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ECOSYSTEMS

Riparian Ecosystems in the 21st Century: Hotspots for Climate Change Adaptation?

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ABSTRACT

Riparian ecosystems in the 21st century are likely to play a critical role in determining the vulnerability of natural and human systems to climate change, and in influencing the capacity of these systems to adapt. Some authors have suggested that riparian ecosystems are particularly vulnerable to climate change impacts due to their high levels of exposure and sensitivity to climatic stimuli, and their history of degradation. Others have highlighted the probable resilience of riparian ecosystems to climate change as a result of their evolution under high levels of climatic and environmental variability. We synthesize current knowledge of the vulnerability of riparian ecosystems to climate change by assessing the potential exposure, sensitivity, and adaptive capacity of their key components and processes, as well as ecosystem functions, goods and services, to projected global climatic changes. We review key pathways for ecological and human adaptation for the maintenance, res-

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toration and enhancement of riparian ecosystem functions, goods and services and present emerging principles for planned adaptation. Our synthesis suggests that, in the absence of adaptation, riparian ecosystems are likely to be highly vulnerable to climate change impacts. However, given the critical role of riparian ecosystem functions in landscapes, as well as the strong links between riparian ecosystems and human well-being, considerable means, motives and opportunities for strategically planned adaptation to climate change also exist. The need for planned adaptation of and for riparian ecosystems is likely to be strengthened as the importance of many riparian ecosystem functions, goods and services will grow under a changing climate. Consequently, riparian ecosystems are likely to become adaptation 'hotspots' as the century unfolds.

Key words: adaptive capacity; ecosystem services; environmental management; floodplains; human adaptation; vulnerability; water resources.

INTRODUCTION

Climate change has had, and increasingly will have, a significant influence on the world's natural ecosystems, their species, and the functions, goods and services that they provide (Hulme 2005). For some highly vulnerable species and ecosystems, persistence may depend on the success of global mitigation efforts or on extreme interventions, such as seed banks or zoos. For many other species and systems, managed adaptation strategies to reduce their vulnerability to climate change and to increase their capacity to adapt to changing conditions are required (Hulme 2005). Identifying and prioritizing effective adaptation options for conservation and natural resources management (for example, through vulnerability assessments) has thus become a major research focus (Palmer and others 2007; Steffen and others 2009; Hansen and Hoffman 2011).

Riparian ecosystems, defined here in their broadest sense as those occurring in semi-terrestrial areas adjacent to water bodies and influenced by freshwaters (Naiman and others 2005), have been identified as being particularly susceptible to climate change impacts, at least partially because they are among the world's most transformed and degraded ecosystems (Tockner and Stanford 2002; Rood and others 2008; Perry and others 2012). However, some authors suggest that riparian ecosystems may be relatively resistant to climate change because they have evolved under conditions of high environmental variability and hydrologic extremes (Seavy and others 2009; Catford and others 2012). Either way, there is growing recognition that successful adaptation to climate change of much aquatic and terrestrial biodiversity, as well as human enterprise, may depend on riparian ecosystem functions and their capacity to adapt, or be adapted, to changing conditions (Palmer and others 2008, 2009; Seavy and others 2009; Davies 2010; Thomson and others 2012).

Here, we suggest that riparian ecosystems will be hotspots for adaptation to climate change over the coming century with respect to the autonomous adaptation of biota and ecosystems across landscapes as well as human adaptation responses, both spontaneous and planned. We make this assertion based on several key points around which this paper is structured:

1. Riparian ecosystems, in the absence of planned human adaptation, are likely to be particularly vulnerable to climate change impacts because of their relatively high levels of exposure and sensitivity to changes in climatic stimuli as well as constraints on their capacity to adapt autonomously due to other stressors;
2. Riparian ecosystem functions, goods and services are disproportionately abundant with respect to surface area and are highly significant in landscapes, with many likely to become more important ecologically and for humans under a changing climate; and
3. Considerable means and opportunity exist for planned human adaptation of riparian ecosystems including numerous low-regret options with the potential for multiple benefits for biodiversity and human well-being at local and landscape scales.

