Environmental Management (2008) 42:310–326
DOI 10.1007/s00267-008-9151-1

ENVIRONMENTAL ASSESSMENT

Rehabilitating Agricultural Streams in Australia with Wood: A Review

Rebecca E. Lester · Andrew J. Boulton

Received: 14 November 2006 / Accepted: 12 May 2008 / Published online: 17 June 2008

Abstract Worldwide, the ecological condition of streams and rivers has been impaired by agricultural practices such as broadscale modification of catchments, high nutrient and sediment inputs, loss of riparian vegetation, and altered hydrology. Typical responses include channel incision, excessive sedimentation, declining water quality, and loss of in-stream habitat complexity and biodiversity. We review these impacts, focusing on the potential benefits and limitations of wood reintroduction as a transitional rehabilitation technique in these agricultural landscapes using Australian examples. In streams, wood plays key roles in shaping velocity and sedimentation profiles, forming pools, and strengthening banks. In the simplified channels typical of many agricultural streams, wood provides habitat for fauna, substrate for biofilms, and refuge from predators and flow extremes, and enhances in-stream diversity of fish and macroinvertebrates.

Most previous restoration studies involving wood reintroduction have been in forested landscapes, but some results might be extrapolated to agricultural streams. In these studies, wood enhanced diversity of fish and macroinvertebrates, increased storage of organic material and sediment, and improved bed and bank stability. Failure to meet restoration objectives appeared most likely where channel incision was severe and in highly degraded environments. Methods for wood reintroduction have logistical advantages over many other restoration techniques, being relatively low cost and low maintenance. Wood reintroduction is a viable transitional restoration technique for agricultural landscapes likely to rapidly improve stream condition if sources of colonists are viable and water quality is suitable.

Keywords Large woody debris · Coarse woody debris · Ecological rehabilitation · Stream restoration · Agricultural impacts · Wood reintroduction

Introduction

Agriculture is the single largest land use in Australia, occurring across more than 60% of Australia's 768 million hectares (Land and Water Australia 2001a). Practices associated with agriculture, including clearing, extraction of water, irrigation and the introduction of exotic species, have led to significant changes in the condition of Australia's catchments and rivers (Boulton and Brock 1999; Lake and Marchant 1990; Norris and others 2001). In 2002, 33% of Australia's river length was estimated to have impaired aquatic biota, and >80% of river length was judged to be affected by catchment disturbance, relating land use to the degradation of streams and rivers (Land and Water Australia 2002). Without urgent improvements in management and rehabilitation, the degradation of Australian rivers was predicted to continue.

Rehabilitation techniques to address ecosystem degradation as a result of agriculture include fencing to exclude stock, revegetation of riparian zones and steep slopes, and the creation of buffer strips to reduce sediment and nutrient

R. E. Lester
School of Applied Sciences and Engineering, Monash University, Gippsland Campus, Churchill, VIC 3842, Australia

R. E. Lester (✉)
School of Biological Sciences, Flinders University, Adelaide, SA 5001, Australia
e-mail: Rebecca.Lester@flinders.edu.au

A. J. Boulton
Ecosystem Management, University of New England, Armidale, NSW 2351, Australia

input to streams (Anbumozhi and others 2005; Boutin and others 2003; Carline and Walsh 2007; Correll 2005; Hefting and others 2005; Parkyn and others 2003). This review focuses on a technique that is less commonly applied in Australia: the reintroduction of natural woody debris to agricultural streams to restore habitat complexity. The technique complements natural riparian vegetation recovery as sources of wood become reestablished along river banks. Although this review specifically addresses Australian rivers, changes in river condition due to human activities have occurred worldwide (Allan 2004; Gurnell 1995), and many of the issues discussed here are global. Because Australia spans a wide variety of climatic zones and agricultural industries, it is likely that rehabilitation approaches are broadly transferable given the similarity of impacts and issues.

In this review, we summarize management practices and pressures associated with agriculture, document the effects of those pressures and their interactions on stream condition in Australia, investigate the role of wood in streams, both in agricultural and forested catchments, and explore the potential for wood reintroduced into streams to redress ecological problems associated with agriculture, using examples where possible.

Agricultural Practices and their Effects on Australia Streams

In Australia, particular agricultural activities tend to be concentrated in specific geographical locations. Inland, dry conditions favor beef, sheep, and wheat production, whereas coastal regions with higher rainfall, particularly in the east, have extensive dairy and horticultural industries (Land and Water Australia 2001a). The concentration of specific types of agriculture in distinct geographic regions has resulted in a variety of impacts in different locations, depending on climatic and edaphic context and the type of agriculture. For example, the fertile floodplains of the Williams River in northern New South Wales (Fig. 1) have been used for cropping and cattle grazing since the mid-19th century (Brooks and others 2004). There, deforestation, flood mitigation, and "river training" have resulted in channel expansion, significant bed instability, and increased bank erosion (Brooks and others 2004). In the Western Australian wheat belt, clearing of deep-rooted vegetation for shallow-rooted crops has increased salinity in rivers such as the Kalgan and Blackwood (Fig. 1; Schofield and others 2000). In these rivers, salinization led to salt-tolerant aquatic invertebrates replacing more sensitive species (Blinn and others 2004; Pinder and others 2004). Even in relatively well-watered areas such as the New England Tablelands (Fig. 1), intensive grazing and

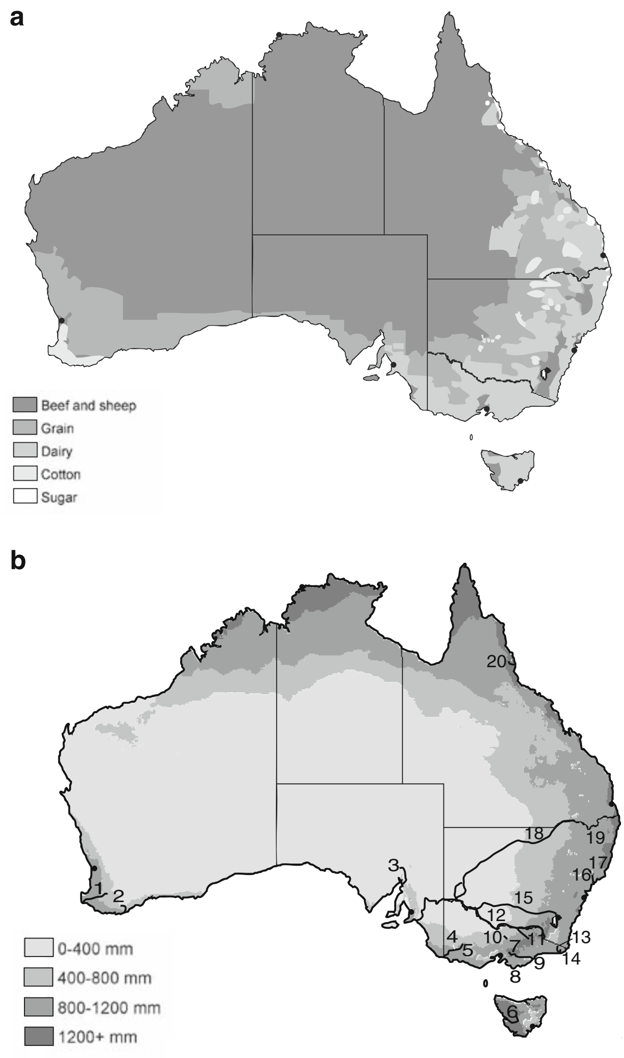

Fig. 1 Predominant agricultural industries and rainfall in Australia. (**a**) Predominant agricultural industries across Australia; (**b**) Average annual rainfall across Australia and the location of rivers used as examples within this review: 1. Blackwood River (WA), 2. Kalgan River (WA), 3. Willochra Creek (SA), 4. Glenelg River (Vic), 5. Wannon River (Vic), 6. Gordon River (Tas), 7. Little Yarra River (Vic), 8. Bunyip River (Vic), 9. Latrobe River (Vic), 10. Castle and Creightons Creeks (Granite Creeks) (Vic), 11. Ovens River (Vic), 12. River Murray (NSW, Vic, SA), 13. Cann River (Vic), 14. Thurra River (Vic), 15. Murrumbidgee River (NSW, ACT), 16. Williams River (NSW), 17. Chichester River (NSW), 18. Darling-Barwon River (Qld, NSW), 19. New England Tablelands (NSW), and 20. Johnstone River (Qld)

poor riparian management have caused sedimentation and impaired river condition (Reid and others 1997).

Despite this variety of agricultural practices across Australia, some common land disturbance themes emerge: catchment and riparian clearing, channelization of streams and rivers, regulation and abstraction of flow, increased pollution entering streams, widespread grazing, and clearing of in-stream wood (desnagging). We discuss each agricultural practice and its effect on stream environments in turn, beginning with processes that operate at a landscape scale through to those operating at a stream-reach scale (Fig. 2). Of course, these spatial scales are continuous (hence the overlap in Fig. 2), but the spatial constructs form a useful hierarchy for discussion and environmental management.

Landscape-Scale Practices

Land Clearing

Throughout temperate and tropical Australia, floodplains and catchments have been cleared for agriculture, as a source of building materials and firewood, and for urban development. More than 500,000 km^2 of eucalypt open forest, woodland, open woodland, and acacia forest and woodlands have been cleared since European settlement in the late 18th century (Land and Water Australia 2001b). The eastern seaboard and southern Western Australia have been most extensively cleared, and Victoria now has the lowest proportion of native vegetation of all Australian states (Land and Water Australia 2006). The pattern of clearing coincides with weed and feral animal encroachment, the location of ecosystems that are "at risk," and the degree of change in hydrological regimes, illustrating the synergistic impacts of the clearing on the landscape as a whole (Land and Water Australia 2006). Clearing patterns also coincide with declines in river condition, highly modified catchments, elevated nutrient and suspended sediment loads, reduced riparian vegetation, and disrupted stream connectivity due to water impoundment (Lake and Marchant 1990; Schofield and others 2000).

