

Wood placement in river restoration: fact, fiction, and future direction

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Abstract: Despite decades of research on wood in rivers, the addition of wood as a river restoration technique remains controversial. We reviewed the literature on natural and placed wood to shed light on areas of continued debate. Research on river ecology demonstrates that large woody debris has always been a natural part of most rivers systems. Although a few studies have reported high structural failure rates (>50%) of placed instream wood structures, most studies have shown relatively low failure rates (<20%) and that placed wood remains stable for several years, though long-term evaluations of placed wood are rare. The vast majority of studies on wood placement have reported improvements in physical habitat (e.g., increased pool frequency, cover, habitat diversity). Studies that have not reported improvements in physical habitat often found that watershed processes (e.g., sediment, hydrology, water quality) had not been addressed. Finally, most evaluations of fish response to wood placement have shown positive responses for salmonids, though few studies have looked at long-term watershed-scale responses or studied a wide range of species.

Résumé : Malgré des décennies de recherche sur le bois dans les rivières, l'ajout de bois comme technique de restauration demeure controversé. Nous avons passé en revue la documentation sur le bois naturel et mis en place pour faire la lumière sur les enjeux qui font toujours l'objet de débat. La recherche en écologie fluviale démontre que les grands débris ligneux ont toujours constitué une composante naturelle de la plupart des réseaux fluviaux. Si quelques études ont signalé des taux élevés de défaillance structurale (>50 %) des structures en bois mises en place dans des cours d'eau, la plupart des études ont noté des taux de défaillance assez faibles (<20 %) et montré que le bois mis en place dans les cours d'eau demeurerait stable pendant plusieurs années, les évaluations à long terme du bois mis en place étant toutefois rares. La grande majorité des études sur la mise en place de bois font état d'améliorations de l'habitat physique (p. ex. fréquences accrues de moulles, couvert, diversité des habitats). Bon nombre des études n'ayant pas constaté d'amélioration de l'habitat physique notaient que les processus hydrographiques (p. ex. sédiments, hydrologie, qualité de l'eau) n'avaient pas été pris en considération. Enfin, si la plupart des évaluations de la réaction des poissons à la mise en place de bois ont relevé des réactions positives en ce qui concerne les salmonidés, peu d'études ont examiné les réactions à long terme à l'échelle du bassin versant ou étudié un grand éventail d'espèces. [Traduit par la Rédaction]

Introduction

Placement of large woody debris (wood) and other structures in streams is one of the most widespread and common techniques to improve riverine fish habitat. Techniques for wood placement range from simply falling, pushing, or hauling trees from the riparian zone into the active stream channel to construction of highly engineered structures such as log weirs or engineered logjams (Roni and Beechie 2013). In part due to the popularity and variety of wood placement techniques, whole books and technical manuals have been developed over the years to guide restoration practitioners and local sportsmen on how to design and implement instream wood projects (e.g., Hunt 1993; Hunter 1991; Tarzwell 1934; White and Brynildson 1967).

The number of projects historically and currently being implemented using various wood placement techniques is staggering. In just one 3-year period from 1933 to 1935, the United States Civilian Conservation Corps constructed more than 30 000 instream structures in more than 400 streams (Hunter 1991; Thompson and Stull 2002). In a database compiled of more than 37 000 river restoration projects implemented in the United States (US) from 1980 to 2005, Bernhardt et al. (2005) reported that nearly 6000 of

these were wood placement or other instream habitat improvement projects. In the Columbia River Basin of the Pacific Northwest, the focus of a large habitat restoration program, at least 2000 wood placement projects have been implemented since 1980 (National Oceanic and Atmospheric Administration (NOAA), unpublished data). Wood placement has also become commonplace in Europe, Japan, Australia, and other parts of the world (Brooks 2006; Nagayama and Nakamura 2010; Reich et al. 2003).

Not only is wood placement one of the most common stream restoration techniques, but it is arguably also the oldest. As early as the 1890s, private land owners in the eastern US, United Kingdom, and western Europe began placing wood and other structures in channels to improve fish habitat (Thompson and Stull 2002; White 2002). Many of the techniques developed in the 1920s and 1930s for use in streams in the northeastern US are still in use today (Roni and Beechie 2013; Thompson and Stull 2002). These include such structures as log weirs, deflectors, sills, K-dams, and other techniques using cut logs or brush primarily designed to create pools or fish cover (Hunt 1993; Hunter 1991; Tarzwell 1934). These techniques were refined in the 1960s and used widely in streams in the US Midwest to improve trout habitat by creating cover (White 2002).

Received 28 July 2014. Accepted 15 November 2014.

Paper handled by Associate Editor Bror Jonsson.

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The apparent success of wood additions and other instream techniques at improving fish numbers and angler harvest in eastern North American streams (e.g., Hunt 1976; Saunders and Smith 1962; Shetter et al. 1949) and a manual on stream restoration (White and Brynildson 1967) resulted in application to other locations such as the Pacific Northwest (Reeves and Roelofs 1982). Concern over high structural failure rates of these treatments in many Pacific Northwest streams (i.e., Frissell and Nawa 1992), which are generally steeper, larger, higher energy, and more dynamic than streams in eastern North America, led to the development of wood placement techniques that more closely mimic natural wood accumulations. Thus, since the 1990s, we have seen a move away from engineered or structural wood placement techniques using cut logs and boulders to placement of whole trees (including root wads) or construction of logjams (Abbe et al. 2002; Reich et al. 2003). The later approaches attempt to emulate natural accumulations and delivery of large woody debris found historically in our streams (Collins et al. 2002; Roni and Beechie 2013; White 2002). However, common approaches to restructure and stabilize stream channels such as the Rosgen (1996) natural channel design often use traditional fixed wood or rock structures to stabilize channels, and liability and safety considerations have led to increasing use of highly engineering approaches for constructing logjams in larger rivers (> ~20 m bankfull width).

Despite its popularity, long history, and a move towards more natural approaches, wood placement remains one of the more controversial restoration techniques. Some studies have reported high “failure” or “damage” rates of large woody debris (LWD) structures (e.g., Ehlers 1956; Frissell and Nawa 1992; Thompson 2002), whereas others have reported low failure rates (Roper et al. 1998; Tarzwell 1937). Others have argued that placed wood has relatively little effect on physical habitat (Chapman 1996; Frissell and Nawa 1992; Miller and Kochel 2010). Even more importantly, several authors have argued that placement of wood leads to little or no biological benefit (Doyle and Shields 2012; Stewart et al. 2009), whereas others have documented significant improvements in fish abundance (Cederholm et al. 1997; Hunt 1976; Solazzi et al. 2000; for a review, see Roni et al. 2008).

