacts of pre-Forest Practices Code clearfell logging and forest regeneration methods on granitic headwater streams are still apparent after 15 years. Observed differences in stream morphology and habitats were significantly correlated with the rating of the harvesting disturbance. We ascribe the differences to direct and indirect effects of harvesting, and deduce that these catchments are still adjusting to that disturbance. Current Code prescriptions will limit impacts of current

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harvesting in similar terrain, though indirect effects of current harvesting methods on headwater stream character may still be significant.

Keywords: Logging; Headwater streams; Geomorphology; Habitats; Vegetation; Australia; Forest Practices Code; Riparian; First-order streams; Tasmania; Forest harvest; Biodiversity

1. Introduction

The effects of land-use change on first-order headwater streams have not been extensively researched. The number of small streams in the landscape, the high proportion of catchment area that they drain, and their consequent potential to have a cumulative downstream effect emphasise their importance for river and catchment management (Wells, 2002). Descamps et al. (1999) suggested that the control of water quality in headwater streams should be a priority for improving downstream river water quality. Davies et al. (1999), recognising the high diversity of headwater streams, their varied geomorphological settings (soils, geology and slopes) and erosion risks, recommended increased research on the protection requirements of headwater streams in the Tasmanian forest estate.

The processes that occur in headwater streams after forest harvesting can be separated into the direct effects on streams and riparian zones, resulting from machine and harvesting disturbance of soil and water, and indirect effects resulting from changes to catchment hydrology and sediment dynamics after harvest.

Direct effects include soil compaction and weakening (Slaymaker and McPherson, 1977), soil erosion due to windthrow (Winfield, 1999), sediment plumes entering riparian zones and streams from harvested areas (Dignan, 1999), soil disturbance and sediment inputs associated with roads, stream crossings and cultivation (Croke et al., 1999), short- to medium-term increases in fine sediment and organic matter transport after steep country harvesting (Davies and Nelson, 1993) and changes in the amount of LWD in streams after logging (Bryant, 1985; Davies and Nelson, 1994; Bunce et al., 2001).

Indirect effects are a consequence of catchment yields and streamflows increasing and peaking in the first few years after harvest, also associated with lower evapotranspiration losses from the harvest area than from unharvested forest (Vertessy, 1999) as well as changes in soil structure and subsurface flow dynamics. In southeast Australian forests, flows generally peak within 3 years after harvest, and then, if regeneration or plantation growth is strong, evapotranspiration losses increase, resulting in pre-harvest streamflows potentially being restored after about 6 years (Vertessy, 1999). After restoration of streamflows to pre-harvest levels, flows may decline further as the greater leaf area of young forest transpires more water than mature forest (Vertessy, 1999; Vertessy et al., 2001). Indirect effects associated with increased streamflows after harvest include water table changes, changes in the nature of overland flow, decreased stream bank stability, changes in stream channel profiles, decreased stream sediment retention and increased sediment transport (Borg et al., 1988; Vanderwel, 1994).

Direct effects of forest harvesting operations include changes in forest structure, with loss of canopy trees, as well as changes in floristic composition and species richness (e.g. Burrows et al., 2002; Wapstra et al., 2003). Direct effects of disturbance on streams may be difficult to distinguish from indirect effects. Bunce et al. (2001) could not conclusively attribute changes in stream sediment size fractions to direct disturbance or increased stream flow after harvest. Croke et al. (1999) questioned whether increases in sediment yield reported in streams were the result of hillslope erosion, and implied that indirect erosion processes affecting channel stability may be more important than credited to date.

This paper compares the geomorphology, in-stream and riparian habitats, and riparian vegetation of small (<50 ha catchment area) logged and unlogged headwater streams in upland granitic terrain in northern Tasmania, Australia. It is an expanded and more detailed appraisal of the streams studied by Bunce (2000) and Bunce et al. (2001). Clearfell logging occurred 15 years prior to the study and before the Tasmanian Forest Practices Code (Forest Practices Board, 2000) governed operations. This paper addresses the question of the persistence of harvesting effects on first order headwater stream riparian forest structure and composition, as well as on stream geomorphology, habitats and sediments. Further papers (Davies et al., submitted for publication; Koch et al., submitted for publication) will describe differences of stream benthic invertebrate fauna and platypus populations associated with this disturbance.

2. Methods

2.1. Study design

Multiple-Control before–after-control-impact (MBACI)-type designs (Underwood, 1997; Stewart-Oaten and Bence, 2001) are a preferred ANOVA-based experimental approach for assessing land-use impacts. However, such a design is often precluded in assessments of the effect of forest operations when seasonal and annual variability in responses, the slow responses of trees and catchment processes and the need for reliable long-term experimental planning and implementation must be allowed for. BACI-type designs require a long-term commitment of land and funding which may not be available. An alternative is to use a retrospective ('space-for time') inferential approach and to compare streams or catchments under different current land uses. This has several disadvantages: the prior condition of the study catchments may not be known, the locations of treatments and controls may be governed by operational considerations (e.g. historical location of roads) rather than scientific criteria, site selection cannot be assumed to be random, and although differences between treatments and controls may be evident, the processes causing these differences may be obscure because they were not observed or monitored as they occurred.

Because this study aimed to investigate medium-term effects, and forestry operations in Tasmania have only been constrained by a Forest Practices Code since 1987, study catchments were chosen that were clearfelled before the code was in operation. Before 1987 there were no restrictions on harvest or machinery use near streams, and machinery entry into streams was commonplace. In addition, clearfelling of the *Eucalyptus delegatensis* forests that predominate in the study area was usual, whereas partial harvest is presently practised as it produces better regeneration (Hickey and Wilkinson, 1999).

A retrospective approach was taken in the study reported here, as resources were not available for a long-term experiment. We took particular care to choose study catchments that were likely to have been highly similar before harvesting operations began. The overall study design conformed to a control versus impact analysis of variance comparison without temporal replication, with a number of factors nested within the logging-control treatments, and with some variables (aspect and stream slope) as covariates.

2.2. Study area

The study streams were located in the upper South Esk catchment on the upland plateau (800–900 m) east of Ben Nevis peak (1368 m), in northeast Tasmania, around latitude 41°25′S, longitude 147°39′E (Fig. 1). Valley slopes are mostly 0–11°. Rainfall exceeds 1400 mm, with a winter (June to September) rainfall maximum. The area is underlain by biotite granite/adamellite (Department of Mines, 1993). Acidic Mellic Brown Kandosols (Isbell, 1996) dominate, which are approximately equivalent to Dystrudepts in the USDA soil classification (USDA, 1998), and have been mapped in the area as well-drained, moderate-erodibility memory soils with sandy clay loam textures (Grant et al., 1995). Undescribed, poorly drained soils (probably redoxic hydrosols) occur in narrow bands (generally 1–10 m wide) next to streams.

The natural catchment vegetation is dry sclerophyll eucalypt forest dominated by *E. delegatensis*, with a shrubby understorey. On slopes adjacent to the riparian zone, the vegetation is wet sclerophyll and mixed eucalypt forest, dominated by *E. delegatensis* and *E. dalrympleana*. In the riparian zone, which is up to 20 m wide (but generally much narrower), the vegetation is either rainforest dominated by *Nothofagus cunninghamii* (myrtle) and *Atherosperma moschatum* (sassafras), or swamp forest dominated by *Leptospermum lanigerum* (woolly tea-tree).

Pre-European human impact on the study streams is believed to have been minimal. The eucalypt forest was maintained by both natural and anthropogenic fires. The entire area was progressively selectively logged following European settlement. Clearfelling using heavy machinery occurred locally in the 1980s.