We begin by assessing the relative vulnerability of riparian ecosystems to climate change impacts in the absence of planned human adaptation. Rather than attempting a comprehensive review of projected impacts of climate change on riparian ecosystems, this synthesis considers how distinguishing characteristics of riparian ecosystems affect the exposure, sensitivity, and adaptive capacity of their key components and processes to projected global changes. Secondly, we provide an overview of key riparian ecosystem functions, goods and services and the mechanisms by which climate change is likely to affect both the supply of and demand for these functions and services. Finally, we assess the capacity for planned human adaptation, with respect to both riparian ecosystems and their management, by reviewing potential adaptation pathways and the factors influencing uptake and likely effectiveness. We conclude by presenting some guiding principles for planned adaptation of riparian ecosystems that emerge from our synthesis.

Vulnerability of Riparian Ecosystems to Climate Change

Exposure

Vulnerability of riparian ecosystems to climate change depends largely on the degree of their exposure to climatic stimuli which, in turn, depends on both regional climate change and climate variability (Figure 1; Füssel and Klein 2006). Most riparian ecosystems are subject to the CO_2 enrichment and rising air and water temperatures associated with anthropogenic climate change, albeit to varying degrees (IPCC 2007a). Additionally, changes in precipitation patterns, consistent with global warming, have been observed for much of the world in recent decades and further changes are widely anticipated, despite high levels of uncertainty associated with hydrological projections (Bates and others 2008). In general, wetter areas are likely to become wetter and drier areas drier with mean precipitation expected to increase in high latitudes and some tropical regions and decrease in lower mid-latitudes and some subtropical regions (IPCC 2007a). Both the frequency of heavy precipitation events and the proportion of annual rainfall falling in intense events are also likely to increase in most regions (IPCC 2007a; Bates and others 2008). In alpine areas, riparian ecosystems may also experience reductions in snow depth and duration (Vicuna and Dracup 2007), whereas those in coastal areas are open to intrusion by marine waters due to sea-level rise and increased storm surge (IPCC 2007a).

Clearly, there is much variation in the degree and type of climate change and climate variability experienced by riparian ecosystems at global and basin-scales, as well as within catchments between upland and lowland reaches (Palmer and others 2008, 2009). Within landscapes, however, riparian ecosystems can be considered to have relatively high levels of exposure to changes in climatic stimuli (for example, rising temperatures) because they are subject to these directly as well as through the effects of these changes in the terrestrial and aquatic environments with which they are connected. Due to their topographic position, riparian ecosystems also tend to be highly exposed to extreme climatic events, including floods, droughts and intense storms, which are expected to increase in frequency and intensity in many regions due to climate change (IPCC 2007a; Bates and others 2008). Riparian ecosystems are often particularly