This controversy has not been limited to the scientific community. Landowners, the whitewater rafting, and boating communities have argued that logs, wood, and other obstructions in streams pose a threat to life and property. Some private land owners will not allow placement of wood into channels on their land for fear of liability and property damage (Piégay et al. 2005). This fear is not unfounded, as either natural or placed wood can redirect flow and lead to scour or channel avulsion, eroding of stream banks and adjacent land (Florsheim et al. 2008; Montgomery 1997; Seo et al. 2010). Wood can move and become trapped at stream crossings and on bridges leading to erosion and damage of private or public infrastructure (e.g., roads and bridges; Lassetre and Kondolf 2012; Wenzel et al. 2014) and pose a danger for boaters.

As a society, we have spent over 100 years removing wood from channels to improve navigation, water conveyance, and transportation (Collins et al. 2002; Erskine and Webb 2003; Montgomery 1997). Natural resource managers, fisherman, and whitewater rafters have routinely removed wood from rivers that may pose a safety hazard, and often oppose wood placement because of the potential safety hazards. Members of the public who are accustomed to channels with little or no wood have argued that wood is not a natural part of their system. This view is not limited to those with little knowledge of ecology. A survey of graduate and undergraduate students in the US and Europe found that even ecology students in some countries view stream channels with wood as less desirable than neatly “cleaned” channels (Piégay et al. 2005). Given the long history of wood removal and rivers, it is not surprising that many members of the public would hold a negative view of wood placement or retention in channels.

The ongoing debate regarding wood placement in streams consists of four main topics: (i) whether wood was ever a natural part of the system, (ii) the structural stability or failure rates of placed wood, (iii) the physical response of stream channels to wood placement, and perhaps most importantly, (iv) the biological response to wood placement. In this paper, we review and summarize the findings from the scientific literature to clarify the current knowledge and misconceptions around these four topics. We close with a discussion of more focused research questions that are needed to improve our understanding of wood placement.

Natural functions of wood in rivers

The first area of debate about wood placement is really a fundamental discussion of the natural function of wood in rivers. The scientific literature on loadings and functions of wood in streams is extensive, dating back to at least the 1970s when the relationship between wood and salmon in the Pacific Northwest became an important research area (e.g., Keller and Swanson 1979; also see reviews in Maser et al. 1988; Salo and Cundy 1987). Although much of the literature focuses on western North America, the importance of wood in rivers throughout the world has been demonstrated by many other studies (most recently Rossetti de Paula et al. 2011; Ruiz-Villanueva et al. 2014; Seo et al. 2010) and was extensively reviewed in the proceedings of the International Conference on Wood in World Rivers (Gregory et al. 2003). This comprehensive volume includes information on wood recruitment, natural wood levels, effects on channel dynamics and morphology, effects on nutrient cycling, and effects on habitat and aquatic biota. Conclusions from this extensive review and more recent studies point to several aspects of natural wood delivery and loading that are important reference points for wood placement efforts in streams. These include (i) wood sources, (ii) wood mobility, (iii) wood loading, (iv) wood functions, and (v) effects of river management on wood and its functions; in the following sections, we summarize the significant findings for each of these reference points.

Wood sources

The primary source of wood in most stream environments is from the near-stream riparian zone, though recruitment to streams occurs via several processes, including mortality and tree fall, bank erosion, and debris flows or landslides (e.g., Martin and Benda 2001; Reeves et al. 2003; Ruiz-Villanueva et al. 2014; Seo et al. 2010; Van Sickle and Gregory 1990). Studies of wood recruitment from mortality and bank erosion indicate that recruitment varies as a function of distance from the stream, decreasing exponentially as one moves away from the stream. Therefore, recruitment distances vary with species and age of trees in the riparian zone (McDade et al. 1990; Van Sickle and Gregory 1990). For example, recruitment distances of old-growth conifer trees that reach heights of more than 70 m are much greater than those of smaller alder trees, which reach heights of only about 35 m (Beechie et al. 2000; McDade et al. 1990).

Wood from landslides also is derived from the near-stream zone, but the wood recruitment occurs through erosion of the near-stream area as debris flow travels down the channel (Mazzorana et al. 2011; Swanson 2003). Therefore, wood delivery to low-gradient stream reaches from landslides depends on runoff of the debris flow, which is a function of channel slope and abrupt changes in channel direction (Benda and Cundy 1990). In general, debris flows and incorporated wood continue downstream from the landslide source as long as the channel slope is greater than 10% and the channel does not have abrupt changes in direction of more than 70° (Benda and Cundy 1990).

In sum, the dominant source of wood in stream channels varies across the landscape and with channel size and gradient, with the dominant wood delivery process being debris flow in steep headwater streams, tree fall in mid-order or mid-sized streams, and

bank erosion in high-order rivers with large floodplains (Kasprak et al. 2012; Ruiz-Villanueva et al. 2014; Seo et al. 2010; Swanson 2003).

Wood mobility

Within streams, the dynamics and mobility of natural wood vary with channel size or position in the stream network. Unfortunately, few data exist to document wood export rates or decay rates in river networks (Hyatt and Naiman 2001). In field studies, quantifying “depletion rate” (the combination of export and decay) is often estimated where the two components cannot be measured directly and the only feasible measure is of retained wood. Among studies that document the two components separately, several studies have found that (i) wood mobility increases (and residence time decreases) with increasing channel size and (ii) decay rates of wood are generally higher for deciduous species than conifer species. For example, in small channels where wood pieces are large relative to channel size, much of the wood is stable, and single pieces of wood can form pools or store sediment (Beechie and Sibley 1997; Jones et al. 2011; Lester et al. 2006; Seo et al. 2010). Therefore, in small channels where wood is immobile, decay is a primary driver of wood depletion over time (Fig. 1). By contrast, in larger channels, export is a significant component of the wood depletion rate (e.g., Curran 2010; Hyatt and Naiman 2001). Estimated depletion rates of wood (export and decay combined) range from 0.5% to 3.5% per year, resulting in an average persistence of stable wood between 70 and 100 years (Naiman et al. 2002). Depletion rates are generally higher (i.e., nearer to 3.5% per year) for smaller wood pieces due to increased mobility and for deciduous species due to faster decay rates (Beechie 1998; Curran 2010; Hyatt and Naiman 2001; Murphy and Koski 1989).

