Received: 1 March 2024 | Revised: 23 May 2024 | Accepted: 28 May 2024
DOI: 10.1002/rra.4331

THEORETICAL AND CONCEPTUAL

WILEY

Working with wood in rivers in the Western United States

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Abstract

Recognition of the important physical and ecological roles played by large wood in channels and on floodplains has grown substantially during recent decades. Although

Funding information
Natural Environment Research Council (NERC), Grant/Award Number: NE/V008803/1

large wood continues to be routinely removed from many river corridors worldwide, the practice of wood reintroduction has spread across the United States, the United Kingdom and western Europe, Australia, and New Zealand. The state-of-science regarding working with wood in rivers was discussed during a workshop held in Colorado, USA, in September 2022 with 40 participants who are scientists and practitioners from across the USA, UK, Europe, and Japan. The objectives of this paper are to present the findings from the workshop; summarize two case studies of wood in river restoration in the western United States; and provide suggestions for advancing the practice of wood in river management. We summarize the workshop results based on participant judgements and recommendations with respect to: (i) limitations and key barriers to using wood, which reflect perceptions and practicalities; (ii) gaps in the use of large wood in river management; (iii) scenarios in which wood is generally used effectively; and (iv) scenarios in which wood is generally not used effectively. The case studies illustrate the importance of the local geomorphic context, the configuration complexity of the wood, and the potential for modification of river corridor morphology to enhance desired benefits. Moving forward, we stress the importance of collaboration across disciplines and across communities of research scientists, practitioners, regulators, and potential stakeholders; accounting for stakeholder perceptions of the use of large wood; and increasing non-scientist access to the latest state-of-science knowledge.

KEYWORDS
engineered logjams, large wood, natural flood management, nature-based solutions, practitioners, stage zero restoration

1 | INTRODUCTION

Recognition of the important physical and ecological roles played by large wood in channels and floodplains largely grew out of research conducted in the northwestern portion of the United States starting in the 1970s (Harmon et al., 1986; Keller & Swanson, 1979; Keller & Tally, 1979; Wohl, 2017). For more than a decade, geomorphic research on large wood in river corridors occurred predominantly in this region, with some notable exceptions such as Gregory's work in the United Kingdom (Gregory et al., 1985; Swanson et al., 2021). Increasing insight into the effects of individual wood pieces and logjams on river process and form led to growing recognition that river corridors in many forested regions had been substantially altered by upland and floodplain deforestation, removal of wood from river corridors, and other human activities (Montgomery et al., 2003; Wohl, 2014). The anthropogenic removal of wood has contributed to increased downstream conveyance and longitudinal connectivity, as well as associated decreases in lateral and vertical connectivity within river corridors (Collins et al., 2012; Keys et al., 2018; Spreitzer et al., 2021; Wohl & Beckman, 2014). These changes in connectivity commonly result in reduced uptake of nutrients and storage of sediment, altered channel planform and lateral mobility (Collins et al., 2012; Fetherston et al., 1995; Marshall & Wohl, 2023), reduced habitat abundance and diversity (Gurnell et al., 2005; Kalogianni et al., 2020; Richmond & Fausch, 1995; Senter & Pasternack, 2011), reduced biomass and biodiversity (Herdrich et al., 2018; Venarsky et al., 2018), and reduced attenuation of downstream fluxes of water, solutes, sediment, and particulate organic matter (Marshall et al., 2021; Marshall et al., 2023; Welling et al., 2021; Wohl & Scott, 2017). Consequently, river restoration now sometimes re-introduces large wood to rivers (Grabowski et al., 2019; Roni et al., 2015).

The deliberate placement of large wood in rivers dates to the 1890s in connection with fish habitat (e.g., Thompson & Stull, 2002), with periods of more extensive use of wood in some regions, such as placement in streams of the continental United States during the 1930s by the Civilian Conservation Corps (Hunter, 1991) and portions of the midwestern US during the 1960s (White, 2002). The most recent phase of wood reintroduction was primarily pioneered by practitioners in the northwestern US, with development of wood structures that more closely mimic natural wood accumulations (Roni et al., 2015).

At present, practitioners working primarily in the U.S. States of Oregon and Washington are taking wood reintroduction to a new level by introducing hundreds to thousands of large logs into individual river corridors a few hundred meters to a few km in length. The intent of these wood additions is to re-establish channel-floodplain connectivity and create a river-wetland corridor (Wohl et al., 2021) and associated functions such as habitat and resilience to disturbance (Flitcroft et al., 2022; Hinshaw et al., 2022). These projects are notable for the magnitude of wood reintroduction and the use of unanchored wood pieces (pieces that lack driven piles, large boulders, chains, and other designs used to artificially prevent wood mobilization) that are allowed to redistribute as discharge varies through time. More commonly, reintroduced individual pieces or engineered logjams are somehow anchored in place because of concerns about hazards associated with downstream movement of the wood or the desire to retain wood-induced features such as pools and overhead cover for fish (Nagayama & Nakamura, 2010; Pess et al., 2012; Polivka & Claeson, 2020).

Engineered logjams take various forms, from a few closely stacked pieces projecting slightly out from the river bank to a more open framework or pieces partly buried in mid-channel bars or the floodplain, sometimes with the intent of trapping and storing smaller, more mobile wood pieces moving down the river corridor (Abbe et al., 2018; Addy & Wilkinson, 2016; Norbury et al., 2021; Pess et al., 2012) (Figure 1). Many engineered logjams do not span the entire active channel. Channel-spanning logjams can be particularly effective at storing sediment (Livers & Wohl, 2021; Welling et al., 2021), as well as inducing channel avulsion and enhanced spatial heterogeneity in the river corridor (Collins et al., 2012; Wohl, 2011), which may or may not be desired by managers at a particular site. Engineered logjams also commonly do not allow for substantial mobility of wood pieces (Wohl et al., in press) or include wood pieces with varying states of wood decay.

