

IMPACTS OF LAKESHORE RESIDENTIAL DEVELOPMENT ON COARSE WOODY DEBRIS IN NORTH TEMPERATE LAKES¹

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Abstract. Coarse woody debris (CWD) is a critical input from forested watersheds into aquatic ecosystems. Human activities often reduce the abundance of CWD in fluvial systems, but little is known about human impacts on CWD in lakes. We surveyed 16 north temperate lakes to assess relationships among CWD, riparian vegetation, and shoreline residential development. We found strong positive correlation between CWD density and riparian tree density ($r^2 = 0.78$), and strong negative correlation between CWD density and shoreline cabin density ($r^2 = 0.71$) at the whole-lake scale. At finer spatial scales (e.g., between sampling plots), correlations between CWD and riparian vegetation were weaker. The strength of relationships between CWD and riparian vegetation was also negatively influenced by the extent of cabin development. Overall, there was significantly more CWD in undeveloped lakes (mean of 555 logs/km of shoreline) than in developed lakes. Within developed lakes, CWD density differed between forested sites (mean of 379 logs/km of shoreline) and cabin-occupied sites (mean of 57 logs/km of shoreline). These losses of CWD will affect littoral communities in developed north temperate lakes for about two centuries. Because CWD is important littoral habitat for many aquatic organisms, zoning and lake management should aim to minimize further reductions of aquatic CWD and woody vegetation from lakeshore residences.

Key words: coarse woody debris; lakeshore; littoral zone; residential development; riparian; shoreline development; snag.

INTRODUCTION

Coarse woody debris (CWD) is a critical input from forested watersheds into aquatic ecosystems. CWD provides physical structure that is used as habitat for aquatic organisms, and it alters water movements and hydrological processes (Tarzwell 1936, Triska and Cromack 1980, Franklin et al. 1981, Harmon et al. 1986, Andrus et al. 1988). CWD affects the flow of organic matter from terrestrial ecosystems into surface waters (Bormann and Likens 1979, Franklin et al. 1981), and the transport of organic materials within aquatic ecosystems (Beschta 1979, Bilby and Ward 1991). Biomass of CWD in fresh waters is determined by the balance among inputs, decomposition rates, and removal processes. Climate, soils, stream flow rates, topography, forest age, forest density, and community composition jointly determine the distribution and abundance of CWD in aquatic ecosystems (Harmon et al. 1986, Spies et al. 1988, Harmon and Chen 1991, Tyrrell and Crow 1994).

Human land-use practices have significantly altered CWD inputs to aquatic systems (Sedell and Froggatt 1984, Harmon et al. 1986, Maser and Sedell 1994). Logging can initially increase CWD inputs by introducing large amounts of slash and other debris (Spies

et al. 1988), but reduces CWD inputs over longer time periods because of the loss of riparian trees (Harmon et al. 1986, Murphy and Koski 1989, Bilby and Ward 1991). Humans also directly impact CWD abundance in many rivers by direct removal (e.g., Sedell and Froggatt 1984). CWD removal policies were in force until around 1912 throughout the U.S., and until the early 1980s in the Pacific Northwest (Harmon et al. 1986). During the 1970s and 1980s, ≈\$6 million was spent annually with the aim to improve passage of anadromous salmonids in rivers and streams (Maser and Sedell 1994). Active removal of CWD from riverine systems highlights the prior ignorance of the importance of CWD in aquatic ecosystems (Sedell and Froggatt 1984, Harmon et al. 1986). Currently, the U.S. Forest Service emphasizes long-term recruitment of CWD in riparian corridors as part of ecosystem management plans for the Pacific Northwest. In Wisconsin the removal of material from lake beds is illegal. However, CWD has not traditionally been considered bed material and therefore remains unprotected. Wisconsin's authority to protect CWD is only invoked when its removal will substantially disturb the lake bed (P. Cunningham, Wisconsin Department of Natural Resources, *personal communication*).

