Stream size influences stream temperature impacts and recovery rates after clearfell logging

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1. Introduction

Water temperature has profound influences on stream ecosystems through effects on rates of key processes, such as surface gas exchange (Elmore and West, 1961), microbial decomposition of detritus (Richardson, 1992), primary production and invertebrate grazing rates (Ahlgren, 1987; Chapra, 1996; Rutherford et al., 2000), and biota growth rates (Hogg and Williams, 1996). Perhaps most importantly, water temperature can cause lethal thermal stress when it exceeds the tolerance limits of cool-adapted groups, such as mayflies, stoneflies, and some native fish (Quinn et al., 1994; Richardson et al., 1994).

The fundamental drivers of water temperature at a stream site include a range of energy fluxes: advective heat inputs from upstream, groundwater discharge and hyporheic exchange; solar radiation incident at the stream surface and absorbed by the streambed and water column; longwave radiation emitted by the atmosphere, terrain and riparian vegetation canopy; longwave radiation emitted (and to a lesser extent reflected) by the surface water; exchanges of sensible and latent heat between the water surface and atmosphere; conductive heat exchange across the stream bed; and frictional heat generation at the stream bed (Webb and Zhang, 1997; Story et al., 2003). These energy exchanges are influenced by a range of natural factors including solar angle, cloud cover, topographic shade, upland vegetation, precipitation, air temperature, wind speed, and relative humidity (Poole and Berman, 2001). Human influences, overlain on these natural factors, include riparian management, upland vegetation management, water withdrawal and addition, channel engineering and dam operation. Poole and Berman (2001) provide a conceptual linkage model of how these factors interact to influence channel water temperature.

There has been widespread deforestation of stream riparian zones, worldwide, as land has been converted to agricultural and urban land use (Gregory et al., 1991; Boon et al., 2000). This loss of riparian forest can result in substantial increases in stream exposure (Beschta and Taylor, 1988; Davies-Colley and Quinn, 1998; Boothroyd et al., 2004) and associated increases in water temperature (Brown and Krygier, 1970; Beschta and Taylor, 1988; Boothroyd et al., 2004; Baillie et al., 2005), particularly in small (shallow) headwater streams (Brown, 1969; Rutherford et al., 1997).

Logging management practices can potentially ameliorate these effects on lighting and stream temperature. For example, retention of unlogged (or partially logged) forest within the riparian area (“riparian buffers”) can reduce the stream temperature response to logging (e.g., Boothroyd et al., 2004; Gomi et al., 2006; Wilkerson et al., 2006), although this mitigation may be reduced if subsequent wind-throw reduces the vegetative shade (MacDonald et al., 2003). Clearfell logging and timber extraction

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often results in substantial input of forest litter ("slash" = mix of stems and foliage) into and across headwater stream channels (Jackson et al., 2001; Baillie et al., 2005). Although this may reduce stream dissolved oxygen as the litter decays (Ponce, 1974; Baillie et al., 2005), it can have the beneficial effect of shading the stream maintaining cool temperatures after logging.

Tree plantations go through a rotation of phases of vegetation establishment, growth of the timber trees to harvestable size and subsequent logging and re-establishment. The “rotation”, from planting to harvesting, averages 27 years for Pinus radiata, which accounts for 90% of the 1.6 M ha of tree plantation in New Zealand (Fahey et al., 2004). It is important to understand the factors influencing both the magnitude and duration of the temperature impact in different sized streams draining such tree plantations to improve the basis for management decisions. Whilst several studies have demonstrated that clear-felling can cause significant increases in stream temperature (e.g., Brown and Krygier, 1970; Swift and Messer, 1971; Beschta and Taylor, 1988; Baillie et al., 2005), there is a lack of detailed quantitative information on factors influencing the duration of this impact (Moore et al., 2005). Whereas Swift (1983) reported a trend of decreasing stream temperature maxima after harvest of Appalachian forest, Johnson and Jones (2000) observed a lag in maximum stream temperature reduction of at least 4 years in a clearfelled and burned Oregon Cascades catchment, due to slow regrowth of riparian vegetation.

