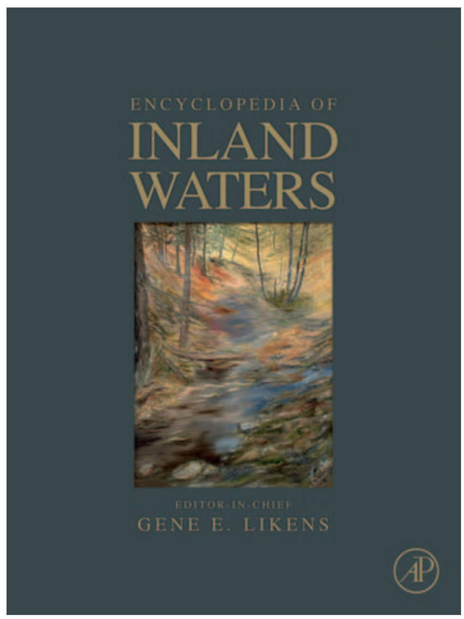

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Coarse Woody Debris in Lakes and Streams

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Introduction

Riparian forests fringe many of the world's unperturbed lentic (i.e., lakes) and lotic (i.e., rivers, streams) systems. Aquatic coarse woody debris (or coarse woody habitat (CWH), coarse woody material, coarse woody structure, large woody debris) can be defined as trees and tree fragments (both living and dead) that have fallen into lakes, streams, and rivers from the riparian zone (Figure 1). Coarse woody debris is a natural feature of many aquatic ecosystems and may play an important role in many ecosystem processes. For example, many ecosystem processes and organisms are dependent upon or evolutionarily adapted to the presence of coarse woody debris pools (i.e., collections of coarse woody debris) in lakes and streams. Anthropogenic land-use change and habitat degradation can threaten the natural balance and ecological contribution of coarse woody debris to aquatic ecosystems. This article focuses primarily on the less understood role of coarse woody debris in lentic systems, and integrates and synthesizes knowledge from studies of coarse woody debris in rivers and streams to compare and contrast ecological function among aquatic ecosystems.

Sources of Coarse Woody Debris to Aquatic Ecosystems

A fringing riparian forest is generally essential for the presence and sustainability of coarse woody debris pools in aquatic ecosystems. General exceptions may include transport of coarse woody debris from the upstream portions of the watershed in lotic systems, physical transport in lakes, and transport by humans and/or other vectors (e.g., American beaver *Castor canadensis*). Common sources of coarse woody debris include:

1. Senescence
2. Windthrow
3. Beavers
4. Logging activities
5. Habitat additions
6. Fire
7. Flooding/erosion
8. Landslides
9. Ice storms

Senescence and felling of riparian trees where tree or snag height is greater than the distance from the tree/snag to the water of lentic and lotic systems may be a large, yet temporally variable, source of coarse woody debris. Early successional tree species stands (e.g., aspen, birch) may be more frequent contributors to coarse woody debris pools compared with late successional tree species stands (e.g., oak, pine). For example, in a study on one Ontario lake, no mature Eastern white pine (*Pinus strobus*) had fallen into the lake over the last 100 years. After senescence, snags falling toward the waterbody will contribute to the coarse woody debris pool if the tree is taller than the distance to the waterbody. Riparian forests located in the compass direction of the prevailing winds may be disproportionate contributors to coarse woody debris pools. Coarse woody debris was most prevalent on moderate-to-steep slopes, on southwest shorelines, and in areas with low levels of lakeshore residential development in four northern Wisconsin lakes. Congregations of coarse woody debris in lotic systems are generally associated with the edge of the floodplain in areas such as islands, concave banks, and side channels. Windthrow, logging activities, fire, and flooding/erosion are infrequent (>100 year) events, yet may be large contributors of coarse woody debris. Variable flooding conditions on streams and rivers can rearrange or contribute new coarse woody debris on various temporal scales. Beaver are a large and frequent contributor of coarse woody debris to aquatic ecosystems (Figure 2). For example, beaver contributed up to 33% of all littoral coarse woody debris examined across 60 lakes in northern Wisconsin, not including wood associated with beaver lodges. Beaver activity was the only source of coarse woody debris input, felling three trees into Little Rock Lake, Wisconsin, from 2002 to 2006 (+0.75 trees year^{-1}), following a whole-lake removal of coarse woody debris in 2002. Net accumulation of coarse woody debris among northern Wisconsin lakes was low and variable (Table 1). Wood input rates may be much higher in rivers, yet little wood may be stored in channels. Humans also add coarse woody debris to waterways for fish habitat (e.g., fish cribs), stabilizing structures, and as docks and piers. Docks and piers may provide structure, yet may not provide the same ecological function as coarse woody debris; docks may shade aquatic vegetation, decrease small fish abundances, and decrease benthic macroinvertebrate abundances.