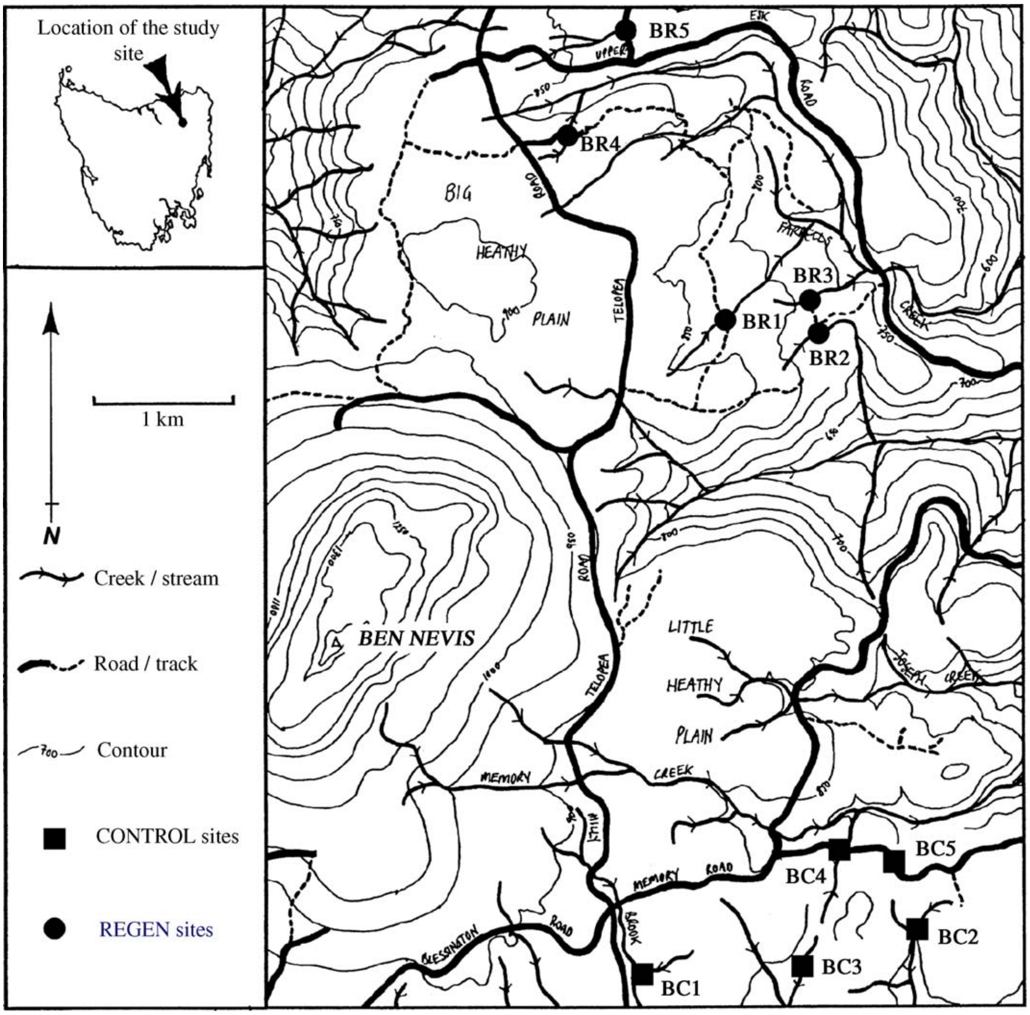

Fig. 1. Map of study site at Ben Nevis, Tasmania, showing location of study reaches in each REGEN (BR1–BR5) and CONTROL (BC1–BC5) headwater stream. Stream channels shown as defined in 1:25,000 scale map.

Activities were not controlled by environmental regulation, and operations next to streams included machinery crossing of streams, and felling of trees into streams. Direct impacts are likely to have been greater than those occurring in present-day clearfell operations which are governed by the Forest Practices Code (Forest Practices Board, 2000).

Five headwater streams (mean catchment area of 23 ha, range = 8–40 ha) were selected in catchments that had been clearfelled and regenerated in 1985 (hereafter called REGEN sites). Five were also selected in minimally disturbed, control (CONTROL) catchments that had historically been lightly selectively logged but had not been clearfelled (mean catchment area of 16 ha, range = 8–23 ha). All streams had similar slopes (grand mean of 0.048, range = 0.024–0.071) and mean channel bankfull widths (mean of 1.91 and 1.87 m for CONTROL and REGEN streams, respectively).

The study catchments all fell completely within the same geology (adamellite—granite type I) and had similar mean elevations, mean annual runoff, stream slopes, catchment sizes and original forest communities.

Multivariate analysis was conducted using variables describing these key catchment and stream characteristics. Mean elevation, stream slope, % area of *E. delegatensis* wet and dry forest types, catchment area, modelled long-term mean annual runoff (MAR, in ML) and MAR per unit area were sourced for each study catchment from state government GIS data bases (Department of Primary Industry Water and Environment, Tasmania, 'CFEV' and 'TasVeg' databases). Multidimensional scaling ordination was conducted in Primer-E version 5.2.8, Clarke and Gorley, 2001) of a Euclidean distance matrix derived from standardised values of these variables. Analysis of similarities (ANOSIM in Primer-E) failed to discriminate the CONTROL and REGEN streams ($p > 0.25$). Differences between CONTROL and REGEN stream for these individual variables were not statistically significant by one-way analysis of variance (all $p > 0.05$).

Stream and study site locations are shown in Fig. 1. A simplified representation of the structure and composition of the vegetation of the CONTROL and REGEN sites is shown in Fig. 2.

The historical pattern of clearfelling in the area dictated that the five REGEN treatments were separated from the five CONTROL treatments by a maximum of 5 km (Fig. 1). The uniformity of the geology, slope, original forest communities and altitude over the study stream catchments (McIntosh, unpublished data) indicated that systematic differences between REGEN and CONTROL stream catchments and drainage characteristics were highly unlikely.

A 50 m study reach was selected to be broadly representative of the downstream reaches of the headwater (1st order) streams. Inspection of historically mapped riparian vegetation forest community and structural data (pre 1970s, Forestry Tasmania unpublished data) for both stream sets, and field inspection of CONTROL and REGEN stream channels and riparian forest indicated that a 50 m reach would be sufficient to characterise the middle and lower reaches of these streams. Active stream channels typically ranged between 200 and 500 m in length between the point where permanent flowing water was observed and the point at which the catchment area reached 40 ha (the upper limit for 'Class 4' headwater streams as defined in the Tasmanian Forest Practices Code). Study reaches were generally located in the lower 200 m of the stream, and were placed after visual inspection of the entire active stream.

2.3. Disturbance rating

A rating for the degree of disturbance by logging operations was developed for all study streams, derived from aerial photograph and field observations. At the REGEN sites, fire was used to induce regeneration following clearfelling, but the regeneration pattern indicates that burns were patchy. The rating was based on the degree of disturbance from forest operations within the catchment and riparian zone. The relative area of forest and under-storey removed and/or burnt, and the intensity of snig tracking was estimated for the catchments from aerial photographs taken immediately after harvesting in 1985. The relative area of forest removed and/or burnt, and the number of snig track stream crossings was estimated for the riparian zones. It was not possible to assess stream channel condition from aerial photographs due to the dense riparian canopy cover. For CONTROL streams, the estimated proportion of trees removed during historic selective logging operations was also assessed by field inspection.

An overall relative disturbance rating for each REGEN stream catchment was then assigned to each catchment, giving a final score ranging between 0 (undisturbed) to 3 (intensely disturbed). The ratings and catchment and riparian descriptions are shown in Table 1.

2.4. Vegetation

2.4.1. Vegetation data collection

Adjacent to each stream, we established six 'riparian' and six 'near-riparian' 10 m × 10 m vegetation plots. Three, adjacent 'riparian' plots were placed immediately adjoining the stream bank on both sides of the marked 50 m study reach, with the three left and right bank plots located directly opposite each other. 'Near-riparian' plots were located adjacent to, and sharing a common boundary with, each riparian plot, 10–20 m from the stream banks. The structure of the vegetation was recorded, height (m) and canopy cover (%) were estimated for each stratum of vegetation, and the dominant vascular species noted.

