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## ESEX Commentary

# Large in-stream wood studies: a call for common metrics

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ABSTRACT: During the past decade, research on large in-stream wood has expanded beyond North America's Pacific Northwest to diverse environments and has shifted toward increasingly holistic perspectives that incorporate processes of wood recruitment, retention, and loss at scales from channel segments to entire watersheds. Syntheses of this rapidly expanding literature can be facilitated by agreement on primary variables and methods of measurement. In this paper we address these issues by listing the variables that we consider fundamental to studies of in-stream wood, discussing the sources of variability in their measurement, and suggesting more consistency in future studies. We recommend 23 variables for all studies of in-stream wood, as well as another 12 variables that we suggest for studies with more specific objectives. Each of these variables relates either to the size and characteristics of in-stream wood, to the geomorphic features of the channel and valley, or to the ecological characteristics of the riparian zone adjacent to the study reach. The variables were derived from an overview of those cited in the literature and from our collective field experiences. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: in-stream wood; field measurements; common metrics

## Introduction

The role of downed wood in terrestrial and aquatic ecosystems has been investigated for decades (Swanson and Lienkaemper, 1978; Brown and See, 1981), and research on the physical and ecological effects of in-stream wood has increased substantially during the past decade (e.g. Gregory *et al.*, 2003a; Montgomery and Piégay, 2003). This research has led to syntheses of in-stream wood characteristics and dynamics (Harmon *et al.*, 1986; Maser *et al.*, 1988; Wohl and Goode, 2008). These syntheses have been useful in identifying regional patterns and gaps in knowledge (Hassan *et al.*, 2005), but stronger inferences have been hampered by the inherently high spatial and temporal variation in in-stream wood and by measurement error (Roper and Scarnecchia, 1995; Roper *et al.*, 2002; Archer *et al.*, 2004; Whitacre *et al.*, 2007). Our review of many studies of in-stream wood also revealed inconsistencies in the type of variables measured and methods of measurement. Agreement on the measurement and reporting of variables could resolve some of the uncertainties associated with understanding in-stream wood patterns (Barker *et al.*, 2002). Thus, our objectives in this commentary are to list the variables that we consider fundamental to studies of in-stream wood and to suggest additions to study design and reporting that would enhance the value of individual studies.

## What is In-stream Large Wood?

The most fundamental questions involving large wood are (1) what are the minimum dimensions of a piece and (2) what portion of a piece should be measured. The decision about piece inclusion can be scaled to the stream dimensions, such as channel width, which govern storage and transport (Gurnell, 2003). In many studies, however, selection of the minimum dimensions of pieces that constitute large wood – minimum diameters of 5 to 20 cm and minimum lengths of 1 to 3 m – is somewhat arbitrary (Ralph *et al.*, 1994). Although some have argued that retaining these dimensions facilitates comparisons with studies of terrestrial large-diameter fuels or large wood in other aquatic systems (Harmon and Sexton, 1996; Gregory *et al.*, 2003a), a more fluvially relevant standard may be to derive the minimum dimensions from the prevalence of piece sizes in channels and riparian zones (Young *et al.*, 2006).

Other sources of variation between studies involve piece measurements *vis-à-vis* the bankfull channel and treatment of that portion of a piece below the minimum diameter. Pieces of wood that lean over or bridge a channel are variously included or excluded. It seems reasonable to measure the portion of wood that falls within the bankfull channel dimensions, but characterize the remainder of the piece as being

within the riparian zone. This is especially relevant if the in-stream wood piece is part of a living tree (Opperman and Merenlender, 2007; Opperman *et al.*, 2008). Similarly, sometimes only the part of a piece above a minimum diameter is measured. This has minimal influence on volume estimates, but can positively bias the mean diameter, negatively bias the mean length, and obscure relations with riparian large wood.

The important point is to clearly state the minimum size criteria and inclusion rules and, ideally, to provide data of wood measurements in an appendix or electronic data repository so that other investigators can sort the data to meet different criteria (e.g., remove all wood pieces with diameters <10 cm where 5 cm was the minimum diameter used).

## Suggested Metrics for In-stream Wood Studies

We identified core variables based on their importance in previous studies and based on our collective experience, and subdivided them into three categories: wood, geomorphic, and riparian (Table I). Variables listed in parentheses are those we describe as Level II, or suggested for studies with more specific objectives. Wood variables include the size, orientation, and characteristics of wood in the bankfull channel, as well as functional parameters directly associated with wood. Geomorphic variables include the physical characteristics of the stream channel, valley, and drainage basin for a reach, defined as the length of channel within which wood is measured. If channel morphology varies substantially within a reach, then the reach should be subdivided into geomorphic channel units and geomorphic variables measured for each unit. Riparian variables include the ecological characteristics of the valley reach beyond the channel; i.e., on the floodplain or in the riparian zone. In the discussion that follows, the potential delivery distance of wood falling directly into the channel defines the riparian zone.

### Wood variables

#### Length

The entire length of a piece of wood that is contained within the bankfull channel can be measured. Alternatively, the length measurement may only include the portion within the bankfull channel or along the portion of the piece that meets the minimum diameter criterion. We suggest measuring both the entire length and the length within the bankfull channel, and clearly distinguishing these when reporting data. The former is likely to prove useful in studies of relative mobility, and the latter is necessary to calculate volume of wood per unit length or area of channel. We also recommend using the vertical and lateral zones described by Robison and Beschta (1990) because wood in these zones functions differently with regard to fluvial processes and aquatic habitat.

