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Freshwater biodiversity conservation through source water protection: Quantifying the potential and addressing the challenges

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Abstract

1. Water insecurity is a defining feature of the Anthropocene, with degraded water quality and unreliable flows putting the well-being of upstream and downstream communities, both human and aquatic, at risk. Within this context, the protection of drinking water at its source – 'source water protection' – is growing as a complementary water security solution to conventional built infrastructure, particularly but not only to address non-point source pollution.
2. An assessment of the likely source catchments of 4000 cities, supplying water to as many as 1.7 billion city dwellers, found that 85% of the total area of the catchments overlaps with freshwater ecoregions of high biodiversity value. Source water protection could contribute to conserving important freshwater biodiversity elements in these catchments, through activities such as land protection, restoration, and agricultural and ranching best-management practices.
3. Empirical evidence supporting the benefits of these types of activities to freshwater species and ecosystems is sparse, especially when considered at the scales required to achieve meaningful conservation objectives. This article explores the potential of source water protection to deliver freshwater conservation benefits, and solutions are proposed to address the challenges related to evidence gaps, trade-offs, and financing.
4. The broader opportunity for leveraging water security investments for biodiversity conservation, and the overall efficiencies that may accrue from optimizing for multiple benefits simultaneously, are discussed in the context of global frameworks such as the Sustainable Development Goals.

KEYWORDS

agriculture, biodiversity, catchment, fish, land use, pollution, stream

1 | THE LANDSCAPE OF SOURCE WATER PROTECTION

In degraded river and lake basins, the ability of terrestrial and freshwater ecosystems to sustain biodiversity is typically reduced, and ecosystem services can be compromised (Sala et al., 2000). Changes to land cover (e.g. the reduction of natural forests, grasslands, and wetlands) and land uses across the globe are implicated as major sources of recent extinctions and continued threats to species. If the rate of these changes is left unchecked, they are projected to be the most influential source of impact to ecosystem functions and biodiversity change by 2100 (Millennium Ecosystem Assessment, 2005). Reductions in water quality and flow reliability from land-cover and land-use changes not only affect species composition, distributions, and population abundances, but can significantly affect human health and economic activities that depend on secure sources of sufficient clean water. As of 2000, almost 80% of the global human population live in locations facing water security or biodiversity threats, and, importantly, the incidence of threats to water security and freshwater biodiversity are highly correlated (Vörösmarty et al., 2010).

The world has made measurable progress in addressing water security issues in some areas with the help of a wide range of solutions (UN Department of Economic and Social Affairs, 2017), but the trend for freshwater biodiversity continues to be downwards, with an 81% decline in populations of monitored freshwater species between 1990 and 2012 (World Wide Fund for Nature (WWF), 2016). This is partly because some of the strategies used to address various aspects of water security either have no benefit to freshwater biodiversity or can adversely affect freshwater ecosystems and the species that they support (Vörösmarty et al., 2010).

Conventional water security strategies typically include built infrastructure or 'grey' solutions: dams, diversions, and point-of-use treatment systems. These infrastructure solutions to water security challenges can be expensive, inadequate, and unsustainable, and can result in human costs such as impaired livelihoods, the increased marginalization of upstream communities, and settlement displacements (National Intelligence Council, 2012). Infrastructure that addresses water quality does not generally attend to the sources of the impacts and can become ineffective or costlier in the future because of heightened levels of non-point nutrient, sediment, and bacterial run-off. Infrastructure that addresses water supply based on current and historical situations may temporarily address availability needs, but may become more expensive, less efficient, not serve the needs of those dependent on urban water supply, or fail if future changes in societal and basin land-use patterns and climate are not considered (McDonald et al., 2014; Vörösmarty, Green, Salisbury, & Lammers, 2000).

Although many countries have implemented strong regulations to curb point sources of pollution, with huge progress achieved in the last several decades, discharges from manufacturing waste, untreated sewage, and other point sources still plague many of the world's waterways (Palaniappan et al., 2010). Even more widespread are the impacts of non-point source pollution, which are a challenge even in countries with strong point source pollution regulations (Carpenter et al., 1998). Incidents of hypoxic zones in near-shore areas, shutdowns of water supply systems because of excessive freshwater algal growth, and illnesses caused by non-point pollution continue to spread (Palaniappan et al., 2010). Grey infrastructure, where it exists, is challenged to keep up with these growing water security stresses.

Natural infrastructure – sometimes referred to as nature-based solutions – can perform some of the same functions as grey infrastructure, and can augment grey infrastructure by taking advantage of nature's ability to capture, infiltrate, store, and filter water to help ensure clean, reliable flows (Harrison et al., 2016; WWAP & UN-Water, 2018). Source water protection – protecting the quality and quantity of drinking water at its source – relies in large part on these nature-based solutions. The most common nature-based source water protection activities implemented in upstream portions of catchments can be grouped into eight categories (Table 1) (Abell, Asquith, et al., 2017). Other nature-based activities, such as floodplain or coastal protection and restoration, focus less on drinking water and more on other water-related benefits such as flood risk reduction (although in some cases they can also help to address drinking water issues, such as through the mitigation of excess nutrients; Roley et al., 2012). Source water protection activities are not exclusive of one another, and many source water protection programmes employ multiple activities in parallel. Because source water protection activities address the sources of water security challenges, and often integrate nature as part of the solution, they have the potential to provide benefits to terrestrial and freshwater ecosystems.

Source water protection programmes are growing in application worldwide. A recent global inventory of investments in catchment (ecosystem) services tracked a total of 419 programmes (including 378 fully active and 41 pilot programmes) in 62 countries, with transactions totalling nearly $25 billion and covering at least 487 million hectares of land in 2015 (Bennett & Ruef, 2016). This represents an average annual growth rate of 12% in catchment investments between 2012 and 2015. Water funds, a type of investment in catchment services with conservation at its core, are growing in number around the world and spring from the source water protection needs of cities, including: Nairobi, Kenya; Quito, Ecuador; and San Antonio, Texas, USA (Abell, Asquith, et al., 2017). Such expansion demonstrates an increasing recognition of the value of investing in natural infrastructure to secure water for both people and nature.

There is potential for water security spending to perform 'double duty' through its benefits for freshwater biodiversity conservation, for which the investments pale in comparison with those of the water sector. Average expenditure on global biodiversity conservation was approximately $21.5 billion annually between 2001 and 2008 for more than 160 countries (expressed in 2005 US$; Waldron et al., 2013), with freshwater ecosystems receiving considerably less conservation investment than most other ecosystems (Darwall et al., 2011). By comparison, global water expenditure in 2005 alone was around $500 billion (estimated from Addams, Boccaletti, Kerlin, & Stuchtey, 2009). If a fraction of the expenditure on grey water infrastructure could be invested in equivalent natural infrastructure, the effective budgets for freshwater biodiversity conservation could grow significantly.