Studying stream temperature recovery after logging may also provide insights into the likely rate of thermal recovery in streams where riparian shrubs and trees are planted as part of stream restoration. Restoration of riparian forest is often carried out to mitigate the effects of agricultural and urban land use on aquatic ecosystems, including effects on stream temperature regimes (Rutherford et al., 1999; Parkyn et al., 2003; Bernhardt et al., 2005). However, there is limited empirical information on the time scales of thermal regime response to riparian restoration in rivers of different size/ease of shading and riparian vegetation type (Parkyn et al., 2003), although some modelling studies have predicted the effects of time after logging/planting and/or riparian vegetation type (Beschta and Taylor, 1988; Collier et al., 2001; Watanabe et al., 2005).

The aims of this study were to quantify the magnitude and duration of the thermal effects of clearfell-harvesting and replanting of P. radiata plantations on the Coromandel Peninsula. We hypothesised that: (1) clearfelling would increase daily maximum temperatures more in small streams than in large streams and (2) the rate of thermal recovery (relaxation towards reference or pre-harvest thermal conditions) of streams after clearfelling would be inversely related to stream size, due to more rapid development of effective shading of small streams by riparian vegetation regrowth. These hypotheses were tested using the reference-difference method to account for inter-annual variations in summer temperatures (Hewlett and Fortson, 1982; Johnson and Jones, 2000; Macdonald et al., 2003).

2. Methods

2.1. Study area

The study streams drain to Whangapoua Harbour (175°35'E, 36°45'N) in the Coromandel Peninsula, North Island, New Zealand (Fig. 1). Monthly mean air temperatures range from 10.5 °C in July...
to 19 °C in January (Meleason and Quinn, 2004). The streams have gravel-cobble-boulder beds (Quinn et al., 2004) with average water and channel widths ranging from 1 to 6.5 m and 2 to 11.9 m, respectively, and thalweg depths from 0.11 to 0.65 m (assessed using methods described in Boothroyd et al., 2004), at the monitoring sites in summer 2005 (Table 1). All sites were between 20 and 140 m above sea level in the mid-lower reaches of short, steep, streams. Sites on unnamed tributaries within single plantation stand management areas (compartments) were labeled by their compartment numbers (22, 49, etc.), whereas larger named streams were coded in relation to stream names and treatments (e.g., ON = Opitonui native forest and OP = Opitonui pine, see Table 1 and Fig. 1). Summer base flows in the area are approximately 8 l km⁻² s⁻¹ (Quinn et al., 2004). Further details on the history of land use and forestry practices are given in Quinn et al. (2004).

The streams in both indigenous forest and pine plantation were well shaded before clear-felling, with diffuse non-interceptance (DIFN, an index of lighting measured using paired canopy analysers; Davies-Colley and Payne, 1998) averaging at stream level of 5% (range 1–16% of open lighting (Table 1)). Previous research showed that stream level lighting averaged 56% after clearfelling and 15% if buffers of un-harvested riparian forest (mean width 18 m) were left in place (Boothroyd et al., 2004). In this study, stream lighting levels shortly after logging at two clearfelled sites were 41% and 85% (Table 1). The analysis focused on temperature differences on each day during summer in daily mean and daily maximum temperatures when annual maximum temperatures typically occur.

The responses of stream water temperatures to clear-fell and rates of thermal regime recovery as riparian vegetation regenerated were monitored at 10 sites on streams draining to Whangapoua Harbour in the Coromandel Peninsula, North Island New Zealand (Fig. 1) between 1995 and 2008 and compared with unharvested reference sites (33 and ON, Table 1). Temperature measurements were made at 15 or 30 min intervals using submersible data-loggers (Onset StowawayTM or TidbiTTM with an accuracy of ±0.2 °C) during mid-summer (ca. 10 December-end of January) when annual maximum temperatures typically occur.

### Table 1

<table>
<thead>
<tr>
<th>Site code</th>
<th>Catch area (ha)</th>
<th>Catch harv.</th>
<th>Catchment harvest period</th>
<th>Site harv.</th>
<th>Water width (m)</th>
<th>Channel width (m)</th>
<th>Thalweg depth DIFN 1999</th>
<th>DIFN 2005</th>
<th>Base flow (l s⁻¹)</th>
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ND = not determined.

The catchments of the smaller stream monitoring sites were mostly clearfelled (85–100%), whereas in the larger streams variable amounts of the headwaters were not logged (Table 1, areas marked as native bush in Fig. 1). The small-medium size streams (49 to W in Table 1) generally lacked effective shade from riparian forest immediately after logging, although there were short (30–60 m long) patches of forested riparian buffer upstream of 30, G and OW. Site A had a patchy buffer starting at 1 km upstream of the monitored site and extending another 1 km upstream, but ca. 80% of the harvested tributary streams lacked any buffer. The largest stream OP had a 10 m forested buffer on the left side at the monitoring site (where the stream flowed in a northeast direction), but the right side was clearfelled to the streambank (Fig. 2). Buffer occurred along ca. 30% of the mainstem between OP and ON mainstem but most tributaries were clearfelled to the stream edge.