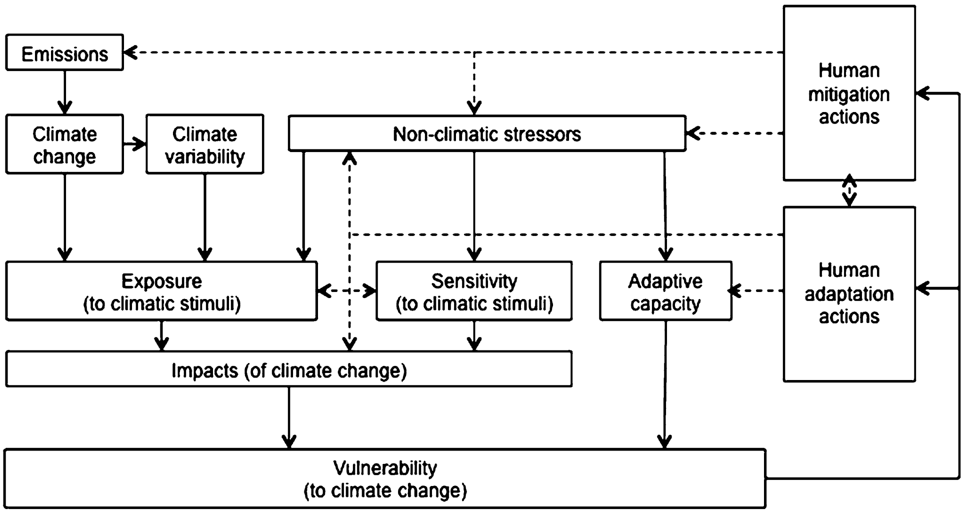

Figure 1. Conceptual framework for assessing vulnerability to climate change showing relationships between exposure, sensitivity and adaptive capacity, and climate change impacts and vulnerability. *Dashed lines* indicate the effects of human actions, including the potential for human climate change adaptation and mitigation actions to influence exposure, sensitivity, and adaptive capacity, both directly and indirectly through their influence on emissions and non-climatic stressors (adapted from Füssel and Klein 2006).

exposed to damaging winds associated with tropical cyclones (Turton 2012).

Sensitivity

As a key dimension of vulnerability to climate change, 'sensitivity' refers to the 'dose–response relationship' between a system's exposure to climate-related stimuli and the potential for this to result in impacts, typically in the absence of adaptation (Figure 1; Füssel and Klein 2006). Riparian ecosystems can be considered to be highly sensitive to changes in climatic stimuli because their major components and processes tend to be strongly influenced by the climate variables that are most likely to be altered by anthropogenic climate change. In particular, hydrologic regimes, generally considered the 'master variable' controlling riparian ecosystem structure and function (Power and others 1995; Poff and Zimmerman 2010), are very sensitive to changes in precipitation and, to a lesser degree, evapotranspiration, with declines in rainfall resulting in proportionally greater reductions in runoff and stream flow (Arnell 1999; Najjar 1999; Goudie 2006; Jones and others 2006). Similarly, increases in annual precipitation result in much greater increases in mean stream flow and proportionately even greater flood discharges (Goudie 2006). Stream flow is also very sensitive to rising temperatures. In Australia's Murray-Darling Basin, for example, recent reductions in annual inflows of approximately 15% can be attributed solely to a 1°C rise in temperature (Cai and Cowan 2008). Groundwater hydrology, significant for many riparian ecosystems, is also highly sensitive to changes in precipitation, temperature, and evapotranspiration. Potential climate change effects include changes in recharge, discharge, and flow direction, the overall impacts of which are anticipated to be detrimental in the majority of cases (Dragoni and Sukhiga 2008).

The sensitivity of runoff, stream flow, and flood discharges to altered rainfall differs considerably among regions in relation to CO_2 concentrations and temperature, depending on emission scenarios (Goudie 2006; Moradkhani and others 2010). Effects are typically greatest in drier catchments, with declines in annual river runoff of up to 40–70% likely in arid and semi-arid catchments in response to a 1–2°C increase in mean annual temperature and 10% decrease in precipitation (Shiklomanov 1999; Goudie 2006; Jones and others 2006). In and downstream of alpine areas, the sensitivity of riparian hydrologic regimes to climate change is exacerbated by current and projected declines in snow depth and season duration, which commonly lead to reduced spring peak flows and higher winter flows (Lapp and others 2005; Goudie 2006; Rood and others 2008). Such effects demonstrate the sensitivity of flow seasonality, as well as volume, to climate change. Indeed, in some regions, shifts in the timing of flow peaks are predicted even where overall hydrograph shapes are insensitive to projected climate changes (for example, Scibek and others 2007).

Fluvial and upland geomorphic processes are also major determinants of physical and biogeochemical patterns and processes in riparian ecosystems (Gregory and others 1991) and are similarly sensitive to projected changes in climate stimuli. In particular, changes in precipitation are expected to have important effects on sedimentation (Nearing 2001; Yang and others 2003; Nearing and others 2004) with a potential for dramatic increases in erosion rates at whole-of-continent scales (Favis-Mortlock and Guerra 1999; Sun and others 2002; Nearing and others 2004). Climate change effects on sediment and flow regimes will lead to changes in channel form and the fluvial dynamics of rivers and their riparian zone. Fine-grained alluvial streams, rather than bedrock or armored channels, are likely to be most sensitive to such effects (Goudie 2006). Streams in arid regions are also especially sensitive to altered precipitation and runoff and relatively minor climate changes can induce rapid shifts between incision and aggradation (Nanson and Tooth 1999; Goudie 2006).