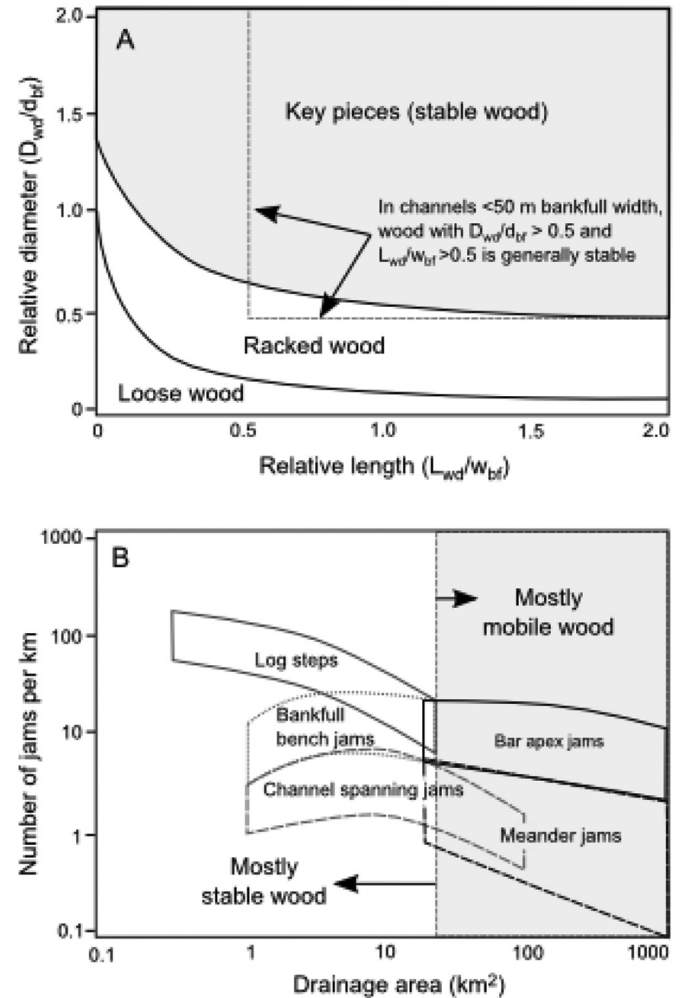
The size of mobile wood increases as channel size increases, but large “key pieces” of wood (i.e., wood that remains independently stable, even throughout large floods) can initiate logjam formation and create pools (Abbe and Montgomery 2003; Fox et al. 2003). Perhaps the most prominent function of key pieces is to initiate formation of bar apex jams, or jams that fully span the channel; such jams are rare where wood is not large enough to function as a key piece (Abbe 2000; Abbe and Montgomery 2003; Fig. 1). These jams create either crescent pools at the bar apex or plunge and scour pools around or downstream of fully spanning jams (Abbe 2000). In the largest rivers, all wood is mobile, with the most common jams being either meander jams, where wood accumulates at the outside of meander bends, or raft jams, where wood accumulates across the width of the channel (Abbe 2000; Abbe and Montgomery 2003; Collins et al. 2012). Residence times of wood in large rivers range from less than 1 to over 1000 years because some wood is transported out immediately, whereas other pieces are trapped in jams and buried in floodplain sediments for centuries (Curran 2010; Hyatt and Naiman 2001).

Wood loading

Gurnell (2003) reviewed 19 studies of wood loading among streams with differing stand ages, channel characteristics, and forest types, including conifer, mixed conifer and hardwood, hardwood-dominated, and deciduous–softwood. Natural wood loading in streams ranged from $\sim 10 \text{ m}^3 \cdot \text{m}^{-2}$ of channel area in deciduous–softwoods (willows) to well over $1000 \text{ m}^3 \cdot \text{m}^{-2}$ in conifer forests (Gurnell 2003). Examples include low loadings of $0.021\text{--}222 \text{ m}^3 \cdot \text{m}^{-2}$ in high-elevation and drier environments (Berg et al. 1998; Dunkerley 2014; Hering et al. 2000; Lester et al. 2006), moderate loadings of $227\text{--}638 \text{ m}^3 \cdot \text{m}^{-2}$ in dense forests (e.g., Baillie et al. 2008; Carlson et al. 1990), and high loadings of over $1000 \text{ m}^3 \cdot \text{m}^{-2}$ in California redwood forests (MacDonald et al. 1982).

Volume of wood per unit area is often lower in larger rivers because they can transport more wood than smaller streams (Gurnell 2003; Naiman et al. 2002; Seo et al. 2010), even though total wood abundance per unit length of channel can be much

higher (Baillie et al. 2008). In some densely forested areas, large logjams (spanning the full channel and more than 1 km long) may have created very high wood abundances per unit of channel area, though exact values have not been calculated (Collins et al. 2002).



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Wood function

Once in the stream, wood affects a number of stream functions, including sediment storage and the creation of alluvial reaches in otherwise bedrock channels (Montgomery et al. 1996), formation of pools (Beechie and Sibley 1997; Montgomery and Buffington 1997; Montgomery et al. 1995), increased retention of organic matter and nutrients (Bilby 1981; Flores et al. 2011), and island formation in large floodplain channels (Fetherston et al. 1995; Gurnell et al. 2001; Montgomery and Abbe 2006).

In small forest streams, wood can reduce the transport of bed load sediment, converting bedrock channels to alluvial channels or decreasing grain size of the bed material (Buffington and Montgomery 1999; Montgomery et al. 1996). Wood can also alter amounts of available spawning area for salmonids and other fishes by controlling substrate size and creating pools for adult

holding and cover for hiding (Montgomery et al. 1999; Nagayama and Nakamura 2010). Greater wood abundance increases the overall number of pools (Beechie and Sibley 1997; Montgomery et al. 1995), pool area (Beechie and Sibley 1997), and residual pool depth (Collins et al. 2002) and can change the overall channel morphology from plane bed to forced-pool riffle channels (Buffington and Montgomery 1999; Montgomery et al. 1996).

In large rivers, wood jams can protect river banks from erosion or force water onto floodplains, creating new channels (Collins et al. 2012). Wood accumulations contribute to landform development such as the creation of forest patches that are ultimately eroded and recruited as wood to the channel (Fetherston et al. 1995; Gurnell et al. 2001; Naiman et al. 2010). Wood recruitment to large rivers with floodplains depends on the channel migration rate and the density, age, and size of trees on the floodplain surface. It is also a function of channel pattern, which controls lateral migration rate (Beechie et al. 2006; Naiman et al. 2010).