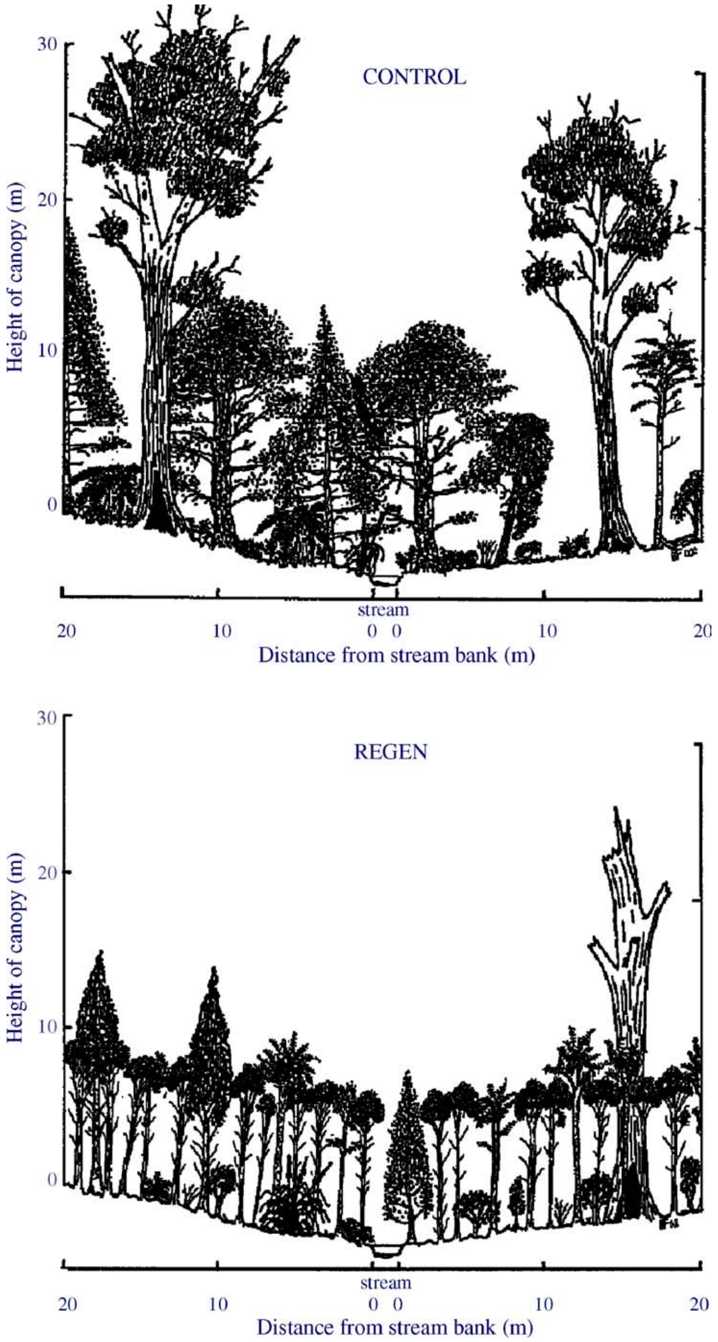

Fig. 2. Typical structure and composition of the vegetation of the CONTROL and REGEN stream sites at Ben Nevis. Note mature *Eucalyptus* trees and more complex structure of CONTROL stream forest, compared with lack of overstorey and more even age of REGEN site vegetation.

Table 1
Study stream features and logging disturbance rating

Treatment	Stream	Catchment area (ha)	Mean stream slope	Mean Bankfull width (m)	Description of logging disturbance	Disturbance rating
CONTROL	BC1	22.56	0.0318	2.052	Intact open canopy forest across catchment, light selective logging	0.25
	BC2	11.8	0.0332	2.168	Closed, intact riparian canopy, minimal selective logging	0.125
	BC3	18.11	0.0234	1.815	Closed intact riparian canopy, one side of catchment lightly selectively logged	0.25
	BC4	21.55	0.0534	1.945	Open canopy forest in catchment, selectively logged, intact riparian forest	0.25
	BC5	8.04	0.0571	1.595	Closed, intact riparian canopy, lightly selectively logged	0.125
REGEN	BR1	40.41	0.0310	1.950	80% of catchment cleared, one side of study reach with scrub retained	2.00
	BR2	26.48	0.0478	2.473	70% of catchment logged but still with scrub cover, two snig track crossings	1.50
	BR3	8.49	0.0636	2.095	65% of catchment logged, still with scrub cover, riparian trees retained	1.00
	BR4	19.25	0.0654	1.521	50% of catchment severely logged, no understorey, and burnt through stream; 50% a marsh, lightly burnt	2.50
	BR5	22.73	0.0341	1.290	90% of catchment cleared and burnt, minimal understorey retention, some scrub retained adjacent to study reach	3.00

Using the taxonomic nomenclature of Buchanan (1999), all vascular species with parts occurring within a plot were recorded as being present (even though their basal parts may have been outside the plot) and assigned a canopy cover score using a modified Braun–Blanquet index (Mueller-Dombois and Ellenberg, 1974) i.e. 1 = <1%; 2 = 1–5%; 3 = 5–25%; 4 = 25–50%; 5 = 50–75%; 6 = 75–100%. Environmental variables were recorded for each plot: slope (degrees); aspect (degrees); rock cover (%); non-vascular cover (%); log (>10 cm diameter) cover (%); topographic position (description); fire history (estimate of time since last fire, description of evidence); logging history (number of cut stumps and style of cut, e.g. modern or historical).

2.4.2. Data analysis—vegetation

Species composition patterns for REGEN and CONTROL sites were described by ordination, using both presence–absence data and abundance data. The abundance of each species at each site was represented by an average of the raw Braun–Blanquet scores recorded for each plot (which were first converted to the midpoint value of their ranges).

Ordination and analysis of similarity were conducted using the MDS and ANOSIM routines in the Primer-E software package (Version 5.0, Carr, 1996; Clarke and Warwick, 2001). MDS was conducted using a Bray Curtis similarity distance matrix derived from the presence–absence or abundance data (the latter square-root transformed), with 1000 random starts. Ordinations were accepted if final stress values fell below 0.15.

Taxa responsible for differences between treatment groups were assessed in two ways. “Similarity percentages” analysis (Clarke and Warwick, 2001) was conducted using the SIMPER routine in Primer-E. Indicator species analysis (Dufrene and Legendre, 1997) was used to assess significant species associations with the CONTROL or REGEN sites, for both the riparian and near-riparian data sets, using the PC-ORD package (version 4.0, McCune and Grace, 2002). This technique calculates relative abundances (RA) and relative frequencies (RF) of taxa in groups and derives an indicator value (IV) for each taxon across the groups (where IV = 100 × RA × RF, and ranges from 0 to 100). The significance of the IV was evaluated for each taxon by Monte Carlo randomisation of all taxa across the groups (with 1000 random reassignments).

Species richness (total number of species) was calculated for each plot. Nested ANOVA was conducted on untransformed plot species richness data (separately for riparian and near-riparian plots) with REGEN and CONTROL as logging treatment factors, and streams nested within logging treatment.

Multivariate patterns in the structural composition of the vegetation for REGEN and CONTROL sites were described by ordination, as above, using untransformed percentage cover scores (averaged across plots for each site) from the tree and shrub vegetation layers only, using height class categories assigned after data collection. The height class categories used were: low shrubs less than 1 m height (H1), low shrubs 1–3 m (H1-3), medium shrubs 3–10 m (H3-10), taller shrubs 10–20 m (H10-20), low trees 20–30 m (H20-30) and taller trees >30 m (H30+).

2.5. Stream morphology and sediments

2.5.1. Morphology and habitat measurements

At 2.5 m intervals along each study reach, we measured bankfull and wetted width, bank height (from the channel midpoint). For each 2.5 m section, the proportion of stream channel which comprised three geomorphic units – channels, bars and pools – was estimated. Pools were defined as depressions or backwaters with a planar or concave bed profile, and invariably contained fine organic sediment.

The percentage of stream bed covered by coarse particulate organic matter (CPOM: primarily leaf, twig and bark debris), organic silt, roots, benthic algae, moss and macrophytes was measured for each 2.5 m section, as well as the proportion of the stream substrate area consisting of boulders, cobbles, gravel, sand and silt. The number of overlying and in-stream logs (defined as being >10 cm in diameter) was also counted throughout the reach. Channel slope was measured for each 2.5 m length within the study reach (‘local’ slope), as well as overall slope across the entire reach, using a tripod-mounted level and staff and tape.

2.5.2. Sediment and soil sampling

At three locations within each stream reach (i.e. within the 0–10 m, 20–30 m and 40–50 m zones), three 20 cm deep by 51 mm diameter core samples of stream bed sediment were taken. The cores were taken from channels, bars and pools (if present) or from the dominant geomorphological units (if all three units were not present). This resulted in nine cores per stream. Core samplers were relocated if a minimum depth of 10 cm of sediment was not obtained.

Riparian soils were sampled by taking 20, 0–10 cm topsoil samples from shallow pits along each bank of the study reach, within the 0–10 m riparian zone. The 20 samples were pooled, giving two pooled representative samples per stream.

2.5.3. Sediment and soil analysis

The streambed sediment cores were extruded, mixed, dried at 80 °C to constant weight for over 24 h and split into two parts. One part was dry-sieved through a 2 mm sieve and the >2 mm fraction weighed. A muffle furnace was used to burn off the organic and any carbonate component in the <2 mm fraction (Brimblecombe et al., 1982), and loss on ignition (LOI) was measured. The particle-size distribution in the <2 mm fraction was sieved with a series of mesh sizes (<0.125–2 mm, Krumbein and Pettijohn, 1938; McCave and Syvitski, 1991). Silt and clay fractions were not studied as less than 2% of the <2 mm fraction was <63 μm (Bunce, 2000). The other part of the <2 mm fraction was analysed for total carbon (C) and total nitrogen (N) using a LECO furnace (Blakemore et al., 1987). The <2 mm fraction of the soil samples was also dried at room temperature and similarly analysed.