Biogeochemical processes influencing water and soil quality in riparian ecosystems are sensitive to changes in climatic stimuli both directly and indirectly through changes to hydrologic and geomorphologic processes. Litter decomposition, for example, is sensitive to CO_2 enrichment, warming and changes in soil moisture, although differing effects of these on microbial activity make it difficult to predict overall impacts (Perry and others 2012). Rates of release of many solutes (for example, nitrate, sulfate, sodium, iron, and so on) from riparian soils are also sensitive to hydrologic changes and riparian soils can shift from sinks to sources of potentially harmful solutes with drier conditions (Freeman and others 1993).

Riparian biota are likely to be directly affected by projected climate changes with physiological responses (for example, altered growth and reproduction), behavioral changes, altered phenology, shifts in species distributions, and disrupted symbiotic and trophic interactions widely anticipated if not already apparent (Steffen and others 2009; Catford and others 2012, 2009; Nilsson and others

2012; Perry and others 2012). Riparian organisms are particularly sensitive to changes in hydrologic and fluvial disturbance regimes because these tend to be the main drivers of life-history processes, population and community structure and interactions among riparian biota (Naiman and others 2005; Perry and others 2012). The composition and structure of riparian vegetation, for example, is usually governed primarily by hydrology and, to a lesser degree, geomorphology. Individual plants, populations, and communities can be sensitive to changes in the timing, duration, depth, frequency, and rates of rise and fall of surface and ground waters (Hupp and Osterkamp 1996; Nilsson and Svedmark 2002). Riparian vegetation can also be more sensitive to tropical cyclones than that of upland areas, especially with respect to wind damage and subsequent weed invasions, with impacts often exacerbated by increased erosion and reduced water quality following such events (Turton 2012).

The sensitivity to climatic changes of animals inhabiting riparian areas, either permanently or occasionally (that is, for feeding, breeding or refuge), will be affected by changes in habitat structure wrought by altered hydrology and geomorphology and resulting changes to riparian vegetation (Catford and others 2012, 2009). Changes in riparian hydrology, for instance, are likely to affect animals such as water birds that breed in riparian areas in response to specific hydrologic cues (for example, water levels; Kingsford and Norman 2002; Chambers and others 2005). Riparian food webs are also sensitive to altered vegetation and faunal assemblages and to changes in processes of production and decomposition.

Because riparian ecosystems are characterized by interactions between adjacent terrestrial and aquatic ecosystems, many of their ecological processes will be especially sensitive to climate change because they will be subject to effects both within the riparian zone and those in the surrounding landscape (Ballinger and Lake 2006). Additionally, the capacity of biota and ecosystem processes to tolerate, resist and recover from changes to climatic stimuli will be affected by other, non-climatic stressors (Figure 1). Riparian ecosystems are highly susceptible to weed invasions, for example, and infestations of some alien plants may prevent the re-establishment of native species following extreme events such as floods or storms (Richardson and others 2007). The sensitivity of riparian ecosystem components and processes to climate change will be particularly influenced by the many anthropogenic pressures to which riparian ecosystems are subject. Some major threats to riparian ecosystems around the world include altered hydrologic regimes due to river regulation and water extraction, vegetation clearing for agriculture and other developments, grazing by livestock, development of human settlements and infrastructure, pollution and mining (Tockner and Stanford 2002; Naiman and others 2005). Climate change is expected to have significant effects on many human activities associated with such threats, including construction of more water storages, water transfers among basins, increased clearing to enable access, and construction of infrastructure to meet greater demand for water and mineral resources, all of which will impact riparian ecosystems. Some CO_2 mitigation measures, such as more plantations for carbon sequestration and construction of hydropower facilities, may further stress riparian ecosystems (for example, Bates and others 2008; Pittock and Finlayson 2011). At the same time, the sensitivity of riparian ecosystem components and processes to these non-climatic threats is likely to grow as a result of climate change effects (Rood and others 2008). Feedback loops of this kind may amplify human effects on riparian ecological dynamics and biodiversity more rapidly in the future, and are likely to increase the effects of synergies among multiple stressors (Mac Nally and others 2011).