Human impacts on CWD are well documented in some types of riverine systems but are poorly understood in lakes. In the littoral zone of lakes, woody debris may affect nutrient cycling and littoral production, and provide refuges from predation (Wege and Anderson 1979, Lynch and Johnson 1989, Savino and

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TABLE 1. Lakes sampled for the survey of coarse woody debris (CWD). Lake surface area, cabins per kilometre of shoreline, and lake-wide mean riparian forest and CWD characteristics are presented. All lakes are in Vilas County, Wisconsin, or Gogebic County, Michigan.

Lake	Location (state)	Surface area (ha)	Cabin density (no./km)	Riparian tree density (no./km)	Riparian tree basal area (m ² /km)	CWD density (no./km)	CWD basal area (m ² /km)
Bay	Michigan	69	0	1270	53	442	121
Bergner	Michigan	9	0	1210	37	338	41
Crampton	Wisconsin/Michigan	24	0	1800	37	965	183
Long	Michigan	8	0	1875	27	833	130
Roach	Wisconsin/Michigan	20	0	1300	43	613	127
Tenderfoot	Wisconsin/Michigan	175	0.6	2150	75	637	134
Palmer	Wisconsin	254	1.9	1330	86	298	65
Street	Wisconsin	22	3.6	964	35	203	52
Laura	Wisconsin	240	4.1	961	33	48	12
Annabelle	Wisconsin	85	4.8	1400	28	278	46
Joyce	Wisconsin	12	6.0	1280	47	316	54
Lake of the Hills	Wisconsin	25	6.7	976	30	269	97
Towanda	Wisconsin	58	11.8	771	31	5	<1
Black Oak	Wisconsin	234	12.3	833	30	36	4
Johnson	Wisconsin	31	17.0	883	40	11	1
Arrowhead	Wisconsin	40	24.6	956	38	17	4

Stein 1989). Changes in CWD characteristics of lakes are most likely to affect large mobile taxa such as fishes and macroinvertebrates that require the large-scale physical heterogeneity provided by CWD for cover. Alterations of littoral habitats can affect recruitment dynamics of dominant fishes, which often have implication for entire food webs (Carpenter and Kitchell 1993). While the necessity of littoral structure has been realized for decades (e.g., Eschmeyer 1936, Tarzwell 1936), it has not been incorporated into lake management and lakeshore development plans. Instead, more emphasis has been placed on the negative effects of increased nutrient and sediment inputs on lake ecosystems caused by residential shoreline development (Dillon and Rigler 1975, Dillon et al. 1994). However, such development may also affect CWD abundance in the littoral zone, and therefore adversely affect lake ecosystems.

In this study, we determine relationships among human disturbance of lakeshores, riparian vegetation, and CWD. We examine impacts of residential development on the abundance of CWD in the littoral zone of temperate lakes by sampling lakes along a gradient of human development. We also assess the variability in CWD that can be attributed to riparian characteristics across three spatial scales, and discuss the long-term implications for ecosystem dynamics.

METHODS

We sampled 16 lakes in two adjacent counties (Vilas and Gogebic) in Northern Wisconsin and Upper Michigan. The lakes are surrounded by mixed northern hardwood-conifer forests (Stearns 1951, Brown and Curtis 1952, Curtis 1959). The region's climax forest communities are dominated by *Acer saccharum* and *Tsuga canadensis*, although old growth is limited to a few scattered reserves (Frelich and Lorimer 1991, Mlad-

enoff et al. 1993). In the more saturated soils found along the riparian corridors, there are significant numbers of *Thuja occidentalis*, *Picea mariana*, and *Larix laricina* (Curtis 1959). Earlier successional dominants are *Abies balsama*, *Acer rubrum*, and *Betula papyrifera*.

Lakes were chosen to span a gradient of cabin densities (Table 1). Five of the 16 lakes had no shoreline cabins and were sampled to determine patterns of CWD inputs in the absence of development. Undeveloped lakes were located at the University of Notre Dame Environmental Research Center (UNDERC). The undeveloped lakes, comprising most of the lakes in the region, were logged extensively around 1890 (Leavitt 1988) and are surrounded by a mixture of mature, and to a lesser extent, climax forests. Thus, undeveloped lakes in our survey are not unimpacted by human activity. Seven lakes had a mixture of developed (cabin-occupied) and undeveloped (forested) shoreline, and four lakes were completely surrounded by cabins. In the mixed lakes, we stratified our sampling effort between the cabin-occupied and forested sites. We sampled each site type in proportion to the relative lengths of cabin-occupied and forested shoreline around the lake.