#### Diameter

As noted earlier, at a minimum we suggest measurements of diameter at both ends of each piece. We prefer this standard, in part, because estimating piece volume is one of the primary variables of interest in studies of large wood in streams. Nonetheless, we believe that estimates of volume should be regarded with some caution. Young *et al.* (2006) found that estimates of piece volume and reach-based volume were imprecise, which they attributed in part to differences in taper characteristics between species (Husch *et al.*, 2002) and between intact and broken pieces (Williams and Gove, 2003). Piece volume is typically calculated using the equation for the volume of a cylinder, but addressing the effects of piece shape on volume would require a third measurement near the midpoint of each piece, which is rarely done.

#### Orientation

Measuring the angle of the wood with respect to the overall flow direction at bankfull (Cherry and Beschta, 1989; Robison and Beschta, 1990; Braudrick and Grant, 2000; Magilligan *et al.*, 2008) provides a readily obtained, quantitative, highly comparable metric for assessing stability and transport processes between pieces at a site and between sites. Alternative measures proposed in the literature include orientation with respect to the local flow vector (Buffington *et al.*, 2002), fall direction or where the piece originated (Sobota *et al.*, 2006) and zones of orientation within a 360° range (Magilligan *et al.*, 2008). Azimuth and plunge of the wood can also be measured to facilitate three-dimensional statistical analyses (e.g., eigenvalue method) and to include the vertical orientation, which is relevant to channel hydraulics and pool scour (Beschta, 1983; Cherry and Beschta, 1989; Buffington *et al.*, 2002).

#### Rootwad

The presence or absence of a rootwad can provide important information on relative stability and function of the piece (Abbe *et al.*, 1997; Braudrick and Grant, 2000). The measurement of a rootwad, however, is rarely addressed. Investigators measuring piece diameters typically ignore the rootwad and the buttswell immediately preceding it, although these portions of the wood piece can influence wood volume and piece mobility. In some instances a piece of wood is composed solely of the rootwad. We suggest measuring the rootwad length from the base of the root ball to the furthest extent of the bole, and measuring the diameter at the base of the bole where it meets the roots.

#### Jams

Previous studies range from those that simply mention the presence of jams to those that inventory jam size and spacing (Gregory *et al.*, 1985; Gurnell and Sweet, 1998; Kaczka, 2003; Comiti *et al.*, 2008) or characterize the effect of jams on hydraulics (Linstead, 2001; Manners *et al.*, 2007) or sediment storage (Jeffries *et al.*, 2003; Douglas and Guyot, 2005). Jams can exert more substantial geomorphic and ecological influences than individual pieces of wood (Bilby and Likens, 1980; Montgomery *et al.*, 1995; Montgomery *et al.*, 2003a; Montgomery *et al.*, 2003b; Abbe and Montgomery, 2003; O'Connor *et al.*, 2003), and can have different spatial distributions (Richmond and Fausch, 1995; Kraft and Warren, 2003; Warren *et al.*, 2007; Wohl and Jaeger, 2009) and greater stability (Wohl and Goode, 2008) than individual pieces of wood. For these reasons, it is important to at least note the spatial distribution and size (either number of pieces of wood or total dimensions) of jams and the criteria for designating a jam. Abbe and Montgomery (2003) proposed three categories for jams (transport, in situ, or combination).

#### Accumulation

More than one of the 11 categories suggested here can be chosen to characterize the mechanism that retains wood within the stream. This is useful for interpreting geomorphic function and relative stability of wood. One of the categories is debris dams, also known as logjams or jams. This is sufficiently important that we suggest that the presence and characteristics of jams deserve separate entries.

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**Table I.** Suggested metrics for research-oriented in-stream wood studies

| Levels | Notes |
|---|---|
| *Wood – measured for each piece* | |
| *Level I* | *Notes* |
| 1. Length | Whole piece and length in bankfull channel |
| 2. Diameter | ≥1 measurement |
| 3. Orientation | Angle with respect to downstream bank |
| 4. Root wad | Note if present, including orientation with respect to flow |
| 5. Jams | Spatial distribution and size (no. pieces per jam, or total dimensions of jam) |
| 6. Accumulation[a] | 11 categories |
| 7. Status[b,c] | Decay class (six categories), burn status (three categories) |
| 8. Stability[d] | Six categories |
| *Level II* | |
| 9. Species | Note species or general category (e.g., deciduous/coniferous) |
| 10. Submergence | Measure in relation to stage |
| 11. Age | Tree-ring counting or radiocarbon dates |
| 12. Biomass/density | Based on volume and wood density |
| 13. Function | Characteristics of wood function include sediment storage (note if present; ideally, measure dimensions and grain size), pool scour (note if present; ideally, measure dimensions), backwater pools (note if present; ideally, measure dimensions), flow deflection, energy dissipation, and bank stabilization |
| *Geomorphic (channel and valley) – measured for each reach* | |
| *Level I* | |
| 1. Channel gradient | Average streambed or water-surface gradient at study reach |
| 2. Channel width | Average bankfull channel width at study reach |
| 3. Flow depth | Either bankfull or at time of measurement |
| 4. Grain size | Bed-material size distribution; $D_{50}$ and sorting at minimum |
| 5. Discharge | Bankfull, mean annual, peak annual, or at time of measurement |
| 6. Reach length | Length of channel along which wood is measured |
| 7. Channel morphology | Cascade, step-pool, plane-bed, pool-riffle, dune-ripple, braided |
| 8. Drainage area | Area drained by study reach |
| 9. Elevation | At study reach, and range for catchment |
| 10. Valley side slope | Average or maximum side slope values |
| 11. Confinement | Ratio of channel width/valley-bottom width |
| 12. Connectedness | Ratio of channel width/distance to valley wall |
| 13. Disturbance history | Wildfire, blowdown, insect infestation, hillslope mass movements, avalanches |
| 14. Management history | Timber harvest, percent roaded, tie-driven, dams, diversions, etc. |
| *Level II* | |
| 15. Bank scour | Visual estimate of percentage of total stream bank length |
| *Riparian – measured for each reach* | |
| *Level I* | |
| 1. Forested | Yes/no, deciduous/conifer, note cover type if not forested (e.g., willow or herbaceous dominated meadow, bedrock) |
| *Level II* | |
| 2. Dominant species | Where forested, note forest type(s)/species of trees |
| 3. Source[e] | Six categories |
| 4. Seral stage | Young, mid-successional, or mature |
| 5. Floodplain survey | Dimensions and spatial density of wood on forest floor |
| 6. Basal area | Measure of the cross-sectional area of standing trees at breast height (may be measured by species) |
| 7. Site potential | Rate of tree growth, time to reach maturity, longevity of trees |