The experimental clearing of a catchment in south-western Western Australia reduced the interception storage of the catchment, increasing peak flows and groundwater recharge and resulting in higher baseflows in the stream (Ruprecht and Schofield 1991). As the saline water table approached the surface, a sharp increase in stream salinity occurred (Ruprecht and Schofield 1991). In South Australia early in the last century, land clearance into the semiarid zone (in the mistaken belief that "rain follows the plough") devastated large areas of native vegetation and led to channel incision and salinization of streams (e.g., Willochra Creek, Fig. 1; Boulton and Williams 1996). Increased catchment erosion rates, partly due to overclearing, can

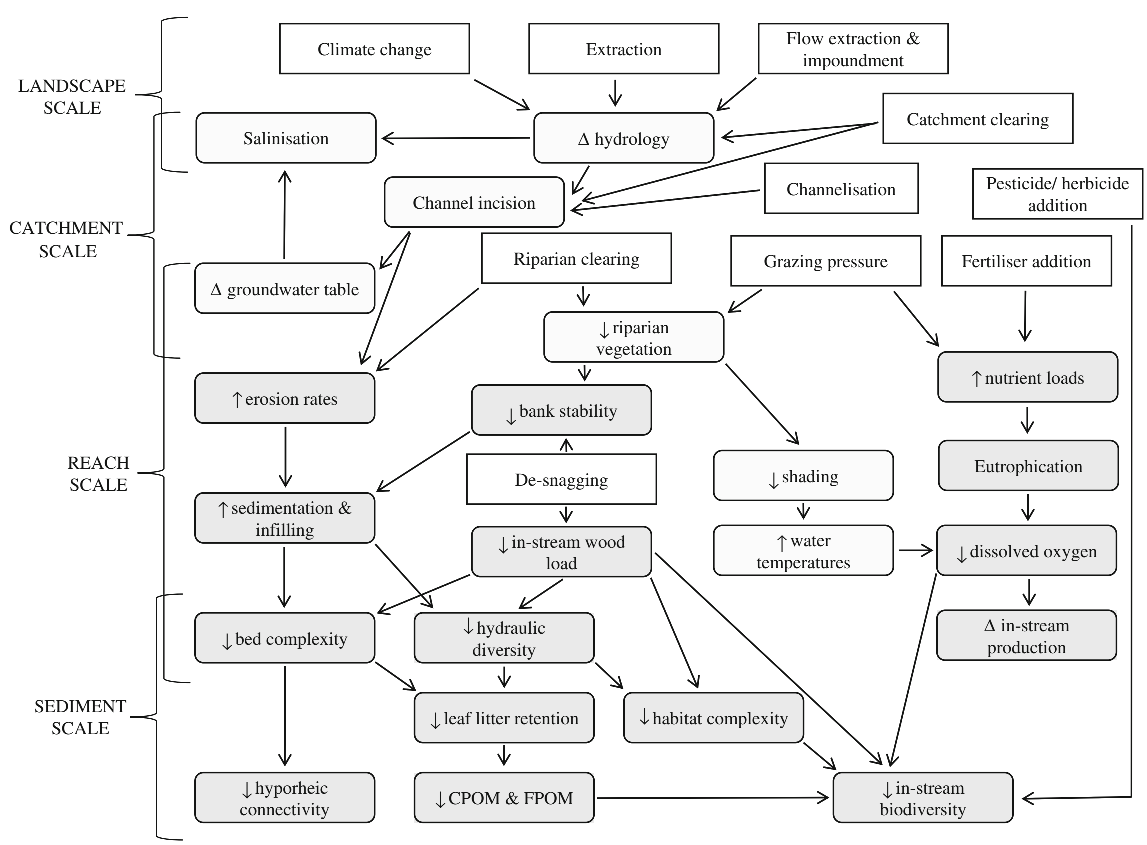

Fig. 2 Agricultural pressures and their effects, and those elements that wood might address. *Note*: Square boxes depict agricultural pressures and rounded boxes show their effects. Effects are either shaded light gray if wood is unlikely to address them or dark gray where wood additions will or might have an effect

deliver increased loads of sediment to streams and rivers, smothering fish spawning and nursery habitats (Hendry and others 2003) or creating large, slow-moving accumulations of sediment known as sand slugs (Bond and Lake 2003). Streams affected by sand slugs in the Strathbogie Ranges (including Granite Creeks; Fig. 1) had higher velocities, shallower depths, and less in-stream wood than unaffected streams (Downes and others 2006). Clearing of catchments and floodplains has had similar effects in other parts of the world (e.g., Europe, Gurnell 1995, and the United States, Allan 2004). Figure 2 summarizes the effect of land clearing on streams, along with the other agricultural pressures reviewed herein.

Flow Regulation and Extraction

Flow regulation has also had a profound impact on streams and rivers, particularly in Australia because flow regimes are naturally extremely variable in space and time (Finlayson and McMahon 1988; Puckridge and others 1998; Robertson and Rowling 2000). Water extraction, storage of large quantities of water, and altered hydrographs have led to lower total flows, fewer small to moderate floods, and higher, more consistent dry season flows (Maheshwari and others 1995). Cooler average water temperatures downstream of impoundments are also a result (Boulton and Brock 1999), as impounded water is typically released from the base of large storages in summer. For example, water released from the Gordon Dam in southwest Tasmania (Fig. 1) was, on average, 5°C cooler than waters upstream, with a significant decline in oxygen saturation and high levels of hydrogen sulfide (King and Tyler 1982; Lake and Marchant 1990). Impacts due to flow regulation are widespread, with almost all water in rivers in New South Wales and Victoria fully allocated or overallocated for human use (Land and Water Australia 2006). More than 70% of water in these areas is used for irrigation purposes and a further 6% is used by rural communities (Land and Water Australia 2006).

Catchment-Scale Practices

Channelization

Channelization of streams has occurred in many areas, often with the objective of improved land drainage (Brock and others 1999). This practice includes straightening channels, removing meander bends from rivers, lining channels with impervious materials such as concrete or clay, and constructing new channels to drain wetlands. One of the major impacts of channelization is a reduction in in-stream variability, with more uniform depths, velocities, and structural diversity as a result (Brooks and others 2004; Harmon and others 1986; Shields and others 1994). This can be seen in the Bunyip River in Victoria (Fig. 1), where a lack of suitable habitat in channelized sections resulted in lower abundance and species richness of fish (Hortle and Lake 1983).

Riparian Clearing

Removal of riparian vegetation is also a widespread practice (Growns and others 2003). Riparian clearing increases stream water temperature (Sovell and others 2000). Strong relationships have been detected between riparian shading and water temperature, with more than 4°C difference in daily maximum temperature between shaded and unshaded streams on agricultural properties in Western Australia and southeast Queensland (Rutherford and others 2004). Quinn and others (1997) also reported that pasture streams in New Zealand had daily maximum water temperatures 6–7°C higher than adjacent uncleared streams. Increased temperatures alter in-stream production rates, saturation levels of dissolved oxygen in the water, and carbon dynamics in the stream ecosystem (Robertson and others 1999). Removal of the source of in-stream wood and particulate organic matter is another effect of riparian clearing, again leading to reduced in-stream habitat complexity. Coarse particulate organic material (CPOM) and fine particulate organic matter (FPOM) are reduced because there is less opportunity for leaf litter to enter the stream, transport rates are higher, and there is less retention of CPOM (e.g., behind accumulations of wood in the stream), reducing the carbon available for processing (Bilby and Likens 1980).

Riparian clearing can also exacerbate channel incision. Channel incision occurs due to a lack of balance between the ability of the stream to transport sediment, the amount of sediment available for transport, and structural controls on the bed (such in-stream wood and riparian vegetation) (Hendry and others 2003; Triska 1984). Incision reduces levels of in-stream habitat diversity (Shields and others 2004) as riffles are eroded and pools are filled in with fine sediment (Brooks and others 2004). Loss of habitat in this manner has contributed to declining abundances of the Green and Golden Bell Frog (*Litoria aurea*) in the southern Tablelands of New South Wales (Hazell and others 2003). In addition to a loss of in-stream habitats, homogeneity of the stream-bed longitudinal profile can also result in a loss of connectivity with the hyporheic zone and with groundwater (Boulton 2007).

Pollution and Eutrophication

There are numerous common sources of pollution to streams in agricultural catchments. Fertilizers, herbicides, and pesticides applied to agricultural land impact directly on stream ecosystems (Leonard and others 1999), with 90% of river reaches surveyed by Land and Water Australia (2002) showing higher nutrients (primarily phosphorus) and suspended sediment than expected naturally. The application of fertilizers to pasture and crops has caused widespread eutrophication of streams and rivers, which can lead to increased growth of macrophytes or algal blooms, with associated oxygen depletion and pH changes (Hendry and others 2003). For example, low-flow conditions, an influx of sulfate-rich saline groundwater, and an increase in the level of N-fixation led to large blue-green algal (cyanobacteria) blooms in the Darling-Barwon River in 1991 (Fig. 1; Donnelly and others 1997). In tropical Queensland, sugarcane cropping has resulted in substantial leaching of nitrogen into the soil and adjacent surface-water and groundwater bodies in the Johnstone River catchment (Fig. 1; Rasiah and others 2003). The effects of such leaching are poorly documented but probably include serious groundwater contamination. Pesticides such as endosulfans also enter waterways via runoff and are considered to be largely responsible for impaired aquatic macroinvertebrate communities in the cotton-growing regions of New South Wales (Hose and others 2003). Roads and road crossings are another source of in-stream pollutants, causing significant increases in in-stream suspended sediment levels (Cornish 2001) that have then been associated with negative effects on biodiversity, such as the decreased tadpole growth and development of the Spotted Tree Frog (*Litoria spenceri*) (Gillespie 2002).