TABLE 1 Source water protection activities and summarized highlights of freshwater biodiversity impacts. Supporting information and additional detail are provided in Appendix 1. Left column adapted from Abell, Asquith, et al. (2017)

Source water protection activity	Summary highlights of findings related to freshwater biodiversity impact
Targeted land protection. Protecting targeted catchment ecosystems, such as forests, grasslands, or wetlands	The extent of freshwater ecosystem benefits depends on spatial scale, location/proximity (upstream vs downstream, upland vs riparian), type and level of protection, and type and intensity of exogenous threats. Similar context-specific parameters relate to all source water protection activities described below
Revegetation. Restoring natural forest, grassland, or other habitat through planting or enabling natural regeneration	The impacts of revegetation, other than in riparian zones, to freshwater ecosystems are poorly documented. Afforestation with non-native species has mixed results for freshwater ecosystems. Generally there are time lags for the impacts of reforestation, and the legacy of past land uses may mask current efforts. The effects of grassland restoration are poorly explored
Riparian restoration. Restoring natural habitat at the interface between land and water along the banks of a river or a stream	Riparian restoration has been well studied in North America, with a concentration on forestry practices and proximal stream responses. The evidence of benefits to freshwater ecosystems is mixed despite a relative wealth of studies. Landscape disturbances and alterations in surface and subsurface flows can obscure the benefits of riparian restoration
Agricultural best management practices (BMPs). Changing agricultural land management to achieve beneficial environmental outcomes	The adverse impacts on freshwater ecosystems from poorly managed agricultural lands have been well documented, but the reverse – the impacts of good stewardship using agricultural BMPs – has been little studied. Positive impacts would generally be anticipated. The extent and proximity of implementation will most likely be critical. No universal thresholds have been firmly established to result in measurable benefits
Ranching best management practices (BMPs). Changing land management practices on ranch lands to achieve beneficial environmental outcomes	The relationship between animal grazing and freshwater ecosystems is complicated as some grassland types require grazing to prevent forest succession, but overgrazing leads to disturbance and degradation. Studies generally confirm the values (largely to plants, birds, and amphibians) of excluding livestock from entering streams and reducing grazing intensity
Fire risk management. Management activities that reduce forest fuels and thereby reduce the risk of high-intensity and catastrophic fires	The impacts of fire – and of fire risk management – on freshwater ecosystems depend on whether the system is historically adapted to fire, and at what level of intensity and frequency. Most studies have examined the impacts of prescribed burning and tree thinning in North American coniferous systems, with mixed findings related to freshwater ecosystem impacts
Wetland restoration and creation. Re-establishing the hydrology, plants, and soils of former or degraded wetlands, or constructing new wetlands for mitigation or ecosystem process purposes	Studies of wetland restoration and creation have largely focused on aquatic and semi-aquatic species within those wetlands, rather than on those living downstream. In general, restored or rehabilitated wetlands provide greater freshwater ecosystem function and biodiversity benefits than constructed wetlands. Individual wetlands generally have lower benefit levels than a network of wetlands
Road management. Avoidance and mitigation techniques aimed at reducing the environmental impacts of roads	There is a dearth of literature on road management impacts (other than removing instream barriers), but road management that meaningfully reduces sediment loading to streams should benefit freshwater ecosystems

In fact, many existing source water protection programmes have developed, or are developing, objectives that go beyond water security for people, encompassing biodiversity conservation, climate change adaptation and mitigation, and human health and well-being (Bennett & Ruef, 2016). Such an integrated approach is consistent with achieving a broad range of Sustainable Development Goals (SDGs), adopted by world leaders in 2015, including those related to water security, ecosystem conservation, sanitation, economic development, and climate change mitigation and adaptation (United Nations, 2015). In a world looking for multiple 'wins', where land-based threats to freshwater ecosystems and species are growing, it is worth considering the extent to which source water protection can deliver freshwater biodiversity benefits, and how those benefits might be realized.

2 | GLOBAL POTENTIAL FOR GENERATING WATER SECURITY AND BIODIVERSITY CO-BENEFITS

Implicit in the term 'source water protection' is a connection between downstream water users and upstream water services. Building on that connection, funding for source water protection programmes is commonly generated through payments for ecosystem services (PES) schemes (sometimes referred to as 'investments in catchment services'), in which a downstream buyer (or service beneficiary) engages in a transaction with an upstream seller (or service provider) (Bennett & Ruef, 2016). Many medium to large cities, along with their water utilities, show especially good potential as sources of funding and long-term financing for investments in source water protection (McDonald & Shemie, 2014). For instance, a water fund business case for potential restoration activities in the main source catchment of Nairobi found a strong positive return on investment (ROI) over a 30-year time frame, principally as a result of sediment reduction benefits (Apse & Bryant, 2015). An analysis of fire risk reduction benefits in northern New Mexico, USA (home to Albuquerque and Santa Fe), also found a positive ROI comparing the cost of tree thinning with the costs of water treatment and property loss associated with representative fires (Hartwell, Kruse, & Buckley, 2016). With these and other examples supplying real-world context, examining the source catchments of larger cities around the world can provide a sense of the ceiling of water security and biodiversity benefits that could accrue from source water protection.

To underpin a global assessment of the range of benefits that source water protection could support, a map of existing and possible source catchments for approximately 4000 of the world's largest cities was developed (Abell, Asquith, et al., 2017). The map began with explicit water withdrawal point data for more than 500 cities (McDonald et al., 2014), from which source catchments were delineated. To generate a more globally comprehensive map, the likely source catchments of an additional 3500 cities were modelled, using documented assumptions about how far away cities of different sizes will go to obtain their water (cities generally draw water from the largest river nearby, and larger cities have more capacity to reach further out; Abell, Asquith, et al., 2017). The resulting map (Figure 1) covers more than 37% of the ice-free terrestrial surface of the earth, with the mapped source catchments supplying water to as many as 1.7 billion city dwellers. Importantly, the map shows substantial areas of overlap among the likely source catchments of cities, suggesting that protecting some catchments will have water security benefits for multiple downstream cities.

Using this source catchment map, the potential for a subset of source water protection strategies to reduce landscape-derived, non-point sediment, or phosphorus pollution was assessed using an approach described previously (McDonald & Shemie, 2014). This assessment represents an approximation of possible global potential, with aggregate results intended to be comparatively illustrative rather than quantitatively predictive (Abell, Asquith, et al., 2017). Three conservation practices representative of nature-based source water protection approaches were considered: forest protection, pastureland reforestation (active or passive forest restoration on grazing lands), and agricultural best management practices (BMPs). Assuming a reduction target of 10%, there is a broad global opportunity for addressing sediment or nutrient pollution through land conservation actions. For example, the model indicates that source water protection activities can reduce landscape-derived, non-point sediment pollution in at least 70% of the area of source catchments across Africa, Asia, Latin America, and Europe. Although more limited in scope, the potential for nutrient reduction is notable in Asia, Europe, North America, and Oceania, where more than 60% of the area of source catchments can benefit from nature-based solutions.

Importantly, this assessment of source water protection potential does not consider the sufficiency of a 10% reduction relative to local pressures. In addition, it does not indicate which source catchment areas offer the greatest opportunity relative to costs or other feasibility constraints. Although a reduction in sediment or nutrients of 10% or more may be achievable, the cost of doing so may be prohibitive or greatly outweigh the value of water security benefits. However, with additional consideration of the potential value of co-benefits such as climate change mitigation and adaptation, human health and well-being improvements, or biodiversity conservation, the aggregate benefits may increase the overall return on investment (Abell, Asquith, et al., 2017).