Note: Level I lists metrics that we propose should be included in all studies; Level II lists those metrics that are more study-specific.
[a] Accumulation classes: debris jam (part of a jam of three or more pieces), tree/rootwad (associated with a living tree or rootwad), boulder (associated with a boulder in the stream), meander (caught on the outside of a bend), bar (sitting on a point, alternate, or mid-stream bar), bedrock (caught on bedrock), beaver dam (incorporated in a beaver dam), bank (embedded in the bank, buried by soil or other bank materials), log step (forms a step in the stream, can be partially buried in streambed or not buried), buried in bed (portion of log buried in streambed, but not functioning as a step), none/other (specify if something else). A piece can have more than one class.
[b] Decay classes: rotten (very soft wood that can be pulled apart easily by hand), decayed (moderately soft wood that cannot be pulled apart easily), bare (no bark or most bark is gone), limbs (limbs still attached, may have most or all bark intact), bark (all bark intact, a relatively new piece of wood), needles/leaves (green or brown needles/leaves still attached, very fresh piece of wood, tree may appear to be living).
[c] Burn classes: unburned, partially burned, completely burned.
[d] Stability classes: unattached/drift (entire piece is contained within bankfull channel and no portion is buried or pinned), bridge (both ends above bankfull channel, center suspended above channel), collapsed bridge (two ends above bankfull channel, broken in middle), ramp (one end in channel, the other end above bankfull channel), pinned (all or a portion is lodged beneath other pieces of wood in the stream), buried (all or a portion is buried in the streambed).
[e] Source classes: unknown (source of wood cannot be determined), riparian (sources of wood appears to be valley bottom adjacent to the channel), hillslope (wood originates from a steeper landform adjacent to the valley bottom; either a depositional feature such as a moraine, or the valley wall), floated (fluvial transport from upstream), hillslope mass movement/debris flow, avalanche (recruitment via moving snow), bank undercutting, other (other clearly defined source such as debris flow; explained in comments section).

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Status
Decay and burn categories are visual assessments of each piece that provide information on relative age and stability. Burn categories are specific to instances where wood input is associated with a wildfire. Robison and Beschta (1990) and Schuett-Hames *et al.* (1999) proposed decay categories based on bark conditions, surface texture, presence of branches, wood shape and wood color.

Stability
This category helps to characterize the relative stability/mobility of the wood based on its position within and above the channel, degree of burial, and association with other wood. This category may also imply something about the geomorphic function of the wood, such as the promotion of scour or retention of sediment, as well as the method of recruitment (Richmond and Fausch, 1995).

Species
Where it is possible to identify the species of wood, this information is useful in studying recruitment, decay rates, and retention of wood. In the Colorado Front Range, for example, wood from deciduous trees has a much shorter residence time in streams than coniferous wood (Wohl and Goode, 2008). This contrasts with patterns observed in the southern Appalachians, where American chestnut (*Castanea dentata*) constituted a large proportion of the wood in streams flowing through mid- and late-successional forests despite its absence from the canopy for decades (Hedman *et al.*, 1996).

Submergence
Noting the dimensions of the wood submerged in relation to stage is needed to calculate the drag coefficient and hydraulic resistance associated with individual pieces (Manga and Kirchner, 2000; Curran and Wohl, 2003; Daniels and Rhoads, 2004), thus improving our understanding of the physical influences of wood on hydraulics, stream morphology, and habitat.

Age
Measures of age are not readily obtainable, but are very informative when feasible. Tree-ring counting or radiocarbon dating can provide a maximum time that wood has been in the channel (Keller and Tally, 1979; Hyatt and Naiman, 2001), because in some environments dead trees may remain standing for many years before entering a stream.

Biomass/density
This variable can be particularly important when quantifying carbon storage in a stream (Seo *et al.*, 2008). Biomass estimation, however, rests on accurate estimates of volume and may be even more problematic because wood density varies with species, age, and stage of decomposition (Brown and See, 1981; Hardy, 1996), which are rarely assessed.

Function
In order to understand the geomorphic function and habitat alteration associated with wood, it is useful to at least note whether sediment is stored in association with individual pieces or jams (Keller and Swanson, 1979). If possible, this should be expanded to a measurement of the volume and grain-size distribution of stored sediment. As with sediment storage, noting the presence of streambed scour and, preferably, measuring basic dimensions and type of scour (Bisson *et al.*, 1982; Buffington *et al.*, 2002), provides information relevant to geomorphic function and fish habitat (Carlson *et al.*, 1990; Fausch and Northcote, 1992; Richmond and Fausch, 1995). Other characteristics of wood function include backwater pools, flow deflection, energy dissipation, and bank stabilization.

## Geomorphic variables

Each of the variables mentioned provides insight into the dynamics of wood recruitment and retention within a reach and facilitates comparisons among sites. Methods for acquiring these data should be fully explained in each case.