Reach-Scale Practices

Grazing

Alteration of riparian and aquatic habitats has often been linked to grazing practices (e.g., Gunderson 1968; Myers and Swanson 1996; Platts and Nelson 1985), which have substantially affected Australian river systems (Robertson and Rowling 2000; Walker 1993). Excluding cattle from several floodplain wetlands in the Murrumbidgee River (Fig. 1) significantly increased the species richness, stem density, and biomass of the littoral plant community (Robertson 1997). Grazing reduces the proportion of overhead canopy and the amount of woody vegetation (Chapman and Knudsen 1980), alters bank stability (Myers and Swanson 1991), encourages the spread of weeds (Boutin and others 2003), and reduces the recruitment of native species (Robertson and Rowling 2000). Cattle also alter the quantity and quality of organic material available in the stream, which can have a major impact on ecosystem functioning, as many of these systems naturally rely on allochthonous carbon to support riverine food webs (Robertson 1997). Waste products from stock elevate nitrogen and phosphorus levels (Robertson 1997; Sovell and others 2000), which might be of particular concern in some naturally nutrient-poor regions in Australia. Trampling of vegetation by cattle can increase in-stream water temperatures (Sovell and others 2000) and damage fragile banks, promoting slumping and sedimentation. In Australian dryland rivers, which are often reduced to a chain of pools, productivity is concentrated in a “bathtub ring” of benthic algae at the littoral margins of these pools (Bunn and others 2003). Damage to these littoral margins by stock trampling is likely to have a large impact on the food web that relies on that algae as a food source (Bunn and others 2003).

Desnagging

The active removal of wood from streams (desnagging) has profoundly changed in-stream environments. Desnagging has been common around the world (Brooks and others 2004; Maser and Sedell 1994; Triska 1984) and was widespread in Australia between the 1880s and mid-1990s (Erskine and Webb 2003). Desnagging resulted in the loss of almost the entire natural wood load from many rivers in Australia (Gippel and others 1992). For example, more than 8000 logs were removed from the Williams and Chichester Rivers in the Hunter Valley, New South Wales, between 1954 and 1991 (Fig. 1; Erskine and Webb 2003). Wood and other channel obstructions were removed to increase maximum flow velocity, decrease erosion and frequency of flooding, and speed drainage of the floodplain (Erskine and Webb 2003). In Victoria, the Glenelg and Wannon rivers (Fig. 1) were desnagged in 1961–1962, resulting in a 20% increase in flow velocity and the increased transport of sediment to the now heritage-listed Lower Glenelg River (Erskine 1994). In some instances, such as the Latrobe River (Fig. 1), desnagging operations increased bed scour, exposing previously buried wood, which was then removed, further increasing bed scour and exposing additional buried wood (Reinfelds and others 1995). This cycle continued, resulting in average channel incision of more than a meter (Reinfelds and others 1995).

Desnagging removes structural diversity within streams, both directly as well as removing the indirect effect of wood on nearby habitats (Brooks and others 2004; Harmon and others 1986; Shields and others 1994). Loss of in-stream habitat as a result of desnagging has been identified as a factor in declining fish populations in the River Murray (Fig. 1; Koehn and O’Conner 1990) and habitat destruction is considered the major cause of extinction for freshwater fish populations worldwide (Collares-Pereira and Cowz 2004; Koehn and O’Conner 1990). Limited physical heterogeneity also removes sources of shelter for other aquatic organisms (Harmon and others 1986), reducing the density and diversity of macroinvertebrates (Nakamura and

Yamada 2005; Probst and others 2005). Although agricultural streams often have high abundances of macroinvertebrates, diversity is reduced and communities are dominated by tolerant taxa such as oligochaetes and mollusks (Stone and others 2005). Overall, there is a trend toward simpler food webs with fewer taxa represented as a result of disturbance to the in-stream environment.

The Role of Wood in Streams

Stream Morphology

At a reach or catchment scale, stream morphology is most likely to be affected by large pieces or accumulations of wood. The movement of water around obstacles alters the velocity profile, which changes patterns of local erosion and sedimentation. Pieces that occupy more than 10% of the channel cross-section can have a significant impact on the conveyance of a river (Gippel and others 1996), which, in turn, can affect velocity profiles and sedimentation patterns (Brooks and others 2004). Orientation and piece stability influence the type and amount of scour caused by a single log (Hilderbrand and others 1998). Pieces oriented perpendicular to the flow have the greatest potential for scour (Gippel and others 1996), whereas pieces angled with the current create the most aggradation (Cherry and Beschta 1989; Hilderbrand and others 1998; Mutz 2000). Log length relative to channel width determines the level of stability of the piece in the channel, with the longest pieces typically moving the shortest distances (Hilderbrand and others 1998). When present in sufficient quantities, however, small pieces also have the capacity to alter channel morphology, as was the case for Schlaube Stream, Germany (Mutz 2000). The total load of wood in a stream can also control flow resistance, sedimentation, bank strength, and channel migration (Abbe and Montgomery 1996; Gurnell 1995; Koehn and others 2004).

Prior to European settlement, large wood might have been the dominant control on geomorphological processes in many rivers in Australia (Brooks 1999). A comparison of the extensively cleared and desnagged Cann River in Victoria with the nearby, relatively pristine Thurra River (Fig. 1) revealed substantial differences in geomorphic processes (Brooks and others 2003). The Cann River has undergone significant channel enlargement, with a 360% increase in depth, a 240% increase in slope, and a 700% increase in channel capacity since European settlement (Brooks and others 2003). In contrast, channel shape in the Thurra River has been controlled by riparian vegetation and in-stream wood, and changes have been minor over the same time period (Brooks and others 2003). These results highlight the importance of physical controls, including riparian vegetation and in-stream wood on the bed and bank, to the stability of the stream system.

Water Chemistry

The presence of wood in streams also alters water chemistry. Increased turbulence as the water flows over pieces of wood causes aeration, increasing dissolved oxygen levels (Wallace and Anderson 1996). Wood can act as a site for the fixation of nitrogen (Buckley and Triska 1978) or other biofilm activity, selectively transforming nutrients (Ryder and others 2006; Vallett and others 2002). It can also alter the amount and sources of carbon available in a stream, even acting as a direct source of carbon that can be broken down by macroinvertebrates, fungi, or bacterial processes (McKie and Cranston 1998). Wood traps organic matter, including leaves, and alters storage of particulate organic matter by creating more pool habitats (Bilby and Likens 1980; Fisher and Likens 1973; Triska 1984), thereby increasing the available carbon for processing by other organisms (Smock and others 1989). Another important effect of wood in a stream is to enhance vertical water movement between surface and subsurface flows (Hester and Doyle 2008). This process increases channel complexity and has the capacity to improve water retention times and enhance nutrient processing within the hyporheic zone (Boulton 2007; Kasahara and Hill 2007).

Habitat and Biological Diversity

Large pieces of wood in streams increase the habitat available for colonization by a range of organisms (Benke and Wallace 2003; Davies and others 2000). Habitat diversity is increased by the creation of pools and scour holes and by the diversity in the depth and velocity profiles of the stream (Abbe and Montgomery 1996; Harmon and others 1986). Such diversity is crucial in providing appropriate habitats for a range of species (Koehn and others 2004), particularly in soft-bottomed streams where there is no other hard substrate available (Wallace and Benke 1984). Wood also traps leaf litter and drifting plant material, which provide an additional habitat for aquatic macroinvertebrates (Scealy and others 2007).

The log structure itself can provide complex cover for fish from predators and high flows (Abbe and Montgomery 1996), whereas the increased pool habitat can provide refuge and a source of recolonists during low-flow conditions (Bond and Lake 2005; Collier and Halliday 2000; Hax and Golladay 1998). Australian threatened fish species, including the Mary River Cod, Murray Cod, and Eastern Freshwater Cod, use logs to define their territories and as cover (Coysh and others 2000; Harris and Rowland 1996; Merrick and Schmida 1984). Other native species also use wood as spawning sites and territory markers (Crook and Robertson 1999).

Wood-associated macroinvertebrates and biofilms are an important source of food for higher-order consumers, including many fish species (Crook and Robertson 1999). Macroinvertebrate communities are also influenced by the availability of wood as a habitat (Benke and others 1984; Benke and Wallace 2003; Wallace and others 1995). Even at low densities, wood has been associated with disproportionately high levels of invertebrate richness and biomass in a stream (Benke and others 1984; O'Connor 1992; Wallace and Benke 1984). In some cases, macroinvertebrates preferentially select different species of wood, altering the community composition of wood-associated macroinvertebrate faunal assemblages (McKie and Cranston 2001) or use wood in preference over other habitats (Anderson and others 1978).

Restoration Projects Involving the Reintroduction of Wood to Streams: A Meta-Analysis

As described earlier, naturally occurring wood in streams influences channel morphology and water chemistry and is associated with increased habitat and biological diversity. A number of studies have been carried out worldwide on whether actively reintroducing wood to streams will restore these characteristics to streams where wood has been removed. We did a meta-analysis of 15 studies in the ecological literature where the goal of the research specifically involved the restoration or rehabilitation of a stream using the introduction of in-stream wood. These studies are summarized in Table 1. Studies that tested hypotheses unrelated to restoration or investigated the effects of extant in-stream wood were excluded.

Of the published examples of restoration projects using wood as a stream rehabilitation tool, most were carried out in the United States. These American projects were usually undertaken on moderate-sized streams (second to fifth order; Crispin and others 1993; Millington and Sear 2007; Shields and others 2006; Wallace and others 1995), whereas elsewhere (e.g., Australia), they have focused on a range of stream sizes from small streams (e.g., Lester and others 2007) to large rivers (Brooks and others 2004; Koehn 1987). Forested landscapes were the most common context for the rehabilitation projects (Crispin and others 1993; Coleman 2006; Gerhard and Reich 2000; Hilderbrand and others 1997; Shields and others 2003; Wallace and others 1995) with fewer studies occurring in agricultural (Bond and Lake 2003; Brooks and others 2004; Moerke and others 2004; Spanhoff and others 2006; Zika and Peter 2002) or urban landscapes (Larson and others 2001; Moerke and others 2004). Almost all projects were reported as a case study on a particular waterway (or paired with a reference stream) except Larson and others (2001), who reviewed six restoration projects and studies undertaken by Roberts and others (2007), Millington and Sear (2007), and Lester and others (2007), who each assessed responses in several rehabilitated streams.