Although large wood continues to be routinely removed from many river corridors, the practice of wood reintroduction has spread across the United States, the United Kingdom and western Europe, and Australia and New Zealand (Cashman et al., 2019; Collier et al., 2009; Kail & Hering, 2005; Lester & Boulton, 2008; Neuhaus & Mende, 2021). Practices and objectives vary widely. In the northwestern US, for example, much of the reintroduction is driven fundamentally by the desire to restore salmon habitat (Roni et al., 2015), whereas wood reintroduction in the UK is driven by a desire to enhance natural flood control measures by using channel-spanning logjams that are not in contact with the channel bed (Grabowski et al., 2019). As with any form of river restoration, practitioners, regulators, and research scientists argue about the most effective and appropriate practices and desirable outcomes. Rivers that include large wood and river morphologies associated with abundant wood—including braiding and anastomosing planforms—remain unattractive to large portions of society (Chin et al., 2014; Kondolf, 2006; Le Lay et al., 2008; Piégay et al., 2005), suggesting that outreach and communication are as important at this stage (Garcia et al., 2020) as ongoing research in promoting the use of large wood in river restoration.

The summary presented here grew from a three-day "Working with Wood I Rivers" workshop held in Colorado, USA in September 2022 with 40 participants from across the USA, UK, Europe, and Japan. Participants were drawn from across academia (70% of participants), private consultancies (22%), and state and government bodies (8%) and came from all career stages. There were no representatives from tribal staff, recreation communities, or non-profit staff organizations. As such, the views herein come from only a portion of the community involved in wood management.

The workshop focused on practitioner perspectives of wood dynamics in natural and managed systems and how those impact upon management practices. Primary objectives were to identify (i) the key challenges and concerns that may limit the use of large wood in river

FIGURE 1 Examples of engineered logjams. Arrows indicate flow direction. (a) Tsirku River, Canada. (b) Tryon Creek, Oregon. (c) All three photos from South Fork Nooksack River, Washington. [Color figure can be viewed at wileyonlinelibrary.com]

management, (ii) gaps in the use of large wood in river management, (iii) common river management objectives that could be facilitated by the use of large wood, and (iv) scenarios in which wood is commonly used effectively and ineffectively, respectively, in the experience of workshop participants.

After the workshop, the project team sought to gather views from the community involved in the use of wood in management on two topics that were highlighted as being important—stakeholder perceptions of large wood in rivers and the breadth of disciplinary collaborations across the academic and practitioner communities and how these might change in the future. A short online survey was publicized on the commonly used International Association of Geomorphologists moderated electronic mail distribution list "Geomorph List." The survey elicited 74 responses with respondents from the academic (47), practitioner (25), and regulatory (2) communities coming from 14 different countries and self-identifying as having a background in geomorphology (36), civil, environmental, and ecological engineering (18), hydrology (7), stream and riparian ecology (8), environmental science (3), water resource education (1), and geography (1). Whilst "Geomorph List" requires a user subscription, it is a commonly used platform for professional communication and responses were used to supplement discussion at the workshop. Basic survey responses are provided in the Supplemental Information.

Our objectives in this paper are to summarize the results of the workshop, briefly review two endmember case studies of working with wood in river management, and conclude with suggestions for advancing the state-of-science and practice of wood in river management.

2 | WOOD IN RIVER MANAGEMENT

This section briefly summarizes the current state of practice for large wood in the context of river management, including restoration, as perceived by participants in the 2022 workshop. The summary focuses on (i) limitations and key barriers to using wood in river corridors, (ii) situations in which wood is not commonly used but could be, (iii) uses of wood that are generally effective, and (iv) uses of wood that are generally ineffective.

The retention or reintroduction of large wood to river channels and floodplains is highly uneven among countries or parts of a single country (e.g., Cashman et al., 2019). Many river restoration projects in the Pacific Northwest region of the United States, for example, reintroduce substantial volumes of wood to rivers (Flitcroft et al., 2022; Scott, 2024) and individual states and local governments in this region mandate the consideration of large wood in river management, whereas wood is still primarily removed from channels in other parts of the United States. In Europe and the UK, periodic or episodic (i.e., post-flood) wood removal is still the norm, while wood reintroduction may occur typically at small-scale restoration projects with the use of very few logs, typically anchored to the banks (Anlanger et al., 2022; Harvey et al., 2018). The barriers and limitations to using large wood that are outlined below can include very site-specific details, but they are common across many projects.

The two primary concerns to using wood in river management are legitimate perceptions over the potential negative aspects of wood introduction and practicalities (Anlanger et al., 2022; Dalu et al., 2022; Grabowski et al., 2019; Pess et al., 2023; Piégay et al., 2005; Roni et al., 2015; Wyżga et al., 2009). Negative perceptions include fear that wood will: (i) enhance flood inundation via increased hydraulic roughness or increased backwater effects at bridges clogged by wood jams (De Cicco et al., 2018; Schalko et al., 2018); (ii) increase rates of bank erosion (Florsheim et al., 2008; Zhang & Rutherfurd, 2020); (iii) damage infrastructure (e.g., bridges, weirs) due to direct impact, increased drag force and hydraulic loading, or due to increased local scouring (e.g., De Cicco et al., 2018; Mazzorana et al., 2018); or (iv) create hazards for recreational users such as paddlers, those floating in inner tubes, and anglers (e.g., Conley & Kramer, 2020). Negative perceptions may also arise because of a lack of knowledge of historical conditions in that people do not expect to see wood in rivers and may therefore consider the wood to be unsightly or unnatural (Chin et al., 2008; Le Lay et al., 2008; Ruiz-Villanueva et al., 2018). Practicalities overlap with perceptions in that wood that becomes mobile during high flows can create hazards for infrastructure within and along rivers. Although rare, people using rivers for recreation have drowned after becoming trapped in large wood accumulations (Conley & Kramer, 2020). Perceptions and the emphasis placed on different perceived hazards is likely to vary among stakeholders (Chin et al., 2014). The general public may be most concerned about safety for recreational users or about flooding private property, whereas practitioners may be especially concerned about legal risk and maintaining good relations with clients, and regulatory agencies may be concerned about risk to aquatic biota (e.g., fish passage) or infrastructure (e.g., bridges), or about the risk of increasing flood stages. In addition, river managers may be under pressure by local administrators and politicians who are asked by citizens to "clear" rivers, wood being still perceived by people as waste or debris. Workshop participants identified 12 additional challenges and concerns to using wood in river management (Table 1), many of which have also been articulated in recent reviews of wood in river management (e.g., Grabowski et al., 2019; Roni et al., 2015).