Channel gradient
Report either the bed gradient or water-surface gradient over the study reach length. This facilitates calculation of hydraulic parameters useful to understanding wood mobility and aquatic habitat.

Channel width
An average value of bankfull channel width should be provided, along with a measure of variability and planform irregularity. Because wood mobility (Gurnell, 2003) and load (Bilby and Ward, 1989; Hassan *et al.*, 2005; Wohl and Jaeger, 2009) vary with channel width (Wohl and Jaeger, 2009), reporting width facilitates understanding of loads and mobility and comparison among sites. Although many studies measure wood within the bankfull channel, different investigators estimate the bankfull dimensions using varying criteria such as flow recurrence interval, breaks in slope along the channel banks, or high-flow indicators (Radecki-Pawlik, 2002; Navratil *et al.*, 2006). Consequently, it is important to state the criteria used to estimate bankfull dimensions.

Flow depth
Report either bankfull (preferred) or some measure of flow depth (mean, maximum) at time of measurement; this is particularly relevant to estimating in-stream transport, which depends partly on the ratio of log diameter to flow depth (Bocchiola *et al.*, 2008). For studies involving fish, residual pool depth (Lisle, 1987) is commonly an important measure that indicates pool depth independent of flow (Richmond and Fausch, 1995).

Grain size
Some estimate of surface bed-material size distribution should be provided, as well as a commonly used metric such as $D_{50}$ or sorting. It is important to explain the method by which grain-size distribution was measured or estimated, given the potential for substantial variation among different methods (Wohl *et al.*, 1996; Faustini and Kaufmann, 2007; Whitacre *et al.*, 2007). The grain size of the channel bed and banks both reflects and influences hydraulics and sediment transport, as well as influencing aquatic habitat and community structure (Haschenburger and Rice, 2004); thus, more detail about bed grain-size distribution is desirable. Useful information includes grain-size distributions upstream and downstream from wood (Faustini and Jones, 2003); associations between channel depositional features such as point or transverse bars and wood (Montgomery *et al.*, 2003a); grain-size distributions for the bed surface and subsurface (Haschenburger and Rice, 2004); and the patchiness or size and spatial distribution of grain-size categories on the streambed (e.g. boulders, cobbles, gravels, sand, silt and clay) (Buffington and Montgomery, 1999).

Discharge
Some measure of discharge is useful when assessing transport capacity and wood retention (Bocchiola *et al.*, 2008). Bankfull

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discharge, as estimated from channel morphology or a recurrence interval for gaged sites, is the most widely used and thus easiest to compare between sites.

Reach length
This value should be provided, as well as the rationale for measuring wood within the specified length. This facilitates calculation of wood load per area of channel.

Channel morphology
Describing the channel morphologic type(s) as per the Montgomery and Buffington (1997) classification characterizes channel stability and sources of flow-energy expenditure.

Drainage area
Provide the area drained by the stream at the study reach. Because wood characteristics can vary between sites within the same watershed in relation to drainage area (Martin and Benda, 2001; Marcus *et al.*, 2002; Wohl and Jaeger, 2009), this facilitates comparison of wood characteristics within and between watersheds.

Elevation
Elevation of the study reach and the range of elevations for the watershed facilitate cross-site comparisons.

Valley side slope, confinement, and connectedness
These variables can be measured in the field or obtained from topographic maps or digital elevation maps. Each provides information on potential recruitment processes and sources.

Disturbance history
This variable incorporates natural disturbances that can influence both wood recruitment to streams over years to centuries (Young, 1994; Kraft *et al.*, 2002; Zelt and Wohl, 2004) and current distribution of pieces within a stream network. The type, presence, spatial extent, and relative age of the disturbance should be noted.

Management history
Like disturbance, management activities in the vicinity, upstream from the study site, or even upstream within the watershed can influence wood recruitment and retention (Murphy and Hall, 1981; Carlson *et al.*, 1990; Nowakowski and Wohl, 2008). Note the type, presence, spatial extent, and relative age of management activities.

Bank scour
A visual estimate of the total percentage of stream bank length that is actively eroding or unstable provides insight into recruitment processes (i.e., bank failure) or channel instability related to wood storage and movement.

### Riparian variables

Forested
Land cover adjacent to the channel can provide important insight into mechanisms and volumes of local wood recruitment. Stream segments within meadows, bedrock gorges, or talus slopes, for example, will have minimal or no riparian recruitment, and this may help to explain variations in wood load among different study reaches (Wohl and Jaeger, 2009).

Dominant species
At a minimum, noting the type (e.g., deciduous versus coniferous) of trees that form the dominant species in forested riparian zones provides information on potential for wood recruitment (Bragg *et al.*, 2000; Welty *et al.*, 2002). Reference to the dominant forest type (e.g. Mesic – Douglas-fir series), which is available for most federal and state forest lands in the United States, can provide insights into the most likely species to be recruited to specific streams.

Source
A visual assessment of the probable source of wood recruitment can be used in developing wood budgets that partition recruitment among various sources (Benda *et al.*, 2003; May and Gresswell, 2003; Webb and Erskine, 2003).

Seral stage
The categorical stage of forest development (young, mid-successional, or mature) and noting whether stands appear even- or uneven-aged provides information on potential recruitment and past forest disturbance (Bragg *et al.*, 2000; Welty *et al.*, 2002).

Floodplain survey
Studies of in-stream wood typically ignore downed wood outside the channel, yet wood on the ground within the floodplain creates pieces available for recruitment. Rates and patterns of recruitment and retention of wood on the floodplain can be related to in-stream wood loading (Jeffries *et al.*, 2003; Pettit and Naiman, 2006; Young *et al.*, 2006).