Encyclopedia of Inland Waters (2009), vol. 1, pp. 60-69

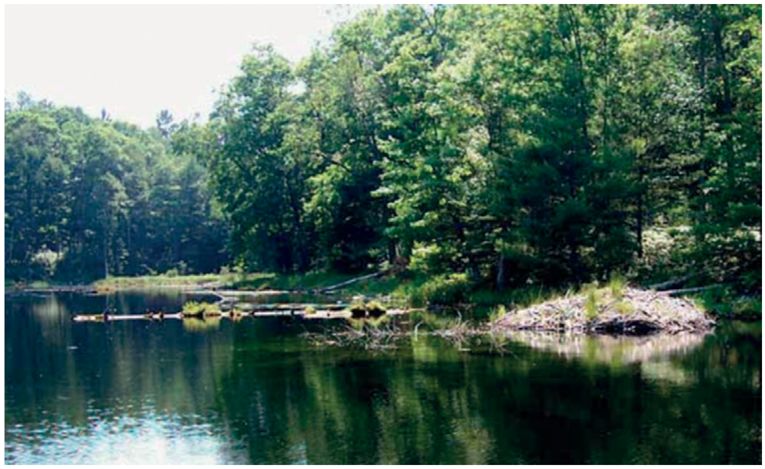

Figure 1 Littoral zone coarse woody debris from Little Rock Lake, Vilas County, Wisconsin. Photograph by Steve Carpenter.

Figure 2 American beaver (*Castor canandensis*) and associated lodges, dams, and ponds can provide major contributions of coarse woody debris to lakes, streams, and rivers. Upper photograph by Steve Carpenter. Lower photograph by the Kansas Department of Wildlife and Parks.

Table 1 Net accumulation of coarse woody debris (CWD) in four northern Wisconsin lakes from 1996 to 2003

Lake	*State*	*Net CWD accumulation (± logs km^{-1} year^{-1})*
Allequash	Wisconsin	+1.7
Big Muskellunge	Wisconsin	+1.9
Sparkling	Wisconsin	−1.1
Trout	Wisconsin	+0.5

Reproduced from Marburg AE (2006) *Spatial and Temporal Patterns of Riparian Land Cover, Forests and Littoral Coarse Wood in the Northern Highland Lakes District, Wisconsin, USA*. Ph.D. Thesis, University of Wisconsin-Madison, Madison, WI, 129 pp.

Loss of Coarse Woody Debris from Aquatic Systems

Natural decomposition of aquatic coarse woody debris is a slow process (centuries to millennia) and highly dependent on tree species. Oxygen concentrations in wet pieces of wood may be insufficient to support fungi, which are the major decomposing agent in terrestrial coarse woody debris. The major decomposing agents for coarse woody debris in lakes and streams are bacteria and actinomycetes, which are limited to the surface of the wood. The mean age of Eastern white pine coarse woody debris in an Ontario lake was 443 years. Mean calendar date of all annual rings in Ontario coarse woody debris samples was 1551 and ranged from 1893 to 1982. Although coarse woody debris more than 1000 years old has been found in rivers, most coarse woody debris in streams degrades within 100 years. Coarse woody debris from nonresin producing tree species likely decomposes at faster rates. Decay rates of different species of coarse woody debris in northern Wisconsin and Canadian lakes and streams were variable, ranging from −0.2 to −3.25 g year^{-1} (Table 2). Decay rates of coarse woody debris species in northern Wisconsin lakes did not differ among lakes or by sand or muck substrate. The functionality of coarse woody debris can be lost from aquatic ecosystems through decomposition, transport, burial, and physical removal. In lakes, ice and wave action can