Differences in physical habitat and channel morphology produced from wood are strongly correlated with fish abundance, particularly for species that prefer pool habitat (e.g., Crook and Robertson 1999; Dolloff and Warren 2003; Harmon et al. 1986; Zalewski et al. 2003), though not all species and life stages benefit from wood placement (Langford et al. 2012). In addition to creating physical habitats for fishes, wood has a number of biological functions in channels, including increasing nutrient retention (Bilby 1981), creation of surfaces that facilitate primary and secondary production (Benke et al. 1985; Coe et al. 2009; Lester et al. 2009), and providing hiding cover or altering depth and substrate to provide spawning areas for fishes (e.g., Beechie et al. 2005; Montgomery et al. 1999). Although much early research was focused on wood and salmonid fishes, subsequent studies have documented functions of wood for a variety of non-salmonid fish and invertebrate species (e.g., Angermeier and Karr 1984; Growns et al. 2004; Lester et al. 2009; Warren et al. 2000; Wright and Flecker 2004). Most of these studies indicate that periphyton and invertebrate production is increased with the presence of wood in streams and that wood provides cover for darters (*Percina* spp. and *Etheostma* spp.), catfishes (*Ameiurus* spp. and *Noturus* spp.), trout cod (*Maccullochella macquariensis*), and a number of other fish species (Dolloff and Warren 2003; Growns et al. 2004; Warren et al. 2000). However, many other non-salmonid fishes do not appear to benefit from the presence of wood in streams (Growns et al. 2004; Langford et al. 2012; Warren et al. 2000).

Effects of river management on wood

River and stream reaches have been routinely cleaned of wood for a variety of reasons. Some of the earliest recorded river cleaning and engineering efforts were to improve navigation in large rivers (e.g., Erskine and Webb 2003; Gippel et al. 1996; Collins et al. 2002) and date back to the Roman era (Herget 2000; Montgomery et al. 2003). Many lowland streams have been straightened and channelized to increase flood conveyance or drain wetlands for agriculture or other development (Cowx and Welcomme 1998; Roni and Beechie 2013).

In such areas, wood is often continually removed and wood loadings are kept at or near zero to assure that drainage and navigation are not impaired by wood accumulations. This may have contributed to the public perception that simplified channels with little wood are the norm and are healthy or in better condition (Piégay et al. 2005). Wood and other habitat structures such as boulders have also been removed from rivers in many parts of the world to facilitate log drives or because they were thought to inhibit fish migration (Herget 2000; Nilsson et al. 2005; Sedell and Luchessa 1982). It was not until the early 1980s that scientists recognized that wood in rivers provided a number of physical and biological functions that were important to sustaining fish populations and other ecological functions (Maser et al. 1988). Clearing or harvest of streamside trees reduces or eliminates potential wood delivery and recruitment to the stream

channel (e.g., Andrus et al. 1988; Bilby and Ward 1991; Ralph et al. 1994), although in some cases, logging practices introduce large amounts of logging slash (debris) to streams (Burrows et al. 2012). Decreased wood loading from management activities reduces the number and size of pools, decreases sediment retention, and increases gravel size, altering organic matter transport and storage (Beechie and Sibley 1997; Bilby 1981; Montgomery et al. 1995). Wood removal has had large and very direct influences on fish habitat characteristics of streams, including losses of spawning gravel and pools for rearing (Bilby and Ward 1991; Montgomery et al. 1999; Ralph et al. 1994). By contrast, removal of riparian vegetation and the resulting elimination of wood recruitment create delayed effects on wood abundance and its functions, as wood is gradually depleted from rivers and not replaced for many decades (e.g., Andrus et al. 1988; Beechie et al. 2000). Recovery of wood to streams that have lost recruitment sources generally will take many decades (e.g., Beechie et al. 2000; McHenry et al. 1998). This long recovery time is another reason that placement of wood in streams has become commonplace (Abbe et al. 2002).

Although some have contended that wood levels were historically low or wood was not ecologically important in some watersheds (Piégay et al. 2005), this is not supported by the literature. The preceding review shows that although wood levels vary among regions and stream reaches within a region, wood was and remains an important component of most river systems (Gurnell 2003; Montgomery et al. 2003). Moreover, the extensive literature on the importance of wood in streams provides the rationale for wood placement in streams and in part explains the popularity of wood placement to improve fish habitat. It also helps inform the areas of debate regarding placed wood discussed in subsequent sections.

Stability of placed wood

Another area of debate involves the stability or mobility of wood once it is placed in a river channel. Until the late 1990s, most wood placed in streams was in the form of structural treatments largely designed to remain static, regardless of the hydrologic or geomorphic conditions associated with the treated streams (Fig. 2) (Reich et al. 2003). This likely coincided with the historical perception of a healthy river channel being geomorphically stable through time (Norris and Thoms 1999). For this reason, many early studies on the efficacy of wood placement projects focused on whether placed wood or log structures remained in place, with “failure” or “success” defined as a log or structure moving from its original location (Frissell and Nawa 1992).

Published structural success (stability) rates have varied widely as has the definition of success or failure. For example, one of the earliest studies reported that only 24% of instream structures in a meadow stream in California were still in place and functioning after 18 years (Ehlers 1956). In perhaps the most long-term study, Thompson (2002) reported that 48% of placed structures were still functioning after 50 years in the Blackledge and Salmon rivers of Connecticut. In probably the most widely cited paper, Frissell and Nawa (1992) reported that 39% of structures that they examined in 15 streams in Oregon and Washington were still functioning, with highest failure rates in streams with high sediment loads and unstable channels. In contrast, many other studies have reported wood structure success or stability rates in excess of 90% (e.g., Carah et al. 2014; Crispin et al. 1993; Tarzwell 1937; White et al. 2011).

To examine structural stability rates in more detail, we searched the literature for studies that reported the physical or biological effectiveness of wood placement in streams. We located 122 studies on wood placement, 22 of which reported stability rates of placed wood (Table 1). “Success” rates based on structure stability averaged 78%, although success rates varied across studies. Only six studies reported success rates less than 75% (or failure

Fig. 2. Examples of common types of wood placement used in North America. Photos on the left represent immobile wood structures commonly used prior to 1990s, although similar designs are still in use today. In contrast, photos on the right show modern techniques using more mobile or natural wood with limited or no anchoring.



rates greater than 20%); most of these (four) were on structures placed prior to 1970. Only eight studies looked at structures more than 10 years after placement (Table 1), and only two of these studies looked at structure stability 20 years or more after placement (e.g., Thompson 2002; White et al. 2011). A handful of studies reported not only the age of projects, but also the magnitude and frequency of high-flow events that the wood structures had withstood (e.g., Ehlers 1956; Frissell and Nawa 1992; Roper et al. 1998; Schmetterling and Pierce 1999; Thompson 2002), although the flow events do not appear to explain differences in stability rates of wood structures. Rather, the structure type and channel morphology appeared to be stronger determinants of structure stability and success rate rather than magnitude or frequency of high flows. This emphasizes the influence and importance of geomorphic conditions (e.g., channel slope, confinement, incision) and watershed processes (i.e., sediment supply, hydrologic regime),

which vary greatly among streams and stream reaches, on stability and function rates of placed wood. All 22 studies reporting wood structure stability varied greatly in the definition of success or failure, number of structures examined, and age of structures or time since they were placed (1 to 60 years) (Table 1). All of these factors can effect determination of stability (success) rates, which confounds comparison across studies. Despite these differences, the reported stability rates in excess of 75% suggest that most wood structures remain in place and provide habitat benefits for a decade or possibly longer.