The logged catchments were replanted with pine seedlings in the winter following harvesting. Variable widths were left unplanted in the riparian area for buffers of (mainly indigenous) forest to regenerate naturally. These unplanted zones were typically at least 10 m wide along streams draining more than 50 ha, ca. 5 m wide along streams draining 20–50 ha, with smaller streams planted to near the stream edge. Rapid regrowth of shrubs and sedges occurred in the unplanted riparian areas (Fig. 2) and resulted in significant shade development with lighting dropping to an average of 20% by 4–7 years after clearfelling in four streams with catchment areas <200 ha (Table 1, see also 49 and 29 photos in Fig. 2). Larger stream reaches, such as sites W and OP (Fig. 2; 6.5 and 11.9 m wide channels, respectively) remained quite open 7–10 years after logging. Further details on riparian vegetation at the study sites are provided in Langer et al. (2008).

#### 2.2. Characterisation of thermal regimes

The responses of stream water temperatures to clear-fell and rates of thermal regime recovery as riparian vegetation regenerated were monitored at 10 sites on streams draining to Whangapoua Harbour in the Coromandel Peninsula, North Island New Zealand (Fig. 1) between 1995 and 2008 and compared with unharvested reference sites (33 and ON, Table 1). Temperature measurements were made at 15 or 30 min intervals using submersible data-loggers (Onset Stowaway™ or TidbiT™ with an accuracy of ±0.2 °C) during mid-summer (ca. 10 December-end of January) when annual maximum temperatures typically occur.

The analysis focused on temperature differences on each day during summer in daily mean and daily maximum temperatures from reference conditions measured simultaneously in an unharvested forest stream, rather than before and after-logging comparison at each site. This reference-difference method (Johnson and Jones, 2000) accounted for effects of inter-annual variations in weather conditions that resulted in variations in mean summer temperature during 2000–2007 at the main reference site (ON) from 15.2 to 17.0 °C for daily means and 17.1 to 19.6 °C for daily maxima. Smaller unharvested streams, used as references for 22 in 1995–1996 (32, 30 ha catchment area (CA)) and 1998–1999 (27, 43 ha CA), had average summer daily mean temperatures of 16.5 and 17.3 °C, respectively, and daily maximum temperatures of 17.4 and 19.0 °C, respectively, within the range measured at ON in 2000–2007. These data suggest that ON can be validly used as a reference for all the sites, although it is acknowledged that the smallest forested streams may naturally have slightly lower temperatures than ON due to factors including greater groundwater influence and heavier shade (Poole and Berman, 2001).

Statistical analyses were carried out in Datadesk (Velleman, 2000) and Microsoft Office Excel.
3. Results

3.1. Clearfelling effects on summer stream temperatures and recovery periods

Summer temperatures recorded at intervals over an 8-year period at 22, a small (48 ha CA) stream that was clear-felled with slash removal by a combination of management and storm scour, demonstrate potential worst-case effects and recovery times (Figs. 3 and 4) for this size of stream in the study area. Daily mean temperatures were commonly 20–22°C, and maxima were frequently in the range 25–30°C, in the first and third summers after logging and slash removal (Fig. 3, note no data were collected in year 2 after logging). Temperature averaged 2.8°C above that in an undisturbed catchment in the first and third summers after logging and the corresponding increases in daily maxima were 5.4 and 6.0°C (Fig. 4). The temperature increment declined from year 3 post-harvest and temperatures overlapped with the reference site in year 8 (Fig. 4). There were significant trends of declining daily mean and maximum temperatures at 22 over the 8 years post-harvest (Fig. 4A and B). However, there was an initial lag in temperature reduction after logging (Fig. 4) until after initial vegetation colonisation and growth occurred in the riparian area. Consequently, the relationship between decline in summer temperature relative to the reference sites and time was stronger when only year 3–8 data were included ($r^2 > 0.92$; Fig. 4A and B).

Continuous monitoring at nine other stream sites in logged catchments covering a range of stream sizes during summers...

