DECAY STATE AND ORIENTATION OF *PINUS RADIATA* WOOD IN STREAMS AND RIPARIAN AREAS OF THE CENTRAL NORTH ISLAND

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ABSTRACT

Forest harvesting can generate large amounts of woody debris, some of which ends up in riparian areas and stream channels where it can pose problems for post-harvest management due to its potential for mobilisation during floods and for affecting stream ecosystem structure and function. We measured the decay state, size, and orientation of *Pinus radiata* D. Don large woody debris (>10 cm diameter; LWD) in and alongside 13 spring-fed streams in the central North Island where harvesting had occurred between 1 and 19 years previously, partly to assess the time-scales associated with any impacts of harvesting debris. Most LWD in the streams and riparian zones was oriented perpendicular to the flow. Similar orientations for riparian and submerged wood indicated that it had moved little since harvesting and was therefore a stable feature of the channels in which it was deposited. Most instream LWD was lying level on the streambed where it could potentially play an important role in channel scour processes. Diameters of riparian LWD tended to be larger than instream LWD, apparently due to "case-hardening" of logs on the land and erosion of decayed material from the outer surfaces of logs in streams. LWD in streams was less decomposed than that in riparian areas where it became severely decayed within 10–15 years. Logarithmic regression of time since harvest, and decay data for submerged LWD considered to be from harvesting, indicated that pine logs remained intact in these spring-fed streams for over 20 years. The persistence and stability of pine LWD throughout the rotation period mean that LWD is likely to play an important role for stream processes and biota in central North Island pumice-bed streams.

Keywords: large woody debris; decay state; debris size; debris orientation; harvesting; stream; riparian; *Pinus radiata*.

INTRODUCTION

Many North American studies have highlighted the important effects on aquatic ecosystem structure and functioning produced by woody debris that has fallen into streams (*see* reviews by Harmon *et al.* 1986; Sedell *et al.* 1988). Large woody debris can alter instream flow conditions (Gippel 1995), influence sediment storage and transport in streams (Keller & Swanson 1979; Mosley 1981), and change stream channel morphology (Hilderbrand *et al.* 1997). For example, LWD oriented perpendicular to the direction of flow was shown to play an important role in channel scour which can lead to the formation of pool habitat suitable for some fish (Abbe & Montgomery 1996; Hilderbrand *et al.* 1998). In addition, LWD can affect conditions for aquatic life by increasing organic matter retention (Wallace *et al.* 1995; Culp *et al.* 1996), and by providing food and stable surfaces for invertebrates, especially where benthic habitats are unsuitable (Wallace & Benke 1984; O'Connor 1992; Collier, Wilcock & Meredith 1997).

Stream size and hydrology are key factors influencing the amount of woody debris that is retained in streams (Anderson *et al.* 1978; Bilby & Ward, 1989; Evans *et al.* 1993a). Many New Zealand native forest streams generally have low amounts of woody debris compared to North American streams because of the smaller volumes of wood and its poor retention in streams with highly variable flow regimes (Winterbourn *et al.* 1981; Evans *et al.* 1993b). Higher levels of LWD than at comparable native forest sites have been reported in some rotational exotic forest streams (Quinn *et al.* 1997) but not in others (Evans *et al.* 1993b). Most LWD enters pine forest streams during harvesting when volumes of submerged wood can increase up to 7-fold (Collier, Bowman & Halliday 1997), particularly where harvesting material is pulled across stream channels (Baillie *et al.* 1999).

The extended period of time required to measure LWD breakdown directly means that there is little information on the temporal effects of LWD in streams, and few studies have examined its function or characteristics in riparian areas. This study quantified the physical characteristics of *P. radiata* LWD that had been deposited in and alongside pumice-bed streams in the central North Island where the most extensive areas of pine forest plantings in New Zealand occur (36% of total; NZFOA 1997). Our objectives were firstly to assess the decay state of LWD in relation to time since harvest to provide information on the likely time-scales of LWD effects on streams and riparian areas, and secondly to compare the orientation of submerged and terrestrial LWD as an indirect measure of its movement after deposition in the stream channel.