The most commonly stated goals for the restoration projects were improved bed and bank stability (Brooks and others 2004; Coleman 2006; Shields and others 2006) and the creation of in-stream habitat (Brooks and others 2004; Bond and Lake 2005; Crispin and others 1993; Hilderbrand and others 1997; Larson and others 2001; Roberts and others 2007; Wallace and others 1995; Zika and Peter 2002). In an urban setting, flood control and erosion control were common goals for restoration (Larson and others 2001). The restoration works typically included the addition of large pieces of wood (>10 cm in diameter; commonly logs, root wads, and boles) using heavy machinery (Brooks and others 2004; Coleman 2006; Crispin and others 1993; Gerhard and Reich 2000; Hilderbrand and others 1997; Shields and others 2006). In one instance in which a rehabilitation technique was trialed, railway sleepers (railway ties) were used so that the introduced elements were of a standard size (Bond and Lake 2003). The use of smaller-size classes of wood (<10 cm in diameter) was not specifically mentioned in the majority of projects, possibly because such pieces are more transient in a reach or more likely to accumulate naturally if there was large wood to stabilize them. They were, however, specifically included in the studies by Lester and others (2007), Spanhoff and others (2006), and Millington and Sear (2007), who focused on the rehabilitation of relatively small streams where small wood was more likely to be stable. In several projects, wood additions were combined with other rehabilitation techniques, including the addition of rocks (Crispin and others 1993; Koehn 1987), riparian plantings (Shields and others 2003), modification to channel shape (Millington and Sear 2007), or the creation of off-channel areas (Crispin and others 1993).

Reach lengths for rehabilitation varied from 10 m (Lester and others 2007) to ~20 km (Bond and Lake 2003) but were usually in the order of 0.5–1 km (e.g., Brooks and others 2004; Hilderbrand and others 1997; Wallace and others 1995). Where possible, studies compared treatment and control reaches both before and after the restoration works (Brooks and others 2004; Coleman 2006; Crispin and others 1993; Hilderbrand and others 1997; Koehn 1987; Lester and others 2007; Roberts and others 2007; Shields and others 2006). Common parameters measured included in-stream habitat elements [including pool and riffle frequency, association of pools with introduced wood and pool depth (Bond and Lake 2005; Brooks and others 2004; Crispin and others 1993; Gerhard and Reich 2000;

Table 1 Synopses of published examples of restoration projects involving the addition of wood to streams and rivers

Stream, location	References	Landscape	Project synopsis	Main findings
Ovens River, Victoria, Australia	Koehn (1987)	Forestry, agriculture, recreation, and gravel extraction	Large rocks were added to a 24-m reach downstream of a constructed log weir as habitat for native fish. Willow debris was incidentally deposited downstream of the control reach, so was also monitored.	Increased habitat diversity and increased cover resulted in a threefold increase in the abundance of fish using the treatment reach.
Williams River, NSW, Australia	Brooks and others (2001, 2004)	Agriculture	Twenty engineered log jams were introduced over a 1.1-km reach to prevent channel incision, trap sediment and create in-stream habitat diversity. Morphological change, bed material, and fish communities were assessed.	Increased bank stability and sediment retention in the reach were observed. There was also increased hydraulic and habitat diversity with greater fish species richness and stability. Longer-term monitoring needed to clarify ecological response to changes in channel morphology.
Little Yarra River, Victoria, Australia	Coleman (2006)	Forested with some agriculture	Wood that had previously been removed from the river was reintroduced into a 1.5-km reach to stabilize bed erosion and increase in-stream biodiversity.	Differing results between taxa highlighted importance of a specified end point, appropriate scales, and appropriate monitoring.
Castle and Creightons creeks, Victoria, Australia	Bond and Lake (2003, 2005)	Agriculture	Reaches totaling 20 km of two streams were treated to create habitat diversity previously lost to sedimentation. Railway sleepers (ties) added to span the stream. Treatments of 0, 1, or 4 structures per reach were added to each site.	Careful consideration should be given to the creation of refugia from adverse conditions (e.g., drought) to improve the resilience of stream ecosystems in the long term.
Eight streams in Victoria, Australia	Lester and others (2007)	Agriculture	Small wood was added to 10-m reaches of eight streams across two regions in Victoria, Australia. Streams were monitored for changes in macroinvertebrate community composition.	Compared to control streams, treated streams had greater family richness and greater richness of all functional feeding groups. Increased richness was not limited to the introduced wood, but was also observed in the benthic and edge communities.
Jossklein and Lüder, Hesse, Germany	Gerard (1995)	Forestry, meadows with some agriculture	The accumulation of wood due to forestry was compared with the introduction of wood in streams that had previously been regulated. Habitat distribution, channel shape, and biodiversity were assessed.	The habitat quality of straightened and regulated rivers was improved by the inadvertent addition of wood. Demonstrates that improvements can occur as a by-product of management in some instances.
Stream Muhleback, Fürstentum, Liechtenstein	Zika and Peter (2002)	Agricultural	Forty-five trees were added across five treatment sections varying in length from 50 to 550 m and the impact on the fish populations was assessed.	Despite some confusion in the logic of the article, it appears that the abundance and biomass of brown and rainbow trout increased, as did fine organic material and the number of pools in the treatment reach.
Lymington River, Hampshire, UK	Millington and Sear (2007)	Forested	Restoration works including bank stabilization, raising bed levels, addition of meanders and log jams, and exotic species removal occurred over 10 km in order to improve the wood retention in the channel. Three sites were assessed by adding dowels as surrogate organic matter.	Distances traveled downstream changed in the 2 years after restoration. One site had higher but more variable transport, whereas the other 2 showed declines in transport distances. Wood jams were the most important trapping location.
Ladberger Muhlenbach, Northrhine-Westphalia, Germany	Spanhoff and others (2006)	Agricultural	Twenty-five packages of branches (3–6 cm in diameter) were added to a 50-m reach. The effect on chironomid pupal exuviae was monitored.	The treated reach showed elevated levels of bed erosion and an initial decline in chironomid diversity. These results might have been due to the wood species used, its placement, or short time frames for monitoring.

Table 1 continued

Stream, location	References	Landscape	Project synopsis	Main findings
Elk Creek, Oregon, USA	Crispin and others (1993)	Forestry	A total of 200 structures, mainly tree boles and some boulders and root wads, were added to a 4.2-km reach to create a series of pools, glides, and riffles in the main channel and 11 side channels.	Substantial changes in habitat diversity were measured and salmon abundances in the stream increased fourfold (in both treatment and control reaches). Similar increases in spawning were not observed in other streams.
Six urban streams, Puget Sound Lowland, Washington, USA	Larson and others (2001)	Urban	A range of urban stream rehabilitation projects were reviewed, assessing changes in channel characteristics, biological condition, project design, and ability to reverse consequences of degradation.	Results were mixed. Objectives for some projects were met. Wood additions could not address all identified issues in all catchments. Many other projects were never monitored for biological improvement.
Cunningham Creek, North Carolina, USA	Wallace and others (1995)	Forested	Logs were added downstream of three riffle reaches within the stream and the impact on nutrient uptake, macroinvertebrates, and stream morphology were assessed.	Stream depth increased, current velocity decreased, sedimentation was observed, and there were increases in CPOM and FPOM. The macroinvertebrate community showed decreased abundance and biomass of scrapers and filterers, increased collectors and predators, and altered shredder composition.
North Fork Stony and North Prong Barbours creeks, Virginia, USA	Hilderbrand and others (1997); Lemly and Hilderbrand (2000)	Forested	Wood was added to two streams to compare differences between the random or systematic placement of pieces. Changes in habitat diversity and macroinvertebrate communities were compared.	Changes in detritus storage and macroinvertebrate community composition were small within pool and riffle habitats, but the distribution and number of each changed, increasing overall retention. Systematic placement had a lower impact on erosion and scour rates than random placement.
Little Topashaw Creek, Mississippi, USA	Shields and others (2003, 2004, 2006)	Forested with some agricultural	Seventy-two large wood structures were installed along eroding banks and 4000 willow cuttings were planted in a 2-km reach to improve physical aquatic habitat and fish community structure.	The long-term success of the project was questionable. Many structures failed over time. Short-term improvements in erosion rates did not persist past the failure of structures. The impact on fish communities was moderate, but appeared to be related to improved in-stream cover.
Four streams in Fort Benning Military Installation, Georgia, USA	Roberts and others (2007)	Forested regrowth (previously agricultural) with military activities	Wood was added to four streams with varying levels of catchment disturbance due to military exercises. Each stream received 10 additions of 3 logs over 100 m to improve hydrodynamic and structural complexity and to increase nutrient uptake rates. Treated streams were compared to four control streams.	Disturbance level was inversely related to uptake of ammonia. Wood additions increased the hydrodynamic complexity and nutrient uptake in the treated streams.

Hilderbrand and others 1997; Koehn 1987; Larson and others 2001; Shields and others 2006; Spanhoff and others 2006)], fish diversity and abundance (Bond and Lake 2005; Brooks and others 2004; Coleman 2006; Crispin and others 1993; Koehn 1987; Shields and others 2006; Zika and Peter 2002), macroinvertebrate community diversity, density, or biomass (Coleman 2006; Gerhard and Reich 2000; Hilderbrand and others 1997; Lester and others 2007; Spanhoff and others 2006; Wallace and others 1995), bank stability (Shields and others 2006), and sediment storage (Brooks and others 2004; Shields and others 2006). Some projects also monitored organic matter storage (Bond and Lake 2005; Gerhard and Reich 2000; Millington and Sear 2007) and processing (Wallace and others 1995), habitat use by platypus (Coleman 2006), nutrient uptake (Roberts and others 2007; Wallace and others 1995), and changes in stream velocity profiles (Brooks and others 2004; Coleman 2006).