Focusing specifically on potential biodiversity conservation benefits, a disproportionately large fraction of the Earth's terrestrial and freshwater biodiversity resides within probable source catchment

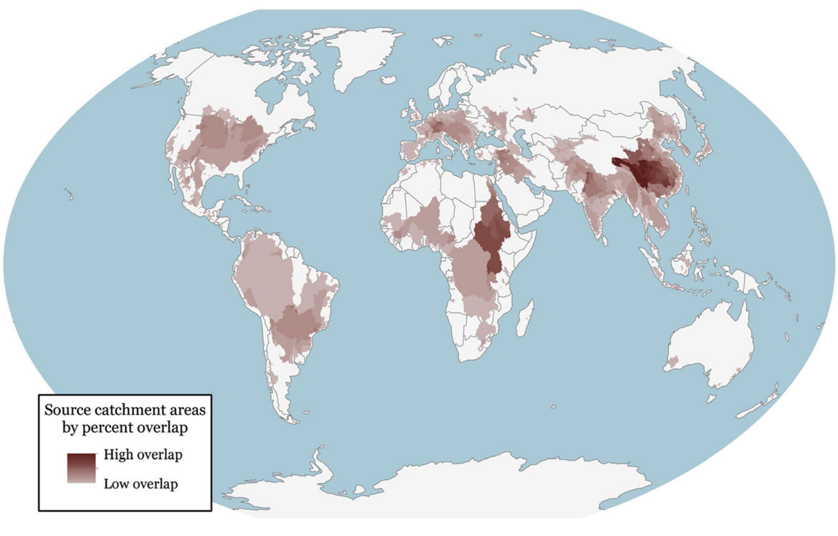

FIGURE 1 Catchment areas that currently, or could, provide surface water supply to cities with populations of greater than 100 000 people. Darker colours indicate overlapping catchment areas, where multiple cities and other water users collect surface run-off from the same upstream land areas. Modified from Abell, Asquith, et al. (2017)

areas. As an indicator, 85 and 79% of the total area of source catchments overlap with freshwater and terrestrial ecoregions of high biodiversity value, respectively, where ecoregions of high biodiversity value are defined as those falling in the top quartile for rarity-weighted richness (Abell et al., 2011; Abell, Asquith, et al., 2017).

Many of the species in these regions are at risk. Global source catchments are home to 51% of the International Union for Conservation of Nature (IUCN) red-listed terrestrial species (including amphibians, birds, and mammals) and 59% of freshwater fish species evaluated by IUCN as threatened in comprehensively assessed regions (which exclude South America, much of Asia, and Oceania) (Abell, Asquith, et al., 2017; BirdLife International & NatureServe, 2015; IUCN, 2016) (Figure 2a, b). In addition, nearly half (47%) of Alliance for Zero Extinction (AZE) sites occur within source catchments, as well as more than one-third (39%) of all Important Bird and Biodiversity Areas (IBAs) and more than one-third of IBAs under the most immediate danger (Abell, Asquith, et al., 2017; Alliance for Zero Extinction, 2010; BirdLife International, 2014, 2016).

The threats to these species are well known to terrestrial and freshwater conservationists alike. For instance, forest loss in source catchments from 2001 to 2014, calculated as a percentage of existing forest in 2001, was especially high in large swaths of South America, Southeast Asia, Indonesia, and other areas known for their especially diverse freshwater and terrestrial biotas (Abell, Asquith, et al., 2017; Hansen et al., 2013). Forest loss is highlighted not only for its well-studied impacts on terrestrial and aquatic species, but also because typical source water protection activities include forest protection and restoration (Bremer et al., 2016). Using species–area relationship models that combine vulnerability indicators to predict species extinctions under different land-use change scenarios (Chaudhary & Kastner, 2016; Chaudhary, Verones, de Baan, & Hellweg, 2015; Pereira, Ziv, & Miranda, 2014), if forest restoration opportunities were fully implemented within source catchments, the risk of global extinction would be reduced for 52 terrestrial species (terrestrial mammals, amphibians, and birds), and the risk of regional extirpation would be reduced for 5408 terrestrial species (Abell, Asquith, et al., 2017).

Forest loss is only one threat to freshwater species. The Incident Biodiversity Threat Index (Vörösmarty et al., 2010) gives a more comprehensive picture of freshwater threats within global source catchments, combining 23 drivers of current stress and charting their downstream impacts. Forty-eight per cent of the area of source catchments has high threat levels, and only 6% has low threat levels (Abell,