2.5.4. Data analysis—morphology, habitat and sediments

All statistical analysis was conducted with SYSTAT Version 10.0 (Wilkinson, 2001). Analysis of variance (ANCOVA) was used to test for significant differences in sediment size composition between logging treatments (CONTROL versus REGEN) for each geomorphic unit (pool, bar, channel), with overall stream reach gradient as a covariate. One-way ANCOVA was used to compare values of all other morphological and habitat variables between CONTROL and REGEN streams, again with stream gradient as a covariate. Values for variables measured in each 2.5 m section were averaged across the study reach for each stream prior to these analyses. Standard deviation and coefficient of variation were also derived for local point gradient and channel width data. Statistical significance was accepted at $p < 0.05$, although results with $0.1 > p > 0.05$ were also reported (as of ‘borderline’ significance) to minimize Type II errors (Yoccoz, 1991).

Principal component analysis (PCA) was conducted on the following stream environmental variables (in SYSTAT 10): standard deviation of gradient within reach; number of logs overlying channel; number of logs in channel; mean % area as channel, bar and pool habitats; mean wetted width under baseflow; mean bankfull width; CV of bankfull width; mean bank height; mean % area of sand, gravel, cobble, boulder substrates; mean % area as leaves, twigs, bark (CPOM) and as organic silts (FPOM); mean % area as tree roots; mean % area as algae, moss and macrophytes; number of algal, moss and macrophyte patches. The principal components describing the majority of the variance in these environmental data were then correlated with the disturbance ratings.

3. Results

3.1. Stream characteristics and disturbance rating

Stream features and disturbance ratings are shown in Table 1. All CONTROL streams had a low disturbance rating (scores from 0.125 to 0.5). These ratings were associated with negligible impact of very low intensity, selective forest harvest on the structure and composition of the riparian and near-riparian vegetation, which was similar to undisturbed vegetation of the area (Wapstra, unpublished data). The degree of disturbance of REGEN streams varied substantially: streams R2 and R3 were moderately to highly disturbed (with some retention of understorey and riparian forest) whereas stream R5 was extremely disturbed (90% of catchment cleared and burnt).

3.2. Vegetation data

3.2.1. Community composition

REGEN and CONTROL streams had significantly different near-riparian vegetation community composition, with both abundance and presence/absence data (by ANOSIM, $p = 0.048$ for both cases; Fig. 3). The riparian vegetation community composition of REGEN and CONTROL streams can be visually discriminated in MDS ordination space (Fig. 3) based on untransformed abundance data. However, riparian plots differed only at the $p = 0.087$ level by ANOSIM for untransformed abundance data, and did not differ significantly for presence/absence data (ANOSIM, $p = 0.44$).

Species that were statistically significant indicators of CONTROL or REGEN stream vegetation communities (by indicator species analysis, all $p < 0.05$) are shown in Table 2. Species identified by SIMPER analysis which best discriminated the CONTROL and REGEN sites (i.e. those accounting for up to 50% of the dissimilarity of the stream group vegetation communities) are as follows, in decreasing order of importance:

Riparian plots: *L. lanigerum*, *E. delegatensis*, *N. cunninghamii*, *Acacia dealbata*, *Blechnum nudum*, *Tasmannia lanceolata*, *Histiopteris incisa*.
Near-riparian plots: *N. cunninghamii*, *L. lanigerum*, *Blechnum wattsii*, *B. nudum*, *T. lanceolata*, *E. delegatensis*, *A. moschatum*, *Persoonia gunnii*.

Overall, there were fewer discriminatory plant species in the riparian than in the near-riparian plots.

3.2.2. Species richness

Total species richness for riparian plots was significantly higher for the REGEN than the CONTROL streams by ANOVA. The near-riparian plots did not show a significant difference between treatment groups (Table 3). Significant differences (at $p < 0.02$) were also observed between streams (within treatments) for both riparian and near-riparian plots, but are not explored further here.

3.2.3. Vegetation structure

There were significant differences in vegetation community structure between REGEN and CONTROL stream riparian and near-riparian plots (Fig. 4). Substantial differences were observed in mean percent cover of each of the shrub and tree height classes between REGEN and CONTROL stream riparian and near-riparian plots (Table 4). The H10-20, H20-30 and H30+ height classes of CONTROL stream plots all had higher mean cover than in of REGEN stream plots. In REGEN stream riparian plots, the percent cover of large trees (H30+) was highly variable, as a result of variable logging intensity, resulting in borderline statistical significance of the difference between treatments ($p < 0.1$, ANOVA, Table 4).

The intermediate height classes H1-3 and H3-10 of both riparian and near-riparian plots had higher mean

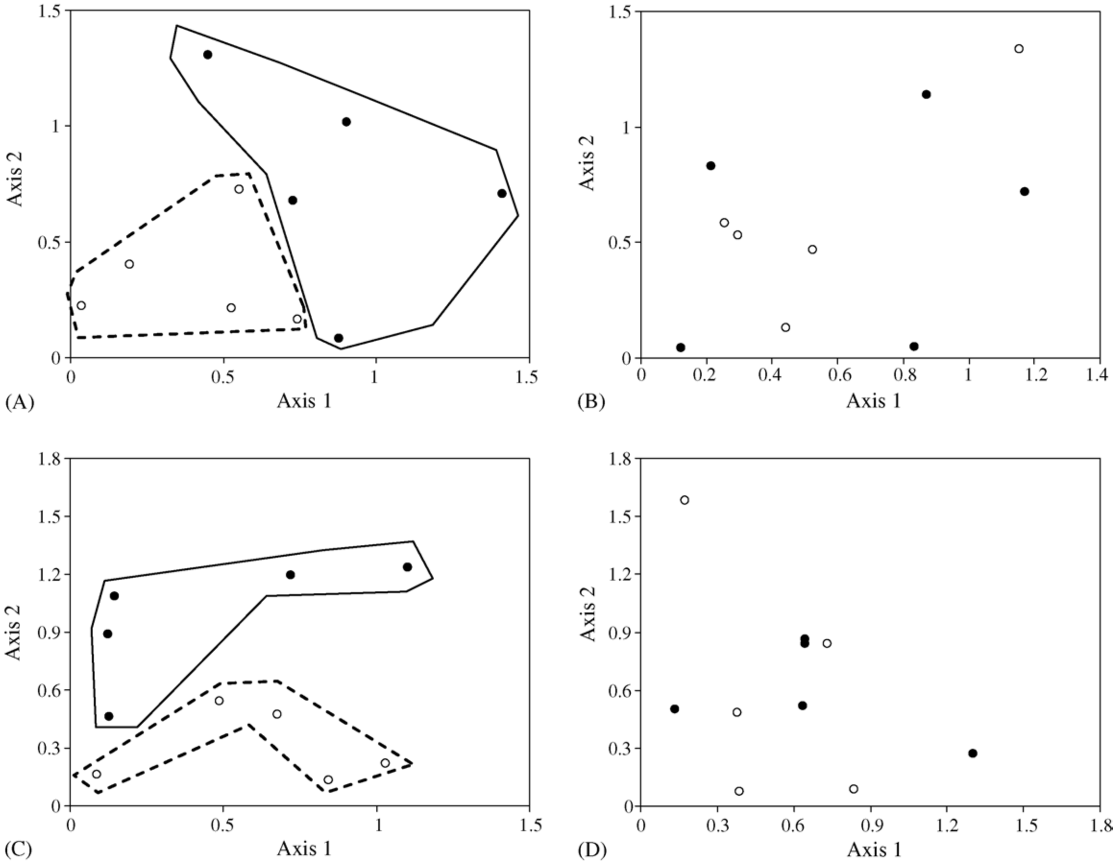

Fig. 3. Two-dimensional MDS ordinations of Ben Nevis stream vegetation community species composition (clear circles = CONTROL streams, filled circles = REGEN streams). Distances between sites approximate dissimilarity in species composition. (A) Near-riparian plots, untransformed species abundance data, stress = 0.07. (B) Near-riparian plots, presence/absence species scores, stress = 0.07. (C) Riparian plots, untransformed species abundance scores, stress = 0.06. (D) Riparian plots, presence/absence species scores, stress = 0.11. Polygons indicate separate groupings of REGEN (solid lines) and CONTROL (dashed lines) sites.

cover alongside REGEN streams than alongside CONTROL streams. High variability of the H1 class in the REGEN streams, possibly reflecting variable ground cover in response to varying degrees of disturbance during logging, contributed to the lack of statistically significant difference between treatments.