Table 2 Half-life and decay rate of 12 coarse woody debris tree species in Wisconsin, Ontario, and Alberta lakes and streams

Common name	*Species*	*Location*	*Half life (years)*	*Decay rate (± g year^{-1})*
Eastern hemlock	*Tsuga canadensis*	N. Wisconsin	30.4	−0.75
Red pine	*Pinus resinosa*	N. Wisconsin	29.4	−0.6
Aspen	*Populus* spp.	N. Wisconsin	23.1	−1.2
Sugar maple	*Acer saccharum*	N. Wisconsin	20.9	−1.9
Paper birch	*Betula papyrifera*	N. Wisconsin	17	−2
Eastern white pine	*Pinus strobus*	N. Wisconsin	16.6	−1.25
Tamarack	*Larix laricina*	N. Wisconsin	7.9	−3.25
Eastern white pine	*Pinus strobus*	S. Ontario	106.6	–
Balsam poplar	*Populus balsamea*	Alberta	57.8	–
Northern white cedar	*Thuja occidentalis*	N. Wisconsin	–	−0.25
Spruce	*Picea* spp.	N. Wisconsin	–	−0.2
Red oak	*Quercus rubra*	N. Wisconsin	–	+0.25
Balsam fir	*Abies balsamea*	N. Wisconsin	–	+0.75

Sources

1. Hodkinson ID (1975) Dry weight loss and chemical changes in vascular plant litter of terrestrial origin, occurring in a beaver pond ecosystem. *Journal of Ecology* 63: 131–142.
2. Guyette RP Cole WG Dey, DC, and Muzika R-M (2002) Perspectives on the age and distribution of large wood in riparian carbon pools. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 578–585.
3. Marburg AE (2006) *Spatial and Temporal Patterns of Riparian Land Cover, Forests and Littoral Coarse Wood in the Northern Highland Lakes District, Wisconsin, USA*. Ph.D. Thesis, University of Wisconsin-Madison, Madison, WI, 129 pp.

transport coarse woody debris to the deepest portions of lakes, to the riparian zone, into sediment (burial), and may also congregate coarse woody debris rafts that accumulate along shorelines. Median distances of in-lake transport of tagged and recaptured coarse woody debris in northern Wisconsin lakes was 24 m from 1996 to 2003 (~3 m year^{-1}). Flooding and water-level fluctuations in lotic systems can redistribute coarse woody debris, permanently or temporarily, into riparian zones with periodic water access. Humans may be the largest, and fastest, physical removers of coarse woody debris from aquatic ecosystems (Figure 3). For example, a strong negative relationship exists between coarse woody debris abundances and lakeshore residential development in Wisconsin, Upper Michigan, Washington State, and British Columbia lakes (Figure 4). Coarse woody debris is also less prevalent in agricultural and urban rivers and streams. Riparian forests and coarse woody debris pools may be decoupled in lakes that are developed. Coarse woody debris density and riparian forest tree density exhibit a positive relationship in undeveloped lakes and no relationship in developed lakes. Surveys of northern Wisconsin lakeshore homeowners in 1998 found that 55% of those polled either rarely thought about logs in their lakes or did not think about coarse woody debris at all, prior to confronting the issue in the questionnaire. Approximately 25% of respondents had removed at least one log from the water, with 64% of those who had removed wood doing so within one year of the survey. Wood that was a boating or swimming hazard was more likely to be removed. The lakeshore residential development process (including road building) also acts to thin the riparian forest, thus decreasing the source pool of coarse woody debris to lakes and streams. In the past, coarse woody debris was actively removed from Pacific Northwest streams to improve salmonid habitats; that practice has been abolished as recent knowledge suggests that coarse woody debris creates pools in streams that provide critical juvenile salmonid nursery habitats.

Physical and Hydraulic Role of Coarse Woody Debris

Coarse woody debris stabilizes shorelines and riparian zones from erosion, promotes sediment retention and burial, and alters flows of lotic systems. Loss of coarse woody debris from littoral zones of lakes promotes sediment resuspension, increases in turbidity, and loss of sediments to the deepest portions of the lake. Sediment disturbance can resuspend buried contaminants, promote microbial activity, and increase mercury methylation rates, similar to dredging activities. For example, a whole-lake removal of coarse woody debris resulted in a threefold increase in waterborne methyl mercury concentrations in a northern Wisconsin lake. Anthropogenic disturbances to littoral zone coarse woody debris can, therefore, potentially lead to elevated methyl mercury concentrations in fishes. Much the same set of

Figure 3 Lakeshore residential development can thin riparian forests and reduce coarse woody debris abundances in lakes, streams, and rivers. Photograph by Michael Meyer.