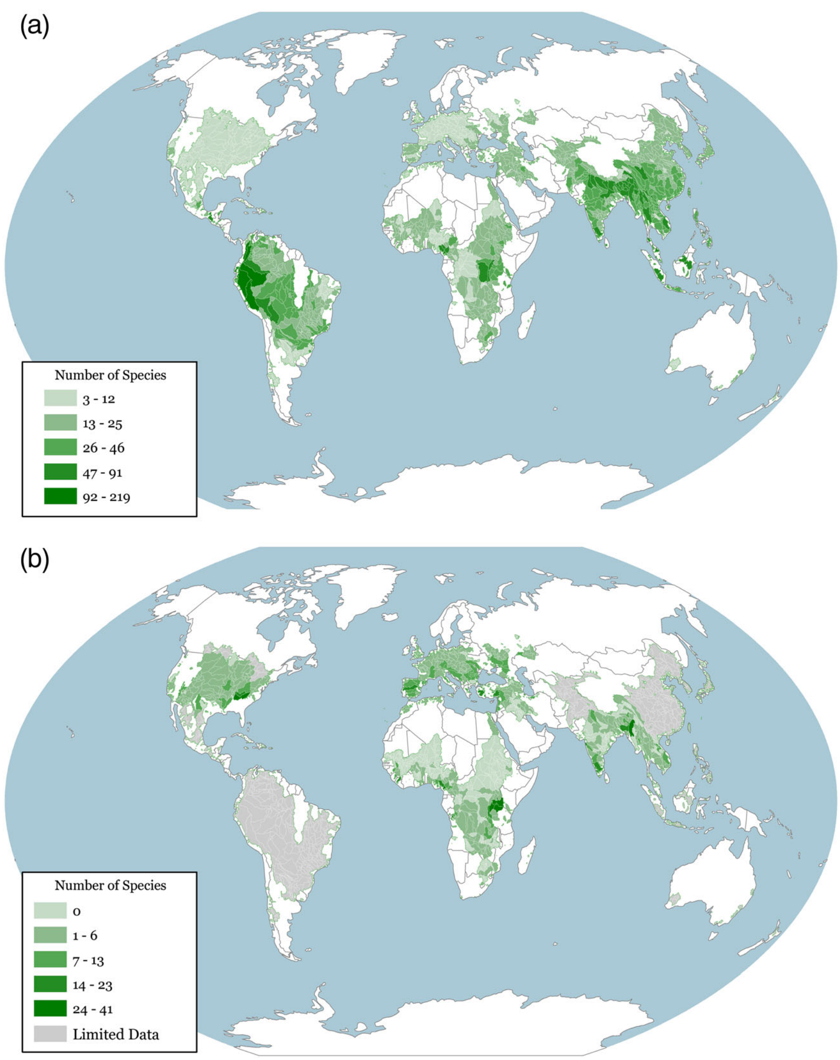

FIGURE 2 (a) The number of threatened terrestrial species, including mammals, birds, and amphibians, per catchment (Level-5 HydroBASINS) within urban source catchments, restricted to where source water protection activities could benefit them. Threatened species are those classified by the International Union for Conservation of Nature (IUCN) Red List as Critically Endangered, Endangered, or Vulnerable. Data classified using Jenks natural breaks (source data: BirdLife International & NatureServe, 2015; IUCN, 2016). (b) Number of threatened freshwater fish per catchment (Level-5 HydroBASINS) within urban source catchments. Only the regions that have been comprehensively assessed are shown. Data classified using Jenks natural breaks (source data: IUCN, 2016). Both panels adapted from Abell, Asquith, et al. (2017)

Asquith, et al., 2017). Given the influence of agriculture on nutrient and sediment loadings, it is unsurprising that source catchments in North America, Western Europe, South Asia, Southeast Asia, and East Asia have among the highest threat levels.

These global numbers – in relation to both biodiversity value and threat – should be interpreted with caution. Species are not distributed uniformly within catchments and especially not within ecoregions (Abell et al., 2008). Source water protection programmes rarely encompass entire catchments, and many existing programmes are located at relatively higher elevations with smaller catchments (Huber-Stearns et al., 2017; Romulo et al., 2018); in these systems, the species richness among freshwater taxa such as fish is most likely to be lower, yet a significant diversity of groups of species and functional assemblages critical for conservation may occur (Matthews, 1998; Pease, González-Díaz, Rodiles-Hernández, & Winemiller, 2012). Although water-related benefits will be transmitted downstream, these benefits are likely to attenuate with distance, presumably with reduced benefits for freshwater species as the distance from source water-related activities increases. Nonetheless, these global numbers signal a potentially high relevance of source water protection for achieving biodiversity conservation benefits, both for terrestrial and freshwater species.

3 | THE EVIDENCE FOR BIODIVERSITY CO-BENEFITS

Beyond the global potential for biodiversity co-benefits, there is the issue of existing empirical evidence for assessing whether source water protection activities can in fact achieve such benefits, including benefits for freshwater species and ecosystems.

There is a wealth of evidence linking excess sediments and nutrients (phosphorus and nitrogen) to adverse impacts on ecological conditions and native biodiversity composition in freshwater ecosystems (Allan, 2004). As such, there is little doubt that the reduction of unnaturally high levels of sediments and nutrients in freshwater ecosystems can confer benefits to aquatic ecosystems and native aquatic species. Many, if not most, freshwater ecosystems and species have multiple types and sources of stressors, however. Reducing non-point pollution via source water protection may result in little or no easily measurable impact, given the predominance of other threats and land use legacies (Maloney et al., 2008). Some source water protection activities aimed at reducing non-point source pollution may even have unintended consequences for freshwater ecosystems and species, such as increasing no-till agriculture to reduce soil erosion and sediment loading into freshwater ecosystems while increasing the use of pesticides (Elias, Wang, & Jacinthe, 2018).

English-language literature, both peer-reviewed and unpublished, was examined for documented impacts on freshwater species and ecosystems from the tactics more commonly implemented in source water protection programmes (Appendix 1; Table 1). A dearth of studies was found that measured the direct impact of these activities on freshwater ecosystems and biodiversity, often with a lack of consensus among existing studies as to the directions or degrees of impacts. This result aligns with a recent synthesis of the effectiveness of a variety of conservation interventions on a number of biodiversity elements, which found an alarmingly small number of available empirical studies, and frequent contradictions among their conclusions (Sutherland, Dicks, Ockendon, Petrovan, & Smith, 2018). For instance, looking at amphibian conservation, an assessment concluded that there was conflicting evidence across conservation interventions, including agricultural management and pollution control, unknown effectiveness on amphibian populations resulting from the management of grazing regimes, and no evidence at all related to reduced tillage farming (Smith, Meredith, & Sutherland, 2018).

Conflicting findings, especially when the overall number of studies is small, may be a function of different taxonomic groups, ecological contexts, scales, intervention practices, measurements, seasons, or any number of other parameters. It is important that the lack of published studies should not be interpreted as a lack of impact on the ground, as projects often suffer from poor written documentation (Palmer, Allan, Meyer, & Bernhardt, 2007). For the most part, the potential impacts of any given tactic are left to be inferred based on known relationships (e.g. there is evidence that rural road management can reduce sediment inputs, and reduced sediment inputs should benefit native freshwater species). The protection or restoration of riparian zones is an exception, with a greater number of studies linking vegetated (primarily forested) riparian buffer zones with maintained or improved ecological conditions of the adjacent and downstream aquatic systems; however, even the specifics of how riparian zones can best be managed to provide species and ecosystem benefits are not entirely resolved (Richardson, 2008). The largest gaps in the scientific literature are around the impacts on freshwater biodiversity of agricultural BMPs, agroforestry, and silvopasture, and for the most part studies are highly skewed towards North America.

4 | REALIZING THE POTENTIAL OF SOURCE WATER PROTECTION FOR FRESHWATER BIODIVERSITY CONSERVATION

How do we build from the limited empirical evidence demonstrating the freshwater biodiversity benefits resulting from source water protection activities to achieve even a fraction of the apparent global potential for those benefits? We argue for three areas of focus: addressing evidence gaps; ensuring effective design and implementation; and acknowledging limitations.

First, this review, although not inclusive of all literature, has identified some priority evidence gaps to fill. Given that many land management activities common to source water protection programmes are also used for biodiversity conservation, it is concerning how poorly established the freshwater biodiversity benefits of those activities are, particularly across a diversity of scales and contexts. A minimum level of evidence must be generated to ensure that limited conservation funding is targeted toward the projects and activities most likely to be effective.

One key evidence gap encompasses the identification of circumstances and contexts under which source water protection activities could potentially harm native freshwater species and ecosystems (rather than benefit them). For instance, there may be unintended consequences of implementing source water protection activities to reduce sediment loading to streams where certain aquatic species may benefit from naturally sediment-rich environments (e.g. for reduced vulnerability to predation). Having a stronger evidence base will support the identification of 'red flags' to be considered in the conception stage of source water management programmes, especially in areas supporting vulnerable freshwater species and communities.

These evidence gaps further emphasize the importance of project monitoring and evaluation of the impacts on biodiversity of source catchment protection activities at multiple scales. Although significant research effort may not be necessary for every project, at a minimum evaluating whether and to what extent biodiversity goals are being achieved should be a component of any monitoring programme. Meta-analyses to discern patterns across activity types would be enhanced through an increase in such data, contributing significantly to scientific research beyond any single project.