3.3. Stream morphology and sediments

3.3.1. Channel morphology and habitats

There were a number of significant and substantial morphological and habitat differences between CONTROL and REGEN streams (Table 5; Figs. 5–7). REGEN and CONTROL streams differed significantly in the number of logs both over and within stream channels (Fig. 5). Cover of coarse particulate organic matter (CPOM) in REGEN streams was 55% of that in CONTROL streams (Fig. 5).

The mean bank height was 40% larger in REGEN than in CONTROL streams (Fig. 6), indicating a net down-cutting of stream channels by a mean of 9 cm from the CONTROL mean of 23 cm bank height. In addition, REGEN streams had a seven times greater area of boulders (6.5% versus 0.9%, of borderline statistical significance, $p < 0.1$).

The standard deviations and coefficients of variation (CV) of local stream gradient were respectively 185% ($p = 0.021$) and 51% ($p = 0.098$) greater in REGEN than in CONTROL streams (Fig. 6). CV of local gradient was also positively correlated with %

Table 2
Plant species which are significant indicators (by indicator species analysis) of CONTROL and REGEN vegetation communities for near-riparian and riparian plots

Treatment[a]	Species	Observed IV from randomised groups			
		IV	Mean	S.D.	p[b]
Near-riparian					
CONTROL	*Blechnum wattsii*	52.5	24.9	4.77	0.001
	Eucalyptus dalrympleana	50.1	22.3	4.58	0.001
	Lomatia tinctoria	46.7	16.5	4.34	0.001
	Pteridium esculentum	43.2	20.4	4.46	0.001
	Lagenophora stipitata	23.3	9.9	3.12	0.004
	Leucopogon hookeri	23.3	10	3.38	0.011
	Blechnum nudum	43.2	30.9	4.85	0.023
	Poa species	20	8.6	3.53	0.03
	Coprosma quadrifida	16.7	8	2.95	0.046
	Persoonia gunnii	38.8	28.3	4.82	0.047
	Nothofagus cunninghamii	43.7	34.4	4.99	0.052
	Acaena novae-zeelandiae	16.7	8.1	3.02	0.058
	Eucalyptus dalrympleana	50.6	44	4.13	0.073
REGEN	*Gahnia sieberiana*	53.7	27.6	4.95	0.001
	Tasmannia lanceolata	63.5	36.9	5.04	0.001
	Zieria arborescens	36.7	13.9	4.02	0.002
	Cyathodes parvifolia	30	12	3.64	0.005
	Olearia lirata	26.7	10.8	3.6	0.007
	Telopea truncata	26.7	11.1	3.85	0.009
	Juncus bassianus	28.2	14.7	3.83	0.014
	Histiopteris incisa	46.8	32.7	5.07	0.017
	Acacia dealbata	47.4	35	4.78	0.019
	Hydrocotyle hirta	33.3	22.2	4.56	0.041
	Pittosporum bicolor	16.7	7.9	2.89	0.049
	Billardiera longiflora	16.7	8	3.04	0.061
Riparian					
CONTROL	*Blechnum nudum*	61.6	45.9	4.34	0.001
	Blechnum wattsii	65.1	38	5.19	0.001
	Lomatia tinctoria	30	12.3	3.81	0.004
	Pteridium esculentum	27.5	17.9	4.3	0.058
	Eucalyptus dalrympleana	20.2	13.1	4.13	0.078
REGEN	*Juncus bassianus*	70.5	30.9	4.74	0.001
	Tasmannia lanceolata	68.1	41.4	4.43	0.001
	Zieria arborescens	40	15	4.18	0.001
	Histiopteris incisa	50	26.6	4.71	0.002
	Uncinia tenella	57	35.5	4.63	0.002
	Deyeuxia species	34.3	16.6	4.39	0.005
	Olearia lirata	26.7	11.1	4.04	0.008
	Telopea truncata	23.3	9.9	3.44	0.012
	Pittosporum bicolor	25.4	12.9	3.94	0.013
	Acacia dealbata	45	34.8	4.67	0.037
	Hydrocotyle hirta	31.3	20.1	4.43	0.041
	Monotoca glauca	38	28.4	4.84	0.047
	Cassinia aculeate	16.7	7.9	2.9	0.049
	Polystichum proliferum	44.3	37.4	4.77	0.086

Only statistically significant ($p < 0.05$) and borderline ($0.1 > p > 0.05$) species shown, in order of decreasing p value. Note fewer discriminatory species for the riparian plots.

[a] Treatment group for which species has maximum IV.

[b] Proportion of randomized trials with indicator value equal to or exceeding the observed indicator value.

Table 3
Plant species richness and results of nested ANOVA to assess differences between logging treatments (with stream nested within logging treatment)

	REGEN mean ± S.D.	CONTROL mean ± S.D.	ANOVA statistic
Riparian treatment	17.83 ± 3.27	13.50 ± 3.45	$F = 31.296$, $p < 0.000001$
Stream (treatment)			$F = 2.857$, $p = 0.011$
Near-riparian treatment	14.00 ± 3.74	13.60 ± 4.19	$F = 0.201$, $p = 0.67$
Stream (treatment)			$F = 3.326$, $p = 0.004$

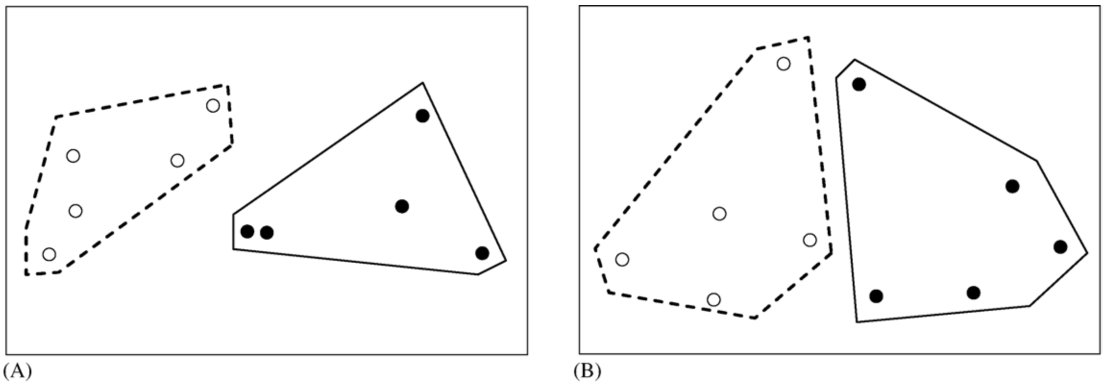
(A) (B)

Fig. 4. Two-dimensional MDS ordinations of stream vegetation community structure (clear circles = CONTROL streams, filled circles = REGEN streams). Distances between sites approximate dissimilarity in vegetation structure. (A) Near-riparian structural MDS, stress = 0.05; (B) riparian structural MDS, stress = 0.04. Polygons indicate separate groupings of REGEN (solid lines) and CONTROL (dashed lines) sites.

area of boulders across all streams ($p = 0.015$, by Pearson correlation, $n = 10$). The CV of local stream widths was 40% greater in REGEN than in CONTROL streams (Fig. 6), with four times the number of stream sections with widths >3 m (11.5% versus 2.8%), mainly associated with log jams, and twice the number of stream sections with widths <1.5 m (51% versus 23%). REGEN streams had a 67% greater channel area than CONTROL streams (Fig. 7), and 50% less area of 'complex' habitat (pools and bars).

PCA of the morphological and habitat attributes of all streams resulted in two factors which accounted for 57% (35.5 and 21.5%, respectively) of the variance in

Table 4
Mean values for vegetation structural variables for riparian and near-riparian plots and two logging treatments

Plot type	Treatment (p)	Structural variables (height classes)					
		H1	H1-3	H3-10	H10-20	H20-30	H30+
Riparian	REGEN CONTROL p (treatment, stream)	2.78	14.77	41.92	3.97	0.40	0.17
		1.22	7.33	17.58	28.38	10.67	2.90
		n.s., n.s.	<0.01, n.s.	<0.0001, <0.0001	<0.0001, n.s.	<0.0001, n.s.	<0.1, n.s.
Near-riparian	REGEN CONTROL p (treatment, stream)	8.00	6.67	52.68	18.85	1.33	1.00
		4.30	1.03	11.83	23.65	22.43	16.22
		n.s., n.s.	<0.05, n.s.	<0.0001, <0.0001	n.s., <0.0001	<0.0001, n.s.	<0.01, n.s.

p = probability levels for differences between treatments and streams, by nested ANOVA.