Basal area
The cross-sectional area of tree cover (in $m^2$/ha) provides insights into stem density and tree size, and this metric allows comparisons across forest types, especially if basal areas are reported by species (Fausch and Northcote, 1992; Nowakowski and Wohl, 2008).

Site potential
Information on the rate of tree growth, time to attain old-growth conditions, and longevity of trees in a region is useful in understanding wood recruitment (Bragg *et al.*, 2000; Welty *et al.*, 2002).

## Additional Information

An explanation of the overall study design deployed in the survey and classification of large wood should be included in publications on in-stream large wood. This would include the following:

(1) *Rationale for reach selection*. It is important to explain whether the study reach was chosen to represent particular characteristics of the area, to avoid certain types of management history, to facilitate repeated access, or based on other criteria. It is often not clear in published papers how or why a particular study reach was chosen, yet this information is useful for determining whether a particular dataset should be included in a synthesis.
(2) *In-stream wood loads*. If all of the variables described earlier are listed in a paper, readers can compute the volume of in-stream wood using one of the typical metrics ($m^3$/100 m, $m^3$/ha, pieces/100 m). Providing at least one of these calculated values in the paper, however, greatly facilitates comparison between sites and regions.
(3) *Large wood monitoring*. There are relatively few short-term (<10 year) published datasets (Lienkaemper and Swanson, 1987; Benke and Wallace, 1990; Young, 1994; Berg *et al.*, 1998) on wood dynamics and extremely few long-term

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(≥10 year) published datasets (Gurnell *et al.*, 2002; Faustini and Jones, 2003; Wohl and Goode, 2008). Datasets based on monitoring of wood dynamics through time are extremely valuable in understanding temporal variations in wood recruitment, retention, and function, and there is a great need for more of them. For tracking individual pieces of large wood over time, we suggest that numbered metal tags be nailed into wood pieces during the initial and follow-up stream surveys (Acker *et al.*, 2003). This facilitates repeat surveys conducted to record movement through time, and changes in status, size, stability, and function between visits. If wood moves out of a study reach, tagged pieces can sometimes be relocated to quantify total distance traveled laterally or downstream. New wood entering the study reach during the monitoring period can be readily identified and tagged. Repeat photography of a reach can also be used to document movement and recruitment of new large wood (Hall, 2001a, 2001b).

## Conclusions

Although the 23 (or 35) variables listed in Table I may appear unmanageable, many of these variables rely on quick visual assessments or measurements derived from maps. Inclusion of these data in all studies of in-stream wood would substantially facilitate the insights and models (e.g. Gregory *et al.*, 2003b) that can result from inter-study compilations.

The great majority of in-stream wood studies to date have been conducted in the US Pacific Northwest, although within the past five years investigators have described different environments in Europe (Piégay and Gurnell, 1997; Gurnell *et al.*, 2000; Kail, 2003; Comiti *et al.*, 2006), Asia (Seo *et al.*, 2008), South Africa (Gomi *et al.*, 2006; Pettit and Naiman, 2006), Australia (Webb and Erskine, 2003), New Zealand (Baillie and Davies, 2002; Meleason *et al.*, 2005), South America (Andreoli *et al.*, 2007; Comiti *et al.*, 2008), and other parts of North America (Thompson, 1995; Downs and Simon, 2001; Hart, 2002; Marcus *et al.*, 2002; Fausch and Young, 2004; Morris *et al.*, 2007; Magilligan *et al.*, 2008). The rapidly growing literature from diverse environments makes it particularly timely to propose standard techniques for measuring and reporting the variables that will allow us to examine regional differences in wood recruitment and retention within different portions of a drainage network.

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## References

Abbe TB, Montgomery DR, Petroff C. 1997. Design of stable in-channel wood debris structures for bank protection and habitat restoration: An example from the Cowlitz River, WA. In *Management of Landscapes Disturbed by Channel Incision*, Wang SSY, Langendoen EJ, Shields FD (eds). University of Mississippi: Oxford, MS; 809–815.

Abbe TB, Montgomery DR. 2003. Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology* **51**: 81–107.

Acker SA, Gregory SV, Liekaemper, G. McKee WA, Swanson FJ, Miller SD 2003. Composition, complexity, and tree mortality in riparian forests in the central Western Cascades of Oregon. *Forest Ecology and Management* **173**: 293–308.

Andreoli A, Comiti F, Lenzi MA. 2007. Characteristics, distribution and geomorphic role of large woody debris in a mountain stream of the Chilean Andes. *Earth Surface Processes and Landforms* **32**: 1675–1692.

Archer EK, Roper BB, Henderson RC, Bouwes N, Mellison SC, Kershner JL. 2004. *Testing Common Stream Sampling Methods for Broad-scale, Long-term Monitoring*, USDA Forest Service General Technical Report RMRS-GTR-122. US Department of Agriculture (USDA): Washington, DC.

Baillie BR, Davies TR. 2002. Influence of large woody debris on channel morphology in native forest and pine plantation streams in the Nelson region, New Zealand. *New Zealand Journal of Marine and Freshwater Research* **36**: 763–774.

Barker JR, Bollman M, Ringold PL, Sackinger J, Cline SP. 2002. Evaluation of metric precision for a riparian forest survey. *Environmental Monitoring and Assessment* **75**: 51–72.

Benda L, Miller D, Sias J, Martin D, Bilby R, Veldhuisen C, Dunne T. 2003. Wood recruitment processes and wood budgeting. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds), American Fisheries Society Symposium 37. American Fisheries Society: Bethesda, MD; 49–73.

Benke AC, Wallace JB. 1990. Wood dynamics in the Coastal Plain blackwater streams. *Canadian Journal of Fisheries and Aquatic Sciences* **47**: 92–99.