We sampled riparian vegetation and CWD abundance on a total of 125 plots at the 16 survey lakes. About 90% of CWD inputs in surface waters originate from within 10 m of shore (Murphy and Koski 1989). Therefore, we restricted sampling to the nearshore area where riparian trees had a high probability of contributing to littoral CWD. Undeveloped lakes were sampled by demarcating the lakeshore into 40-m segments on a map, and randomly selecting sampling sites from these segments. At developed lakes, all cabins with lakefront access were counted from the water, and a random subset was then selected to survey for CWD and riparian

forest characteristics. At least 10% of the cabins were sampled at each lake, with a minimum sample size of five cabins for lakes with few cabins. The one exception was Tenderfoot Lake, where we could access only three cabins. Forested sites on developed lakes were sampled by random selection of each site within the forested shoreline area.

We sampled CWD, riparian vegetation, and physical attributes (slope and aspect) at 5–13 randomly selected sites per lake. On undeveloped lakes, a plot 40 m along the lake and 10 m into the riparian forest (400 m²) was surveyed for forest attributes. On developed lakes, the plot size used was 30 m along the shore by 10 m into the riparian forest (300 m²). The smaller plot width was necessary to account for the minimum lot size on some lakes. All measurements were standardized to a common transect length. Within each plot, all live, and standing dead trees (snags) >5 cm in diameter were identified to species and measured at breast height for stem diameter. At the same sites, a 40-m line transect (30 m on developed lakes) was established in the water along the 0.5 m depth contour. All CWD >5 cm in diameter that intersected the line transect was measured with a caliper. CWD that did not intersect the 0.5 contour was not counted. Therefore, our measurements of CWD abundance are relative and represent a standardized subset of the total CWD.

We analyzed data at three spatial scales: by development site type, weighted whole-lake means, and individual plots. For analysis by site type, we used ANOVA with unequal replication and three treatment levels to test for differences between sites on undeveloped lakes, forested sites on developed lakes, and cabin-occupied sites on developed lakes. At the whole-lake scale, regression analysis was used to compare CWD density and basal area to tree density and basal area of the riparian forest, and to cabin density. Regression analysis was done on both scalar and log-transformed weighted lake means. Weighting accounted for the relative proportion of the shoreline that was occupied by cabins and by forest. At the scale of individual plots, Pearson correlation analysis was used to determine relationships among CWD characteristics and riparian forest characteristics.

RESULTS

Coarse woody debris (CWD) density was significantly correlated to riparian forest characteristics, but the strength of the relationship was dependent on the spatial scale at which it was measured. At the whole-lake scale, CWD density and CWD basal area were positively correlated to riparian tree density ($r^2 = 0.78$ and $r^2 = 0.66$, respectively; Fig. 1). Tree density was a better predictor of CWD abundance than riparian basal area, although positive correlations between riparian dominance and CWD abundance were significant (not shown, both $P < 0.01$).