Table 5
Mean values of stream morphology and habitat variables for the five CONTROL and five REGEN streams at Ben Nevis

	CONTROL		REGEN		p
	Mean	S.D.	Mean	S.D.	
Slope					
Overall site slope**	0.040	0.016	0.049	0.010	n.s.*
CV of local slope	0.735	0.279	1.102	0.328	0.024
Channel dimensions					
Wetted width (m)	1.413	0.089	1.150	0.162	0.084
Bankfull width (m)	1.915	0.138	1.866	0.291	n.s.
Bank height (m)	0.229	0.032	0.320	0.045	0.050
CV of bankfull width	0.370	0.078	0.517	0.106	0.036
N logs					
Overlying#	18.200	2.756	36.400	9.422	0.033
In-stream#	19.400	3.361	36.800	9.150	0.038
% of channel area as					
Channel	43.446	7.068	58.600	12.500	0.033
Bar	18.886	4.924	16.926	4.121	n.s.
Pool	37.668	9.172	24.848	11.150	0.064
% of channel area as					
Sand	17.856	9.095	20.554	10.526	n.s.
Gravel	21.293	3.208	21.796	5.996	n.s.
Cobble	1.698	1.669	4.512	2.907	n.s.
Boulder	0.876	0.863	6.537	3.530	0.063
CPOM	30.917	4.001	17.306	2.736	0.0046
Organic silt	21.157	4.711	14.191	3.983	n.s.
Root mass	3.159	3.028	3.385	0.807	n.s.
Mosses	1.782	1.131	3.709	2.877	n.s.
Algae	0.320	0.444	4.661	3.066	0.053
Macrophytes	0.000	0.000	2.484	1.479	0.041
PCA factor					
Factor 1	−0.773	0.543	0.773	0.678	0.002

p = probability level for difference between CONTROL and REGEN streams derived from one-way ANOVA (with overall site slope as covariate, except *). S.D. = standard deviation. Values derived from 20 measures per stream, except # (measured over whole reach) and ** (summed over whole reach).

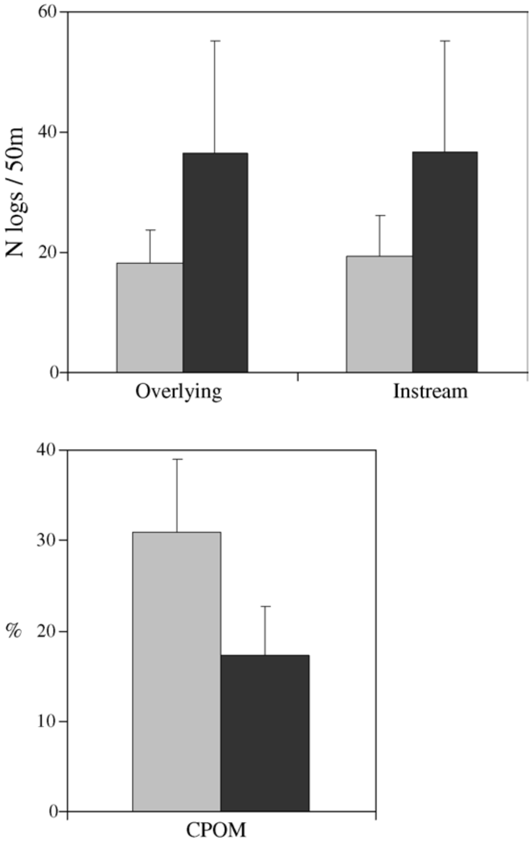

Fig. 5. Number of overlying and in-stream logs and CPOM (as percent cover of stream bed), in CONTROL and REGEN streams (grey and black bars, respectively). Error bars indicate two standard deviations.

the data. The first factor (Factor 1) was positively correlated with S.D. of local gradient, number of logs, % area as channel, mean bank height, and % area as boulders, and negatively correlated with % area as pool, mean bank full width, and % area as CPOM and as organic silt (all Pearson $r > 0.65$, $n = 10$, $p < 0.05$). Factor 1 scores were significantly higher in REGEN than in CONTROL streams (by separate variance t-test, $t = -4.68$, d.f. = 7.7, $p = 0.0017$). Factor 1 was also significantly positively correlated with the disturbance rating scores ($r = 0.92$, $p < 0.0001$, Fig. 8). There was no correlation between Factor 1 and catchment area or overall stream gradient. The second PCA factor did not differ between treatments and was uncorrelated with disturbance rating score (both $p < 0.05$).

3.3.2. Sediments

Bars and channels in REGEN streams had a significantly higher proportion of coarser (>0.5 mm) sands and a lower proportion of finer fractions (<0.25 mm) than CONTROL streams (Table 6; Fig. 9). No differences between treatments were observed for pools. There was no difference in LOI and total N between sediment samples from of CONTROL and REGEN streams (both $p > 0.2$ by ANOVA, Table 7). Total C was slightly lower in REGEN stream sediments

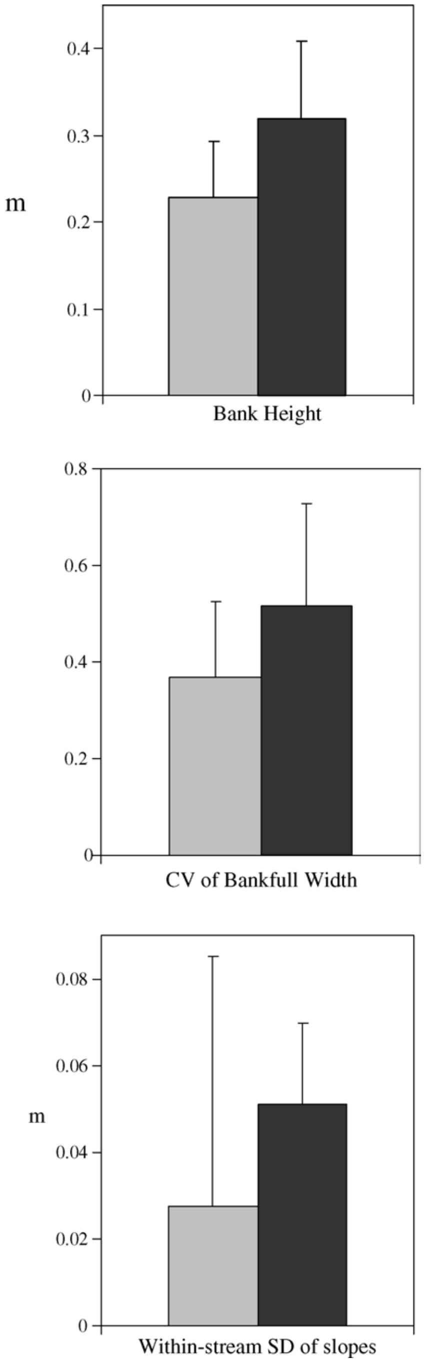

Fig. 6. Channel properties – mean bank height, covariance (CV) of bankfull channel width, and standard deviation (S.D.) of local slopes within stream study section – in CONTROL and REGEN streams (grey and black bars, respectively). Error bars indicate two standard deviations.

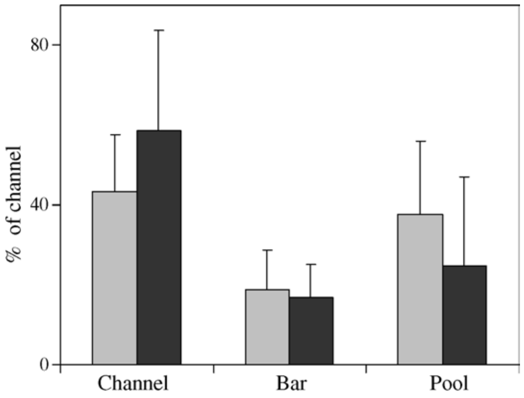

Fig. 7. Proportion of channel, bar and pool features in CONTROL (grey shading) and REGEN (black shading) streams. Error bars represents two standard deviations.

(2.4% versus 2.7%, $p < 0.1$ by ANOVA), and the C/N ratio was lower (24.2 versus 33.3, $p < 0.001$ by ANOVA) (Table 7).

3.3.3. In-stream vegetation

REGEN streams had 14.5 times more algal cover than CONTROL streams (Table 5), with a mean of 4.7 algal 'patches' per 50 m of stream versus 0.2 per 50 m in CONTROL streams. REGEN streams also had a substantially greater macrophyte cover than CONTROL streams, with a mean of 2.1 'patches' per 50 m of stream versus 0.2 per 50 m in CONTROL streams.