The results of the individual projects varied with location, land use, and stream order. For example, there was a threefold increase in native fish abundance (but not richness) in the treatment reach of the Ovens River, Victoria (Koehn 1987) that has persisted for more than 10 years (Koehn, Arthur Rylah Institute for Environmental Research, Australia, personal communication, 13 March, 2008), a significant increase in fish abundance and richness at the Williams River, New South Wales (Brooks and others 2004), and a significant increase in coho salmon spawning in Elk Creek, Oregon (Crispin and others 1993), but no changes in fish richness or abundance were detected in the Little Yarra River, Victoria (Coleman 2006). Prior to drought conditions, improvements in abundance of common fish species were observed at Granite Creek, Victoria (Bond and Lake 2005). The addition of wood increased the bank stability of the Williams River (Brooks and others 2004), but there was no persistent effect of wood introduction on erosion in Little Topashaw Creek, Mississippi (Shields and others 2003, 2006). Wood addition led to increased nutrient retention in some cases (Roberts and others 2007), but results were mixed in others (Wallace and others 1995). The most consistent responses across the different studies have been increased habitat diversity (greater diversity of depths, velocities, and habitat elements; Brooks and others 2004; Gerhard and Reich 2000; Roberts and others 2007; Wallace and others 1995) and increased sediment and organic matter storage (Brooks and others 2004; Gerhard and Reich 2000; Millington and Sear 2007). For the most part, the addition of wood led to greater diversity of macroinvertebrate communities (Gerhard and Reich 2000; Hilderbrand and others 1997; Lester and others 2007), sometimes specific to particular groups of taxa (e.g., trichopteran and dipteran shredders; Wallace and others 1995), although such increases were not detected in urban environments (Larson and others 2001) or in the primarily forested Little Yarra River, Victoria (Coleman 2006). Based on these studies, Fig. 2 highlights those agricultural pressures on streams where wood addition is likely to have an impact.

Among the projects undertaken in agricultural landscapes, Lester and others (2007) detected an increase in diversity of macroinvertebrate communities, whereas Zika and Peter (2002) observed increases in abundance and biomass of trout, along with increased fine organic material and the number of pools in the reach. One of the streams studied by Gerhard and Reich (2000) was in an agricultural catchment. The stream did show some improvement in microhabitat diversity, but effects were minor. This might have been due to the lack of large flows during the project (Gerhard and Reich 2000). Brooks and others (2004) reported substantial improvement in bank stability and sediment storage within the treated reach in a New South Wales river, but in a sand-slugged Victorian stream, no refuge habitats were created that were sufficient to hold free water during a severe drought (Bond and Lake 2005). This was attributed to the lack of flushing flows prior to the dry conditions (Bond and Lake 2005). In a German stream, the addition of groups of branches led to changes in channel morphology, including increased erosion during high flow and resulted in an initial depletion of the target chironomid community (Spanhoff and others 2006). The authors ascribed the initial negative finding to the choice of wood species, the placement of the wood, and insufficient time of monitoring (Spanhoff and others 2006). The recommendation that longer time frames were needed to fully understand the effects of wood addition on stream morphology was common (Bond and Lake 2005; Brooks and others 2004; Shields and others 2003, 2004).

Although all of the studies reviewed here have undergone assessments of the response of the stream to the rehabilitation attempt, few, if any, have been assessed for ecological success according to criteria proposed by Palmer and others (2005). The results of this meta-analysis should be considered with caution because the various studies reviewed were undertaken using different methods with different objectives in a variety of stream orders and across different landscapes. Criteria for ecological success include the use of a guiding image, improvement of an ecosystem relative to that image, increased resilience, no lasting harm results, completed ecological assessment (Palmer and others 2005) and that specific hypotheses are tested (Jansson and others 2005) and attainment of ecological success must remain a primary goal for restoration (Palmer and others 2005). In order to maximize the value of each rehabilitation project and inform future strategies for stream restoration, future projects should insist on measuring the ecological success of the rehabilitation as well as trying to identify the mechanism of response (Jansson and others 2005). This will enable projects to be compared objectively and for lessons to be applied in future stream restoration research.

Does Wood Have the Potential to Address Stream Degradation Associated with Agriculture?

Although most previous rehabilitation and restoration works involving the addition of wood to streams have been undertaken in forested landscapes, some insights can be gained into the potential for wood reintroductions to redress stream degradation associated with agriculture. As reviewed earlier, there are a number of common effects arising from agricultural practices. These include channel incision, excessive sedimentation, reduced structural diversity in the channel, including fewer pool and riffle sequences, increased transport of water and organic material in the channel, less riparian and in-stream vegetation, changes to water temperature, and increased inputs of pollutants.

Introduction of wood potentially increases pool formation and hydraulic diversity of stream channels (Montgomery and others 1995; Webb and Erskine 2005), altering the pool–riffle sequence of the stream and typically increasing the amount of pool habitat available (Abbe and Montgomery 1996; Keller and Tally 1979). This has consequences for the hydrology of the stream, influencing energy dissipation (Gippel and others 1996), sediment storage (Bilby and Ward 1991; Wallerstein and Thorne 2004), and flood peaks (Gurnell 1995). In agricultural landscapes, large wood is likely to accelerate the recovery of a stable channel profile in streams affected by channel incision (Wallerstein and Thorne 2004). Accumulations of wood have increased sediment storage within a stream reach (Wallerstein and Thorne 2004) and the introduction of in-stream habitat components (stone and planted willows) increased the depth of pools, although channel planform geometry and the stage–discharge relationship did not change (Shields and others 1997). Large wood has the potential to decrease bed-transport rates by up to an order of magnitude, thereby contributing to channel stability (Brooks 1999). For example, a reach of the Williams River, New South Wales (Fig. 1) that was rehabilitated with engineered log jams showed a net gain of 40 m^3 of sediment per 1000 m^2 of channel area over 12 months, whereas an untreated reach experienced a net loss of 15 m^3 per 1000 m^2 over the same time period (Brooks and others 2004).

Improvements in water quality due to the addition of wood to streams are also possible. The introduction of obstacles like wood creates diversity in the velocity profile and increases turbulence. Higher levels of turbulence can elevate dissolved oxygen levels and contribute to the mechanical breakdown of CPOM (Hendry and others 2003). Organic matter storage has also been shown to increase with the addition of wood (Lepori and others 2005; Trotter 1990). The effect of wood additions on nutrient cycling is not clear, with studies finding variable relationships between wood loads and phosphate, ammonia, and nitrate uptake rates (Roberts and others 2007; Vallett and others 2002; Wallace and others 1995; Warren and others 2007). Preliminary work undertaken in the Hunter River in New South Wales indicates that wood additions can also increase surface–subsurface connectivity by enhancing exchange with the hyporheic zone (Boulton 2007; Mika, University of New England, Australia, personal communication, 24 March 2008), although no increase in hyporheic storage was noted for a US sand-bed stream (Stofleth and others 2008). Other restoration work in agricultural areas, although not involving wood additions, has shown that improving horizontal channel complexity can also increase lateral connectivity and enhance hyporheic flows (Kasahara and Hill 2007).

The presence of wood in several agricultural streams in the United States increased macroinvertebrate richness in both Minnesota and Michigan (Johnson and others 2003) and was associated with more diverse fish communities in the Midwest (Talmage and others 2002). Wood additions in agricultural regions in Victoria, Australia also led to increased macroinvertebrate diversity (Lester and others 2007). Given suitable water quality, the habitat available in a stream influences the biotic communities supported by that stream (Davies and others 2000). Factors including condition and position of wood, water depth, and current velocity are known to influence macroinvertebrate colonization and community composition on a piece of wood (Johnson and others 2003; Nilsen and Larimore 1973; Scealy and others 2007). Fish communities should benefit from the presence of woody debris given the increase in cover and food provided, the associated reduction in siltation, and the formation of additional pool habitats (Angermeier and Karr 1984; Talmage and others 2002).

Although we believe it is too simplistic to identify regions within Australia (or elsewhere) where wood is more or less likely to be beneficial, the restoration projects reviewed here can give some insight into conditions under which wood reintroduction are most likely to be of use. Despite the wide range of streams, landscapes, and objectives for rehabilitation, the majority of authors recommended wood introductions as a stream rehabilitation tool (e.g., Brooks and others 2004; Hilderbrand and others 1997; Kail and others 2007; Roberts and others 2007). Benefits to stream stability, habitat heterogeneity, and macroinvertebrate and fish diversity were observed in clay/silt, gravel, and sand-bed streams, in small to medium streams and in larger rivers. There was also evidence that using larger accumulations of wood was more likely to affect channel morphology (Gerhard and Reich 2000). Together, these findings suggest that wood introductions can be successful over a wide range of conditions.

Situations in which wood might be less likely to be beneficial include areas that experience severe channel incision, as wood might not be sufficient to stabilize the banks and improvements might be short term if structures fail (e.g., Larson and others 2001; Shields and others 2006). In these circumstances, restoration of the stream bank might be necessary before in-stream habitat can be considered and the choice of wood and placement of accumulations needs to be carefully considered. Given the lack of biological rehabilitation in urban areas (Larson and others 2001), highly degraded agricultural areas might also be unsuitable for restoration using wood reintroductions.

Factors such as poor water quality might override any benefit derived from additional in-stream habitat diversity. Another factor likely to slow response to wood in urban or highly degraded agricultural areas is the location of the nearest source population of colonists and the diversity of that population. This is important for biological restoration to facilitate colonization of the improved habitat (Schriever and others 2007). There was also a suggestion by Larson and others (2001) that the benefits of wood addition were lowest in the steepest streams. Finally, wood additions might not be appropriate for streams that were not originally in a forested ecosystem and would have a negligible natural in-stream wood load.

Conditions likely to affect wood transport and decay should also be considered. Streams where wood is likely to be transported out of a reach of interest (i.e., due to a flashy hydrograph) might mean that anchoring will be necessary. The density of wood should be considered, although this is less likely to be an issue in Australia, where most native species are denser than water. In addition, flows need to be sufficient to induce change in channel morphology before significant benefits are likely, either to habitat diversity or to biodiversity. The relevant conditions at each target stream should be assessed individually to determine whether wood additions are likely to aid in restoration.

Wood Reintroduction to Streams in Agricultural Landscapes: Synthesis and Conclusions

Wood has been shown to have a positive effect on the bed and bank stability, to increase the sediment storage capacity of a reach, and to increase the diversity of the depth and velocity profiles. Reintroducing wood has increased these properties in previously cleared reaches in forested and in agricultural landscapes. Most studies undertaken in agricultural landscapes detected at least short-term improvements in biological diversity attributable to enhanced physical complexity. This is encouraging for the general applicability of the technique.