Only one study looked at the stability of logs felled or placed in the stream with little to no anchoring (Carah et al. 2014), and we found no published studies that looked exclusively at nonstructural or mobile wood placement (i.e., unanchored logs). We know from studies on natural wood in streams that although some logjams and other wood may persist for decades or even hundreds

Table 1. Summary of published studies on wood and instream structure placement stability including percent of structures still functioning, number and age of structures examined, and definition of “functioning” structure (function = stability).

Reference (chronological order)	Structures functioning (%)	No. of structures	Age of structures (years)	Definition of functioning
Tarzwil (1937)	91	2235	5	Structure lost or not (little detail provided)
Ehlers (1956)	24	41	18	In place and functioning as intended
Wilkins (1960)	100	13	4	No structural damage
Saunders and Smith (1962)	96	25	1	No damage or partially damaged (not washed out)
Jester and McKirdy (1966)	30	1600	30	Functioning properly
Gard (1972)	56	9	12	Good or excellent condition (not washed out)
House et al. (1989)	86	812	1–8	In place and functioning as intended
Armantrout (1991)	85	362	5	Improving habitat
Frissell and Nawa (1992)	39	155	1–8	Functioning as intended
Crispin et al. (1993)	98	200	5	In place and functioning as intended
Binns (1994)	90	111	18	Functioning as intended
House (1996)	100	22	1–4	In place and functioning as intended
Thom (1997)	86	143	6–12	No movement or moved less than one bankfull width
Roper et al. (1998)	84	3946	Not reported	In place or largely in place but shifted
Schmetterling and Pierce (1999)	85	66	1	Intact and pool twice as deep as riffle
D’Aoust and Millar (2000)	90	90	1	Partially or fully functional
Thompson (2002)	48	27	40–60	Improving habitat
Shields et al. (2006)	64	72	3	Remained in place (not clearly defined)
MacInnis et al. (2008)	89	250	12	Not damaged or destroyed by beaver
Miller and Kocheil (2010)	76	Not reported	1–6	Intact (not damaged, failed, or impaired)
White et al. (2011)	98	53	20	In place and functioning
Carah et al. (2014)	92	1973	2–6	Retained within project reach
Mean	78			

of years, wood is not completely static (see previous section). When a natural log first falls or is transported into a stream, its movement is a function of its diameter and length relative to the width and depth of the stream, and therefore, wood should not be expected to remain entirely static (Hassan et al. 2005; King et al. 2013). Moreover, a small but significant percentage (<5%) of wood in natural streams moves or is transported out of the system annually (Naiman et al. 2002).

As discussed previously, wood placement techniques that do not anchor wood in place and allow it to function and move naturally have become more common, particularly in smaller streams (<20 m bankfull width) (Fig. 2). These include placing logs and whole trees with heavy equipment or helicopter or felling nearby trees into a stream and letting the channel do much of the work distributing the wood (Carah et al. 2014; Nichols and Ketcheson 2013). That being said, fixed wood structures or limiting the mobility of wood have become commonplace in larger managed streams (>20 m bankfull width) where liability, engineering, and human safety concerns dominate project design objectives (Abbe et al. 2002) or in newly constructed channels where vegetation is not yet established and bank erosion concerns are high.

Physical response to wood placement

Although considerable debate on physical response to wood placement has focused on wood stability, a more important question is the response of physical habitat to wood placement. Obviously, changes in physical habitat are linked to the stability of wood, which appears to be relatively high in many cases (Table 1). A major goal of wood placement in streams and rivers is to improve physical habitat such as increasing pool area, habitat complexity, instream cover, and other metrics of fish-habitat quality. These changes are also linked to the amount or intensity of treatment, as there is a strong positive correlation between amount of wood and both physical habitat quality and fish numbers for both natural (Beechie et al. 2005; Murphy et al. 1984; Naiman et al. 2002) and placed wood (Jones et al. 2014; Roni and Quinn 2001a). Thus, if the placed wood or wood structures remain on site or function as designed, there typically are significant improvements in habitat.

Improvements in physical habitat following wood placement, including increased pool area, cover, and habitat complexity (number and diversity of habitats), have been well documented (Jones et al. 2014; Roni et al. 2008). In fact, many studies report large (>50%) and significant increases in pool frequency, pool depth, woody debris, habitat heterogeneity, complexity, spawning gravel, or sediment and organic matter retention following placement of instream structures, particularly in mountain streams and rivers (e.g., Binns 1999; Brooks et al. 2004; Cederholm et al. 1997; Gerhard and Reich 2000; Pierce et al. 2013; Reeves et al. 1997; Roni and Quinn 2001a). Studies in low-gradient (<1.5%) streams such as those in the US Midwest or western Europe have demonstrated physical habitat changes, including increased depth, cover, narrower channels, and increased organic matter retention, as a result of wood placement projects (e.g., Gerhard and Reich 2000; Hunt 1988; Laitung et al. 2002; Zika and Peter 2002). Other projects designed to aggrade incised stream channels have produced increases in water depth, width, pool area, and bed elevation (reduced incision) (Newbury and Gaboury 1988; Shields et al. 2004, 2006).

We reviewed 122 papers that evaluated effectiveness of wood placement. Of those, 83 reported some type of physical response other than structure stability. Summarizing the results of all these studies is difficult because habitat metrics vary greatly from one study to the next. Therefore, we categorized these simply by whether they reported a positive physical response, no response, or a negative habitat response. Seventy-seven of the 83 studies reported a positive response for at least one habitat metric. We assume that these studies are representative of projects on the ground, but only a small percentage of all restoration projects are ever monitored for effectiveness (Bernhardt et al. 2005), and it is not clear whether the published literature is biased towards positive results.