Participants in the workshop identified several river management objectives for which large wood could be more commonly employed (Table 2).

In addition to these scenarios in which large wood could better support and facilitate river management, workshop participants made three recommendations. (1) Use wood that is already on site whenever possible. (2) Increase the use of wood in urban river settings (Blauch & Jefferson, 2019; Lassettre & Kondolf, 2012; Wohl et al., 2016). (3) Increase the diversity of river corridors (geographic location, spatial distribution within river networks, stream types) in which wood is used.

Drawing on personal experience workshop participants created a list of scenarios in which large wood is mostly likely to be used effectively as part of river management (Table 3); participants were keen to

TABLE 1 Challenges and concerns for using large wood in river management.

Challenge or concern
Limited technical awareness of the potential benefits of wood and knowledge of diverse ways in which wood can be used in river management, by both practitioners and regulators
Opposition by local communities and stakeholders, in part due to a lack of effective communication to non-scientists of the state-of-science and understanding of wood in rivers by the research community
Lack of good technical guidance on how to include large wood from an engineering design perspective, especially jams with multiple large wood pieces
Lack of understanding of the wood regime in a particular river and hence of the reaches likely to retain wood under natural conditions, as well as the abundance, spatial distribution, supply, decay and breakage rate, and mobility of wood
Limited conceptualization of reference reaches based primarily on channel form, rather than the use of functional reference reaches based on river processes—this can also create a misunderstanding of the goals of process-based restoration
Simplistic views of river restoration, and the need for increased recognition that different river projects and locations can benefit from different approaches and project designs
Lack of suitable wood (with respect to size, piece complexity, tree species, resistance to decay) that is available close to the project site for a reasonable cost, and the relative installation and maintenance costs of wood versus traditional techniques such as rock riprap
Addition of cost and time to a project because of permitting requirements from regulatory agencies and/or engagement with stakeholders/to increase public acceptance of using wood
Uncertainties associated with timespan for, and nature of, channel and floodplain adjustment to introduced wood—linking wood characteristics to river adjustments and processes (e.g., creation of fish habitat) is likely to be more challenging to model and predict than for riprap and other traditional, well-studied, structures
Uncertainties regarding the stability of the wood during design floods such as the "100-year flood"
Site constraints such as vulnerable downstream infrastructure or lack of space for channel adjustment following wood introduction
Lack of monitoring of previous projects employing wood and the difficulty and expense of collecting monitoring data in a river corridor dynamically adjusting to introduced wood
Lack of evaluation in the processes that create risk conditions associated with wood movement at both catchment and reach scales and across different geographical contexts

stress the word "effective" given that not all use of wood in management scenarios has or will be effective and should be carefully used.

Scenarios in which wood is less likely to be used effectively in river management include those described in Table 4.

3 | CASE STUDIES

This section briefly reviews two endmember case studies from the western United States to illustrate the diversity of contemporary use of wood in river management in this region. The project from Washington involved introduction of a substantial number of unanchored wood pieces and represents one endmember of the contemporary range of wood use in river management. The project from Colorado involved use of a smaller number of anchored wood pieces and represents the other endmember of wood use in river management. Two additional Colorado-based case studies (Big Thompson River and St Vrain Creek) that reflect different types and volumes of wood additions are presented in Supplemental Information.

3.1 | North Fork Teanaway River, Washington, USA

The North Fork Teanaway drains 126 km^2 in Washington. The project site (47.3456° N, −120.8511° W) has a valley gradient of 1.5% and valley floor width of 100 m. The flow regime includes snowmelt and rain-driven peak flows. Stakeholders involved in the restoration project were the Yakima Nation, Mid-Columbia Fisheries Enhancement Group, Bonneville Power Administration, Washington State Departments of Natural Resources and Fish and Wildlife, and the National Oceanic and Atmospheric Administration.

The project site lacked salmonid spawning and rearing habitat, with an incised mainstem channel that had eroded to bedrock and boulders. Wood placement in summer 2020 sought to trap gravel, cause bed aggradation, increase floodplain inundation, spur vegetation establishment in the channel, and allow the river to rearrange the valley floor, sustaining a multichannel, complex river corridor.

Logs were placed throughout the mainstem in a well-distributed pattern, with the exception of two denser jam-like accumulations: one built by stacking logs loosely atop one another and the other built by deliberately burying and stacking logs in a dense configuration to increase stability (Figure 2). Most logs were smooth and were placed with little interaction between wood pieces and the channel boundaries or riparian vegetation that might reduce wood mobility. The loosely placed wood covered ~200 m of the mainstem length over an area of ~4000 m^2, and the site had negligible wood supply other than from restoration.

After a peak flow that inundated part of the floodplain in summer 2021, numerous gravel patches formed in the interstices of the placed wood. Some logs rearranged slightly, but very few logs moved more than a few meters. Wood placement appeared to be functioning as designed, achieving objectives of trapping sediment that could lead to floodplain reconnection. However, most of the placed wood moved downstream during moderate winter flows. This substantially reduced in-channel roughness and facilitated mobilization of the gravel previously trapped by the wood, returning most of the project reach to a pre-restoration condition.

This project provides an instructive comparison to a substantial introduction of unanchored wood at Deer Creek, Oregon, which is summarized in Scott (2024). Differences in wood characteristics and placement at the two sites (Table 5) led to contrasting outcomes after moderate winter flows at each site.

TABLE 2 River management objectives that could be facilitated by use of large wood.