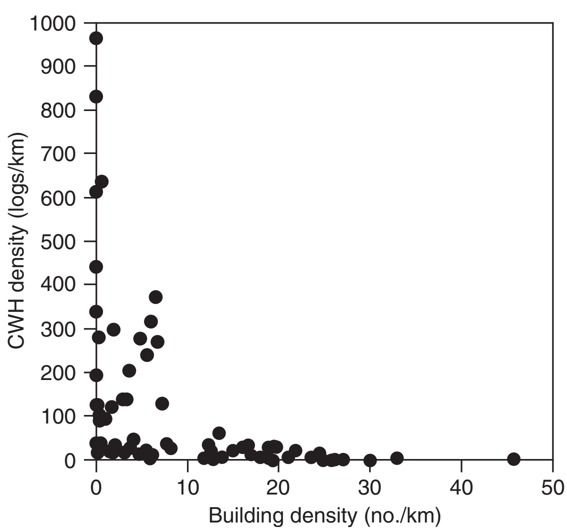

Figure 4 Relationship between CWH abundance and the number of buildings per km of shoreline for several Northern Wisconsin and Upper Michigan lakes. Reproduced from Sass GG, Kitchell JF, Carpenter SR, *et al*. (2006) Fish community and food web responses to a whole-lake removal of coarse woody habitat. *Fisheries* 31: 321–330.

consequences can be expected with coarse woody debris loss and other contaminants that occur in sediments.

Coarse woody debris and congregations of coarse woody debris forming snags in lotic systems alter flow regimes, stabilize banks, and promote undercut and pool formation. The cross-flow field (i.e., a cross-section of water currents around a log) for a single cylindrical log perpendicular to the flow of water is related to the Reynold's number and log diameter. Reynold's numbers for logs in lotic systems range from 100 to 1 million with symmetrical cross-flow patterns resulting in reduced velocities behind the log. Recirculating vortices develop in front and behind logs buried or partially-buried into streambeds. Large coarse woody debris aggregations can be considered solid structures where flow field is determined by bluff surface size and shedding from edges obtuse to the flow direction. Coarse woody debris and associated root wads naturally buffer lakes and streams, thus dampening wave action and preventing erosion and sluffing of shoreline sediment. Stable pieces of coarse woody debris in lotic systems can

1. influence rates of bank erosion;
2. create pools;
3. initiate sediment deposition and bar formation.

Lotic systems with abundant coarse woody debris may retain more sediment, have steeper slopes, and have lower sediment transport rates than coarse woody debris depauperate rivers and streams. Removal of coarse woody debris from a 200 m stretch of a New Hampshire stream resulted in a sevenfold increase in sediment transport and particulate organic matter. Undercuts, pools, and slack water conditions are energetically favorable for salmonids as refuge, feeding, and juvenile nursery and rearing habitats. Coarse woody debris creates fish habitat by increasing the size and depth of stream pools and by providing refuge from predators. Retention of coarse woody debris has been critical in stream salmonid habitat restoration efforts.