Recent evidence suggests that instream restoration projects (including wood placement) used for mitigation are unsuccessful at improving sediment and water quality under the Clean Water Act (Doyle and Shields 2012). However, the goal of wood placement is typically to improve habitat complexity and cover rather than improving water quality or reducing fine sediment. A few

studies have reported increased bank erosion as a result of in-stream structures (Frissell and Nawa 1992; Thompson 2002, 2006), though the majority of published studies have reported significant improvements in fish habitat (Fig. 3). It should also be noted that for some floodplain restoration projects, the goal is to increase channel migration and erosion through wood placement (Abbe et al. 2002). This suggests that channel migration or erosion caused by wood placement is highly context dependent and thus may be viewed negatively or positively depending on the context and project goals.

The magnitude of physical response to wood placement appears to be largely linked to size (length, diameter), type (e.g., natural with attached root wad, fixed, or mobile), and amount of placed wood, as well as its stability, longevity, and geomorphic setting (e.g., channel slope, sediment supply, hydrology). Guidelines for the size of wood for stream placement have been developed by some states and entities (e.g., Brooks 2006; Nagayama and Nakamura 2010; Oregon Department of Forestry and Oregon Department of Fish and Wildlife 1995). However, published studies have used highly variable amounts and types of wood placement, making it unclear how much or how intense wood placement needs to be to elicit a change in physical habitat conditions. Studies on natural wood do provide information on the size, type, and location of stable wood accumulations in channels of varying size and geomorphic setting (Fig. 1), which can be used as a guide for wood placement.

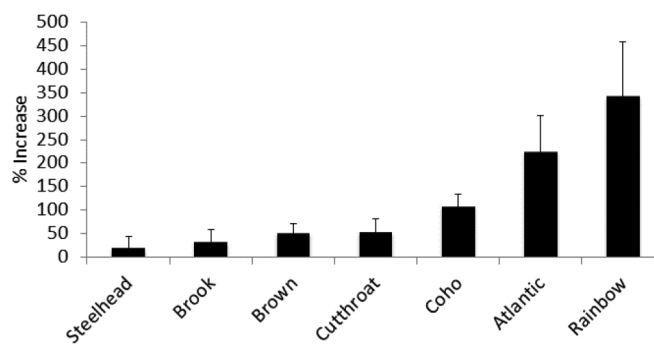
Biological response to wood placement

The effectiveness of wood placement techniques for increasing fish and other biota abundance has been an area of debate for more than 75 years. As early as the 1930s, Tarzwell (1937) called for more rigorous monitoring and evaluation to determine physical and biological effectiveness. Since then, many studies have reported improved habitat and fish production, particularly for salmonid fishes (e.g., Binns 1999; Hunt 1976; Pess et al. 2012; Roni and Quinn 2001a; Shetter et al. 1949; for a review, see Roni et al. 2008), whereas others have reported no detectable changes (e.g., Chapman 1996; Rosi-Marshall et al. 2006; Stewart et al. 2009; Thompson 2006).

Literature on the topic is extensive, and a handful of reviews and meta-analyses have been conducted in the last 10 years, although they also have produced varying conclusions. For example, reviews of the literature on effectiveness of instream habitat improvement and wood placement have reported significant improvements in physical habitat (pool area and cover) and localized juvenile or adult fish abundance (Roni et al. 2002, 2008; Smokorowski and Pratt 2007). These studies generally conclude that wood placement leads to physical habitat change, which produced localized increases in fish abundance. In contrast, in a re-analysis of historical data from studies prior to 1980, Thompson (2006) found few significant responses of trout to instream structure placement. He concluded that results of historical studies were largely inconclusive in part due to experimental design issues. Stewart et al. (2009) conducted a meta-analysis of 17 studies on engineered wood and rock structures, and although some fish metrics showed positive response to structural treatments, they concluded that the evidence regarding effectiveness of instream structures was inconclusive.

The most thorough meta-analysis of habitat and biological response to instream structure placement was conducted by Whiteway et al. (2010). They examined salmonid response to wood and other structure placement using data from 211 streams from 51 different studies and found significant improvements in physical habitat and positive and significant responses for most species of salmonid fishes (Fig. 3). In addition, Whiteway et al. (2010) found errors in the meta-analysis by Stewart et al. (2009); after correcting

Fig. 3. Response of various salmonid species to wood placement and other instream habitat improvement projects ($n = 211$) examined by Whiteway et al. 2010. Response is in percent increase, and error bars represent 95% confidence intervals (modified from Whiteway et al. 2010).



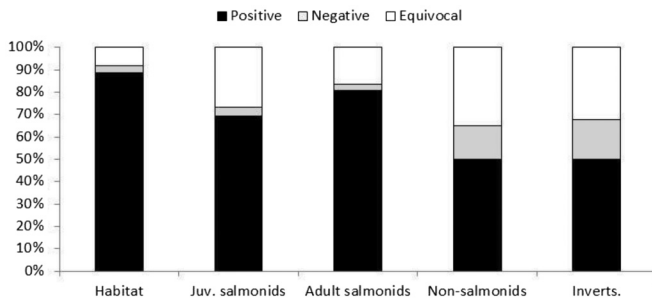
errors and reanalyzing the same data, they found significantly positive results for salmonid fishes.

The strict data requirements of a formal meta-analysis often exclude the vast majority of studies done on wood placement (i.e., Stewart et al. 2009; Whiteway et al. 2010). Therefore, we conducted a simpler summary of results of papers that we located that examined fish response to wood placement to see how many reported positive, negative, or no fish response to wood placement. Of the 122 studies that we located evaluating wood placement, 96 reported biological responses to wood placement, including 81 that reported changes in fish abundance, biomass, species diversity or richness, or survival. Because of the array of species, metrics, analysis, and study designs, drawing firm conclusions is difficult. Of the 81 studies examining fish response, 68 reported a positive response in fish abundance, biomass, or survival for at least one fish species and life stage (juvenile or adult), 27 reported no increase for one or more species or life stage, and seven reported a negative response (Fig. 4). Most positive responses reported were for juvenile and adult salmonids (69% and 80% of studies, respectively), with results for non-salmonid fishes being equivocal. This supports previous reviews by Roni et al. (2002, 2008) and meta-analyses by Smokorowski and Pratt (2007) and Whiteway et al. (2010) that instream structures lead to localized increases in fish abundance (number or density) for salmonid fishes. Although most studies on adult salmonids reported increased numbers, relatively few looked at changes in numbers of adult spawners or success of spawning.