METHODS

Study Sites

Twelve sites in Kinleith Forest and one site in Whirinaki Forest, central North Island, were visited in summer 1996. All sites were in catchments managed for *P. radiata* production forestry, and had been harvested between 1 and 19 years prior to sampling (Table 1). The streams were characterised by stable flow regimes derived predominantly from groundwater inputs, and mainly mobile beds of pumice sand and small gravels which are generally unsuitable for aquatic life (Collier, Baillie, Bowman, Halliday, Quinn & Smith 1997). Summer water temperatures at the time of sampling were between 10.8° and 13.8°C, and water conductivities were between 50 and 90 µS/cm (CDM Model 83 meter; values adjusted to 25°C using factors given by Golterman 1969) (Table 1). Dissolved oxygen levels measured at the time of sampling with a YSI Model 55 meter were all above 8.5 g/m^3 or 85% saturation at prevailing stream temperatures, except at the most recently harvested site (1) where dissolved oxygen was 7.3 g/m^3 and 67%. Channel widths measured at five evenly-spaced transects perpendicular to the direction of flow along 100-m reaches averaged between 1 m and 4.5 m, and mean depths (five points across each transect) ranged from 0.25 to 0.74 m (Table 1).

TABLE 1–Physico-chemical characteristics of sampling sites. ND = no data.

Site No.	Years since harvest	Water temp. (°C)	DO (g/m^3) (%)	Cond. (µS/cm @25°C)	Mean depth (m)	Mean width (m)
1	1	11.7	7.27 (67.1)	74.1	ND	1.14
2	1	11.7	9.70 (90.1)	78.2	0.29	1.05
3	3	11.9	9.44 (87.4)	82	0.25	1.05
4	5	11.8	10.1 (93.3)	63.4	0.65	1.96
5	6	10.8	10.40 (94.0)	82	0.74	3.3
6	10	11.7	10.49 (96.6)	72.9	0.5	1.92
7	10	11.2	10.20 (93.0)	50.7	0.62	2.07
8	11	12.6	10.25 (95.8)	60.9	0.28	1.4
9	11	13.5	10.20 (96.2)	67.6	0.3	1.51
10	12	13.8	10.15 (97.9)	89.4	0.41	2.88
11	17	10.8	10.54 (94.6)	53.3	0.41	1.42
12	18	11.3	9.41 (95.0)	83.6	0.61	4.5
13	19	11.8	8.80 (90.7)	65.1	0.35	1.33

Assessment of Large Woody Debris (LWD)

Lengths of stream between 100 m and a maximum of around 500 m were waded, and the first 50 pieces of submerged pine wood >10 cm across were assessed for diameter, orientation in relation to the direction of flow and the streambed, and decay state. Only 11 and 29 pieces of LWD were found at sites 1 and 2, respectively. To enable terrestrial and submerged LWD decay states to be compared, the same measurements were made for 50 pieces of LWD encountered in riparian areas (within about 20 m of the stream) of each site using a random walk procedure.

Decay state of LWD was assessed visually using two methods. Method A used a 7-point qualitative scale adapted from the decay grades of AWPA (1997) as follows:

1 sound (fresh material)
2 slight decay
3 lightly-established decay
4 well-established decay
5 established and deepening decay
6 severe decay
7 failure (breaks under pressure).

Qualitative methods such as this are used widely overseas to assess wood decay (e.g., Forestry Tasmania 1997; McHenry *et al.* 1998). Training was received in the use of this method from the Wood Protection Group at the New Zealand Forest Research Institute to standardise interpretation between observers. A screwdriver was used to probe each LWD piece along its length to assess average decay state; for assessing submerged LWD an underwater viewer was used.