At the scale of individual plots, the relationship be-

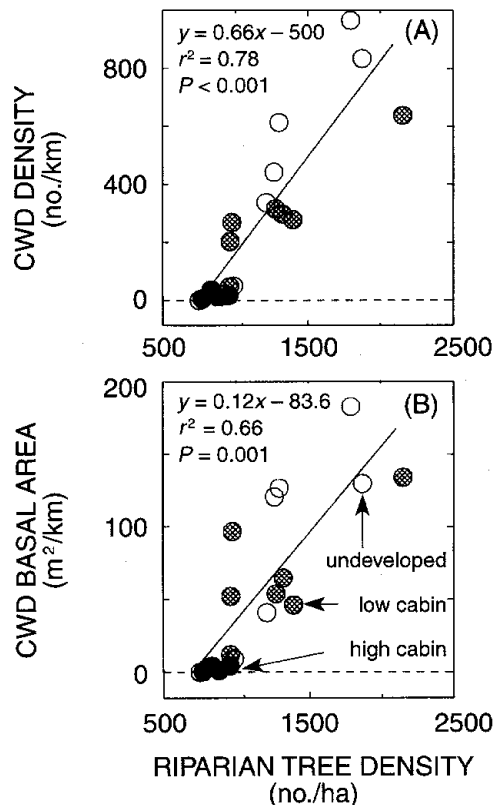


FIG. 1. Coarse woody debris (CWD) density (A) and basal area (B) as a function of tree density in riparian forest. Each dot represents a weighted lake mean. Open circles are undeveloped lakes, hatched circles are lakes with low cabin density (0.1–10/km), and the solid filled circles represent lakes that were completely surrounded by cabins (>10/km). Regressions are least squares models of lake mean CWD density and basal area as a function of riparian tree density. Standard errors associated with slope, intercept, and estimate in (A) are 0.097, 127, and 151, respectively, and in (B) are 0.023, 30.6, and 36.3, respectively.

tween riparian characteristics and CWD abundance was weaker than at the whole-lake scale (Fig. 2). Furthermore, increasing human impacts decreased the strength of correlation between riparian characteristics and CWD abundance. Riparian tree density was significantly correlated to CWD in undeveloped sites ($P < 0.01$; Fig. 2A) and on forested plots on developed lakes ($P < 0.05$; Fig. 2B). The relationship between CWD density and riparian tree density was not statistically different between sites on undeveloped lakes (slope \pm SE = 0.33 ± 0.11) and forested sites on developed lakes (slope \pm SE = 0.17 ± 0.08). The cabin-occupied sites had no statistically significant relationship between riparian vegetation and CWD density ($P > 0.5$; Fig. 2C), possibly due to the small range of riparian tree densities observed at these sites. Across all site types, riparian dominance, community composition (i.e., deciduous/conifer abundance), aspect, and slope had nonsignificant relationships with CWD abundance ($P > 0.05$).

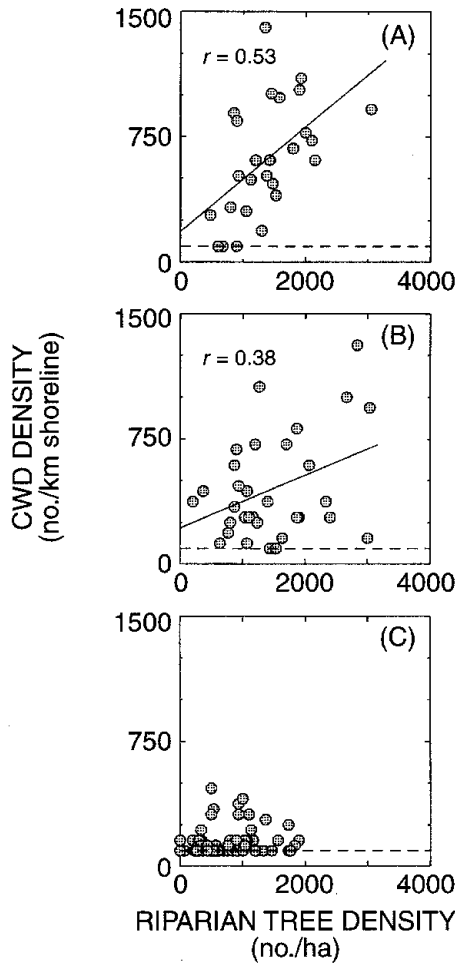


FIG. 2. Coarse woody debris (CWD) density as a function of riparian tree density for undeveloped lakes (A), forested plots on developed lakes (B), and cabin plots on developed lakes (C). Each dot represents one transect. Correlation coefficients are shown for significant relationships.

Development had strong negative effects on CWD abundance at the whole-lake scale (Fig. 3). Weighted lake mean CWD density and basal area were negatively correlated to cabin density ($r^2 = 0.71$ and $r^2 = 0.65$, respectively; Fig. 3). High variability in CWD density among undeveloped lakes reduced the precision of these relationships (Fig. 3, open circles). Transformation of the dependent variables in Fig. 3 did not improve these relationships.