In contrast, some impacts that are primarily due to agriculture, such as increased nutrients, input of pesticides and herbicides, and reduced shading, might not be ameliorated by wood reintroduction. Additionally, broad-scale factors such as climate change or change in land-use practices are not likely to be affected by wood addition. Indeed, these larger-scale impacts might act as environmental filters (Poff 1997), constraining the viability or sources of potential recolonists, regardless of the habitat complexity and the amount of wood in the channel. The overlapping spatial scales at which processes occur are depicted in Fig. 2. Where processes cause large-scale impairment, the addition of wood to streams is unlikely to improve biological diversity and might not be an appropriate use of resources.

Propagation of realistic expectations regarding likely improvements due to wood addition is important for ensuring that stakeholders (including landholders) are satisfied with the results of a restoration attempt. In agricultural landscapes, achieving stakeholder success is potentially as important as ecological success. Without landholder support, benefits arising from projects on private property might be eroded over time through production-focused management practices (Bennett and Mac Nally 2004). Some studies have found that initial negative outcomes might result but expect that benefits will become apparent over time (e.g., Spanhoff and others 2006). Unrealistic expectations for changes in biodiversity might foster disillusionment and an unwillingness to participate in future projects.

Another barrier to stakeholder success is community perception about wood. Some communities tend to view rivers as having lower aesthetic value, higher danger, and greater need for improvement when wood is present than when it is absent (Chin and others 2008; Piegay and others 2005). These perceptions might effectively prevent landholders from participating in restoration projects involving the addition of wood to streams. Consideration should also be given to identifying and managing any risks to infrastructure. Identifying variables where improvement is obvious to stakeholders might also be important. For example, tracking improvements in water clarity, algal biomass, fish abundance, or pool depth, for example, might be an easy way to give stakeholders a sense of success. Stakeholder success is touched upon infrequently (see Brooks and others 2004) in published restoration projects, despite its importance to long-term success in managed ecosystems like streams in agricultural areas and restoration works on private land where ongoing access is essential.

To adequately assess the applicability of the addition of wood, additional assessment of rehabilitation projects is required in agricultural landscapes. In particular, a better understanding of the factors responsible for differences in the findings of previous studies is required along with testing of hypotheses regarding the mechanisms underlying different responses. From the empirical evidence collected to date, water quality and flow regimes are likely to be important factors driving these differences, along with the location of source populations. Explicitly testing how these factors interact and how this affects wood-based restoration across a range of streams might be useful in identifying where wood additions would be most successful.

A range of guidelines and advice exists for the reintroduction of wood into streams for restoration purposes (e.g., Erskine and Webb 2003; Kail and others 2007; Rutherfurd and others 2000; Treadwell 1999). Recommendations include mimicking the natural loading and distribution of wood and sourcing wood from "waste" wood supplies so as not to remove valuable habitat from other ecosystems (Erskine and Webb 2003; Kail and others 2007; Treadwell 1999). Locally indigenous wood species are also recommended, as exotic species are less palatable to native macroinvertebrates in some Australian streams (McKie and Cranston 2001) and to minimize the spread of disease and pests. Anchoring the wood must be considered where there is a risk of damage to infrastructure downstream, and downstream orientations are recommended to limit the potential for problems with localized scour (Treadwell 1999). These, along with local conditions and farmer attitudes, should be considered for any restoration project involving wood addition.

Irrespective of the applicability of the technique to individual streams, reintroducing wood should only be one part of the stream restoration strategy. It is a transient step that can introduce habitat and biological diversity and physical stability in the short term. It is not a self-sustaining long-term restoration strategy, as pieces will be lost to decay and transport processes. Complementary strategies such as the revegetation of riparian zones and selective exclusion of excess grazing pressure are needed to ensure that a source of wood exists to replenish pieces over time and to address other problems associated with agricultural landscapes that are not remedied by the addition of wood to the stream.

Compared with restoration methods currently used in agricultural landscapes, such as engineered erosion control devices (Comoss and others 2002; Wu and Feng 2006), wood reintroduction has some distinct advantages, and these should be reviewed with landholders and farmers. One is that the technique is focused on the in-stream environment and uses minimal productive riparian land (although, ideally, the wood introduction would be linked with riparian revegetation). The second is that the stream ecosystem responses are often quite rapid, especially regarding morphological changes and increased physical heterogeneity, and there are a number of variables, like increased fish density and improved water quality, that will be evident to the landholders. Third, many farmers have the machinery and technical expertise to install wood in their stream reaches, guided by professional managers and resource management agencies. This direct involvement confers a strong sense of ownership of the project and increases the likelihood of initiation in other areas. Finally, the longer-term maintenance is often less than in riparian revegetation projects where weeding and fence maintenance might be ongoing and a substantial investment of time and money, making it an attractive addition to a rehabilitation strategy without adding significantly to the required resources.

Acknowledgments This review was written as part of the senior author's Ph.D. studies, supported by a scholarship from the School of Applied Sciences and Engineering, Monash University and in-kind support from the Department of Primary Industries, Ellinbank. We thank Dr. Wendy Wright and Dr. Nick Bond, R. Lester's thesis examiners, and four anonymous reviewers for their constructive comments on earlier drafts of this manuscript.

References

Abbe TB, Montgomery DR (1996) Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research and Management 12:201–221

Allan JD (2004) Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution and Systematics 35:257–284

Anbumozhi V, Radhakrishnan J, Yamaji E (2005) Impact of riparian buffer zones on water quality. Ecological Engineering 24:517–523

Anderson NH, Sedell JR, Roberts LM, Triska FJ (1978) The role of aquatic invertebrates in processing of wood debris in coniferous forest streams. American Midland Naturalist 100:64–82

Angermeier PL, Karr JR (1984) Relationships between woody debris and fish habitat in a small warmwater stream. Transactions of the American Fisheries Society 113:716–726

Benke AC, Van TC Arsdall Jr, Gillespie DM, Parrish FK (1984) Invertebrate productivity in a subtropical blackwater river: the importance of habitat and life history. Ecological Monographs 54:25–63

Benke AC, Wallace JB (2003) Influence of wood on invertebrate communities in streams and rivers. In: Gregory SV, Boyer KL, Gurnell AM (eds) The ecology and management of wood in world rivers. American Fisheries Society, Bethesda, MD, pp 149–177

Bennett AF, Mac Nally R (2004) Identifying priority areas for conservation in agricultural landscapes. Pacific Conservation Biology 10:106–123

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

Bilby RE, Ward JW (1991) Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and 2nd-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48:2499–2508

Blinn DW, Halse SA, Pinder AM, Shiel RJ, McRae JM (2004) Diatom and micro-invertebrate communities and environmental determinants in the western Australian wheatbelt: a response to salinization. Hydrobiologia 528:229–248

Bond NR, Lake PS (2003) Characterizing fish-habitat associations in streams as the first step in ecological restoration. Austral Ecology 28:611–621

Bond NR, Lake PS (2005) Ecological restoration and large-scale ecological disturbance: the effects of drought on the response by fish to a habitat restoration experiment. Restoration Ecology 13:39–48

Boulton AJ (2007) Hyporheic rehabilitation in rivers: restoring vertical connectivity. Freshwater Biology 52:632–650

Boulton AJ, Brock MA (1999) Australian freshwater ecology: processes and management. Gleneagles Publishing, Glen Osmond, South Australia