Method B was based on the cumulative score for the appearance of bark, twigs, wood texture, shape, and colour following Robison & Beschta (1990) for submerged wood, and an adaptation of this for riparian LWD (*see* Table 2). Each variable was scored from 1 to 3 or 4, and cumulative scores possible ranged from 5 for very fresh material to 17 for extremely decayed material.

TABLE 2–Decay state characteristics assessed for submerged and riparian wood using Method B. Characteristics were scored as indicated, and cumulative scores were used to indicate decay state.

	Score			
	1	2	3	4
Submerged				
Bark	Firm	Loosening	Trace	Absent
Twigs (<1cm)	Present	Trace	Absent	–
Texture	Intact	Smooth, may be some minor surface abrasion	Abrasion, some holes and openings	Vesicular, many holes and openings
Shape	Round	Round/oval	Irregular	–
Color	Original	Original but darkening	Dark	–
Riparian				
Bark	Firm	Loosening	Trace	Absent
Twigs (<1cm)	Present	Trace	Absent	–
Texture	Fresh	Upper surface dry but not case-hardened	Decay well-established with some insect infestation	All but centre decayed and occupied by insect larvae, collapses when stood on
Shape	Round with no growths	Some fungal fruiting and/or encroaching vegetation disrupts round shape	Moss cover, seedlings, etc. cause irregular shape	–
Color	Original	Original but darkening	Dark	–

Data Analysis

Some sites could have contained LWD from thinning operations and windfall as well as from harvesting. To distinguish between these potential sources, frequency distributions of decay scores from each method were examined visually to identify peaks believed to be from harvesting. The data points associated with harvesting peaks were used to examine the relationship between mean decay state of submerged or riparian LWD and time since harvesting (years). Site 7 was excluded from this analysis as large amounts of windthrow material appeared to have entered the stream and made it difficult to distinguish harvesting peaks in frequency distributions. ANOVA was used to investigate the effects of location (submerged *v.* riparian) and time since harvest on diameters of LWD.

RESULTS

Size and Orientation

Mean diameters of LWD assessed in this study ranged from 0.11 to 0.21 m for submerged wood (harvesting plus other material), which were less than for riparian wood (0.16 to 0.28 m). Analysis of variance on log-transformed data indicated that both time since harvest and location (i.e., submerged or riparian) had highly significant effects (F = 77.05 and 7.27, respectively; $p < 0.001$) on the mean diameters of LWD measured at a site.

Most pieces of submerged LWD for all sites combined were oriented across the flow (81–90°; 145 pieces or 25%); next most common were those in the direction of flow (i.e., 0°; 85 pieces or 14%) (Fig. 1A). Most LWD in riparian areas was also lying perpendicular to the direction of flow in the nearby stream (Fig. 1A). The other riparian LWD pieces were