Berg N, Carlson A, Azuma D. 1998. Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California. *Canadian Journal of Fisheries and Aquatic Sciences* **55**: 1807–1820.

Beschta RL. 1983. The effects of large organic debris upon channel morphology: a flume study. *Proceedings of the D.B Simons Symposium on Erosion and Sedimentation*, Fort Collins, CO; 8·63–8·78.

Bilby RE, Likens GE. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology* **61**: 1107–1113.

Bilby RE, Ward JW. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* **118**: 368–378.

Bisson PA, Nielsen JL, Palmason RA, Grove LE. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. *Proceedings of a Symposium on Acquisition and Utilization of Aquatic Habitat Inventory Information*, Portland, OR; 62–73.

Bocchiola D, Rulli MC, Rosso R. 2008. A flume experiment on the formation of wood jams in rivers. *Water Resources Research* **44**: W02408.

Bragg DC, Kershner JL, Roberts DW. 2000. *Modeling Large Woody Debris Recruitment for Small Streams of the Central Rocky Mountains*, USDA Forest Service General Technical Report RMRS-GTR-55. Rocky Mountain Research Station: Fort Collins, CO.

Braudrick CA, Grant GE. 2000. When do logs move in rivers? *Water Resources Research* **36**: 571–584.

Brown JK, See TE. 1981. *Downed Dead Wood Fuel and Biomass in the Northern Rocky Mountains*, USDA Forest Service General Technical Report INT-117. US Department of Agriculture (USDA): Washington, DC.

Buffington JM, Montgomery DR. 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. *Water Resources Research* **35**: 3507–3522.

Buffington JM, Lisle TE, Woodsmith RD, Hilton S. 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Research and Applications* **18**: 507–531.

Carlson JY, Andrus CW, Froehlich HA. 1990. Woody debris, channel features, and macroinvertebrates of streams with logged and undisturbed riparian timber in northeastern Oregon, USA. *Canadian Journal of Fisheries and Aquatic Sciences* **47**: 1103–1111.

Cherry J, Beschta RL. 1989. Coarse woody debris and channel morphology: A flume study. *Water Resources Bulletin* **25**: 1031–1036.

Comiti F, Andreoli A, Lenzi MA, Mao L. 2006. Spatial density and characteristics of woody debris in five mountain rivers of the Dolomites (Italian Alps). *Geomorphology* **78**: 44–63.

Comiti F, Andreoli A, Mao L, Lenzi MA. 2008. Wood storage in three mountain streams of the Southern Andes and its hydro-morphological effects. *Earth Surface Processes and Landforms* **33**: 244–262.

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Curran JH, Wohl EE. 2003. Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology* **51**: 141–157.

Daniels MD, Rhoads BL. 2004. Effect of large woody debris configuration on three-dimensional flow structure in two low-energy meander bends at varying stages. *Water Resources Research* **40**: W11302.

Douglas I, Guyot JL. 2005. Erosion and sediment yield in the humid tropics. In *Forests, Water and People in the Humid Tropics*. Bonnell M, Bruijnzeel LA (eds). Cambridge University Press: Cambridge; 407–421.

Downs PW, Simon A. 2001. Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, central Mississippi, USA. *Geomorphology* **37**: 65–91.

Fausch KD, Northcote TG. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. *Canadian Journal of Fisheries and Aquatic Sciences* **49**: 682–693.

Fausch KD, Young MK. 2004. Interactions between forests and fish in the Rocky Mountains of the USA. In *Fishes and Forestry: Worldwide Watershed Interactions and Management*, Northcote TG, Hartman GF (eds). Blackwell Science: Oxford; 463–484.

Faustini JM, Jones JA. 2003. Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology* **51**: 187–205.

Faustini JM, Kaufmann PR. 2007. Adequacy of visually classified particle count statistics from regional stream habitat surveys. *Journal of the American Water Resources Association* **43**: 1293–1315.

Gomi T, Sidle RC, Noguchi S, Negishi JN, Nik AR, Sasaki S. 2006. Sediment and wood accumulations in humid tropical headwater streams: Effects of logging and riparian buffers. *Forest Ecology and Management* **224**: 166–175.

Gregory KJ, Gurnell AM, Hill CT. 1985. The permanence of debris dams related to river channel processes. *Hydrological Sciences Journal* **30**: 371–381.

Gregory SV, Boyer KL, Gurnell AM (eds). 2003a. *The Ecology and Management of Wood in World Rivers*, American Fisheries Society Symposium 37. American Fisheries Society: Bethesda, MD.

Gregory SV, Meleason MA, Sobota DJ. 2003b. Modeling the dynamics of wood in streams and rivers. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds), American Fisheries Society Symposium 37. American Fisheries Society: Bethesda, MD; 315–335.

Gurnell AM. 2003. Wood storage and mobility. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds), American Fisheries Society Symposium 37. American Fisheries Society: Bethesda, MD; 75–91.

Gurnell AM, Sweet R. 1998. The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms* **23**: 1101–1121.

Gurnell AM, Petts GE, Hannah DM, Smith BPG, Edwards PJ, Kollmann J, Ward JV, Tockner K. 2000. Wood storage within the active zone of a large European gravel-bed river. *Geomorphology* **34**: 55–72.

Gurnell AM, Piégay H, Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. *Freshwater Biology* **47**: 601–619.

Hall FC. 2001a. *Photo Point Monitoring Handbook: Part A – Field Procedures*, General Technical Report PNW-GTR-526. USDA, Forest Service, Pacific Northwest Research Station: Portland, OR; 48 pp.