Setting priorities for research to fill gaps should also consider what evidence may be required to attract investment in source water protection activities, especially when biodiversity co-benefits are a primary motivation. Evidence for the simultaneous generation of multiple co-benefits – for water quality, biodiversity, and other areas such as climate change mitigation, adaptation, and human health and well-being – will be particularly compelling, especially when there is potential to save costs through optimization.

Second, even in cases where there is sufficient evidence to substantiate an expectation of biodiversity benefits resulting from source water protection activities, realizing such benefits necessarily depends upon well-designed programmes and effective implementation. Design considerations include activity type, location, scale, and extent, and management plans should align with biodiversity conservation objectives. For instance, the design of a protected area (PA) or 'other effective area-based conservation measure' (OECM) to prevent the conversion of natural land cover would ideally consider where aquatic species of high conservation value occur (e.g. within or downstream of the areas under consideration); it would focus on areas that would contribute most to maintaining processes and functions in proximal and downstream areas; and it would include management that is sensitive to broader freshwater species and ecosystem needs (such as through the prohibition of aquatic species introductions, the construction of instream barriers, and alterations to flow).

When there are competing benefits at stake, relevant stakeholder groups will need to reach consensus around goals. For instance, protecting land to avoid non-point source pollution impacts may conflict with other goals (such as increased agricultural development), or may preclude other activities (such as hydropower development or the introduction of non-native fish species for fisheries production) that might be detrimental to freshwater biodiversity conservation (Hermoso, Cattarino, Linke, & Kennard, 2018). Implementing source water protection programmes that support freshwater biodiversity conservation is likely to need strong constituencies for freshwater biodiversity to be built, especially where the economic values of conserved biodiversity are relatively low compared with other potential uses, or where they cannot be monetized. These constituencies must also be convinced to invest in the long-term maintenance of source water protection areas; even natural infrastructure generally requires practical management to ensure the continued provision of benefits.

Realizing the potential of source water protection for freshwater biodiversity conservation requires a counter-intuitive approach that acknowledges the limitations of source water protection programmes. Many efforts may be necessary but insufficient to achieve biodiversity goals, as source water protection activities are likely to be just one piece of a freshwater biodiversity conservation (and water security) solution. Even the best-designed and implemented projects are likely to fall short of full protection or the restoration of freshwater species populations or ecosystems, given the panoply of threats that may affect them. Source water protection, especially when implemented at meaningful scales and in priority locations, can be an important tool within a larger biodiversity conservation toolbox (Abell, Allan, & Lehner, 2007). Making the most of this strategy requires the active participation of a broad range of conservationists throughout the project cycle of source water protection efforts: from conception, to design, to continuing adaptive management.

5 | LEVERAGING OTHER WATER SECURITY INVESTMENTS AND COMMITMENTS IN THE SERVICE OF BIODIVERSITY CONSERVATION

In addition to source water protection and management, there are various other water security approaches, tools, programmes, and partnerships that can provide measurable benefits for freshwater biodiversity. For example, floodplain restoration is an effective tool for reducing flood risks under present and future climate conditions, especially when used in conjunction with source water protection activities that promote infiltration. Floodplain restoration, which includes setting back or removing levees or other barriers to allow river water to return to the floodplain, and restoring degraded floodplains to a more natural state, can also help meet an array of freshwater biodiversity objectives (Ward, Tockner, & Schiemer, 1999). Integrated source water protection and floodplain restoration can thus reduce water-related risks and produce freshwater ecosystem benefits, but key participants in the areas of source water protection (often city water utilities), flood risk reduction (e.g. city disaster risk reduction managers or insurance companies), and biodiversity conservation (e.g. conservation non-governmental organizations) have only recently begun to collaborate towards achieving these multiple benefits (European Climate Adaptation Platform, 2014; The Nature Conservancy, 2013).

The private sector has until now played a relatively limited role in source water protection, but as the World Economic Forum's Water Risk Report demonstrates, companies are concerned about water security (World Economic Forum, 2018). In just one year (2017), companies committed $23.4 billion to hundreds of water security projects in 91 different countries (CDP, 2017). Corporations that recognize the risks that water insecurity poses to the growth and success of their business, and that have developed water stewardship programmes to address these risks, have an opportunity to incorporate freshwater biodiversity as an outcome of a holistic stewardship programme. As more companies engage in corporate water stewardship by supporting nature-based solutions and engaging in catchment-level collective action, they can identify and work towards specific freshwater biodiversity goals as part of their investment (The CEO Water Mandate, 2011). The private sector will continue to be an important player in improving water security in the places where its operations and supply chains touch down, and including freshwater biodiversity as a component of a comprehensive water stewardship programme can be an important pathway for slowing the decline of freshwater species.

Another potential partner is the portion of the development community focused on water, sanitation, and hygiene (WASH). WASH programmes have long invested in providing access to high-quality water supplies at the point of use, with great success (WHO & UNICEF, 2017); however, as water sources become more degraded owing to upstream land-use change, there is a need to link WASH efforts with source water protection interventions to avoid rendering current point-of-use investments inadequate or greatly increasing the cost of treatment (McDonald, Weber, Padowski, Boucher, & Shemie, 2016; NRDC, 2014). As development organizations and institutions widen their gaze to the protection of water at the source, there is an opportunity to provide benefits to freshwater biodiversity, whether explicitly through a more holistic set of goals or implicitly through the conservation or restoration of source catchments (Bonnardeaux, 2012). Moreover, as WASH programmes address water quality issues, either through water supply treatment or sanitation, there can be residual benefits to freshwater ecosystems.

The 2030 Agenda for Sustainable Development, with its component SDGs, provides a foundation and rationale for marrying freshwater conservation and development. Nearly all of the SDGs reflect connections to water security (Abell, Asquith, et al., 2017), and Target 6 of SDG 6 (the ‘water goal’) emphasizes the importance of protecting and restoring water-related ecosystems. Other global frameworks such as the Ramsar Convention on Wetlands and the UN Convention on Biological Diversity (CBD), through its Aichi Targets, focus on the conservation of ecosystems, emphasizing the importance of terrestrial and freshwater ecosystems both for biodiversity and for the services that they provide to people.

6 | CONCLUSION

The Anthropocene has produced degraded catchments worldwide, with implications for both freshwater biodiversity and water security for people. The escalating costs associated with the long-term provision, via built infrastructure, of clean, reliable water supplies to consumers argue for increased investment in complementary nature-based solutions. Designed and implemented with care, and at meaningful scales, source water protection activities have good potential for producing both water security and freshwater biodiversity conservation benefits, especially considering the overlap between areas of importance for source water protection and areas of high freshwater biodiversity value.

Measuring and evaluating indicators of both water security and biodiversity will be critical to establishing the conditions under which source water protection activities can contribute to both sets of objectives simultaneously. As this review has found, limited empirical evidence exists for the freshwater biodiversity benefits of many activities, but our knowledge of impact pathways suggests that those benefits can and should accrue under the right circumstances. Those circumstances will almost certainly relate to the scale of implementation and to the types, sources, extent, and intensity of threats addressed by source water protection programmes. These benefits may not be expressed fully until other critical sources of threats are mitigated by separate efforts.