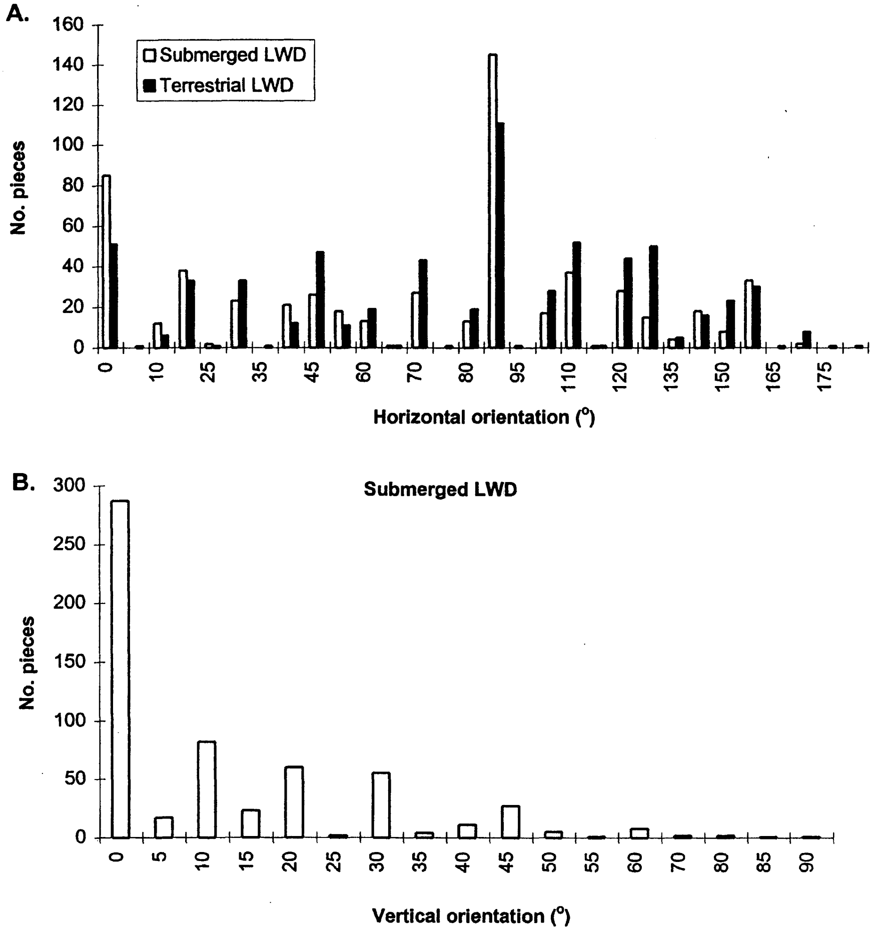

FIG. 1–Frequency histograms of (A) horizontal orientation for submerged and riparian LWD, and (B) vertical orientation for submerged LWD.

distributed fairly evenly across the remaining range of possible orientations. The large majority of submerged pieces of wood over all sites combined (287 pieces) was lying level with the streambed (i.e., 0° in Fig. 1B), although not necessarily in contact with the bed.

Decay State

Mean decay scores of all submerged wood measured (i.e., from harvesting and other sources) ranged from 1.7 to 4.7 and 7.0 to 15.2 for Methods A and B, respectively. Maximum decay scores were greater for riparian wood using Method A (range 1.3–6.2) but not Method B (9.1–15.7). Nevertheless, the two decay score methods were highly correlated ($p < 0.001$), although this relationship was stronger for submerged LWD ($r_S = 0.804$, $n = 590$) than for riparian LWD ($r_S = 0.642$; $n = 650$), which suggests that Method B was more effective for wood in streams. In addition, the latter method failed to differentiate decay peaks of harvesting material clearly whereas these peaks were usually obvious using Method A. Furthermore, when results not associated with decay score peaks in Method A were excluded, there was a poor relationship between decay score and time since harvest using data from Method B for both submerged and riparian LWD (Fig. 2A). In contrast, these relationships were strong using data from Method A (Fig. 2B). The above results suggest that direct qualitative assessments of decay state by probing wood surfaces are more reliable than assessments based on appearance, particularly for LWD pieces at more advanced stages of decay.

Logarithmic relationships between the decay scores of harvest wood from Method A and time since harvest explained 89–94 % of the variation in the dataset (Fig. 2B). Decay scores were similar for riparian and submerged LWD for 2–3 years after harvesting, but terrestrial decay processes appeared to become much more rapid after this (Fig. 2B). On average, riparian wood had reached an advanced stage of decay (decay class 6 on the 7-point scale) within 13 years of harvesting, whereas submerged wood generally appeared to have reached a similar level of decay within around 20 years and to be likely to persist in these streams for much longer.

DISCUSSION

Our finding that submerged *P. radiata* LWD is likely to persist in central North Island streams for more than 20 years indicates that the instream effects of harvesting material persist throughout most of the rotation period (usually c. 25–28 years). Submerged LWD retained in stream channels persisted for a much longer period than riparian LWD which became severely decayed within 13 years. Percival & Hawke (1988) recorded similar turnover times for pine slash from pruning and thinning at a farm forestry site near Rotorua where larger pieces of wood had disappeared within 12–14 years.