Boulton AJ, Williams WD (1996) Aquatic biota. In: Twidale CR, Tyler MJ, Davies M (eds) The natural history of the Flinders Ranges. Royal Society of South Australia, Adelaide, pp 102–112
Boutin C, Jobin B, Belanger L (2003) Importance of riparian habitats to flora conservation in farming landscapes of southern Quebec, Canada. Agriculture, Ecosystems and Environment 94:73–87
Brock MA, Smith RGB, Jarman PJ (1999) Drain it, dam it: alteration of water regime in shallow wetlands on the New England Tableland of New South Wales, Australia. Wetlands Ecology and Management 7:37–46
Brooks A (1999) Large woody debris and the geomorphology of a perennial river in southeast Australia. In: Rutherfurd ID, Bartley R (eds) Second Australian stream management conference proceedings: the challenge of rehabilitating Australia's streams. Cooperative Research Centre for Catchment Hydrology, Adelaide, pp 129–136
Brooks AP, Abbe TB, Jansen JD, Taylor M, and Gippel CJ (2001) Putting the wood back into our rivers: an experiment in river rehabilitation. In: Rutherfurd ID, Sheldon F, Brierley G, and Kenyon C (eds) Third Australian stream management conference proceedings: the value of healthy streams. Cooperative Research Centre for Catchment Hydrology, Brisbane, pp 73–80
Brooks AP, Brierley GJ, Millar RG (2003) The long-term control of vegetation and woody debris on channel and flood-plain evolution: insights from a paired catchment study in southeastern Australia. Geomorphology 51:7–29
Brooks AP, Gerhrke PC, Jansen JD, Abbe TB (2004) Experimental reintroduction of woody debris on the Williams River, NSW: geomorphic and ecological responses. River Research and Applications 20:513–536
Buckley BM, Triska FJ (1978) Presence and ecological role of nitrogen-fixing bacteria associated with wood decay in streams. Verhandlungen Internationale Vereinigung fur Theroetische und Angewandte Limnologie 20:1333–1339
Bunn SE, Davies PM, Winning M (2003) Sources of organic carbon supporting the food web of an arid zone floodplain river. Freshwater Biology 48:619–635
Carline RF, Walsh MC (2007) Responses to riparian restoration in the Spring Creek Watershed, Central Pennsylvania. Restoration Ecology 15:731–742
Chapman DW, Knudsen E (1980) Channelization and livestock impacts on salmonid habitat and biomass in western Washington. Transactions of the American Fisheries Society 109:357–363
Cherry J, Beschta RL (1989) Coarse woody debris and channel morphology: a flume study. Water Resources Bulletin 25:1031–1306
Chin A, Daniels MD, Urban MA et al (2008) Perceptions of wood in rivers and challenges for stream restoration in the United States. Environmental Management 41:893–903
Coleman R (2006) Ecological and physical responses to large woody debris reintroduction in the Little Yarra River, Victoria, Australia. MSc thesis, Monash University, Melbourne
Collares-Pereira MJ, Cowz IG (2004) The role of catchment scale environmental management in freshwater fish conservation. Fisheries Management and Ecology 11:303–312
Collier KJ, Halliday JN (2000) Macroinvertebrate-wood associations during decay of plantation pine in New Zealand pumice-bed streams: stable habitat or trophic subsidy? Journal of the North American Benthological Society 19:94–111
Comoss EJ, Kelly DA, Leslie HZ (2002) Innovative erosion control involving the beneficial use of dredge material, indigenous vegetation and landscaping along the Lake Erie shoreline. Ecological Engineering 19:203–210
Cornish PM (2001) The effects of roading, harvesting and forest regeneration on streamwater turbidity levels in a moist eucalypt forest. Forest Ecology and Management 152:293–312
Correll DL (2005) Principles of planning and establishment of buffer zones. Ecological Engineering 24:433–439
Coysh J, Nichols S, Ransom G et al (2000) AUStralian RIVer Assessment System (AusRivAS) national river health program predictive model manual. Cooperative Research Centre for Freshwater Ecology, Canberra
Crispin V, House R, Roberts D (1993) Changes in instream habitat, large woody debris and salmon habitat after the restructuring of a coastal Oregon stream. North American Journal of Fisheries Management 13:96–102
Crook DA, Robertson AI (1999) Relationships between riverine fish and woody debris: implications for lowland rivers. Marine and Freshwater Research 50:941–953
Davies NM, Norris RH, Thoms MC (2000) Prediction and assessment of local stream habitat features using large-scale catchment characteristics. Freshwater Biology 45:343–369
Donnelly TH, Grace MR, Hart BT (1997) Algal blooms in the Darling-Barwon River, Australia. Water, Air and Soil Pollution 99:487–496
Downes BJ, Lake PS, Glaister A, Bond NR (2006) Effects of sand sedimentation on the macroinvertebrate fauna of lowland streams: are the effects consistent? Freshwater Biology 51:144–160
Erskine W (1994) River response to accelerated soil erosion in the Glenelg River catchment, Victoria. Australian Journal of Soil and Water Conservation 7:39–47
Erskine WD, Webb AA (2003) Desnagging to resnagging: new directions in river rehabilitation in southeastern Australia. River Research and Applications 19:233–249
Finlayson BL, McMahon TA (1988) Australia v the world: a comparative analysis of streamflow characteristics. In: Warner RF (ed) Fluvial geomorphology of Australia. Academic Press, Marrickville, NSW, pp 17–40
Fisher SG, Likens GE (1973) Energy flow in Bear Brook, New Hampshire: an integrative approach to stream ecosystem metabolism. Ecological Monographs 43:421–439
Gerhard M, Reich M (2000) Restoration of streams with large wood: effects of accumulated and built-in wood on channel morphology, habitat diversity and aquatic fauna. International Review of Hydrobiology 85:123–137
Gerard PW (1995) Agricultural practices, farm policy and the conservation of biological diversity. USDI Biological Sciences Report No 4, Washington, DC
Gillespie GR (2002) Impacts of sediment loads, tadpole density, and food type on the growth and development of tadpoles of the spotted tree frog *Litoria spenceri*: an in-stream experiment. Biological Conservation 106:141–150
Gippel CJ, Finlayson BL, O'Neill IC (1996) Distribution and hydraulic significance of large woody debris in a lowland Australian river. Hydrobiologia 318:179–194
Gippel CJ, O'Neill IC, Finlayson BL (1992) The hydraulic basis of snag management. Centre for Environmental Applied Hydrology, Melbourne
Growns I, Gerhrke PC, Astles KL, Pollard DA (2003) A comparison of fish assemblages associated with different riparian vegetation types in the Hawkesbury-Nepean River system. Fisheries Management and Ecology 10:209–220
Gunderson DR (1968) Floodplain use related to stream morphology and fish populations. Journal of Wildlife Management 32:507–514
Gurnell AM (1995) Vegetation along river corridors: hydrogeomorphological interactions. In Gurnell A, Petts G (eds) Changing river channels. John Wiley & Sons, Chichester, pp 117–146
Harmon ME, Franklin JF, Swanson FJ et al (1986) Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133–302

Harris JH, Rowland SJ (1996) Family Percichthyidae: Australian freshwater cods and basses. In: McDowall RM (ed) Freshwater fishes of south-eastern Australia. Reed Books, Chatswood, NSW, Australia pp 150–163

Hax CL, Golladay SW (1998) Flow disturbance of macroinvertebrates inhabiting sediments and woody debris in a prairie stream. American Midland Naturalist 139:210–223

Hazell D, Osborne W, Lindenmayer D (2003) Impact of post-European stream change on frog habitat: Southeastern Australia. Biodiversity and Conservation 12:301–320

Hefting MM, Clement J-C, Bienkowski P et al (2005) The role of vegetation and litter in the nitrogen dynamics of riparian buffer zones in Europe. Ecological Engineering 24:465–482

Hendry K, Cragg-Hine D, O'Grady M, Sambrook H, Stephen A (2003) Management of habitat for rehabilitation and enhancement of salmonid stocks. Fisheries Research 62:171–192

Hester ET, Doyle MW (2008) In-stream geomorphic structures as drivers of hyporheic exchange. Water Resources Research 44:1–17

Hilderbrand RH, Lemly AD, Dolloff CA, Harpster KL (1997) Effects of large woody debris placement on stream channels and benthic macroinvertebrates. Canadian Journal of Fisheries and Aquatic Sciences 54:931–939

Hilderbrand RH, Lemly AD, Dolloff CA, Harpster KL (1998) Design considerations for large woody debris placement in stream enhancement projects. North American Journal of Fisheries Management 18:161–167

Hortle KG, Lake PS (1983) Fish of channelized and unchannelized sections of the Bunyip River Victoria Australia. Australian Journal of Marine and Freshwater Research 34:441–450

Hose GC, Lim RP, Hyne RV, Pablo F (2003) Short-term exposure to aqueous endosulfan affects macroinvertebrate assemblages. Ecotoxicology and Environmental Safety 56:282–294

Jansson R, Backx H, Boulton AJ et al (2005) Stating mechanisms and refining criteria for ecologically successful river restoration: a comment on Palmer et al (2005). Journal of Applied Ecology 42:218–222

Johnson LB, Breneman DH, Richards C (2003) Macroinvertebrate community structure and function associated with large wood in low gradient streams. River Research and Applications 19:199–218

Kail J, Hering D, Muhar S, Gerhard M, Preis S (2007) The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria. Journal of Applied Ecology 44:1145–1155

Kasahara T, Hill AR (2007) Instream restoration: its effects on lateral stream-subsurface water exchange in urban and agricultural streams in southern Ontario. River Research and Applications 23:801–814

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

King RD, Tyler PA (1982) Downstream effects of the Gordon River power development, south-west Tasmania. Australian Journal of Marine and Freshwater Research 33:431–442

Koehn J (1987) Artificial habitat increases abundance of two-spined blackfish (*Gadopsis bispinosis*) in Ovens River, Victoria. Technical Report Series No 56. Arthur Rylah Institute for Environmental Research, Heidelberg

Koehn JD, Nicol SJ, Fairbrother PS (2004) Spatial arrangement and physical characteristics of structural woody habitat in a lowland river in south-eastern Australia. Aquatic Conservation 14:457–464

Koehn JD, O'Conner WG (1990) Threats to Victorian native freshwater fish. Victorian Naturalist 107:5–12

Lake PS, Marchant R (1990) Australian upland streams: ecological degradation and possible restoration. Proceedings of the Ecological Society of Australia 16:79–91

Land and Water Australia (2001a) Australian agriculture assessment 2001. National Land and Water Resources Audit, Braddon

Land and Water Australia (2001b) Australian native vegetation assessment 2001. National Land and Water Resources Audit, Braddon

Land and Water Australia (2002) Australian catchment, river and estuary assessment 2002. National Land and Water Resources Audit, Braddon

Land and Water Australia (2006) Australian natural resources atlas. National Land and Water Resources Audit, Braddon

Larson MG, Booth DB, Morley SA (2001) Effectiveness of large woody debris in stream rehabilitation projects in urban basins. Ecological Engineering 18:211–226

Lemly AD, Hilderbrand RH (2000) Influence of large woody debris on stream insect communities and benthic detritus. Hydrobiologia 421:179–185

Leonard AW, Hyne RV, Lim RP, Chapman JC (1999) Effect of endosulfan runoff from cotton fields on macroinvertebrates in the Namoi River. Ecotoxicology and Environmental Safety. Environmental Research, Section B 42:125–134

Lepori F, Palm D, Malmqvist B (2005) Effects of stream restoration on ecosystem functioning: detritus retentiveness and decomposition. Journal of Applied Ecology 42:228–238

Lester RE, Wright W, Jones-Lennon M (2007) Does adding wood to agricultural streams enhance biodiversity? An experimental approach. Marine and Freshwater Research 58:687–698

Maheshwari BL, Walker KF, McMahon TA (1995) Effects of regulation on the flow regime of the River Murray, Australia. Regulated Rivers: Research and Management 10:15–38

Maser C, Sedell JR (1994) From the forest to the sea: the ecology of wood in streams, rivers, estuaries and oceans. St. Lucie Press, Delray Beach, FL

McKie B, Cranston PS (2001) Colonisation of experimentally immersed wood in south eastern Australia: responses of feeding groups to changes in riparian vegetation. Hydrobiologia 452:1–14

McKie B, Cranston PS (1998) Keystone coleopterans? Colonization by wood-feeding elmids of experimentally immersed woods in south-eastern Australia. Marine and Freshwater Research 49:79–88

Merrick JR, Schmida GE (1984) Australian freshwater fishes: biology and management. Griffin Press, Netley, NSW, Australia

Millington CE, Sear DA (2007) Impacts of river restoration on small-wood dynamics in a low-gradient headwater stream. Earth Surface Processes and Landforms 32:1204–1218

Moerke AH, Gerhard KJ, Latimore JA, Hellenthal RA, Lamberti GA (2004) Restoration of an Indiana, USA, stream: bridging the gap between basic and applied lotic ecology. Journal of the North American Benthological Society 23:647–660

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

Mutz M (2000) Influences of woody debris on flow patterns and channel morphology in a low energy, sand-bed stream reach. International Review of Hydrobiology 85:107–121

Myers TJ, Swanson S (1991) Aquatic habitat condition index, stream type, and livestock bank damage in northern Nevada. Water Resources Bulletin 27:667–677