Comparisons among plot types suggest that residential development has multiple effects on CWD. Riparian tree density differed significantly between the three site-types (ANOVA, $P < 0.001$), but density at undeveloped lake sites (mean = 1381 stems/ha) and forested sites on developed lakes (mean = 1473 stems/ha) were not significantly different from one another (Scheffé's test, $P > 0.05$). Cabin-occupied sites on developed lakes had significantly fewer trees (mean = 809 stems/ha) than the other two site-types (Scheffé's

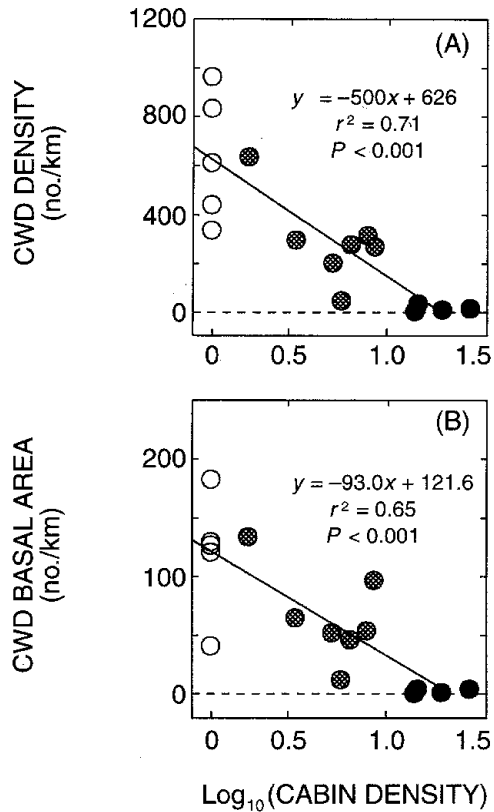


FIG. 3. Coarse woody debris (CWD) density (A) and basal area (B) as a function of the logarithm of shoreline cabin density for 16 lakes considered in this study. Symbols are as in Fig. 1. Standard errors associated with slope, intercept, and estimate in (A) are 86.2, 65.8, and 167, respectively, and in (B) are 18.3, 14.0, and 35.5, respectively.

test, $P < 0.05$). Riparian snag density and CWD density had similar patterns to each other and were significantly different among all three site types (ANOVA, both $P < 0.001$; Fig. 4A, B). Unlike live trees, snags and CWD were significantly less abundant at forested sites on developed lakes than at sites on undeveloped lakes (Scheffé's test, $P < 0.05$).

Riparian tree size differed significantly between site types (ANOVA, $P < 0.001$; Fig. 4C). However, CWD size was not different between site types (ANOVA, $P > 0.15$) resulting in a large difference between the mean size of trees and the mean size of CWD at cabin-occupied sites (Fig. 4C). Thus, it appears that many of the relationships between riparian vegetation and CWD are complex responses to residential shoreline development resulting from the dual effects of altering riparian vegetation and removing of aquatic coarse woody debris.

DISCUSSION

Development and CWD

Historically, investigations of the responses of lakes to development of lakeshore properties have focused

on nutrient loading (e.g., Dillon and Rigler 1975, Dillon et al. 1994). Our study demonstrates that there are also substantial impacts of shoreline residential development on littoral CWD. We found strong relationships among cabin density, riparian forest characteristics, and CWD abundance in the survey of 16 north temperate lakes. The strength of correlation between riparian characteristics and CWD varied with both the spatial scale of analysis and the intensity of human impacts. Previous studies have quantified similarly strong correlation between forest characteristics, such as stand age (Spies et al. 1988, Tyrrell 1991) or basal area of living trees (Harmon et al. 1986, Spies et al. 1988) and abundance of CWD. These studies have not, however, linked the interactions between human impacts and riparian vegetation in determining the abundance of CWD in aquatic ecosystems.

Humans reduce CWD in lakes apparently through both direct removal of CWD and by altering riparian vegetation. CWD and riparian tree sizes were similar in the undeveloped lakes and forested plots of developed lakes (Fig. 4C), but mean CWD size at cabin sites was significantly smaller than the mean tree size at the same sites. Thus, while forested-site CWD in developed and undeveloped lakes reflected riparian tree size characteristics, CWD at cabin-occupied sites did not, and may reflect active and selective removal of CWD by humans. Alternative explanations for differences in CWD size and riparian tree size at cabin sites are (1) CWD currently in the water may be a legacy from the previous forest stand (Spies et al. 1988, Tyrrell and Crow 1994) and (2) developers preferentially preserve large trees on cabin sites. We did not attempt to estimate the relative importance of each of these mechanisms in causing the discrepancy in log size between riparian trees and aquatic CWD. Regardless of the mechanism, the net effect of development is to uncouple the natural relationship between riparian vegetation and aquatic CWD.