A willingness to engage across sectors and interests – between conservationists and city managers, the private sector, academia, and the development sector – may be a prerequisite for establishing the conditions necessary for designing nature-based solutions that can promote opportunities for freshwater biodiversity as well as water security objectives. The growth of investments in catchment services provides an opportunity for making meaningful progress towards achieving global freshwater biodiversity goals, and empirical demonstrations of conservation and water security impact should produce an enabling environment for even greater investment in the future.

The SDGs offer an aspirational set of goals to address a range of development challenges, including but not limited to water security and biodiversity conservation, but the opportunity to achieve these goals rests on finding integrated solutions that can simultaneously meet multiple objectives at local scales. Source water protection offers one integrated approach to this agenda by targeting investments in areas where biodiversity conservation needs intersect with source water dependency. Interconnectivity between these objectives can foster a cohesive approach to measuring the contributions of source water protection activities toward meeting global commitments such as the SDGs and Aichi Targets, recognizing that each requires aggregating or disaggregating basin measures to national-level reporting units.

At the catchment scale, source water protection programmes can help to clarify actions with local stakeholders, who are often accountable for meeting multiple mandates, and can sometimes be faced with complex trade-offs between biodiversity conservation and ecosystem services. Addressing evidence gaps and understanding limitations can demonstrate the potential of meeting multiple goals, such as water security and biodiversity conservation, and can help align investments, harness limited capacity for implementing strategies that are mutually beneficial, and amplify impacts.

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CONFLICT OF INTEREST

None to declare.

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APPENDIX

SUMMARY OF EMPIRICAL EVIDENCE LINKING SOURCE WATER PROTECTION ACTIVITIES WITH FRESHWATER SPECIES AND ECOSYSTEM BENEFITS

Targeted land protection

Protecting intact, native terrestrial ecosystems should rarely if ever produce adverse consequences for freshwater ecosystems, but benefits are not assured. Although protected terrestrial ecosystems themselves are beneficial, the size and locations of them in a catchment can affect their efficacy for freshwater conservation. The freshwater ecosystem benefits of formal protected areas (PAs) have been little studied, in part because a relatively small number of protected areas in many regions of the world have been designated based on freshwater ecosystem processes and objectives (for a review, see Hermoso, Abell, Linke, and Boon, 2016). This is not the case everywhere, however: in Europe, for instance, many large rivers and lakes are protected specifically for their freshwater habitats and/or species through the European Habitats Directive, among other legislation (Council of the European Communities, 1992). Nonetheless, a 2016 global analysis of integrated local and upstream river protection found that most basins around the world fell short of the Convention on Biological Diversity (CBD) Aichi Target 11, which sets a 2020 goal of 17% protection for inland water areas. A contemporary paper concluded that there was 'no comprehensive assessment of what needs to be achieved to meet Target 11 for freshwater biodiversity' (Abell, Lehner, Thieme, & Linke, 2017; Convention on Biological Diversity, 2011; Juffe-Bignoli et al., 2016).

Existing studies of PAs have pointed to several critical factors influencing impact and effectiveness:

- **Spatial scale –** Small PAs may have little impact, although if they drain to or comprise small headwater streams the impact may be proportionately greater than if they are located further downstream in river networks (Thieme et al., 2016). Although there is no universal threshold for how much of a catchment should be protected to conserve freshwater ecosystems and biodiversity, some studies (Death & Collier, 2010) have attempted to identify thresholds for particular settings.

- **Location** – Some subcatchments or even stream reaches may support higher priority freshwater biodiversity elements and ecosystem processes than others, but most terrestrial PAs have not been sited with these elements in mind (Abell et al., 2007; Herbert, Mcintyre, Doran, Allan, & Abell, 2010; Juffe-Bignoli et al., 2016; Thieme et al., 2016).
- **Upland versus riparian** – Protecting riparian buffers is almost universally considered an effective conservation activity, although larger upstream catchment conditions may override riparian benefits (see 'Riparian restoration' below).
- **Type and level of protection** – Even well-protected land cannot provide comprehensive protection for freshwater ecosystems and species if there are direct threats such as overfishing, instream barriers, and water withdrawals (Chessman, 2013; Hermoso, Filipe, Segurado, & Beja, 2018). The designation of a terrestrial PA does not in itself ensure the existence and maintenance of natural land cover (Mancini et al., 2005), and the legacy of past land uses may continue to produce stresses on local and downstream aquatic communities via water quality and flow impacts (Harding, Benfield, Bolstad, Helfman, & Jones, 1998).
- **Exogenous threats** – Freshwater ecosystems typically sit at the lowest point on the landscape in valley bottoms and are subject to hydrologically mediated threats travelling downslope and downstream. As a result, threats outside the borders of a PA (e.g. dams, water withdrawals, agriculture, mining, forestry, or urbanization) can impinge upon the ecosystems and species within them (Rodríguez-Jorquera et al., 2017; Thieme et al., 2016). In addition, many freshwater species are highly mobile, and they may encounter threats outside a PA that reduce their viability inside the PA. Climate change is already manifesting itself largely through hydrological impacts; PAs may be able to build resilience for freshwater species (e.g. through providing thermal refugia or serving as dispersal corridors), but there will be limits to their potential for mitigating threats (Kingsford, 2011).

Formally designated PAs are only one form of targeted land protection, and other effective area-based conservation measures (OECMs) may be equally if not more relevant to source water protection programmes (Laffoley et al., 2017). A formal designation does not ensure effective management, and other land protection approaches (e.g. through indigenous or community-managed areas) may also produce beneficial freshwater ecosystem outcomes. River basin management plans, such as those required by the European Water Framework Directive (Council of the European Communities, 2000), are another important land protection approach relevant to source water protection.

Revegetation

- **Afforestation** – Many but not all studies of afforestation, i.e. the planting of stands of trees where there were none previously, focus on plantation forestry, looking primarily at the impacts of afforestation with non-native (typically conifer) species on stream chemistry (Friberg, Rebsdorf, & Larsen, 1998). There are a few studies that generally confirm the adverse impacts of afforestation on native aquatic biota (Sievers, Hale, & Morrongiello, 2017; Tierney, Kelly-Quinn, & Bracken, 1998), although this response is not uniform (Quinn, Croker, Smith, & Bellingham, 2009; Tierney et al., 1998). Most afforestation studies have taken place in Europe and New Zealand, with a focus on riparian zones.
- **Reforestation** – Reforestation studies are largely focused on riparian zones (see below). Despite the prevalence of reforestation (active and passive) in some regions (e.g. in North America), there appear to be virtually no studies that evaluate the impacts of upland reforestation on freshwater biodiversity. It may be assumed that on balance the impacts of reforestation using native species should be positive for freshwater biodiversity in the long term, but there are few empirical data to confirm that assumption. One modelling study of re-establishing old-growth forests suggested potentially adverse impacts on the productivity of freshwater fisheries, at least in the short term (Nislow, 2005), underscoring the possibility of unintended consequences of more natural conditions on native species composition and abundance. The potential reduction in water yield and/or base flow following forest restoration (including reforestation using native species, afforestation, and forestry), as shown in a recent review (Filoso, Bezerra, Weiss, & Palmer, 2017), may also drive shifts in biotic composition depending on the magnitude and scale of the flow changes (Bunn & Arthington, 2002). The legacy of past land use (e.g. agriculture or mining) within a catchment may be a stronger indicator of present-day environmental status than current land uses, suggesting that upland or riparian reforestation may in some circumstances have limited benefits for native species recovery (Harding et al., 1998; Ogden, Crouch, Stallard, & Hall, 2013; Scott, 2006). In addition, the biotic impacts of reforestation may manifest over longer time scales than water quality impacts (Yeung, Lecerf, & Richardson, 2017).
- **Grassland restoration** – There is virtually no literature exploring the impacts of grassland restoration on freshwater ecosystems and biodiversity, but depending on the classification some grassland types may be considered wetlands (Dixon, Faber-Langendoen, Josse, Morrison, & Loucks, 2014), and as noted below (see 'Wetland restoration and creation') there is a richer literature on wetland restoration. Some grasslands will need to be maintained by natural disturbance processes, such as fire or grazing, and re-created disturbances may have adverse impacts on aquatic systems if not carefully designed and implemented (see 'Ranching BMPs' below).