![Representative photographs showing changes in shade after clearfelling at sites over the size range of streams included in the study. Photo dates and time (years) since clearfelling (in brackets) are shown. See Table 1 for site characteristics.](image-url)
(early December to end of January) between 2000 and 2008 showed that daily maxima and mean temperatures differences from reference decreased with time after logging (Fig. 5), reflecting regrowth of vegetation in the catchment and riparian areas (Fig. 2). The overall average summer daily mean and maximum temperatures at the reference (ON) over this period were 16.7 and 18.5 °C, respectively (individual summer mean ranges: 15.2–17.6 °C for daily mean and 17.1–19.6 °C for daily maximum).

In 2000–2001, shortly after logging had been completed at most sites (Table 1), the average increases in daily maximum temperature ($T_{\text{max}}$) ranged from 3.9 to 6.0 °C and increases in summer mean temperatures ranged from 1.5 to 3.9 °C (Fig. 5). The greatest increase in average summer $T_{\text{max}}$ over reference was 7.4 °C at site W (with a summer mean $T_{\text{max}}$ of 26.9 °C) during summer 2003–2004, 18 months after logging was completed next to the 5.2 m wide study reach below a medium sized catchment (441 ha).

The increases in $T_{\text{max}}$ tended to be higher in the medium sized streams (OW, G, 29 and W) in the first few summers after logging (2000–2001 to 2003–2004), but from 2005 to 2007 there were significant positive correlations between $T_{\text{max}}$ increase and log of catchment area ($r = 0.76–0.78$, $p < 0.05$). The increases in mean summer temperature over reference at the clearfelled sites were positively correlated with log catchment area in all years ($r = 0.80–0.98$, $p < 0.05$).

By summer 2006–2007, 6–7 years after harvesting was completed above most reaches (Table 1), the smaller streams (29–49, channel widths < 4 m) had similar daily mean temperatures to the native reference in 2006–2007, and their daily maxima were < 1 °C above the reference (Fig. 5), indicating restoration of forest stream thermal conditions. By 2005–2006, the smallest stream (49, 32 ha catchment) had become cooler than the medium sized reference native forest stream (ON, catchment area = 469 ha), reflecting the heavy shade that had developed at this site by 2007 (Fig. 2). In contrast, the largest stream (OP) still had daily mean and maximum temperatures 2.4 and 2.9 °C higher than the reference in summer of 2007–2008, indicating much slower recovery of the stream thermal regime after logging (Fig. 5).

Stream size also influenced the diurnal temperature response to clearfelling (Fig. 6). The small–intermediate sized streams, 27, 29 and G, heated and cooled more rapidly than the two largest streams (A and OP, Table 1) under all cloud conditions. Small–intermediate streams reached higher maximum temperatures than the larger streams on the clear-sky day (18 December 2000), but the smallest streams also cooled to similar night-time minimum temperatures as occurred in the unharvested reference site (ON), whereas the larger clear-felled streams cooled more slowly and remained more than 1 °C warmer than the reference at night (Fig. 6).
The rates of stream thermal regime recovery were investigated further by regressing mean summer period values of daily mean and maximum stream temperature increase over the unharvested reference (Fig. 5) against time to estimate overall annual temperature reduction rates for each stream site as the slope of the regression line, as shown in Fig. 4 for 22. Regression results (Table 2) are presented for the period from 2 years post-logging because we observed that regrowth of riparian vegetation only began to exert shading influence after 2 years and removing the “vegetation regeneration lag phase” improved the model fits ($r^2$) appreciably.

The rate of annual decline in average summer temperature during the “vegetation regrowth” phase (i.e., excluding the initial, 2 years, lag phase) were 0.25–1.86 °C year$^{-1}$ for daily maximum temperature and 0.18–1.39 °C year$^{-1}$ for daily mean temperature (Table 2). The rates of decline in temperature were strongly inversely related to stream size, as indexed by the strongly inter-correlated ($r = 0.94–0.99$) variables catchment area, channel width, and summer baseflow (Fig. 7), although the highest correlation coefficients were for channel width which is most directly connected to shading.