The greater decomposition rates for riparian LWD measured in our study are thought to reflect contact with the ground which regulates moisture levels and facilitates greater penetration by microbes in a well-oxygenated environment, and the burrowing and feeding activities of terrestrial insects (Harmon *et al.* 1986; Rice *et al.* 1997; Sedell *et al.* 1988). Fallen wood in contact with the ground is successively colonised by bacteria, mould, sapstain, and decay fungi. The latter comprise three main types: brown rot, white rot (Basidiomycetes), and soft rot (mainly Ascomycetes). Brown rot fungi attack only cellulose and hemicelluloses

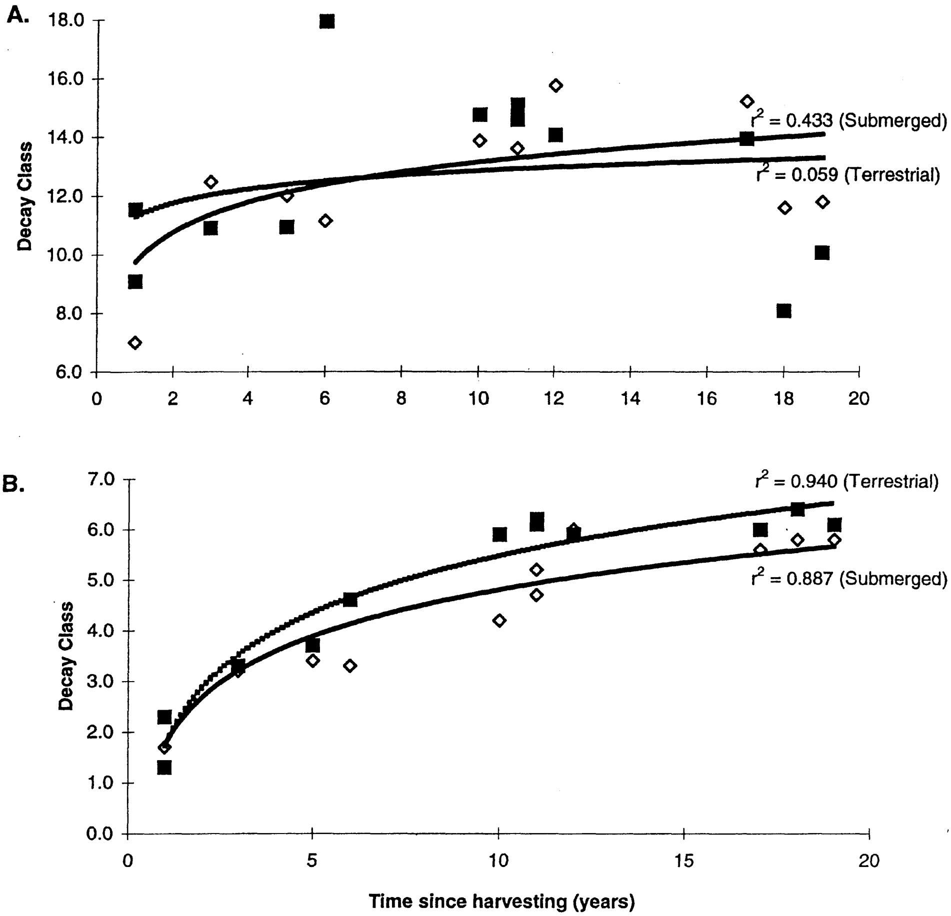

FIG. 2–Relationships between mean decay state using (A) Method B and (B) Method A (*see* Table 2) and time since harvesting, for riparian and submerged LWD attributed to harvesting at each site during the survey. The lines represent logarithmic curves of best fit. Site 7 has been excluded as windthrow made it difficult to distinguish harvesting material.

whereas white rot can also utilise lignin. Both tend to decompose wood more rapidly than soft rot, but are intolerant of high wood-moisture levels (>65%) and are therefore uncommon in aquatic environments (Rayner & Boddy 1988).