Myers TJ, Swanson S (1996) Long-term aquatic habitat restoration: Mahogany Creek, Nevada, as a case study. Water Resources Bulletin 32:241–252

Nakamura F, Yamada H (2005) Effects of pasture development on the ecological functions of riparian forests in Hokkaido in northern Japan. Ecological Engineering 24:539–550

Nilsen HC, Larimore RW (1973) Establishment of invertebrate communities on log substrates in the Kaskaskia River, Illinois. Ecology 54:366–374

Norris RH, Prosser I, Young B et al (2001) The Assessment of River Condition (ARC). An audit of the ecological condition of Australian rivers. National Land and Water Resources Audit Office, Canberra

O'Connor NA (1992) Quantification of submerged wood in a lowland Australian stream system. Freshwater Biology 27:387–395

Palmer MA, Bernhardt ES, Allan JD et al (2005) Standards for ecologically successful river restoration. Journal of Applied Ecology 42:208–217

Parkyn SM, Davies-Colley RJ, Halliday NJ, Costley KJ, Croker GF (2003) Planted riparian buffer zones in New Zealand: do they live up to expectations? Restoration Ecology 11:436

Piegay H, Mutz M, Gregory KJ et al (2005) Public perception as a barrier to introducing wood in rivers for restoration purposes. Environmental Management 36:665–674

Pinder AM, Hasle SA, McRae JM, Shiel RJ (2004) Aquatic invertebrate assemblages of wetlands and rivers in the wheatbelt region of Western Australia. Records of the Western Australian Museum Supplement 67:7–37

Platts WS, Nelson RL (1985) Stream habitat and fisheries response to livestock grazing and instream improvement structures, Big Creek, Utah. Journal of Soil and Water Conservation 40:374–379

Poff NL (1997) Landscape filters and species traits: towards mechanistic understanding and prediction in stream ecology. Journal of the North American Benthological Society 16:391–409

Probst M, Berenzen N, Lentzen-Godding A, Schulz R, Liess M (2005) Linking land use variables and invertebrate taxon richness in small and medium-sized agricultural streams on a landscape level. Ecotoxicology and Environmental Safety 60:140–146

Puckridge JT, Sheldon F, Walker KF, Boulton AJ (1998) Flow variability and the ecology of large rivers. Marine and Freshwater Research 49:55–72

Quinn JM, Cooper AB, Davies-Colley RJ, Rutherford JC, Williamson RB (1997) Land use effects on habitat, water quality, periphyton, and benthic invertebrates in Waikato, New Zealand, hill-country streams. New Zealand Journal of Marine and Freshwater Research 31:579–597

Rasiah V, Armour JD, Menzies NW, Heiner DH, Donn MJ, Mahendrarajah S (2003) Nitrate retention under sugarcane in wet tropical Queensland deep soil profiles. Australian Journal of Soil Research 41:1145–1161

Reid N, Boulton A, Nott R, Chilcott C (1997) Ecological sustainability of grazed landscapes on the Northern Tablelands of New South Wales, Australia. In: Klomp N, Lunt I, (eds) Frontiers in ecology: building the links. Elsevier, Oxford, pp 117–130

Reinfelds I, Rutherfurd I, Bishop P (1995) History and effects of channelisation on the Latrobe River, Victoria. Australian Geographical Studies 33:60–76

Roberts BJ, Mulholland PJ, Houser JN (2007) Effects of upland disturbance and instream restoration on hydrodynamics and ammonium uptake in headwater streams. Journal of the North American Benthological Society 26:38–53

Robertson AI (1997) Land-water linkages in floodplain river systems: the influence of domestic stock. In: Klomp N, Lunt I (eds) Frontiers in ecology: building the links. Elsevier, Oxford, pp 207–218

Robertson AI, Bunn SE, Boon PI, Walker KF (1999) Sources, sinks and transformations of organic carbon in Australian floodplain rivers. Marine and Freshwater Research 50:813–829

Robertson AI, Rowling RW (2000) Effects of livestock on riparian zone vegetation in an Australian dryland river. Regulated Rivers: Research and Management 16:527–541

Ruprecht JK, Schofield NJ (1991) Effects of partial deforestation on hydrology and salinity in high salt storage landscapes I: Extensive block clearing. Journal of Hydrology 129:19–38

Rutherford JC, Marsh NA, Davies PM, Bunn SE (2004) Effects of patchy shade on stream water temperature: how quickly do small streams heat and cool? Marine and Freshwater Research 55:737–748

Rutherfurd ID, Jerie K, Marsh N (2000) A rehabilitation manual for Australian streams. CRC Catchment Hydrology and Land and Water Resources Research and Development Corporation, Canberra

Ryder DS, Watts RJ, Nye E, Burns A (2006) Can flow velocity regulate epixylic biofilm structure in a regulated floodplain river. Marine and Freshwater Research 57:29–36

Scealy JA, Mika SJ, Boulton AJ (2007) Aquatic macroinvertebrate communities on wood in an Australian lowland river: experimental assessment of the interactions of habitat, substrate complexity and retained organic matter. Marine and Freshwater Research 58:153–165

Schofield NJ, Collier KJ, Quinn JM, Sheldon F, Thoms M (2000) River conservation in Australia and New Zealand. In: Boon PJ, Davies BR, Petts GE (eds) Global perspectives on river conservation: science, policy and practice. John Wiley & Sons, London, pp 311–333

Schriever CA, Hansler Ball M, Holmes C, Maund S, Liess M (2007) Agricultural intensity and landscape structure: influences on the macroinvertebrate assemblages of small streams in northern Germany. Environmental Toxicology and Chemistry 26:346–357

Shields FD Jr, Knight SS, Cooper CM (1994) Effects of channel incision on base flow stream habitats and fishes. Environmental Management 18:43–57

Shields FD Jr, Knight SS, Cooper CM (1997) Rehabilitation of warmwater stream ecosystems following channel incision. Ecological Engineering 8:93–116

Shields FD Jr, Knight SS, Morin N, Blank J (2003) Response of fishes and aquatic habitats to sand-bed stream restoration using large woody debris. Hydrobiologia 494:251–257

Shields FD Jr, Knight SS, Stofleth JM (2006) Large wood addition for aquatic habitat rehabilitation in an incised, sand-bed stream, Little Topashaw Creek, Mississippi. River Research and Applications 22:803–817

Shields FD Jr, Morin N, Cooper CM (2004) Large woody debris structures for sand-bed channels. Journal of Hydraulic Engineering 130:208–217

Smock LA, Metzler GM, Gladden JE (1989) Role of debris dams in the structure and functioning of low-gradient headwater streams. Ecology 70:764–775

Sovell LA, Vondracek B, Frost JA, Mumford KG (2000) Impacts of rotational grazing and riparian buffers on physicochemical and biological characteristics of southeastern Minnesota, USA, streams. Environmental Management 26:629–641

Spanhoff B, Riss W, Jakel P, Dakkak N, Meyer EI (2006) Effects of an experimental enrichment of instream habitat heterogeneity on the stream bed morphology and chironomid community of a straightened section in a sandy lowland stream. Environmental Management 37:247–257

Stofleth JM, Shields FD Jr, Fox GA (2008) Hyporheic and total transient storage in small, sand-bed streams. Hydrological Processes 22:1885–1894

Stone ML, Whiles MR, Webber JA, Williard JKW, Reeve JD (2005) Macroinvertebrate communities in agriculturally impacted southern Illinois streams: patterns with riparian vegetation, water quality, and in-stream habitat quality. Journal of Environmental Quality 34:907–917

Talmage PJ, Perry JA, Goldstein RM (2002) Relation of instream habitat and physical conditions to fish communities of

agricultural streams in the northern Midwest. North American Journal of Fisheries Management 22:825–833
Treadwell S (1999) Managing snags and large woody debris. In: Price P, Lovett S (eds) Riparian land management technical guidelines: on-ground management tools and techniques. Land and Water Resources Research and Development Corporation, Canberra, pp 15–32
Triska FJ (1984) Role of wood debris in modifying channel geomorphology and riparian areas of a large lowland river under pristine conditions: a historical case study. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 22:1876–1892
Trotter EH (1990) Woody debris, forest-stream succession, and catchment geomorphology. Journal of the North American Benthological Society 9:141–156
Vallett HM, Crenshaw CL, Wagner PF (2002) Stream nutrient uptake, forest succession and biogeochemical theory. Ecology 83:2888–2901
Walker KF (1993) Issues in the riparian ecology of large rivers. In: Bunn SE, Pusey BJ, Price P (eds) Ecology and management of riparian zones in Australia. Land and Water Resources Research and Development Corporation and Centre for Catchment and In-stream Research, Canberra, pp 31–40
Wallace J, Benke A (1984) Quantification of wood habitat in subtropical coastal plain streams. Canadian Journal of Fisheries and Aquatic Sciences 41:1643–1652
Wallace JB, Anderson NH (1996) Habitat, life history, and behavioral adaptations of aquatic insects. In: Merritt RW, Cummins KW (eds) An introduction to the aquatic insects of North America. Kendall/Hunt Publishing, Dubuque, IA, pp 41–73
Wallace JB, Webster JR, Meyer JL (1995) Influence of log additions on physical and biotic characteristics of a mountain stream. Canadian Journal of Fisheries and Aquatic Sciences 52:2120–2137
Wallerstein NP, Thorne CR (2004) Influence of large woody debris on morphological evolution of incised, sand-bed channels. Geomorphology 57:53–73
Warren DR, Bernhardt ES, Hall RO Jr, Likens G (2007) Forest age, wood and nutrient dynamics in headwater streams of the Hubbard Brook Experimental Forest, NH. Earth Surface Processes and Landforms 32:1154–1163
Webb AA, Erskine WD (2005) Natural variability in the distribution, loading and induced scour of large wood in sand-bed forest streams. River Research and Applications 21:169–185
Wu H-L, Feng Z-Y (2006) Ecological engineering methods for soil and water conservation in Taiwan. Ecological Engineering 28:333–344
Zika U, Peter A (2002) The introduction of woody debris into a channelized stream: effect on trout populations and habitat. River Research and Applications 18:355–366