Management objective	Description and relevant references
Bank stability	Large wood can be positioned to enhance bank stability or to create instability that may create new germination sites for riparian plants or overhead cover for fish (Shields et al., 2004)
Sediment dynamics	Wood can be very effective in trapping and storing sediment, especially in settings with enhanced sediment yields, such as burned catchments or those with changes in land cover; by storing sediment, wood can also enhance substrate heterogeneity and habitat diversity
Hyporheic exchange	Wood can promote hyporheic exchange flows and these flows can have additional water quality benefits (Marshall et al., 2023)
Aquifer recharge	Wood increases hydraulic roughness in channels and floodplains, reduces average velocity, and, by prolonging overbank inundation, could promote aquifer recharge (Doble et al., 2012)
Organic carbon and nutrient dynamics	By trapping and retaining sediment and particulate organic material, and facilitating hyporheic exchange flows, wood can enhance storage of nutrients adsorbed to fine sediment (e.g., P) and retain dissolved and particulate carbon (Beckman & Wohl, 2014; Livers & Wohl, 2016)
Aquatic habitat	Although wood is likely to be employed to create fish habitat, wood can also provide substrate beneficial to aquatic macroinvertebrates and microbial communities that are an important part of stream food webs (Gerhard & Reich, 2000; Nakano et al., 2018)
Floodplain habitat	Large wood can help to trap plant propagules moving downstream and provide favorable germination sites for these propagules; floodplain large wood also provides habitat for a wide array of organisms, from microbes and fungi through reptiles, amphibians, small mammals, and birds (Braccia & Batzer, 2001; Collins et al., 2012; Fetherston et al., 1995; MacNally et al., 2001)
Channel planform dynamics	Large wood can enhance channel avulsion and the formation of a multichannel planform (braided or anastomosing); these natural disturbances can enhance aquatic and riparian habitat abundance and diversity (Collins et al., 2012; Fetherston et al., 1995)
Restoring the natural wood regime	River management can restore a self-maintaining large wood regime by introducing large, stable wood pieces that can help to trap and retain smaller, mobile wood pieces, and create logjams; by introducing wood with diverse piece sizes, shapes, and decay states; by allowing/expecting some wood pieces to be relatively mobile under annual high flows; and by recognizing spatial variation within the river corridor and river network in terms of sites at which wood would naturally be recruited, transported, or retained (Scott, 2024)
Facilitating beaver (*Castor* spp.) presence	Where an incised channel concentrates peak flows in a manner that limits the ability of beavers to maintain dams, introduction of large wood may provide a platform on which beavers can build stable dams

3.2 | Cache La Poudre River, Colorado, USA

The Cache La Poudre River (Poudre River) catchment is a snowmelt-dominated system that heads in the Rocky Mountains and drains 4300 km^2. At the project reach (40.4829166° N, −104.956291° W) in the Great Plains portion of the catchment, the valley gradient is 0.004, the valley floor width averages 500 m, and the channel gradient is 0.0036 m/m. Stakeholders involved in the project are Larimer County, Colorado; Colorado Department of Transportation; and Colorado Parks and Wildlife.

The Poudre River is a primarily single-thread sinuous channel with pool-riffle bedforms, but the downstream half of the project reach was historically straightened in the mid-20th century. The dominant native riparian tree species is Plains cottonwood (*Populus deltoides*), but non-native species are also prevalent including Siberian elm (*Ulmus pumila*) and crack willow (*Salix fragilis*). The wood regime within the project reach is relatively more functional than other more urbanized areas of the catchment but has been greatly impacted by human alterations.

The Poudre River catchment and project reach have an extensive history of human alterations. Catchment hydrology is greatly altered by water extraction from instream diversion structures for agriculture and municipal water storage. The downstream half of the project reach was historically straightened and the channel was widened, and a berm was installed along river right to disconnect the channel and floodplain in the 1950s. Agricultural lands occupy the riparian area along both sides of the river, and riprap is present along several portions of the banks.

The main project goal was to increase overall river health and function by reconnecting the main channel, floodplain, and secondary channels. The entire reach is owned by Larimer County and is a designated publicly accessible Open Space. Bridges are present at the upstream and downstream sides of the project reach and constrict floodplain flow during most flows. The project reach is mapped as a regulatory floodway for the Federal Emergency Management Agency (FEMA) flood insurance program and therefore requires the proposed restoration design to have "no-rise" in the 100-year water surface elevation based on 1D hydraulic modeling using the Hydrologic Engineering Center River Analysis System (HEC-RAS) software. Additionally, the Colorado Department of Transportation (CDOT), which owns the bridge at the downstream end of the project reach, required all large wood structures to be designed (remain stable) to the 100-year flood to reduce risk of mobile wood at the bridge and

TABLE 3 Likely scenarios for effective use of wood in river management.

Management action & sample references	Description
Bank stabilization (Sudduth & Meyer, 2006; Testa et al., 2011)	Although typically used where there is a low-value asset to be protected from bank erosion, or where the wood can be deeply submerged, this use of wood can be very successful
Habitat diversity (Clark et al., 2019; Whiteway et al., 2010)	Large wood is primarily used to enhance habitat for salmonids by creating hydraulic and substrate heterogeneity, overhead cover, and greater abundance and volume of pool habitat
Sediment retention & enhanced substrate diversity (Elosegi et al., 2017; Osei et al., 2015; Skalak & Pizzuto, 2010)	By obstructing flow and creating backwater effects and zones of lower velocity, large wood can enhance retention of sediment, especially pebble to sand-sized sediment, although also suspended fine sediment; this typically creates more patchiness of bed substrate and enhances substrate diversity
Channel planform & attenuating downstream fluxes (Fixler, 2022)	This application of large wood is more widespread in Oregon and Washington, where large wood has been used very effectively to increase channel complexity (e.g., multithread planform) and channel-floodplain connectivity; this also increases resilience to disturbance
Grade control (Berg et al., 2020)	Large wood can limit channel incision and headcut migration by creating relatively stable points along the longitudinal profile, increasing hydraulic roughness and retaining sediment
Wood retention (Millington & Sear, 2007; Scott, 2024)	Introduction of large volumes of wood as part of channel-floodplain reconnection projects in Oregon and Washington has created sites that effectively trap and retain mobile wood
Stakeholder engagement (Grabowski et al., 2019; Shulz-Zunkel et al., 2022)	With increasing awareness and acceptance of nature-based solutions, stakeholders have become more open to the aesthetic appeal of wood-rich river corridors, especially when wood becomes associated with improved recreation (e.g., fishing, birdwatching), increased access to the river corridor, and a sense of ownership of the local environment

show no increase in shear stress along the highway from proposed floodplain reconnection at the 100-year and 500-year floods.

TABLE 4 River management scenarios characterized by ineffective use of large wood.