Riparian restoration

The role of riparian zones in sustaining healthy freshwater ecosystems has received ample research attention (Naiman & Decamps, 1997); however, more research is focused on physical habitat attributes than on biotic indicators, and long-term studies of the biotic impacts of riparian restoration (as opposed to management, often as part of forestry practices) are relatively sparse (Roni, Hanson, & Beechie, 2008; Sievers et al., 2017). Measures of benefits to freshwater ecosystems have often focused on representative species and ecosystem attributes – often measured with indices of biotic integrity or ecosystem functioning – and the responses of those attributes to riparian land use (sometimes in comparison with upland land use). In other cases – generally in North America and Europe – restoration has been driven by one or more endangered fish species, such as salmon in the Pacific Northwest (Palmer et al., 2007; Sievers et al., 2017). Our review focused primarily on riparian restoration within agricultural contexts, recognizing that the abundance of literature has focused on riparian management in the context of forestry practices.

There is a consensus that vegetated riparian zones can serve as filters for nutrients and sediment, thereby improving water quality; they can contribute important woody and other organic materials that are essential to sustaining freshwater ecosystems and species; they can regulate stream temperature (especially in the case of forests); they can contribute freshwater and terrestrial invertebrates and detritus, important for sustaining downstream systems; and they can provide habitat for diverse assemblages of riparian-dependent species (Naiman & Decamps, 1997). It is important to note that these generalizations apply to restoration, rather than to afforestation. Despite largely positive results, empirical studies of the biotic impacts of riparian restoration have not been uniform in their findings for riparian-dependent and freshwater biota (Marczak et al., 2010; Quinn et al., 2009; Sievers et al., 2017), and time lags of a decade or more may occur before native biota are restored (Becker & Robson, 2009; Orzetti, Jones, & Murphy, 2010). Mixed results have occurred for a variety of reasons, including but not limited to an inability to recreate natural ecosystem composition, structure, and functioning through plantings or passive restoration (Faulkner, Barrow, Keeland, Walls, & Telesco, 2011). The dependencies of riparian zones on natural flow patterns for appropriate seasonal inundation can also determine the potential for riparian restoration in systems with altered flows, and flow management may be the primary tactic for riparian restoration (Rood et al., 2005).

As with all source water protection activities, the degree to which these benefits can be realized is context specific, and in the case of extensive natural land-cover conversion or development, catchment-scale and instream conditions may override the services that riparian zones can provide (for a review, see Allan, 2004).

Despite a rich literature, most studies of riparian restoration have been focused on North America and Oceania, with a smaller number from Europe. There are few relevant studies from Latin America, Africa, or Asia.

Agricultural best management practices

Although there is a wealth of literature on the impacts of land use and land cover on freshwater ecosystem conditions and biotic responses, there are few empirical studies of the effects that agricultural best management practices (BMPs) have on them, other than riparian buffer zone management. As with the other source water protection tactics detailed above, there is a presumption that reductions in sediment and nutrients will benefit freshwater ecosystems and species, but few studies have documented the impact (Holmes, Armanini, & Yates, 2016). Measures of ecological impact in the context of agricultural land use are frequently based on indicator species, indices of biotic integrity, or habitat measures. These specify overall habitat quality but by definition give no information about the particular species of concern; these species may fail to show improvement because of a range of factors outside the influence of spatially limited BMPs (Wang, Lyons, & Kanehl, 2006).

Of the existing literature on how agricultural BMPs affect freshwater biodiversity and environmental conditions, many show positive (although sometimes limited) impacts (Barton & Farmer, 1997; Sallenave & Day, 1991). Other studies have found that, as with other source water protection activities, the observed impacts, or the lack thereof, may result from broader catchment-wide land use, as well as the legacy of past practices and additional threats (Maret, MacCoy, & Carlisle, 2008; Pearce & Yates, 2015). Thresholds of areas of BMP implementation resulting in benefits to biodiversity may exist (Yates, Bailey, & Schwindt, 2007), and BMPs applied only in riparian zones may be necessary but insufficient in scope (Wang, Lyons, & Kanehl, 2002).

Literature exploring the impacts on freshwater biodiversity of agroforestry systems was not found, although there is a relatively abundant literature on agroforestry in general.

Ranching best management practices

The relationship between animal grazing and freshwater ecosystems is complicated. Because grasslands can require natural disturbance or active management to prevent succession to forest, grazing at certain levels and times of the year may be an appropriate and necessary activity in some systems, and can contribute to maintaining native freshwater biodiversity (Bloom, Howerter, Emery, & Armstrong, 2013; Marty, 2015; Mester, Szalai, Mero, Puky, & Lengyel, 2015); however, overgrazing can have impacts on sediment and nutrient delivery, as well as on hydrology. Furthermore, livestock congregating in riparian zones and entering streams in order to cross or gain access to water can have direct impacts on stream banks and can introduce bacterial and nutrient contaminants into the water, as well as increase sediments (Fitch & Adams, 1998).

The literature examining the impacts of livestock or ranching BMPs on biodiversity is focused primarily in three areas: (i) impacts on grassland plant, bird, and amphibian species from changes in grazing intensity or timing, with an emphasis on wet grasslands and wetland birds; (ii) impacts on native riparian plants, birds, and mammals from livestock exclusion (by fencing); and (iii) impacts on stream ecosystem condition from livestock exclusion. Studies generally confirm the value of excluding livestock from streams, reducing grazing intensity, and providing livestock with alternative water sources (Ellison, Skinner, & Hicks, 2009; Jansen & Robertson, 2001; Sievers et al., 2017); however, the degree and scope of benefits may be localized and overwhelmed by larger catchment land uses (Magierowski, Davies, Read, & Horrigan, 2012; Ranganath, Hession, & Wynn, 2009), and exclusion may also facilitate the establishment and spread of invasive plant species (Loo, Mac Nally, O'Dowd, & Lake, 2009). The effects of intensive grazing may also persist over many years after the removal of livestock, and recovery times for species will depend on a variety of factors (such as dispersal ability) (Homyack & Giuliano, 2002). Some other ranching BMPs (e.g. rotational grazing) may be appropriate in different contexts (Magner, Vondracek, & Brooks, 2008), although there is little information to support a significant positive impact on freshwater ecosystems or species, and other factors (e.g. riparian buffer functioning) may be more important (Brand, Vondracek, & Jordan, 2015). A main discriminator may be whether or not a system historically experienced natural grazing pressure. In the absence of native grazers, the creation and maintenance of wetlands (e.g. vernal pools) may depend on cattle grazing, with benefits for native freshwater species (Marty, 2005; Mero, Lontay, & Lengyel, 2015).