Hall FC. 2001b. *Photo Point Monitoring Handbook: Part B – Concepts and Analysis*, General Technical Report PNW-GTR-526. USDA, Forest Service, Pacific Northwest Research Station: Portland, OR; 86 pp.

Hardy CC. 1996. *Guidelines for Estimating Volume, Biomass, and Smoke Production for Piled Slash*, USDA Forest Service General Technical Report PNW-GTR-364. US Department of Agriculture (USDA): Washington, DC.

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW. 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* **15**: 133–302.

Harmon ME, Sexton J. 1996. *Guidelines for Measurements of Woody Detritus in Forest Ecosystems*, Publication 20. US LTER Network Office, University of Washington: Seattle, WA.

Hart EA. 2002. Effects of woody debris on channel morphology and sediment storage in headwater streams in the Great Smoky Mountains, Tennessee-North Carolina. *Physical Geography* **23**: 492–510.

Haschenburger JK, Rice SP. 2004. Changes in woody debris and bed material texture in a gravel-bed channel. *Geomorphology* **60**: 241–267.

Hassan MA, Hogan DL, Bird SA, May CL, Gomi T, Campbell D. 2005. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. *Journal of the American Water Resources Association* **41**: 899–919.

Hedman CW, Van Lear DH, Swank WT. 1996. In-stream large woody debris loading and riparian forest seral stage associations in the southern Appalachian Mountains. *Canadian Journal of Forest Research* **26**: 1218–1127.

Husch B, Beers TW, Kershaw JA. 2002. *Forest Mensuration*, 4th edition. John Wiley & Sons: New York.

Hyatt TL, Naiman RJ. 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* **11**: 191–202.

Jeffries R, Darby SE, Sear DA. 2003. The influence of vegetation and organic debris on flood-plain sediment dynamics: Case study of a low-order stream in the New Forest, England. *Geomorphology* **51**: 61–80.

Kaczka RJ. 2003. The coarse woody debris dams in mountain streams of central Europe, structure and distribution. *Studia Geomorphologica Carpatho-Balcanica* **38**: 111–127.

Kail J. 2003. Influence of large woody debris on the morphology of six central European streams. *Geomorphology* **51**: 207–223.

Keller EA, Swanson FJ. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes* **4**: 361–380.

Keller EA, Tally T. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. In *Adjustments of the Fluvial System*, Rhodes DD, Williams GP (eds). Kendall/Hunt Publishing: Dubuque, IA; 169–197.

Kraft CE, Schneider RL, Warren DR. 2002. Ice storm impacts on woody debris and debris dam formation in northeastern U.S. streams. *Canadian Journal of Fisheries and Aquatic Sciences* **59**: 1677–1684.

Kraft CE, Warren DR. 2003. Development of spatial pattern in large woody debris and debris dams in streams. *Geomorphology* **51**: 127–139.

Lienkaemper GW, Swanson FJ. 1987. Dynamics of large woody debris in old-growth Douglas-fir forests. *Canadian Journal of Forest Research* **17**: 150–156.

Linstead C. 2001. The effects of large woody debris accumulations on river hydraulics and implications for physical habitat. In *Hydroecology: Linking Hydrology and Aquatic Ecology*, Acreman MC (ed.), IAHS Publication 266. IAHS Press: Wallingford; 91–99.

Lisle TE. 1987. *Using 'Residual Depths' to Monitor Pool Depths Independently of Discharge*, Research Note No. PSW-394. USDA Forest Service: Berkeley, CA.

Magilligan FJ, Nislow KH, Fisher GB, Wright J, Mackey G, Laser M. 2008. The geomorphic function and characteristics of large woody debris in low gradient rivers, coastal Maine, USA. *Geomorphology* **97**: 467–482.

Manga M, Kirchner JW. 2000. Stress partitioning in streams by large woody debris. *Water Resources Research* **36**: 2373–2379.

Manners RB, Doyle MW, Small MJ. 2007. Structure and hydraulics of natural woody debris jams. *Water Resources Research* **43**: W06432.

Marcus WA, Marston RA, Colvard CR, Gray RD. 2002. Mapping the spatial and temporal distributions of large woody debris in streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology* **44**: 323–335.

Martin DJ, Benda LE. 2001. Patterns of instream wood recruitment and transport at the watershed scale. *Transactions of the American Fisheries Society* **130**: 940–958.

Maser C, Tarrant RF, Trappe JM, Franklin JF (eds). 1988. *From the Forest to the Sea: A Story of Fallen Trees*, US Forest Service General

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Technical Report PNW-GTR-229. US Department of Agriculture (USDA): Washington, DC.

May CL, Gresswell RE. 2003. Processes and rates of sediment and wood accumulation in headwater streams of the Oregon Coast Range, USA. *Earth Surface Processes and Landforms* **28**: 409–424.

Meleason MA, Davies-Colley R, Wright-Stow A, Horrox J, Costley K. 2005. Characteristics and geomorphic effect of wood in New Zealand native forest streams. *International Revue de Hydrobiologie* **90**: 466–485.

Montgomery DR, Buffington JM, Smith RD, Schmidt KM, Pess G. 1995. Pool spacing in forest channels. *Water Resources Research* **31**: 1097–1105.

Montgomery DR, Buffington JM. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin* **109**: 596–611.

Montgomery DR, Piegay H. 2003. Interactions between wood and channel forms and processes. *Geomorphology* **51**: 1–5.

Montgomery DR, Collins BD, Buffington JM, Abbe TB. 2003a. Geomorphic effects of wood in rivers. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds), American Fisheries Society Symposium 37. American Fisheries Society: Bethesda, MD; 21–47.

Montgomery DR, Massong TM, Hawley SCS. 2003b. Influence of debris flows and log jams on the location of pools and alluvial channel reaches, Oregon Coast Range. *Geological Society of America Bulletin* **115**: 78–88.