Alterations in riparian vegetation are a potentially more extensive, if indirect, contributor to the reduction of CWD in developed lakes. The importance of riparian alterations to the changes in CWD abundance is evident from the strong relationships between the intensity of development and both riparian vegetation and CWD abundance (Figs. 3 and 4). Riparian trees were present at significantly lower densities at cabin sites (809 stems/ha) than the other site types ($P < 0.05$), and there were similar trends in snag density and CWD density across site types (Fig. 4A and B). Snags can be thought of as precursors of CWD; trees often stand dead for several years before falling (Triska and Cromack 1980, Harmon and Chen 1991). Thinning of trees by landowners could reduce mortality by reducing competition, disease transmission, and the pool of living trees available to become snags (Franklin et al. 1981, Harmon et al. 1986). Snags may also be cut down for firewood by landowners, thereby reducing rate of ri-

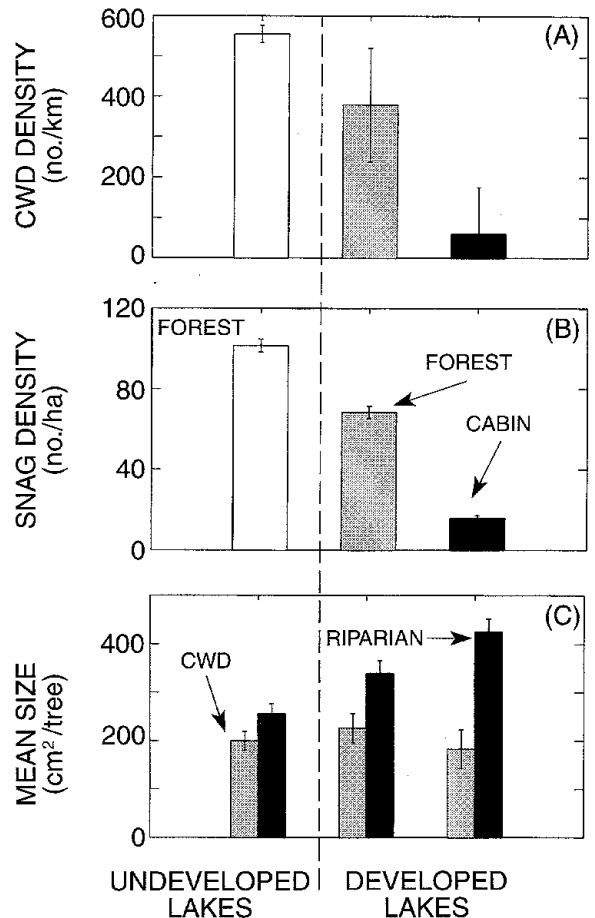


FIG. 4. Mean and 95% confidence intervals for undeveloped, developed-forested, and developed-cabin plots. (A) Coarse woody debris (CWD) density. (B) Snag (standing dead tree) density. (C) Mean basal area of CWD and riparian trees.

parian inputs to aquatic CWD. Snag densities at undeveloped and forested sites (≈ 60 – 100 stems/ha) were similar to studies in both nearby old growth (30–180 stems/ha, Tyrrell and Crow 1994) and old growth in the Pacific Northwest (30–60 stems/ha, Spies et al. 1988). Snag density at the cabin sites was much lower.