Activity	Description
Any project that is "one and done"	Projects that neglect monitoring and adaptive management of wood as an inherently transient component of the riverscape
Inappropriate location or design	Inappropriately located or designed wood additions, including inappropriately spaced and sized deflector jams for bank stabilization
Fixed targets	Targets for wood introduction based on fixed metrics that do not account for wood function, channel adjustments, wood sustainability, and characteristics of the wood regime at a project site (e.g., a specified number of wood pieces per length of river)
Lack of consideration of secondary effects	Ignoring potential secondary effects of wood, such as destabilization of channel planform via bank erosion, or bed incision or aggradation, clogging of spawning gravels by fine sediment accumulating in wood-induced backwaters, or changes in water temperature because of changing channel cross-sectional area

The project was constructed in Spring 2019 with a focus on a 0.6-km-long reach. Project earthwork removed historical berm material and riprap, narrowed the channel width from the historically widened (dredged) condition, graded the channel profile to initiate riffle and pool bedforms, and graded floodplain areas to reconnect relic and contemporary flow paths. Large wood structures were installed in the active channel and floodplain to help create flow roughness following construction, increase flow complexity to develop diverse habitat conditions in the channel and floodplain, and help increase wood storage in the reach (Figure 3). Revegetation used native wetland, riparian, and upland species.

During the first 3 years after the project, the aquatic and riparian habitat availability and diversity greatly increased from pre-project conditions and a much greater amount of in-channel and floodplain wood was retained in the project reach (Figure 4). Specifically, the volume of wood in the initially placed, in-channel logjam doubled, the diversity of wood piece sizes increased, and the depth of the associated pool nearly doubled. Additional logjams formed naturally and each created an adjacent pool. Improved site conditions are reflected in the greatly increased abundance and diversity of riparian plant species, increased wildlife sightings in the reach, and increased fish species presence based on surveys conducted by Colorado Parks and Wildlife before and after the project.

The project has been particularly successful on the local scale to showcase the importance of dynamic river processes, floodplain connection, and the wood regime. Most river management and restoration practitioners in the region do not feel that dynamic rivers are healthy and/or dynamic river processes and wood jams are too dangerous in proximity to urban areas.

FIGURE 2 Repeat, orthorectified, georeferenced aerial photo mosaics showing the post-restoration wood assemblage along the North Fork Teanaway and its evolution over 2 years. Dotted black lines outline where fine sediment aggraded during 2020–2021. Credit Dan Scott. [Color figure can be viewed at wileyonlinelibrary.com]

3.3 | Insights from the case studies

The case studies highlight at least three important influences on the success of using large wood in river management. First, the local geomorphic context is critical (Gurnell et al., 2018; Wohl et al., 2019; Wohl et al., 2024). In the case of the North Fork Teanaway project, the lack of hydraulic roughness of the river corridor strongly influenced the retention of unanchored wood pieces. Features such as multichannel planform, islands and bars, and floodplain vegetation can help to trap and retain unanchored wood pieces, allowing introduced wood to form jams that create local habitat diversity (Scott, 2024; Scott & Wohl, 2018; Wyżga & Zawiejska, 2005).

Second, the piece complexity of introduced wood strongly influences both its stability and physical function, especially where wood is not anchored. Smooth, simply shaped wood pieces are less stable and less likely to create local erosion and deposition. Pieces with branching complexity and/or rootwads are both more stable when unanchored and more able to create pool scour or bar formation (Merten et al., 2010; Ravazzolo et al., 2022).

Third, the Poudre River project included modification of the river corridor morphology, as well as large wood reintroduction. Where past human alterations such as channelization, construction of artificial levees, and flow regulation have hydrologically disconnected the channel and floodplain, it may be necessary to modify river corridor topography (Flitcroft et al., 2022; Powers et al., 2019), as well as introducing large wood, to achieve project goals such as lateral connectivity, planform complexity, and channel mobility.

TABLE 5 Contrasts between the Deer Creek, Oregon, and North Fork Teanaway, Washington wood restoration projects.

	Deer Creek	NF Teanaway River
Placed wood characteristics	Logs mostly rough, with either rootwads or branches	Logs mostly smooth
Wood placement style	Most pieces loosely placed, but some buried, tipped in from terraces or valley walls, ramped on valley walls, or placed just upstream from living vegetation	Most pieces loosely placed in low-flow channel with limited burial or ramping on valley walls
Wood response to moderate winter flow	Loose wood reorganized on stable, nucleation points (buried logs, logs ramped on valley walls, near-channel vegetation) to form jams	Most logs moved downstream, with half remaining in a densely packed jam at the downstream end of the reach
Morphologic response after wood reorganization	Jams formed pools, trapped sediment, and diverted flow overbank, driving channel avulsions	Logs initially trapped gravel, but gravel was removed after log mobilization
Restoration outcome	Decrease in the threshold discharge needed to overtop channel banks, allowing potentially beneficial aggradation, avulsion, and floodplain disturbance to occur at lower, more frequent flows	Return to pre-restoration condition but with limited change around wood structures that did not move; transported wood may be trapped at downstream restoration projects

4 | RECOMMENDATIONS MOVING FORWARD

Workshop participants discussed potential ways in which stakeholders involved in using large wood as a management and restoration tool could work more effectively together. The recommendations from these discussions are augmented with results from the online survey and are summarized below. We offer these suggestions based on the evidence that rivers historically altered by diverse human activities and subject to changing disturbance regimes associated with climate warming and ongoing human manipulations can benefit from a greater understanding and use of wood in river corridors.

4.1 | Collaboration across disciplines

The sustainable use of wood in rivers as a management technique requires an inherently interdisciplinary approach, with a need to consider knowledge from geomorphology, sedimentology, riparian and stream ecology, and civil and environmental engineering. Working with a wide range of people can increase the diversity of knowledge brought to management, and it is important to increase the diversity of people participating in river management. This includes the need to cross traditional disciplinary silos as well as between the researcher and practitioner communities. This was reflected in the online survey of researchers and practitioners, all of whom currently collaborate within and beyond their own discipline (Figure 5a and Supplemental Information tables). When participants were asked who they would like to work with in the future, the number and scope of potential

FIGURE 3 Examples of wood structures emplaced in the floodplain and channel. Yellow arrows indicate flow direction. Credit Johannes Beeby. [Color figure can be viewed at wileyonlinelibrary.com]