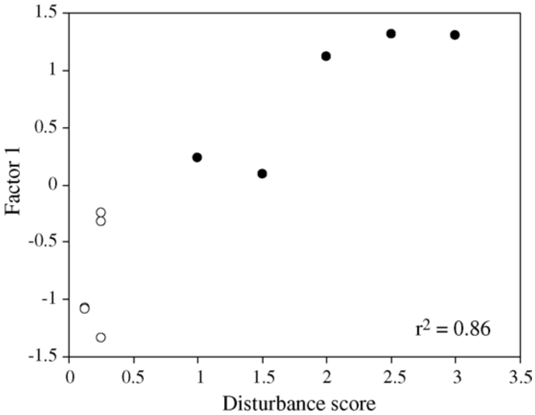

Fig. 8. Relationship between Factor 1 from principal components analysis (PCA) of stream morphological and habitat variables and the disturbance rating score for headwater stream catchments at Ben Nevis. Clear circles = CONTROL catchments ($n = 5$); filled circles = REGEN catchments ($n = 5$).

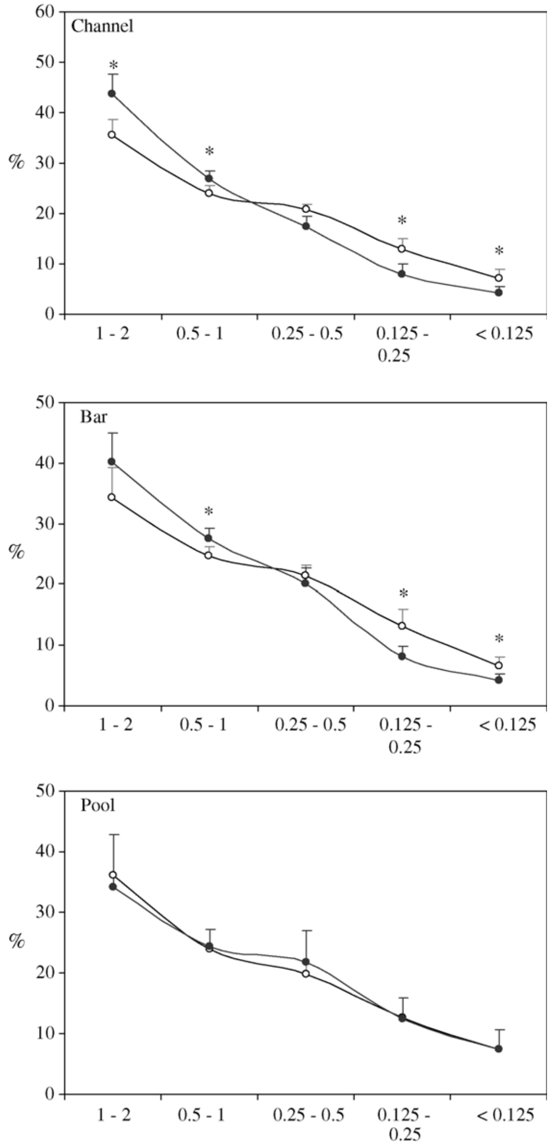

Fig. 9. Mean particle size distribution of <2 mm stream bed sediments, by in-stream geomorphic feature. Upper 95% CL limits shown. Filled circles = REGEN streams, clear circles = CONTROL streams. (*) Indicates significant difference between REGEN and CONTROL values by ANOVA, at $p < 0.05$.

Table 6
Mean particle size analysis (<2 mm) of in-stream sediments, over all morphological units

Size class (mm)	Mean CONTROL	Mean REGEN	p
1–2	35.3	40.2	< 0.05
0.5–1	24.2	26.5	0.0001
0.25–0.50	20.7	19.3	NS
0.125–0.25	12.8	9.0	< 0.0001
<0.125	7.00	5.0	< 0.01

p indicates significance level by one-way ANOVA of REGEN vs. CONTROL treatments (with mean site slope as covariate, n = five streams, means derived from nine sediment core samples per stream). From Bunce et al. (2001). NS = not significant at alpha of 0.05.

3.3.4. Riparian soils

Riparian soils had a lower proportion of coarse sands (>0.5 mm) and a higher proportion of fine sands (<0.25 mm) than stream sediments, but soils and streams had equal amounts of sand in the 0.25–0.50 mm fraction (Table 8). There were no significant differences of riparian soil particle size distribution between CONTROL and REGEN streams ($p > 0.5$ by Kolmogorov–Smironoff test), or in the relative proportions of different size classes (all $p > 0.05$ by ANOVA). However, total N levels were 58% higher in REGEN riparian soils ($p < 0.05$ by ANOVA) and their C/N ratio was lower ($p < 0.05$). REGEN riparian soils were also slightly more acid than those of CONTROL streams ($p < 0.10$).

Table 7
Mean loss on ignition (LOI) and organic matter analysis of in-stream sediments

	CONTROL	REGEN	Significance
LOI (%)			
Bar	4.6	5.1	NS
Channel	4.6	4.4	NS
Pool	5.8	7.2	NS
Overall	4.7	5.3	NS
Total C (%)			
Bar	2.7	2.0	NS
Channel	2.3	1.6	NS
Pool	3.3	4.0	NS
Overall	2.7	2.4	$p < 0.10$
Total N (%)			
Bar	0.085	0.080	NS
Channel	0.077	0.068	NS
Pool	0.100	0.162	NS
Overall	0.083	0.098	NS
C/N ratio			
Bar	34.9	23.4	$p < 0.001$
Channel	30.9	23.1	$p < 0.001$
Pool	34.4	25.9	$p < 0.001$
Overall	33.3	24.2	$p < 0.001$

From Bunce et al. (2001). NS = not significant at alpha of 0.05.

Table 8
Mean riparian soil characteristics for CONTROL and REGEN treatment streams (n = five streams, means derived from 2 × 20 pooled soil samples per stream)

	Soil chemical properties				LOI (%)
	pH (soil H_2O)	C (%)	N (%)	C/N ratio	
CONTROL	4.39	9.3	0.34	28	22.5
REGEN	4.21	11.6	0.51	23	27.8
ANOVA (p)	< 0.10	< 0.10	< 0.05	< 0.05	< 0.10

	Particle size (<2 mm fraction)				
	1–2 mm (%)	0.5–1 mm (%)	0.25–0.5 mm (%)	0.125–0.25 mm (%)	<0.125 mm (%)
CONTROL	28.9	22.4	19.5	14.6	14.5
REGEN	26.6	23.6	20.6	13.7	15.6
ANOVA (p)	NS	NS	NS	NS	NS

From Bunce et al. (2001). NS = not significant at alpha of 0.05.

4. Discussion

4.1. Vegetation

The impact of forestry activities on headwater stream riparian vegetation has not been previously studied in Tasmania, and has received little attention elsewhere in Australia or the rest of the world. Also, while the effect of forestry activities on vascular flora composition is relatively well documented in Tasmania (e.g. Hickey, 1994; Wapstra et al., 2003) and elsewhere (e.g. Burrows et al., 2002), the present study is the first account of the effects of timber harvesting on Tasmanian headwater stream catchment and riparian flora.

The effects of disturbance on the floristic composition, species richness and forest structure of riparian and near-riparian forest is still evident 15 years after harvesting and regeneration. Mature, eucalypt-dominated forest has a characteristic structure. A sparse to dense cover of tall eucalypts is usually present over a secondary eucalypt layer (regeneration following disturbance) over one to several shrub layers, often with distinctive ground fern, sedge or grass layers. In contrast to the near-riparian (10–20 m) forest dominated by eucalypts, the rainforest and swamp forest that dominates the riparian zone immediately adjacent to the streams is structurally simple, with a more even upper canopy and few shrub layers. In our study area, logging has resulted in the near-riparian eucalypt-dominated zone having a more even-aged and structurally simpler stand (i.e. fewer layers of vegetation) than the unlogged near-riparian zone. The impact of logging disturbance on vegetation structural diversity in the riparian zone is less marked, but it has resulted in a shorter but similarly even-aged, upper canopy.

The impact of disturbance on floristic composition is more marked in the near-riparian (10–20 m) zone than in the riparian (0–10 m) zone. The riparian zone is a relatively homogenous environment that is suitable for only a limited number of moisture-loving and moisture-tolerant species. It appears that even intensive disturbance will not eliminate species from such sites. In addition, the intensity of forest disturbance associated with logging and burning was greater on the hillslopes (including the near-riparian (10–20 m) zone) than within the riparian zone.