Most studies of grazing impacts have examined North American systems, although a smaller number have examined grazing and ranching in Europe and South America (e.g. in the Pantanal). Literature exploring the impacts on freshwater biodiversity of silvopastoral systems was not found.

Fire risk management

The impacts of fire risk management on freshwater ecosystems and species are complicated, and in general have received relatively little attention (Bisson et al., 2003; Pilliod, Bury, Hyde, Pearl, & Corn, 2003). The question of whether, and how severe, wildfire in itself is damaging to freshwater ecosystems and species is context specific. Fires mobilize nutrients, sediments, and debris, increase run-off and river discharge, and have impacts on turbidity, light, temperature, and organic inputs. The types and time lags of biotic responses are influenced by the scope of fires and the pre- and post-fire patterns of droughts and floods. Biotic responses vary by life cycles, habitat specificity, dispersal abilities, and the availability and distribution of refugia (for a summary of impacts of fires on patterns, processes and biological responses, see Bixby et al., 2015).

A meta-analysis of studies of amphibian responses to severe wildfires found both positive and negative impacts and noted that the natural recovery of species populations affected by fire may be hampered by land-use change and fragmentation (Hossack & Pilliod, 2011). A review of the impacts of forest fires on fishes in North America found that although some populations might be extirpated by severe fires, recolonization by more mobile species is relatively rapid (Gresswell, 1999). For species with low mobility (either naturally or through habitat fragmentation), high habitat specificity, or for those species with highly reduced population numbers, the impacts may be greater and more long lasting (Dunham, Young, Gresswell, & Rieman, 2003).

Activities designed to lessen the severity or risk of fires can affect stream biota. Of those studies that have addressed the impact of fire risk management activities on freshwater species and ecosystems, virtually all have examined North American coniferous systems. Typically, studies have investigated combinations of prescribed burning and tree thinning. Some freshwater species are adapted to systems that experience lower-level periodic fires, so in principle might benefit from prescribed burns, especially in conjunction with the mitigation of other threats (Whitney, Gido, Pilger, Propst, & Turner, 2016); however, species with low population viability that are already vulnerable may be an important exception (Driscoll & Roberts, 1997). Stream ecosystems flowing through forested landscapes are also typically reliant on terrestrial inputs of coarse woody materials, and forest thinning in the service of reducing the risk of catastrophic fires may deprive streams of that material if the cut trees are removed (Rieman et al., 2003). In addition, forest thinning activities may involve the construction of logging roads, with their concomitant chronic impacts (Rieman et al., 2003). The importance of retaining riparian buffer zones is a common theme across many studies (Olson, Leirness, Cunningham, & Steel, 2014), as is the importance of being aware of unintended consequences (Rieman & Clayton, 1997). Based on the limited literature, the impacts of forest fuel reduction on freshwater species are mixed and highly context specific.

Wetland restoration and creation

There is reasonably good literature on the impacts of wetland restoration and creation on biodiversity. In general, restored or rehabilitated wetlands are found to provide greater benefits for freshwater biodiversity and ecosystem functioning than created wetlands, yet these benefits are not as great as those provided by natural wetlands (Meli, Rey Benayas, Balvanera, & Martinez Ramos, 2014; Sebastián-González & Green, 2016; Spadafora et al., 2016). Some studies examining wetland birds, invertebrates, and amphibians have found evidence of positive change in population abundance or species presence, although these changes are not necessarily sustained over time (Brown, Smith, & Batzer, 1997; Hapner et al., 2011; Ruhi et al., 2012). Restored peatlands have been shown to support freshwater communities comparable with those in natural wetlands (Brown, Ramchunder, Beadle, & Holden, 2016). Created compensatory wetlands often fail to achieve the same ecosystem functions as restored or rehabilitated natural wetlands (Brown & Veneman, 2001; Español, Gallardo, Comín, & Pino, 2015; Spadafora et al., 2016; Whigham, 1999). ‘Dual purpose ponds’ or multi-objective wetlands in agricultural landscapes, aimed at biodiversity conservation as well as nutrient retention or flood abatement, result in generally positive impacts, but there is also a recognition that no single wetland can provide all of these services indefinitely (Zedler, 2003). Wetland restoration for biodiversity conservation may be most effective when a higher density of wetlands is achieved within a landscape, both to facilitate dispersal among species and because wetlands undergo successional processes (Thiere et al., 2009).

It is important to note that these studies have looked at the impacts within the created or restored wetlands themselves, rather than examining downstream freshwater biodiversity, which presumably would benefit to some extent from improved water quality and flow characteristics. Many of the wetlands studied are not connected directly to river systems, so there would be minimal exchange of obligate aquatic species among them.

Studies of the effects of wetland restoration and creation on biodiversity and ecosystem integrity are almost exclusively focused on North America and Europe, with a small number examining wetlands in Asia.

Road management

Roads, especially but not exclusively those that are unpaved, are widely acknowledged to be substantial sources of sediment to streams, but even that conventional wisdom has been challenged empirically (Al-Chokhachy et al., 2016). Literature on the impacts of road management, including road removal, on freshwater species is sparse (for a review, see Switalski, Bissonette, DeLuca, Luce, and Madej, 2004), with much of it focused on the forested landscapes in the Pacific Northwest of North America (Jones, Swanson, Wemple, & Snyder, 2000). Many studies of the impacts of roads on freshwater biodiversity focus on the barriers that road–stream crossings pose to species movement. Others look at the storm water-related impacts of urban roads, but these are often modelled (Roni et al., 2008). There is some literature providing guidance on managing unpaved roads (typically associated with forestry operations) to reduce sediment impacts, but the literature is largely focused on the USA (Roni et al., 2008). At the same time, the sediment contributions of roads at basin scales may be dwarfed by other contributors, such as those from wildfire (Goode, Luce, & Buffington, 2012), underscoring the multi-faceted nature of the threats to freshwater ecosystems. A study in the Amazon found that reduced-impact logging, which includes minimizing the construction of access roads, can reduce the adverse impacts on freshwater communities (Dias, Magnusson, & Zuanon, 2010).

Whereas there is a dearth of literature on the measured freshwater biodiversity impacts of road management (other than removing instream barriers), there seems to be a reasonably clear pathway between road management that successfully reduces sediment loading to streams and benefits to freshwater species (with the caveat that many species will be affected by multiple threats, of which sediment will be only one).