Although the evidence strongly suggests that wood placement leads to localized increases in salmonid numbers, few of these studies were over a long term or at a population or watershed scale. We know of only five studies that examined watershed-scale response to wood placement either individually or coupled with other restoration treatments (Johnson et al. 2005; Jones et al. 2014; Reeves et al. 1997; Solazzi et al. 2000; White et al. 2011). Both Solazzi et al. (2000) and White et al. (2011) found large and significant increases in coho salmon (*Oncorhynchus kisutch*) or trout numbers following wood placement. White et al. (2011) is the only long-term published study (>20 years) conducted on wood placement (and instream restoration). The other population studies and the vast majority of all studies on wood and instream structure placement are less than 10 years in duration. The two other watershed-scale evaluations of wood placement (Johnson et al. 2005; Reeves et al. 1997) did not find significant increases in salmonid populations.

A related topic of debate centers on whether observed increases in fish abundance in a restored reach or a watershed are the result of local, project-related increases in production or simply attraction of fish from other unrestored areas. This is based in part on

Fig. 4. Proportion (%) of published studies on wood placement that reported positive, negative, or no change (equivocal) in physical habitat, fish (juvenile (Juv.) and adult salmonids, or non-salmonids), and macroinvertebrate (Inverts.) density or diversity. Number of studies (*n*): 83, 67, 33, 17, and 21 for habitat, juvenile salmonids, adult salmonids, non-salmonids, and macroinvertebrates, respectively. Note that some studies reported different responses for multiple species and life stages and thus contribute counts to more than one category.



observation of long-lived marine fishes being attracted to artificial reefs (Lindberg 1997). In addition, one of the more thorough evaluations of log structures and fish movement in six Colorado alpine streams found that in the initial years after restoration, increases in adult trout abundance were in part due to immigration into the restored reaches (Gowan and Fausch 1996). However, a follow-up study at the same sites 20 years later found that the restored reaches had higher numbers of adult trout and that this was the result of increased production rather than immigration (White et al. 2011).

Furthermore, studies on movement of fishes among nearby restored and unrestored reaches have found few fish moving from one reach to another and most fish moving less than 100 m during summer low-flow periods (Kahler et al. 2001; Roni and Quinn 2001b). Salmonids in habitats with abundant wood cover or complex pool habitats move shorter distances than fish in simple habitats with little complexity or wood cover (e.g., Bjornn 1971; Giannico and Hinch 2003; Harvey et al. 1999; Heggenes et al. 1991; Rinne 1982; Wilzbach 1985). Moreover, recent tagging studies on juvenile salmonid movement have indicated that although most fish do not move long distances during low-flow periods in summer and winter, a portion of juvenile salmonids move long distances or emigrate out of watersheds or subwatersheds in fall or winter (Achord et al. 2012; Ibbotson et al. 2013; Pess et al. 2011; Roni et al. 2012).

These migrations appear to be unrelated to reach-level conditions such as wood loading. Thus, there is little evidence to suggest that instream structures concentrate fish, and long-term studies indicate that wood placement leads to increased fish abundance, although there is evidence that some short-term concentrations of adult fish may occur (i.e., Gowan and Fausch 1996). This short-term concentration is less of a concern for juvenile anadromous fishes such as Pacific salmon, which usually spend 2 years or less in freshwater and produce a new cohort of fry to colonize available habitats every year (Reeves and Roelofs 1982; Roni et al. 2005).

Macroinvertebrates, which are an important food source for fish and indicators of ecosystem health, are also sometimes used to examine the success of wood placement. We found 21 studies of macroinvertebrate response (diversity, density) to wood placement: 14 showed increases in macroinvertebrate diversity or density following wood placement for at least one family or functional feeding group, whereas five studies found negative and nine no response to one or more metrics (21 studies with 28 responses for diversity or density; Fig. 4). Some studies showed that placed wood was an important substrate for macroinvertebrate and periph-

ton production and that placed wood had higher density and diversity of macroinvertebrates than cobble substrates (Bond et al. 2006; Coe et al. 2009). A meta-analysis of 24 studies evaluating macroinvertebrate response to various restoration techniques found significant increases in density and diversity, with the largest increases being for six wood placement projects examined (Miller et al. 2010).

Thus, although some studies have shown positive macroinvertebrate response to wood placement, the results are equivocal, suggesting that macroinvertebrate response is often localized to the specific wood structure or mesohabitat changed by wood placement (i.e., Coe et al. 2009; Hilderbrand et al. 1997). One could conclude, therefore, that macroinvertebrates are not sensitive to wood placement projects and thus are not a good measure of biological success of wood placement. Alternatively, macroinvertebrates may respond at a much finer scale than examined in most studies on wood placement. This may not be surprising given that wood placement is often not intensive enough to create changes in primary productivity and is typically designed only to improve fish habitat throughout a reach.

Discussion

Our review highlights several key conclusions regarding natural and placed wood in streams. Most notably, the literature indicates that wood was and is an important ecological component in rivers throughout the world, that most placed wood structures remain stable in stream channels for more than a decade, and that wood placement typically leads to improvements in physical habitat characteristics such as increased pools, cover, and habitat complexity, especially when matched to an appropriate geomorphic setting. Furthermore, most studies on salmonids have shown an increase in fish numbers following wood placement, though studies are lacking for some salmonid species, and results for non-salmonids are highly variable and relatively rare. Below we discuss in more detail these findings and areas in need of additional research.

Natural function of wood in rivers

Although some have argued that wood is not a natural part of stream ecosystems (Piégay et al. 2005), the literature indicates that wood was and is an important part of stream ecosystems throughout the world (Gregory et al. 2003). The amount of wood does, however, vary among ecoregions and channel types: in some environments and channel types, wood levels were historically low or little wood accumulated (i.e., confined bedrock channels >20% stream gradient or meadow streams with riparian areas dominated by shrubs and grasses), and in some stream locations, wood typically does not accumulate in relatively large amounts (Fox and Bolton 2007; Gurnell 2003; Rossetti et al. 2011). Moreover, levels of wood in many areas heavily managed by humans have been very low for many decades or even centuries, leading to the perception that wood was not historically present (Fox and Bolton 2007; Piégay et al. 2005). Therefore, rather than debate whether wood was ever present, the following questions are more appropriate.

- What were the historical or natural levels of wood in the stream reach in question?
- What are the current and historic sources of wood?
- Where did wood naturally accumulate in the channel historically and where would it accumulate now?
- What is the stability and longevity of natural accumulations of woody debris?

The first three questions are reach- or watershed-scale specific and require an assessment of historic, current, and potential riparian conditions, wood delivery processes, and current and potential stream morphology. The fourth question is best addressed by re-

gional studies on the stability and longevity of woody debris in relatively undisturbed sites (Fox and Bolton 2007).