The breakdown of submerged wood is attributable to a combination of processes including physical abrasion and fragmentation, microbial degradation, and invertebrate feeding (Harmon *et al.* 1986). Wood exposed to freshwater is prone to attack by soft-rot fungi, which degrade cellulose and hemicellulose, and lignolytic bacteria (Eaton & Hale 1993; Rayner & Boddy 1998). Tank & Winterbourn (1996) observed fungal hyphae, actinomycete-like filaments, and unicellular bacteria colonising wood (including *P. radiata*) in a Canterbury forest stream, but actinomycetes are likely to play a minor role in wood decay (Eaton & Hale 1993).

Many factors influence the microbial invasion and colonisation, and the consequent decomposition of wood; these include moisture content, aeration, temperature, interactions between micro-organisms, and the constantly changing nutrient status of the wood during decay (Eaton & Hale 1993). Uptake of water in submerged wood initially leads to saturation of cell walls, followed by binding with hydroxyl groups in the walls, and then accumulation of free water in wood cell lumina, at which point gaseous diffusion slows down and oxygen can become limiting (Eaton & Hale 1993). Slow rates of oxygen diffusion and cool water temperatures (10.8°–13.8°C at the time of this study) may have limited microbial activity and restricted it to the surface layers of the LWD (Sinsabaugh *et al.* 1992; O'Connor 1992), resulting in slower breakdown rates than that for riparian wood at our sites.

Various invertebrate species, including Coleoptera, Isoptera, and Lepidoptera, are involved in the breakdown of wood deposited on the land, and many of these can tolerate relatively low moisture levels (Eaton & Hale 1993). In North America, terrestrial invertebrate communities are more diverse and are thought to have a greater impact on wood breakdown than stream invertebrates (Sedell *et al.* 1988), and the same is likely to be true in New Zealand. Anderson (1982) reported fewer wood-associated invertebrates in New Zealand streams than in Oregon, United States, and in particular fewer species that feed directly on submerged wood. However, recent work on invertebrate communities in central North Island pumice-bed streams has shown that some stream invertebrate species feed extensively on wood (Collier, Baillie, Bowman, Halliday, Quinn & Smith 1997; Collier & Halliday in press).

The greater diameters that we recorded for terrestrial LWD partly reflect different breakdown processes that occur in terrestrial and aquatic environments. *Pinus radiata* logs lying on the land become "case-hardened" and often maintain close to the original diameter even though internal wood can be highly decayed, whereas erosion by the stream current of decayed material from log surfaces gradually decreases the diameters of submerged LWD pieces. Ward & Aumen (1986) estimated that erosion rates of wood varied from 0.5 to 11 mm per year in an Oregon stream, and that this process could generate significant amounts of fine particulate organic matter that was potentially available to aquatic biota.

Similar orientations of submerged and riparian wood suggest that movement of LWD that is retained in the channel was relatively minor. This reflects the stable, spring-fed flow regimes that prevail in these pumice-bed streams. We observed that instream LWD tended to be regularly spaced along the study reaches, and that debris dams formed by wood transported in the flow typically occurred where LWD length exceeded channel width. Factors other than flow, such as the direction that harvested material was extracted (e.g., by pulling back from the stream) or the direction of the prevailing wind causing windthrow, may also influence orientations of LWD at some sites. In addition, orientation patterns of LWD can reflect the tendency of trees to lean towards streams due to phototropism and bank erosion (Robison & Beschta 1990).

The stable nature of LWD means that it is a long-term and predictable feature of central North Island pumice bed streams. Inorganic benthic substrates in these streams provide relatively poor invertebrate habitat, and wood has been shown to provide an important substrate for invertebrate colonisation (Collier & Halliday in press), as has also been found in sandy prairie streams in northern Texas, United States (Hax & Golladay 1998). The persistence of submerged LWD through the rotation period means that material remaining

after harvesting operations is likely to play a significant role in the structure and function of central North Island pumice-bed streams.

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