Morris AEL, Goebel PC, Palik BJ. 2007. Geomorphic and riparian forest influences on characteristics of large wood and large-wood jams in old-growth and second-growth forests in northern Michigan, USA. *Earth Surface Processes and Landforms* **32**: 1131–1153.

Murphy ML, Hall JD. 1981. Varied effects of clear-cut logging on predators and their habitat in small streams of the Cascade Mountains, Oregon. *Canadian Journal of Fisheries and Aquatic Sciences* **38**: 177–145.

Navratil O, Albert M-B, Hérouin E, Gresillon J-M. 2006. Determination of bankfull discharge magnitude and frequency: Comparison of methods on 16 gravel-bed river reaches. *Earth Surface Processes and Landforms* **31**: 1345–1363.

Nowakowski AL, Wohl E. 2008. Influences on wood load in mountain streams of the Bighorn National Forest, Wyoming, USA. *Environmental Management* **42**: 557–571.

O'Connor JE, Jones MA, Haluska TL, 2003, Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. *Geomorphology* **51**: 31–59.

Opperman JJ, Merenlender AM. 2007. Living trees provide stable large wood in streams. *Earth Surface Processes and Landforms* **32**: 1229–1238.

Opperman JJ, Meleason M, Francis RA, Davies-Colley R. 2008. 'Live-wood': Geomorphic and ecological functions of living trees in channels. *BioScience* **58**: 1069–1078.

Pettit NE, Naiman RJ. 2006. Flood-deposited wood creates regeneration niches for riparian vegetation on a semi-arid South African river. *Journal of Vegetation Science* **17**: 615–624.

Piégay H, Gurnell AM. 1997. Large woody debris and river geomorphological pattern: Examples from S.E. France and S. England. *Geomorphology* **19**: 99–116.

Radecki-Pawlik A. 2002. Bankfull discharge in mountain streams: Theory and practice. *Earth Surface Processes and Landforms* **27**: 115–123.

Ralph SC, Poole GC, Conquest LL, Naiman RJ. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* **51**: 37–51.

Richmond AD, Fausch KD. 1995. Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* **52**: 1789–1802.

Robison EG, Beschta RL. 1990. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences* **47**: 1684–1693.

Roper BB, Scarnecchia DL. 1995. Observer variability in classifying habitat types in stream surveys. *North American Journal of Fisheries Management* **15**: 49–53.

Roper BB, Kershner JL, Archer E, Henderson R, Bouwes N. 2002. An evaluation of physical stream habitat attributes used to monitor streams. *Journal of the American Water Resources Association* **38**: 1637–1646.

Schuett-Hames DAE, Pleus AE, Ward J, Fox M, Light J. 1999. *TFW Monitoring Program Method Manual for the Large Woody Debris Survey*, Washington State Department of Natural Resources, TFW-AM9-99-004. Washington State Department of Natural Resources: Seattle, WA; 33 pp.

Seo JI, Nakamura F, Nakano D, Ichiyanagi H, Chin KW. 2008. Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales. *Water Resources Research* **44**: W04428.

Sobota D, Gregory SV, Van Sickle J. 2006. Riparian tree fall directionality and modeling large wood recruitment to streams. *Canadian Journal of Forest Research* **36**: 1243–1254.

Swanson FJ, Lienkaemper GW. 1978. *Physical Consequences of Large Organic Debris in Pacific Northwest Streams*, USDA Forest Service General Technical Report PNW-69. US Department of Agriculture (USDA): Washington, DC.

Thompson DM. 1995. The effects of large organic debris on sediment processes and stream morphology in Vermont. *Geomorphology* **11**: 235–244.

Warren DR, Bernhardt ES, Hall RO, Likens GE. 2007. Forest age, wood and nutrient dynamics in headwater streams of the Hubbard Brook Experimental Forest, NH. *Earth Surface Processes and Landforms* **32**: 1154–1163.

Webb AA, Erskine WD. 2003. Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. *Geomorphology* **51**: 109–126.

Welty JJ, Beechie T, Sullivan K, Hyink DM, Bilby RE, Andrus C, Pess G. 2002. Riparian aquatic interaction simulator (RAIS): A model of riparian forest dynamics for the generation of large woody debris and shade. *Forest Ecology and Management* **162**: 299–318.

Whitacre HW, Roper BB, Kershner JL. 2007. A comparison of protocols and observer precision for measuring physical stream attributes. *Journal of the American Water Resources Association* **43**: 923–937.

Williams MS, Gove JH. 2003. Perpendicular distance sampling: an alternative method for sampling downed coarse woody debris. *Canadian Journal of Forest Research* **33**: 1564–1579.

Wohl EE, Anthony DJ, Madsen SW, Thompson DM. 1996. A comparison of surface sampling methods for coarse fluvial sediments. *Water Resources Research* **32**: 3219–3226.

Wohl E, Goode JR. 2008. Wood dynamics in headwater streams of the Colorado Rocky Mountains. *Water Resources Research* **44**: W09429.

Wohl E, Jaeger K. 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. *Earth Surface Processes and Landforms* **34**: 329–344.

Young MK. 1994. Movement and characteristics of stream-borne coarse woody debris in adjacent burned and undisturbed watersheds in Wyoming. *Canadian Journal of Forest Research* **24**: 1933–1938.

Young MK, Mace EA, Ziegler ET, Sutherland EK. 2006. Characterizing and contrasting instream and riparian coarse wood in western Montana basins. *Forest Ecology and Management* **226**: 26–40.

Zelt RB. Wohl EE, 2004. Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming. *Geomorphology* **57**: 217–233.

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