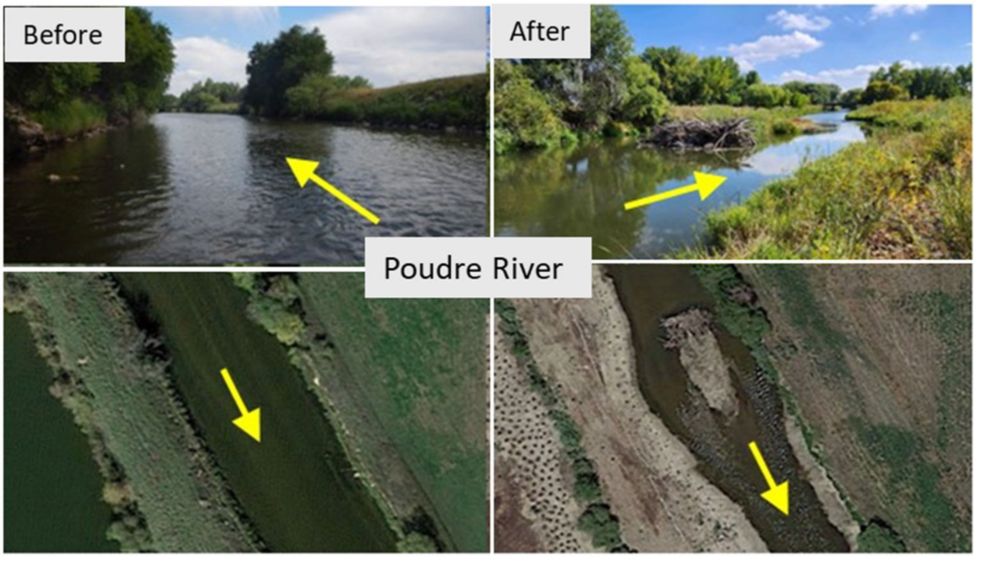


FIGURE 4 Matched ground views (above) and aerial views (below) of a portion of the project reach before and after restoration. Yellow arrows indicate flow direction. Credit Johannes Beeby. [Color figure can be viewed at wileyonlinelibrary.com]

collaborations increased to disciplines beyond what we may consider "traditional" within the field. This included a desire to work with people across the creative writing, policy, climate science, pre-university education, artistic, and legal sectors (Figure 5b). Further, although not included in this survey, there was also a desire to work with indigenous people to incorporate traditional ecological knowledge into restoration.

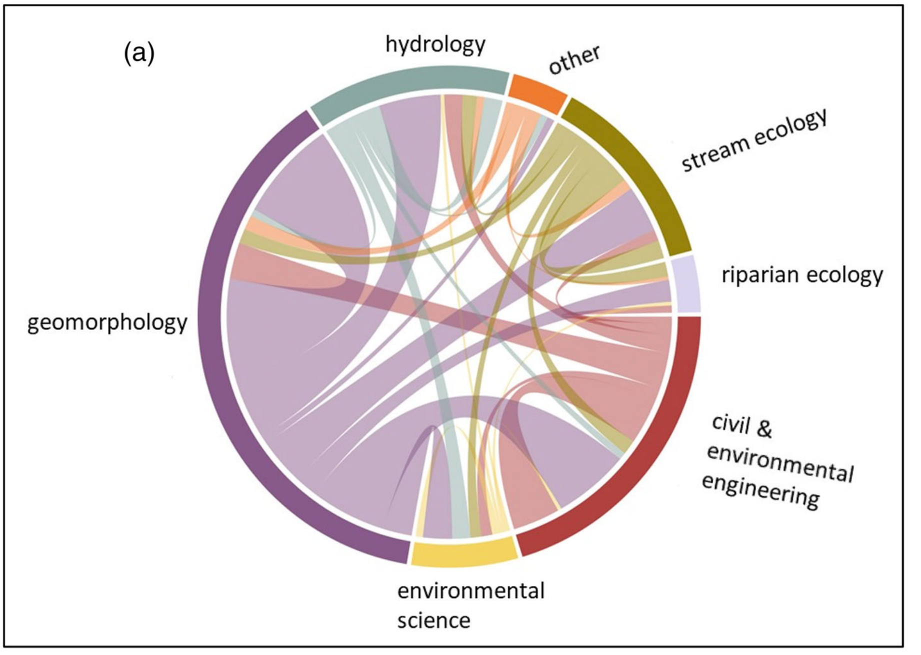
The desire to work with a more diverse group potentially reflects the changing practice of how and why we use large wood in rivers. There is a clear need to engage with audiences beyond the academic and practitioner community because stakeholders such as the public, regulatory authorities, landowners, and utilities companies have an important role in integrated management approaches. This engagement needs to be undertaken using dissemination methods that are effective for different stakeholder groups, for example, via creative writing or art-based outreach. Communication tools such as online story maps (e.g., Deer Creek, Oregon), community outreach events (including artistic activities or displays), cross-disciplinary conferences such as the Wood in World Rivers conferences (e.g., Gregory et al., 2003), and the workshop summarized here are useful, important, and must expand. There is also a clear suggestion that our relationship with rivers and the techniques we use to manage them, including large wood, will have to evolve in the future to reflect changes in climatic conditions.

However, despite a recognition of the need to increase collaborative opportunities, workshop participants also noted that deep, engaged, collaboration between different stakeholder groups is often difficult. For example, in the practitioner community, restoration and management projects using wood are commonly driven by specific client requests with short timescales from project inception to delivery. Conversely, within the academic community, there is typically an ability to work on curiosity-driven projects that happen over longer timescales with larger budgets and capacity to undertake post-intervention monitoring. To overcome these disparities and work more effectively together, workshop participants identified three key ideas.

First, establish preliminary relationships and collaborations with each other prior to working together on a specific project. This would allow projects to be co-designed and delivered such that outputs are of use to all partners and can form the basis of ongoing collaborations. Second, identify existing knowledge gaps that need to be filled and worked towards from each other's perspectives and then better communicate those to each other so as to design projects that fulfill those needs. Third, enhance the education and experience of undergraduate and graduate students by more effectively integrating them in collecting pilot data or longer-term monitoring data that can be shared between the academic and practitioner communities. This has the additional benefit of developing capability and capacity through investment in students who then go on to careers in the practitioner community. The importance of this is being increasingly recognized via the development of schemes such as NSF INTERN and NERC research experience placements, which allow students to develop real-world experience.