Analysis of the presence/absence vegetation data suggests relatively little impact of logging on floristic composition. However, the impact is more marked (though not statistically significant) when abundance data are used, suggesting that there has been a shift in the dominance of certain species, supported by the indicator species analysis. Species known to proliferate after disturbance such as sedges (e.g. *Gahnia sieberiana*), rushes (e.g. *Juncus bassianus*) and shrubs with wind-dispersed seed (e.g. *Cassinia aculeata*, *Olearia lirata*) or shrubs with long-lived soil-stored seed (e.g. *Zieria arborescens*), were statistically significant indicators of vegetation disturbance in the riparian zone. The near-riparian (10–20 m) zone is assumed to have had more available niches for vascular plant species because of more variable aspect, gradient, substrate and disturbance history (Wapstra et al., unpublished data).

Larger differences between treatments were evident in this more heterogenous environment, which created greater opportunities for pioneer species to proliferate on sites that were previously unavailable (Appleby, 1998). For example, grass species may colonise canopy gaps, fern species may locally proliferate on sites with soil puddling, and some species that prefer a denser overstorey may be temporarily lost from a site or reduced in abundance. In contrast, species richness did not differ significantly between REGEN and CONTROL treatments in the near-riparian (10–20 m) zone, but did differ in the riparian (0–10 m) zone, with an increase in species in disturbed sites. The heterogeneity of the near-riparian zone has apparently 'smoothed' differences between REGEN and CONTROL treatments (i.e. some species have been lost and some have established, as described above). In the more homogenous riparian zone, fewer species have been lost, but gaps in the canopy and alterations to local drainage creating areas of bare soil have provided an opportunity for pioneer species such as the composite shrubs and herbs (most with light and small wind-dispersed seed), to establish. This increase in species richness on disturbed sites is consistent with other studies (e.g. Wapstra et al., 2003) but is likely to be relatively short-lived as the canopy becomes denser. Most of the pioneer species (including the ubiquitous herbaceous exotics) are ruderal (i.e. light-demanding, short-lived and short-statured) and as regeneration ages, these species will probably become less abundant.

4.2. Stream morphology, habitat and sediments

Overall, the REGEN streams were more entrenched and were overlain by more logs. They contained more channel habitat and less 'complex' (pool/bar) habitats, contained less stored organic debris, and had more variable bankfull widths, exposed granite boulder surfaces and locally variable gradients than CONTROL streams. The observation of more wood but wider, more down-cut streams with fewer pools is in contrast to observations elsewhere of increased snag inputs leading to greater numbers and volumes of pools (Bisson et al., 1987). The granitic soils in this area down-cut rapidly, leaving many snags suspended above the channel bed, and small-scale stream morphology is mainly dictated by boulders and bedrock exposed by down-cutting. In addition, stream power in these catchments is low, which is known to limit pool development (Jackson and Sturm, 2002).

REGEN streams also had coarser sediments and a lower C/N ratio in sediments than CONTROL streams. Riparian soils of REGEN streams were higher in N than those of CONTROL streams.

Davies et al. (submitted for publication) have also found that REGEN streams contained less fine particulate organic material (FPOM) than CONTROL streams, primarily in channels, and that the amount of FPOM per unit area was strongly negatively correlated with the disturbance index.

Mean bank height was 40% larger in REGEN than CONTROL streams, and equated to 17 t net loss of stream bed sediment per kilometre in REGEN streams. Davies and Nelson (1994) observed that small Tasmanian headwater streams in steeplands underwent a period of enhanced fine sediment and carbon transport during the first 4–6 years after clearfelling and burning. The results of this study are consistent with the REGEN streams having degraded through enhanced peak flows and channel erosion following harvest. The net effect after 15 years is a deficit of fine sediment and organic material storage, coupled with increases in logs and changes in the light regime. These changes are likely to be strong drivers of change in in-stream and stream-dependent fauna (Davies et al., submitted for publication; Koch et al., submitted for publication).

The similarity of particle-size distribution in CONTROL and REGEN riparian soils (Table 8) supports the initial assessment that stream environments were likely to have been similar geomorphologically and botanically before clearfelling. Greater litter fall from the more mature forest of the CONTROL riparian zone is suggested by the greater litter cover of CONTROL plots compared to REGEN riparian plots (means of 65 and 50% for CONTROL and REGEN riparian plots respectively, $p = 0.0002$ by nested ANOVA). However, supplies of organic C from this source have not increased the total C content of 0–10 cm soils. The higher C content of REGEN riparian soils than CONTROL soils, and the lower C/N ratio of the former, indicates that in riparian soils greater light intensity may be encouraging greater N fixation, most likely by *A. dealbata*.

The fact that both REGEN stream sediments and riparian soils have lower C/N values than CONTROL stream sediments and riparian soils could indicate that riparian soil erosion has influenced stream sediment character. This inference is supported by the greater bank height and stream widths of REGEN streams, with these changes occurring at the expense of riparian topsoils (0–10 cm soils). It is also possible that winnowing and export of charcoal by higher flows in REGEN streams has contributed to their lower sediment C/N ratio.

A number of stream characteristics were correlated with the disturbance index, indicating that stream channel and habitat responses to harvesting are strongly controlled by the degree of disturbance during harvesting and burning operations, and that this relationship is still evident more than a decade later. The general nature of the differences we attribute to logging impacts of harvesting are similar to those observed elsewhere, though the role of local geomorphological context appears to be a dominant factor in determining headwater stream responses to forest harvesting (Jackson et al., 2001; Jackson and Sturm, 2002).

5. Summary and conclusions

We attribute the following changes in these upland granitic headwater streams to 15-year old clearfell harvesting operations:

5.1. Vegetation

- A shift to more even-aged and structurally simpler stands.
- Greater species richness in riparian zones.
- Shifts in community composition and species dominance in both riparian and near-riparian forest, with greater representation of species which are disturbance-tolerant, have wind-dispersed seed and/or long-lived soil-stored seed.

5.2. Stream channels and habitats

- Reduction in stream channel complexity.
- Stream channel entrenchment and net loss of channel sediment.
- Increases in variability of stream gradient and channel width.
- Increases in coarse sediment fractions and exposure of bedrock/boulders.
- Increases in logs in and over the channel.
- Changes in sediment and riparian soil C/N ratios.
- Loss of organic material, both as CPOM and FPOM.

We have also documented a gradient of response that appears to be dictated by the intensity of historical catchment disturbance. Direct effects of harvesting at these sites are those caused by the immediate impact of past logging, which included felling of trees into streams and machine entry into stream channels and riparian zones. The Tasmanian Forest Practices Act (1985) and Code (1993, 2000) severely limits machine entry into riparian zones, prohibits machine entry into streams and forbids felling of trees into streams unless it is unavoidable. In addition, measures which increase protection of headwater streams on erosion-prone sites (McIntosh and Laffan, 2004) are currently being trialled, and retention of headwater streamside reserves is increased where threatened aquatic fauna occur (Forest Practices Board, 2001). Present-day logging should therefore not have comparable direct effects.

In contrast, indirect effects are attributed to the greater peak streamflows that follow forest harvest (Vertessy, 1999). The greater stream incision and coarser sediments in the clearfelled catchments, along with higher proportions of channel habitat and exposed boulders and locally more variable gradients, would primarily be the result of higher peak flows during the first 1–3 years post-harvest. In this particular study area, slow and/or poor forest regeneration may have caused such effects to persist longer than usual. We could not distinguish direct from indirect effects. For example, coarser sediment in streams of logged catchments could be attributed to bank and streambed disturbance by machines as well as to enhanced stream erosion and export of fines.

Effects attributed to the indirect influence of changed hydrology could also occur under present logging practices. However, in the upland terrain where the study was conducted, clearfelling is no longer practised as regeneration of eucalypts is poor on exposed clearfelled sites. The preferred method of logging is selective harvest, in which 50–70% of the trees are felled, with about 30–50% of the evapotranspiration potential of the forest retained. On erosion-prone sites there may be an additional requirement to retain streamside reserves next to headwater streams (McIntosh and Laffan, 2004). The net effect of current Tasmanian forest practices system is therefore likely to be a reduction of the severity of direct and indirect effects on stream morphology and habitat, although significant post-harvest peak flow increases will undoubtedly occur.

To trial the effects of different stream protection measures (e.g. different buffer widths, patch harvesting, etc.) for their efficacy in reducing changes in stream character, a replicated experiment with a BACI-style design (Underwood, 1997), incorporating monitoring of disturbance, hydrology and stream characteristics before, during and after forestry operations, is required. Such an experiment is a priority for headwater stream research in SE Australian forest catchments, and is the subject of our current research.

The aquatic biological implications of the differences between the two groups of streams in this study are the subject of two other papers in this series (Davies et al., submitted for publication, Koch et al., submitted for publication).

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