Nutrient Properties and Primary Production Associated with Coarse Woody Debris

Coarse woody debris is generally considered to be chemically inert in nitrogen and phosphorus; however, this may be highly dependent and positively related to coarse woody debris age. For example, decayed coarse woody debris may act as a substrate, and likely provides nutrients, to promote algal growth. Periphyton growth is limited by light, but may also be limited by phosphorus when it grows on nonnutrient diffusing substrates such as most coarse woody debris. Epixylic production (i.e., algal growth on wood) (4%) is generally lower than epipelic (i.e., algal growth on sediment) benthic production (50–80%) in lakes. Although the direct contribution of epixylic algae to whole-lake primary productivity is relatively minor, the indirect influences of coarse woody debris, such as increased organic sediment retention, may be important for primary productivity derived from epipelic algae. Removal of coarse woody debris may lead to decreases in lake productivity through loss of organic sediments from the littoral zones of lakes. Organic content of littoral zone sediment and the density of coarse woody debris were negatively related across a lakeshore residential development gradient of Washington State and British Columbia lakes. Littoral sediments of undeveloped lakes ranged from 34 to 77% organic by mass, while developed lakes sediment was 1–3% organic. Accumulations of sedimentary organic matter were highest in littoral zones of lakes with coarse woody debris, and decreased with distance from the shore; the opposite relationship was noted for lakes without coarse woody debris. Organic sediments sequester nutrients. Epixylic algal growth was higher at the sediment–water interface where algae could tap the sediment for nutrients. Epixylic production is likely dependent on nutrient concentrations in surrounding waters, water clarity, proximity to organic sediment, and may be coarse woody debris species-specific. Little information exists on the nutrient leaching properties of certain coarse woody debris species and over time. Loss of coarse woody debris may decouple benthic–pelagic energy and nutrient linkages in lake ecosystems.

Coarse Woody Debris and Secondary Production

Many invertebrates require coarse woody debris for food and habitat. In many streams, the highest values of invertebrate diversity are in areas with accumulations of wood. Zoobenthos secondary production is higher on coarse woody debris than on adjacent habitats, such as sand and muck. Geomorphic properties provided by coarse woody debris serve as rearing sites and habitat for macroinvertebrates. In rivers, 60% of total invertebrate biomass was found on coarse woody debris (4% of habitat availability) compared to sand (80% habitat availability). In Southeastern United States rivers, snags support invertebrate production that is among the highest found in lotic systems. Epixylic algae may attract grazers, thus attracting invertebrate predators (e.g., odonates, crayfish). In streams and rivers, loose streambed wood is generally colonized by shredders (gougers) and stable coarse woody debris is dominated by filterers and gatherers. Zoobenthos secondary production is an important energetic pathway to upper trophic levels in lentic systems and may be underestimated in a continuum of benthic–pelagic coupling in aquatic ecosystems. Production in lentic systems may be dominated by terrestrial and allocthonous sources of carbon, mediated through microbial processes, and enhanced by coarse woody debris presence.

Coarse Woody Debris and Fishes

Coarse woody debris is an essential physical, biological, and chemical attribute of lakes and streams for many fish species. Over 85 species of fish are recognized to rely on coarse woody debris during all or part of their life histories. For fishes, coarse woody debris provides:

1. food
2. refuge
3. spawning substrate
4. nursery and rearing habitat

Coarse woody debris is a direct and indirect source of food to fishes. Directly, several fishes consume decomposing wood and bark, while many fish species are dependent on fruits and seeds provided by felled or flooded coarse woody debris. Indirectly, coarse woody debris forms the base of the food web in many aquatic ecosystems by providing a substrate and nutrients for epixylic algal production to herbivorous fishes and benthic macroinvertebrate grazers. Zoobenthos secondary production is the dominant energetic pathway to upper trophic levels in many aquatic ecosystems, comprising 65% of the total prey consumed by fishes. Coarse woody debris attracts small fishes, and thus serves as a focal point for predator–prey interactions. Coarse woody debris, particularly complex and branchy coarse woody debris,

Figure 5 Bluegill (*Lepomis macrochirus*) associated with coarse woody debris refuge in Anderson Lake, Vilas County, Wisconsin. Photograph by Greg Sass.

Figure 6 Largemouth bass (*Micropterus salmoides*) cruising the edge of coarse woody debris refuge in Anderson Lake, Vilas County, Wisconsin. Photograph by Greg Sass.