4.2 | Stakeholder perceptions of the use of large wood

Workshop participants noted that the use of wood as a restoration or management measure and the subsequent success or failure of a scheme will partly depend on the perceptions of stakeholders involved. The word clouds generated from the online survey clearly indicate the recognized importance of large wood in creating habitat and reflect several desirable attributes, as reflected in words such as beneficial, natural, important, essential, necessary, complexity, and heterogeneity (Figure 6a). However, the word debris is notably present, along with danger, despite ongoing attempts among river scientists to drop the use of debris (as in large woody debris) because of the pejorative connotations of debris. This led to our choice of images for the graphical abstract for this paper. Figure 6b suggests that potential hazards to infrastructure remain a major limitation to using



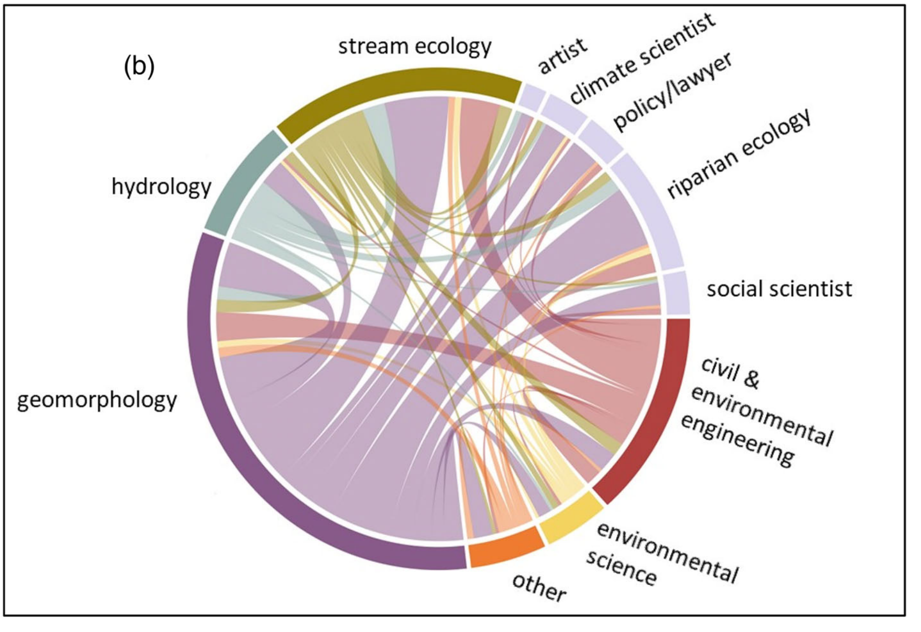


FIGURE 5 Chord diagrams illustrating patterns of collaboration between disciplines. (a) Current collaborations among survey respondents. (b) Desired collaborations among survey respondents. Boundary colors indicate discipline of individual choosing collaborative disciplines and columns within each figure indicate source discipline and chosen discipline. Many geomorphologists collaborate with other geomorphologists, for example (a), but a significant proportion also collaborate with civil and environmental engineers and with hydrologists. "Other" in part A includes fish biology, agriculture, and critical zone science. "Other" in part B includes pre-university educator and creative writer. Respondent data analyzed using program from Gu (2014). Data are drawn from 74 responses with respondents from the academic (47), practitioner (25), and regulatory (2) communities. [Color figure can be viewed at wileyonlinelibrary.com]

wood in river management, as do concerns about recreation, safety, hazard, risk, blockage, flooding, and permitting. Figure 6c mirrors Figure 6a in suggesting widespread recognition of habitat benefits associated with large wood in rivers, as well as diversity, complexity, and natural conditions.

These perceptions are further complicated where there is a need to consult and work with stakeholder groups beyond the academic and practitioner communities. For example, the public, utilities, landowners, and regulators are commonly found to have a different perception of large wood that typically focuses on ideas of risk, fear, and operational and practical issues. Consequently, the management or restoration approaches utilized are likely to be the result of an interplay between the physical processes governing the wood regime at a particular site and the range, experience, and perceptions of stakeholders involved. This highlights the issues of using wood in rivers as a management tool because it will likely be highly site, stakeholder, and situation dependent. To alleviate some of these issues, workshop participants suggested using methods of communication and engagement that are suitable for the range of stakeholders involved in a restoration project, as discussed previously.

4.3 | Communication across between communities

As noted above, being better to able communicate with each other in language that is accessible to a range of audiences, including between research scientists, practitioners, regulators, and the broader society of potential stakeholders in river restoration, was identified as a key