Answering these questions will be important in determining whether wood placement in a reach is appropriate, where to place wood, how much wood to place, and what other actions might need to be taken to restore natural sources of wood. Should the low levels of wood be due to a young riparian or upland forest, it will also be important to determine how long it will take for natural wood levels to recover (e.g., Beechie et al. 2000).

Stability of placed wood

The stability or longevity of placed wood varies greatly from one study to another, although most studies report stability rates over 75% during the first decades after placement (Table 1). If one assumes that success rates in excess of 75% or 80% are high, then the argument that there are high failure rates of placed wood is not supported by the literature. On the contrary, the literature suggests that we can expect the majority of placed wood to persist in its original location for a decade or longer for recent wood placement projects (e.g., MacInnis et al. 2008; White et al. 2011). The question remains: precisely how long do natural accumulations of wood persist?

Review of the literature on natural wood accumulations suggests that the persistence of logs that are naturally delivered to the channel varies depending on wood size and channel size (i.e., Fig. 1) but that many larger pieces of wood may remain in the same general location for years to decades and, in some cases, centuries (Montgomery et al. 2003). Rather than debate the stability of placed wood, key restoration planning questions should include the following.

- What is the longevity and dynamics of placed wood of different sizes, species, and types?
- How do stream channel type, location in the channel, and wood placement type influence wood longevity and stability?
- What other restoration measures need to be taken to restore long-term delivery of natural wood to the system and maintain instream habitat?

It is also important to realize that anchoring wood structures, which may be necessary to protect infrastructure, may prevent wood from functioning similarly to wood naturally delivered to the channel. Moreover, placing wood does not restore natural wood delivery and function, which require restoration of riparian and upslope processes to assure a long-term natural source of woody debris (Beechie et al. 2010; Roni and Beechie 2013). If riparian and other areas that deliver wood naturally to stream channels are not restored or do not recover for many decades and shorter term improvements in wood and habitat are the goal, then it will be important to determine how often wood will need to be placed in the channel to maintain fish habitat while natural forests and sources of wood recover.

Physical response to placed wood

Studies on the physical response of placed wood, as well as studies on natural wood, have consistently shown that wood leads to increases in pools, cover, habitat complexity, and other measures of aquatic habitat quality known to be important for fish. The magnitude of physical response varies from one study to another, and most studies do not report consistent metrics. These discrepancies make development of guidelines on appropriate size, type, and placement of wood difficult. Ideally, the level of wood placement should be linked to natural or historical wood loading, accumulation, location, and function in the particular reach of interest (Fig. 1). Our review of the literature suggests that future research on the effects of placed wood on physical habitat should focus on addressing the following questions.

- What is the amount, type, and size of wood needed to achieve a physical response in different sizes and types of stream channels?
- How do responses differ among the types of wood placement (e.g., anchored, mobile)?
- How quickly will physical response be observed and how long can the observed improvements be expected to last?
- In what stream channel types or geomorphic settings can wood placement result in minimal or even detrimental physical change (i.e., increased erosion and habitat degradation)?

Answering these questions will require detailed long-term physical monitoring of many wood placement projects across a region.

The literature suggests that wood placement projects that were not successful in improving physical habitat failed because relatively little wood was placed, wood, pools, and habitat complexity were not degraded, and (or) larger reach- or watershed-scale processes such as sediment and hydrology were not addressed or considered. It is therefore important to confirm that the lack of large wood is the major factor that needs to be addressed in the reach and watershed in question. This emphasizes the need for watershed assessment and a more holistic approach to watershed restoration planning (Roni and Beechie 2013), which will also be required to restore long-term deliveries of natural wood.

Biological response

Most studies have reported positive biological responses, particularly for adult and juvenile salmonids. Evidence is strongest for a few species such as coho and Atlantic salmon (*Salmo salar*) salmon and resident brown (*Salmo trutta*) and rainbow (*Oncorhynchus mykiss*) trout. However, most of these studies are from small streams and focused on reach-level increases in abundance. Responses of non-salmonid fishes and macroinvertebrates are less consistent, and it appears that macroinvertebrate response to wood placement is limited to colonization of organisms on the wood itself.

Although the biological response appears to be well supported for some fishes, several additional questions remain unanswered, including the following.

- What is the response of juvenile and adult Chinook salmon, steelhead, and other less-studied fishes to wood placement?
- What is the response of fish in larger streams (>20 m bankfull width) to wood placement?
- What is watershed-scale or population-level fish response to reach-level wood placement for individual and multiple projects?
- How much physical habitat change is needed to produce a measurable change in fish abundance?
- What is the effect of wood placement on fish survival rather than fish abundance?
- What is the long-term impact of wood placement on food resources and fish production?

Most of these questions related to biological response will require well thought out and coordinated monitoring and evaluation of wood placement projects.

Several efforts to monitor watershed-scale response to wood placement are underway in the Pacific Northwest (Bilby et al. 2005; Roni et al. 2015), but more studies are needed in large streams to examine non-salmonid fishes and to evaluate the intensity of wood placement needed to produce physical and biological responses within a reach. In addition, most monitoring has been short term, and long-term studies are needed to quantify long-term responses and short-term change in abundance from increased production (Roni et al. 2008; Whiteway et al. 2010). Moreover, we located no studies that linked changes in the food web from wood additions to changes in fish growth and produc-

tion, although there is evidence that the placed wood itself is colonized by periphyton and macroinvertebrates (Coe et al. 2009).

Conclusions

In summary, our review of the current literature suggests that wood naturally occurred in most stream channels, failure rates of placed wood are relatively low, and positive physical and biological responses have been reported at the reach scale in most studies. There are, however, several unanswered questions that would help determine whether wood placement is appropriate for specific channel types or target species and that would explain why some projects do not appear to be successful. Answering these questions would be more fruitful than continuing to debate previous hypotheses that no longer appear relevant and would help to design more natural and effective wood placement and river restoration projects in the future.

Finally, although wood placement may meet short-term physical and biological objectives of some restoration programs, it does not address the process that delivers wood to stream channels. Long-term and sustained levels of natural wood in rivers and high-quality fish habitat will require coupling wood placement with restoration of riparian and upslope processes that are natural sources of woody debris.

Acknowledgements

We thank Sarah Whiteway for providing the data for Fig. 3 and Casey Rice, Jon Drake, JoAnne Butzerin, Rich Zabel, and two anonymous reviewers for helpful comments on earlier versions of this manuscript.

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