decreases predator foraging success, thus creating refuge habitat for small fishes (Figure 5). Complex coarse woody debris causes visual interference for predators and interstices prevent predators from entering complex coarse woody debris arrangements. The presence of coarse woody debris may act to create heterogenous fish distributions with prey and small fishes located in the coarse woody debris refuge and large predatory fishes located on or near the coarse woody debris refuge edge (Figure 6). For example, largemouth bass (*Micropterus salmoides*) home range size is negatively correlated with coarse woody debris abundance in northern Wisconsin lakes. Loss of coarse woody debris may result in homogenous predator–prey distributions and greater largemouth bass home ranges. Experimental relocation of coarse woody debris in lakes altered largemouth bass movement patterns to focus on redistributed coarse woody debris. Loss of coarse woody debris refuge can cause extirpations of prey species (e.g., yellow perch *Perca flavescens*, cyprinids) and ultimately determine species assemblages in lakes. Persistence of predator and prey populations is enhanced when intense interspecific competition and predation occur between juvenile predators and adult prey fishes located in refuge areas; this is often called a trophic triangle and an example can be found with juvenile largemouth bass and adult yellow perch. Many fish species are dependent upon coarse woody debris for spawning. As one example, yellow perch may use coarse woody debris as a spawning substrate. Experimental removal of coarse woody debris in a northern Wisconsin lake resulted in no perch reproduction in subsequent years. Large- and smallmouth bass (*Micropterus dolomieu*) tend to build nests in association with littoral coarse woody debris. Black basses (*Micropterus* spp.) prefer nesting near physical structure because it increases mating, hatching, and nesting success. A positive, saturating relationship exists between the number of largemouth bass nests $100\,m^{-1}$ of shoreline and coarse woody debris abundance in northern Wisconsin lakes. Coarse woody debris is indirectly associated with juvenile nursery habitats in streams and rivers. Juvenile survivorship of salmonid smolts is considerably higher in streams with coarse woody debris than those without. Coarse woody debris in streams was associated with increased densities of salmonids such as coho salmon (*Oncorhynchus kisutch*), cutthroat trout (*O. clarkii*), rainbow trout (*O. mykiss*), brook trout (*Salvelinus fontinalis*), and brown trout (*Salmo trutta*) by increasing suitable habitat for both adults and juveniles and by providing ample prey resources. Coarse woody debris-rich sites in lotic systems worldwide exhibit more fish species diversity and numbers of fish compared to sites without wood. Fish species diversity and numbers of fish in rivers ranged from 1.3 to 2 and 1.6 to 50 times higher in sites with and without coarse woody debris, respectively. Loss of coarse woody debris from streams generally results in loss of pool habitat, complexity, and smaller individuals of coldwater and warmwater fish species.

Coarse Woody Debris and Other Organisms

Specific plant assemblages (e.g., leatherleaf *Chamaedaphne calyculata*, *Sphagnum* spp., sundew *Drosera* spp.) are associated with emergent and floating coarse woody debris and rafts in north-temperate lakes. Invertebrates, such as crayfish and some freshwater mussels, are dependent upon coarse woody debris during their life histories. Amphibians, such as frogs and toads, use coarse woody debris as a spawning substrate and for refuge during breeding. A negative relationship exists between turtle abundances and coarse woody debris abundances in lentic and lotic systems. Aquatic and shore birds use coarse woody debris for nesting habitat (e.g., common loon *Gavia immer*) and perching areas (e.g., herons *Ardea* spp., cormorants *Phalacrocorax* spp., kingfishers *Megaceryle* spp., wood ducks *Aix sponsa*). Mammals use coarse woody debris for shelter (beaver) and for ambush points (e.g., raccoon *Procyon lotor*, river otter *Lutra canadensis*, mink *Mustela vison*). Dams built by beavers can affect groundwater recharge rates and stream discharge, may influence valley floor morphology through sediment retention, and enhance stream habitat quality for fishes. Over 82 species of fish have been known to use beaver ponds. Loss of beavers and removal of dams may accelerate stream incision and promote lowering of groundwater levels and stream drying. Coarse woody debris associated with riparian and littoral areas of lentic and lotic systems provides organisms with proximity to water, unique plant assemblages, and diverse microhabitats that provide habitat structure, shelter, patchiness of habitat, and increased food resources (Figure 7).

Riparian Forest/Coarse Woody Debris/ Aquatic Food Web Models

Most models of lotic systems have focused on the amounts and distributions of coarse woody debris in streams and rivers. Fewer models have addressed processes determining patterns such as riparian tree mortality, input, breakage, decomposition, mechanical breakdown, and transport. In most models, forest stand age directly influences the abundance of coarse woody debris in lotic systems and wood dynamics are most sensitive to rates of input and decomposition.