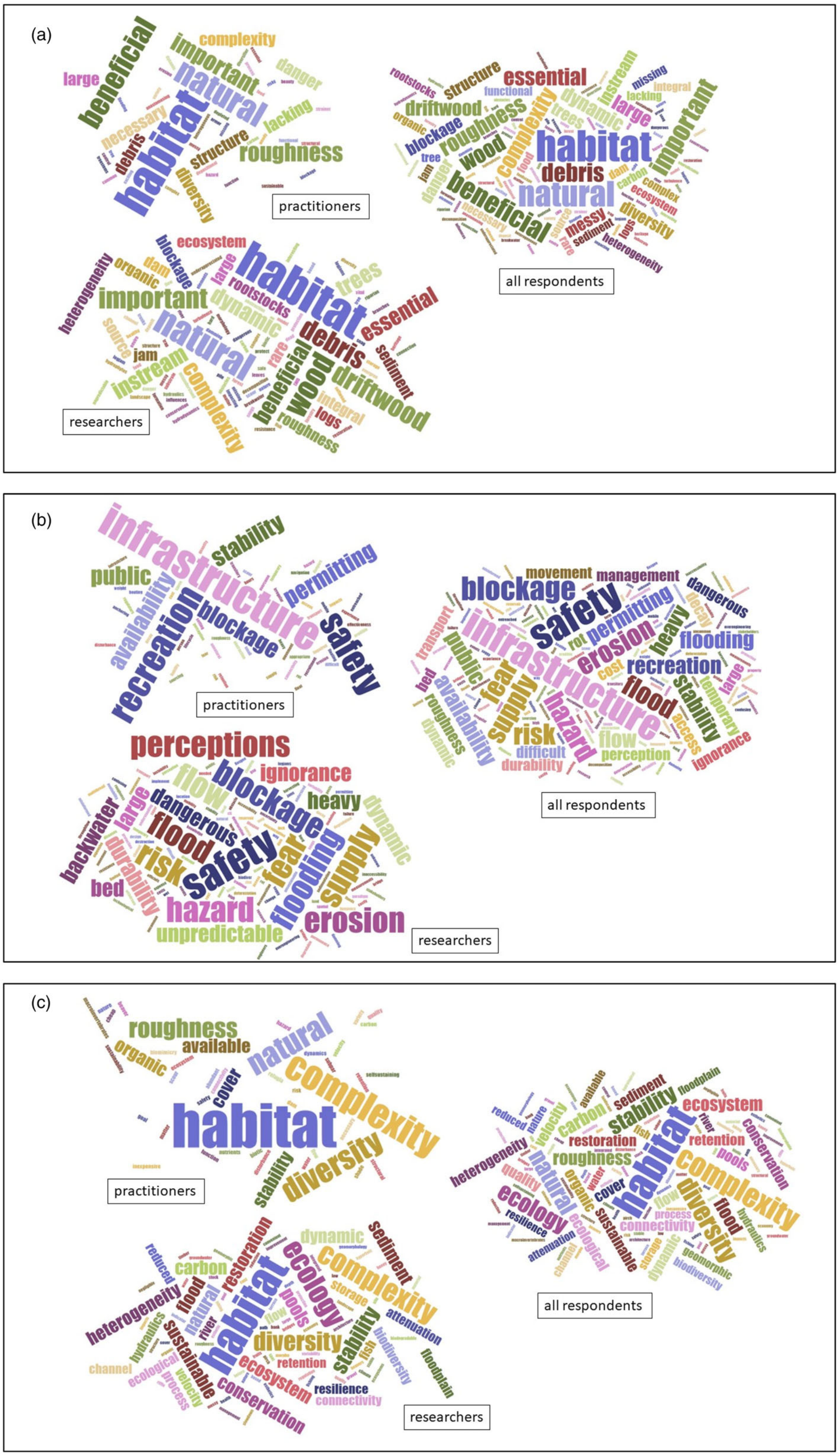


FIGURE 6 Word clouds generated from the 74 respondents illustrating (a) the top three words used to describe wood in rivers, (b) limitations to using wood in rivers, and (c) benefits to using wood in rivers, by practitioners, researchers, and all respondents combined. The larger the size of the word, the more times it appeared in survey responses. Data are drawn from 74 responses with respondents from the academic (47), practitioner (25), and regulatory (2) communities. Words included in each cloud are listed in the Supplemental Information. [Color figure can be viewed at wileyonlinelibrary.com]

priority for the future. This form of open, transferable communication could be aided by a standardized terminology between disciplines and communities. This is not a new theme in the context of river management and restoration (e.g., Bernhardt et al., 2005; Shuker et al., 2012; Shulz-Zunkel et al., 2022; Wohl et al., 2016) but may be particularly essential given the generally negative perceptions of large wood with respect to esthetics and potential hazards, and the corresponding lack of understanding of the historical abundance of large wood in river corridors, as well as the associated physical and ecological functions associated with wood.

Among the issues identified that could benefit from more effective communication are disconnects between research-derived recommendations for working with wood in rivers and the realities faced by practitioners and regulators. Research-derived recommendations can focus on simply more wood in appropriate portions of the river corridor and less active management (e.g., stabilizing) of introduced wood. Practitioners and regulators may have fundamental questions about just how much wood and exactly where, but the more immediate issues they face are likely to involve regulatory compliance with flood conveyance and hazards to infrastructure or recreation from the presence of mobile or stationary wood. There are also notable issues about the lack of regulation regarding how much wood can be extracted from a river and how much should be left within the channel.

Finally, a major barrier to engagement between the researcher and practitioner community is accessibility to the latest state-of-science. Researchers typically publish their findings in academic-facing journals that are commonly paywalled and therefore inaccessible to the practitioner community or the broader public. Where practitioners and researchers collaborate, findings are still typically published in the academic literature. To promote collaborative work between these two communities, there is a need to consider both where and how results are published. Outlets that are practitioner facing (e.g., governmental briefings or white papers) may be more appropriate to the non-academic community. We also recommend the creation of a publicly accessible website that can serve as a resource for accessing (i) syntheses and annotated bibliographies of papers on topics relevant to working with wood in rivers, (ii) a photo catalog of natural and managed wood in rivers, (iii) relevant, Open Access publications, (iv) links to other resources, such as the WooDDAM database or the US Large Wood National Manual, and (v) an online forum for open discussions such as the wood in rivers community Discord Server. Such a website could benefit the research community by enhancing availability and application of insights developed from research and by providing opportunities for professionals and students to engage in outreach via creation of syntheses and annotated bibliographies. The website could benefit practitioner and regulator communities by allowing individuals to access the most recent relevant science without hitting paywalls or restricted access; by distilling key information in the syntheses; and by providing examples of wood in rivers. Finally, the interactive portion of the website could enhance ongoing communication between diverse individuals interested in working with wood in rivers.

ACKNOWLEDGEMENTS

We thank the participants of the September 2022 Working with Wood in Rivers Workshop. In addition to those listed as authors on this manuscript, these include Samuel Fixler, Caleb Fogel, Antonio Reveles Hernandez, and Mickey Means-Brous. An earlier version of this manuscript benefited from comments by Dan Cadol and two anonymous reviewers. Finally, the world lost two individuals who did fundamental work on wood in rivers. We would like to dedicate this paper to the memory of Edward A. Keller and Bartłomiej Wyżga.

FUNDING INFORMATION

This research was supported by the Natural Environment Research Council (NERC) of the UK through (NE/V008803/1).

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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How to cite this article: Ockelford, A., Wohl, E., Ruiz-Villanueva, V., Comiti, F., Piégay, H., Darby, S., Parsons, D., Yochum, S. E., Wolstenholme, J., White, D., Uno, H., Triantafillou, S., Stroth, T., Smrdel, T., Scott, D. N., Scamardo, J. E., Rees, J., Rathburn, S., Morrison, R. R., … Aarnink, J. (2024). Working with wood in rivers in the Western United States. *River Research and Applications*, 1–16. https://doi.org/10.1002/rra.4331