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4. Discussion

4.1. Effects of logging on stream temperature

Removal of stream shade during the logging/replanting phase of the pine plantation rotation had immediate and marked impacts on stream temperatures in the study streams. Stream size influenced the magnitude and duration of these temperature responses at both diurnal and inter-annual time scales. Increases in average daily maximum temperature during summer were greater in small-intermediate sized streams than in the larger streams (as predicted), whereas increases in average daily mean summer temperatures were greater in the larger streams (Fig. 5). Factors likely to have contributed to the lower maximum daily temperatures in the larger streams (e.g., A and OP) were: (i) greater stream depths in the larger streams so that heating was slower for a given sunlight exposure (Brown and Krygier, 1970) and (ii) the influence of the upland catchment condition, with smaller proportions of the larger catchments in recent clearcut condition (with very low stream shade) due to logging of the larger catchment being spread over 6–9 years compared with 1–2 years in the small catchments (Table 1). The greater increases in daily mean summer temperatures in the larger catchments following logging may reflect slower cooling at night (Fig. 6), presumably due to the greater depth (and hence greater thermal inertia) of the larger streams and lesser influence of cool groundwater inflows (Poole and Berman, 2001).

The increases in daily mean and maximum stream temperatures we observed during or shortly after clearfelling and slash removal (2–3.8 and 4–7.3 °C, respectively) were similar to previous New Zealand studies. A small (118 ha) pine forest catchment stream in Northland, New Zealand, at a similar latitude to our site, increased 1.8 °C in daily mean temperature and 5.6 °C in daily maximum in response to clearfelling and “stream-cleaning” (Baillie et al., 2005), and daily maximum temperature in a small (185 ha catchment), clearfelled, pine stream in Nelson (latitude = 41°30'S) averaged 4.3 °C warmer than a reference stream during late summer (March) (Graynoth, 1979). Mean summer temperatures in two very small streams (4–5 ha catchments) at Maimai, in Westland (42°05'S) peaked at 3.7 and 6.5 °C above control streams 2–3 years after clearcutting and burning (Rowe and Taylor, 1994). The unusually high mean summer temperature increase of 6.5 °C occurred after a debris avalanche increased solar exposure of the channel. Increases of similar magnitude have been reported in overseas studies. For example, clearcutting or conversion from forest to farmland in the southern Appalachians increased the maximum temperatures of very small streams (9–16 ha) by 3.3–6.6 °C (Swift and Messer, 1971), average monthly maximum temperature increased 8 °C in the year after clearcut logging and burning of a small (70 ha) Oregon Coast Range stream (Brown and Krygier, 1970), and average maximum temperatures increased by 5.4–6.2 °C during four summers after clearcutting and burning of a <100 ha catchment in a western Oregon Cascades stream (Johnson and Jones, 2000). Moore et al. (2005) reviewed harvest effects on small (<100 ha) Pacific North West streams where summer maximum temperatures increased 1.8–11.6 °C. Binkley and Brown (1993) summarised the results from 20 North American watershed studies and found that forest harvest without riparian buffers typically allowed stream maximum summer temperatures to increase by 2–6 °C, whereas in most cases keeping riparian buffer kept the increase in maximum summer temperature increase to <2 °C.

Poole and Berman (2001) predict that thermal effects of changes in processes affecting heat transfer into rivers were likely to be greatest in mid-reaches of river networks, because stream
temperatures may be dominated by groundwater temperature (or snowmelt) in headwaters and have considerable inertia around the equilibrium temperature in downstream reaches near the river mouth. Our sites only included small to intermediate sized streams (up to 12 m width and 1671 ha catchment area); however, the positive relationships we found between catchment area and increases in summer daily mean temperatures shortly after logging are consistent with the predictions of Poole and Berman. The lower daily mean temperatures in our small streams were due to lower night-time temperatures (Fig. 6), since the smallest clearcut streams (27, 29 and G; 43–161 ha CA) reached similar (or higher) daily maximum temperatures to the larger streams on clear-sky days. This greater night-time cooling in these streams was probably driven by increased groundwater influence and greater night-time heat losses from the small (shallow) streams.