The strength of the relationships between riparian vegetation and CWD depended on the scale of data aggregation; relationships were much stronger at the whole lake than at a site-by-site scale (compare Figs. 1 and 2). There are several explanations for this phenomenon. The dominant disturbance regime for this region is that of frequent, small-scale windthrows. Large-scale disturbance is relatively rare, as catastrophic disturbances ($> 60\%$ canopy loss) affect forest stands > 1 ha less than once every 1000 yr (Canham and Loucks 1984, Frelich and Lorimer 1991). More commonly, disturbances affecting 10–20% of a forest stand will occur approximately once in 90 yr (Frelich and Lorimer 1991). Such disturbances would affect forest patches around a lake, and thus cause high variability between sites, whereas large disturbances could

alter the entire shoreline forest. Our results may also reflect movement of downed logs in the water. Strong correlation between stand characteristics and CWD has been documented in terrestrial systems (e.g., Spies et al. 1988, Tyrrell 1991). In contrast, Andrus et al. (1988) found few direct relationships between aquatic CWD abundance and stand characteristics in *Pseudotsuga menziesii* forests. Instead, stream transport of CWD caused logs to accumulate at sites of deposition and low water energy. In our study, log movement could have been caused by wind-induced waves, water level changes, or ice scour. These factors could relocate logs at downwind sites. We did observe several sites at the far eastern lake edges (with prevailing westerly winds) that had extremely high CWD abundance. Such movement around the lake would cause high variability at a site-by-site level. However, the total amount of CWD in the lake would remain constant, and thus would not affect relationships between CWD and riparian vegetation on the whole-lake scale.

Study implications

Extensive reduction of CWD in developed lakes may have dramatic long-term consequences for littoral community and lake ecosystem structure. Dynamics for CWD accumulation are slow, with the processes of input and decay often requiring centuries. Evidence for slow change comes from our observations of significant numbers of logged trees as a component of the CWD in lakes adjacent to sites logged ≈ 100 yr ago (Stearns 1951, Leavitt 1988). Little is known about decay rates of CWD in standing waters. Hodgkinson (1975) estimated decay rates of small (<10 cm diameter) logs of *Populus* spp. to be $\approx 1\%$ /year in beaver ponds. Large boles decay at much slower rates than smaller boles (Harmon et al. 1986, Murphy and Koski 1989). Furthermore, conifers, which decay more slowly than deciduous trees (Harmon et al. 1986), were prevalent in the sites on undeveloped lakes. The aquatic CWD were very likely to have been large *T. canadensis* and *Pinus* spp. from late 19th century logging operations.

In contrast to phosphorus inputs and fish harvests, which affect lake dynamics on decadal time scales (Carpenter and Kitchell 1987, Edmondson 1991), losses of CWD may affect lake ecosystems at longer time scales and in less obvious ways. Recruitment of CWD has been estimated in temperate deciduous forests at ≈ 2.52 logs \cdot ha $^{-1}\cdot$ yr $^{-1}$ (MacMillan 1981). At this replacement rate, and with conservative assumptions of no decomposition and a 10 m width of riparian forest contribution to CWD inputs (Murphy and Koski 1989), it would take ≈ 200 yr to replace the deficit in CWD density at cabin-occupied plots (≈ 500 logs/km shoreline). This estimate is comparable to the time needed for equilibrium CWD biomass to be achieved in nearby *T. canadensis* old-growth forests (300 yr, Tyrrell and Crow 1994). Aquatic CWD in nonflowing water decays more slowly than terrestrial CWD (Hodgkinson 1975),

and thus equilibrium biomass for aquatic CWD in *T. canadensis* forests would not be reached for an even longer period.

Forest managers explicitly include the maintenance of aquatic and terrestrial CWD in management plans (e.g., Franklin et al. 1981, Andrus et al. 1988). Regional land planners and lake managers should follow similar recommendations. CWD quality, which is related to the volume of water that CWD occupies, is reduced in streams by human activities (Spies et al. 1988). Although we did not attempt to assess the changes in CWD quality in this survey, human activities may similarly reduce the structural complexity (branches, twigs) of the remaining CWD in lakes, and therefore reduce the benefits as littoral habitat (Lynch and Johnson 1989, Savino and Stein 1989). We have shown, however, that CWD was significantly less abundant in developed lakes, and that impacts of increasing residential development along the shoreline on the abundance of CWD were additive. Our data suggest that management of lakeshores to retain fallen trees in lakes, maintain riparian tree density, or reduce/limit cabin density could all reduce future losses of CWD. However, lost CWD from current residential development may take centuries to be restored. The long-term impacts of such losses of this important littoral feature on lake ecosystem structure and function need to be evaluated.

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