Simulation models that incorporate the riparian forest, coarse woody debris pools, and aquatic food webs show variable effects on fish populations dependent upon lakeshore residential development and harvest rates of the top predator. Prior to development, late successional tree species dominate the riparian forest. During development, both late and early successional tree species decline to low levels and are maintained over time. As a consequence of development, coarse woody debris pools decline and are not replenished over time due to loss of the source pool and active physical removal. Declines in coarse woody debris result in two outcomes in the fish population that are dependent on the harvest rate of the top predator:

1. Without fishing, adult and juvenile top predator biomass increases and dominates and prey fish are extirpated.
2. With high top predator harvest rates, adult and juvenile top predator biomass is suppressed and prey fish biomass dominates.

Figure 7 Organisms associated with floating coarse woody debris in Little Rock Lake, Vilas County, Wisconsin. Organisms include sundew (*Drosera* spp.), leatherleaf (*Chamaedaphne calyculata*), *Sphagnum* spp., and Eastern painted turtle (*Chrysemys picta picta*). Photograph by Matt Helmus.

Ecosystem-Scale Coarse Woody Debris Experiments

Largemouth bass and bluegill (*Lepomis macrochirus*) growth rates are positively correlated with coarse woody debris abundances and negatively correlated with lakeshore housing density in northern Wisconsin and Upper Michigan lakes. Decreases in coarse woody debris alter spatial distribution patterns of fishes in Washington state lakes. Mechanisms for the observed patterns in fish growth and distribution with coarse woody debris are unknown. A whole-lake removal of coarse woody debris was conducted on the treatment (north) basin of Little Rock Lake, Vilas County, Wisconsin, in 2002 (Figure 8). The reference (south) basin was left unaltered. Coarse woody debris removal in Little Rock Lake resulted in:

1. a decrease in largemouth bass growth rates;
2. increased reliance by largemouth bass on terrestrial sources of prey, such as insects, reptiles, birds, and mammals;
3. the extirpation of the yellow perch population from the treatment basin;
4. a threefold increase in waterborne methyl mercury concentrations;

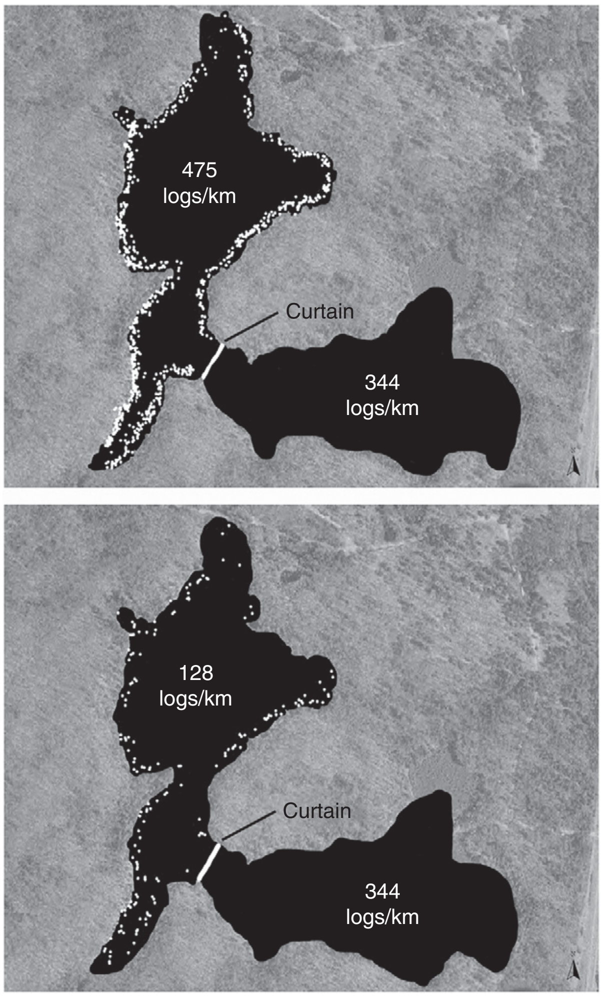

Figure 8 Aerial photographs of Little Rock Lake, Vilas County, Wisconsin with abundances of large (>10 cm diameter) CWH labeled and represented by white dots before and after the CWH removal in the treatment basin (north) in 2002. Reproduced from Sass GG, Kitchell JF, Carpenter SR, *et al*. (2006) Fish community and food web responses to a whole-lake removal of coarse woody habitat. *Fisheries* 31: 321–330.