4.2. Post-logging recovery of summer thermal regimes

Previous studies indicate that stream size, harvest debris management and regrowth of riparian vegetation influence the time for stream thermal regime recovery after clear-cutting (Brown and Krygier, 1970; Swift, 1982; Beschta and Taylor, 1988; Johnson and Jones, 2000; Moore et al., 2005). Recently, Gomi et al. (2006) observed summer temperature recovery within 2 years in two very small streams (bankfull widths 0.5–1.1 m) in coastal British Columbia, whereas recovery had not occurred after 4 years at two slightly larger streams (bankfull widths 1.9 and 2.3 m). The more rapid thermal recovery of the smaller streams was attributed to greater shading by riparian vegetation (Gomi et al., 2006), consistent with our results. Similarly, Gravelle and Link (2007) reported that two very small (wetted widths < 0.5 m) clearcut streams in Idaho showed thermal recovery 2–3 years after clearcut logging and a third stream showed 60% recovery after 4 years. These very small streams’ recovery rates were faster than in small (<100 ha) Pacific Northwest streams, reviewed by Moore et al. (2005), where several showed no obvious recovery 4–5 years after clearcutting, ca. 70% to full recovery after 6–7 years, and apparent full recovery after 15 years. Two small streams (in 4–5 ha catchments) at Maimai, South Westland, New Zealand, showed 60% and 40% recovery 7–8 years after clearcutting and burning, with less recovery at a site affected by a debris avalanche that created a high level of solar exposure (Rowe and Taylor, 1994).

Our small study streams (<200 ha, <6 m wide channel) tended to have a lag of only 2–3 years after logging was completed before reductions in temperature were observed (Figs. 3–5). Clearcut riparian areas at Whangapoua are most often initially recolonised by adventive weed species that form dense cover but are low growing (<3 m height) (e.g., Fig. 2 sites 49 and W) (Langer et al., 2008). However, where native shrub species in the riparian vegetation had been crushed during harvesting operations, but some stem and root systems remained, it was common for coppice regrowth to be abundant and this often resulted in rapid restoration of native cover (e.g., Fig. 2 sites 29 and OP) (Langer et al., 2008). The species most commonly observed with this regeneration strategy were mahoe, rangiora, karamu and the tree ferns (Langer et al., 2008).

After this initial riparian vegetation recolonisation period (2–3 years), we found that stream size had strong effects on the duration of logging impacts on summer temperatures. Average summer daily maximum temperatures declined 0.25–1.9°C year⁻¹ for the smallest and largest streams, respectively whereas respective mean summer temperatures declined 0.18–1.4°C year⁻¹ (Table 2). The smallest stream (49, 32 ha) had lower average and daily maximum summer temperatures than the native reference 5 years after logging (Fig. 5). Other small clearcut streams (27, 22, 29, <4 m wide channels) had similar summer mean temperatures to the native reference after 5–8 years (Figs. 4 and 5), and the trends in Fig. 5 indicated summer daily maxima would be restored after about 8 years at these sites (as observed at 22, 48 ha CA, Fig. 4). Daily mean temperature was also similar to reference at site G (5.6 m wide channel) in summer 2007–2008, 8 years after harvesting, but daily maxima were still 1.3°C higher, indicating incomplete recovery.

Summer temperatures in the larger streams (6–12 m wide) had not been restored to reference condition by summer 2007–2008 (Fig. 5), 6–10 years after upstream harvesting was completed. Thermal regime recovery times for these sites were predicted using the regression equations for decline in temperature ‘excess’ in relation to channel width (Fig. 7B). These predictions assumed: (i) an initial lag phase of 2 years after harvesting was completed before effective shading commenced; (ii) initial increases in temperatures that varied with stream size as in Figs. 4 and 5; and (iii) that the summer temperature is naturally 1°C warmer at OP than the native reference (average of 10 monthly observations before harvesting (Authors’ unpublished data)), due to its greater channel width and lighting (Table 1) and 0.5°C warmer at A (50% wider channel than ON, Table 1). This approach predicted thermal restoration intervals, for 6–12 m wide streams, of approximately 12 years for summer maximum temperatures and 14–16 years for summer average temperatures. These predictions involve extrapolation beyond the range of the data, but provide initial estimates of the likely recovery times after logging is complete. They indicate that clearcutting may result in some disturbance to stream thermal regimes of medium sized streams (6–12 m wide channels) that persist for a third to a half of the typical pine forest rotation of 27 years, although the magnitude of the effects decreased with time.

Acknowledgements

Thanks to the staff of Ernslaw One Ltd. (particularly Chris Nelson and Graeme Lister) for access to Whangapoua Forest and provision of information on catchment forestry activities. Thanks to Sanjay Wadhwa for drawing Fig. 1. This study was funded by the New Zealand Foundation for Research Science and Technology as part of the Protection and Enhancement of the Environment through Forestry programme (CO4X0304). The paper was improved by constructive review by Drs. Rob Davies-Colley and Kit Rutherford and three anonymous reviewers.

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