5. a decrease in largemouth bass nest density and spawning success;
6. an increase in largemouth bass home range size.

A reciprocal whole-lake coarse woody debris addition was completed on Camp Lake, Vilas County, Wisconsin, in 2004. Over 300 trees (one tree 10 m^{-1} of shoreline) of various species and complexities were added (Figure 9). Coarse woody debris addition to Camp Lake resulted in:

1. increased reliance by largemouth bass on fish prey;
2. an increase in proportions of trophy size (>457 mm) largemouth bass;
3. an increase in largemouth bass nest density and nest success;
4. a decrease in largemouth bass home range size;
5. a fourfold increase in usage of complex coarse woody debris by largemouth bass and bluegill;
6. no change in bluegill population dynamics;
7. an increase in yellow perch abundances.

Forty to 70% of the coarse woody debris was removed from three Ontario lakes to determine the link between submerged wood and production of periphyton and invertebrates. Removal of coarse woody debris resulted in:

1. little loss of whole-lake invertebrate productivity, despite greater biomass of invertebrates on wood than in adjacent sediments;
2. highly decayed wood showing higher chlorophyll concentrations and invertebrate biomass and diversity than fresh wood;
3. no measurable effect on whole-lake water chemistry or on residual epixylic periphyton and invertebrate biomass.

Large wood was added to three headwater tributaries of the Jumbo River in the Upper Peninsula of Michigan. Organic matter retention is typically low in these sandy-bottomed, low-gradient systems. Two years after wood addition, there were no significant differences in density or biomass of stream fishes, but selected ecosystem metrics, such as nutrient spiraling and ecosystem metabolism, were higher in treatment reaches. Changes in geomorphology and microbial biofilm dynamics associated with wood addition occurred quickly, but responses by higher trophic levels (e.g., macroinvertebrates and fishes) may lag behind.

Habitat enhancement projects that have added coarse woody debris to streams generally create new habitat and rapidly increase the density of salmonids associated with the habitat. Similarly, coarse woody debris additions to lakes and reservoirs increase the abundance of fishes associated with the structures and subsequently increase angler catch rates.

Temporal Dynamics and Coarse Woody Debris Restoration

Coarse woody debris is a natural attribute to many lakes, rivers, and streams. The fast dynamics of removal rates (days to years; logging, development) and slow rates of natural replacement and decomposition (centuries to millennia) suggest that coarse woody debris removal can have long-lasting or permanent consequences on aquatic ecosystems. The use of the

Figure 9 Littoral zone CWH addition to Camp Lake, Vilas County, Wisconsin in the spring of 2004. CWH was distributed as one piece 10 m^{-1} of shoreline lake wide. Photograph by Michele Woodford.

terms CWH or coarse woody structure may be more appropriate than coarse woody debris and may give a positive connotation to wood presence, conservation, and restoration in aquatic ecosystems. Discontinuation of physical removal, logging practices that maintain riparian buffers, and active additions can ameliorate the effects of coarse woody debris loss on aquatic ecosystems. Tree drops (active felling of riparian trees), preservation of intact riparian forests, preservation of pristine systems, and management of riparian forests specifically to accelerate recruitment of coarse woody debris may be effective mitigation tools for restoration efforts. For lotic systems, soft placement of wood to allow movement and transport may be preferable to hard engineering approaches that anchor wood permanently. In addition to reintroduction of coarse woody debris, restoration of natural hydrologic cycles, riparian vegetation, selected floodplains, and an associated natural disturbance regime should be considered in rehabilitation efforts.

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Relevant Websites

http://limnology.wisc.edu – University of Wisconsin-Madison, Center for Limnology, Arthur D. Hasler Laboratory of Limnology.
http://limnosun.limnology.wisc.edu – University of Wisconsin-Madison, Center for Limnology, Trout Lake Station, North Temperate Lakes Long Term Ecological Research.
http://biocomplexity.limnology.wisc.edu – University of Wisconsin-Madison, Center for Limnology, Arthur D. Hasler Laboratory of Limnology, National Science Foundation Biocomplexity Project.
http://www.tlws.ca – Turkey Lakes Watershed (TLW) Study.
http://www.fsl.orst.edu/lter/ – HJ Andrews Experimental Forest and Andrews Long Term Ecological Research.