Adaptive Capacity

Adaptive capacity is the ability of a system to adjust to external changes, such as climate change, so that it moderates, copes with or exploits the consequences of these (Füssel and Klein 2006). Autonomous adaptation refers to that which 'does not constitute a conscious response to climatic stimuli' (IPCC 2007b) and in the case of ecosystems typically refers to the capacity of organisms, species, biological communities, and ecosystems to adapt to changes in climatic stimuli. Pathways for autonomous adaptation (that is, 'adaptation that does not constitute a conscious response to climatic stimuli'; IPCC 2007b) of individual organisms or species include acclimation, morphological or physiological plasticity, behavioral change, genetic adaptation and migration, the outcome of which may be range contraction, expansion or movement (Palmer and others 2007, 2009). Shifts in interspecific dependencies (for example, changes in mutualisms) or the composition of assemblages (for example, more salt-tolerant or fire-retardant species) may be regarded as adaptive if resulting novel ecosystems have greater resistance to climate changes or an improved capacity to recover from disturbances associated with climate change (for example, more intense fires; Catford and others 2012, 2009).

Unlike exposure and sensitivity, adaptive capacity is negatively correlated with vulnerability (Figure 1). In general, a system's capacity to cope with existing climate variability can be interpreted as an indication of its ability to adapt to climate change in the future (Füssel and Klein 2006). Natural riparian ecosystems may have relatively high adaptive capacity overall because they have evolved under, and are structured by, relatively great environmental variability, much of which is associated with variation in climatic stimuli. Riparian plants, for instance, exhibit a wide array of traits that enable their persistence under variable fluvial disturbance regimes (Dwire and Kauffman 2003). Such adaptations are potential mechanisms for acclimation to increased frequency and severity of extreme events in riparian ecosystems due to climate change, including fires. Additionally, many aquatic and semi-aquatic riparian plants have morphological and physiological plasticity (for example, heterophylly or the ability to elongate roots or shoots) that enable them to respond to water-level fluctuations (Cronk and Fennessy 2001; Horton and Clark 2001). Many riparian biota may also have relatively high adaptive capacity because of their high levels mobility. Diaspores of riparian plants, for example, often have traits that facilitate their dispersal by several vectors including wind, water, and animals (Nilsson and others 1991). High levels of connectivity within and between riparian ecosystems provide pathways for the movement of propagules and individuals as climatic conditions shift within catchments (for example, from lower to upper reaches with rising temperatures) or, where dispersal is facilitated by wind or water birds, between regions (Raulings and others 2011). The characteristic heterogeneity of many riparian ecosystems (for example, Stromberg and others 2007) also increases the probability that dispersing organisms will find appropriate habitats for recolonization. Furthermore, riparian biotic assemblages are typically dynamic, demonstrating considerable capacity to shift in composition and structure in response to fluvial disturbances (for example, Junk and others 1989; Capon 2003). Autonomous transitions to more fire-retardant or salt-tolerant vegetation are therefore possible in riparian areas where climate change effects include greater fire frequency or elevated salinity (Nielsen and Brock 2009).

A critical influence on the adaptive capacity of natural ecosystems with respect to climate change is exposure and sensitivity to non-climatic threats because the effects of these may limit the scope of adaptations to climate change that organisms or ecosystems might otherwise be able to express. Riparian ecosystems often are sites of intensive human activity and have been much transformed and degraded (Tockner and Stanford 2002). Thus, the capacity of riparian ecosystems to adapt autonomously to climate change is much constrained (Palmer and others 2008, 2009). Altered hydrologic regimes, fragmentation, and encroachment onto riparian lands by agriculture and human settlements all reduce connectivity and heterogeneity of riparian ecosystems and are likely to aggravate the exposure and sensitivity of their ecosystem components and processes to climate change (Palmer and others 2008, 2009). The time and space available for organisms and assemblages to adjust to altered conditions, either in situ or through migration, may be significantly reduced due to these other pressures. Additionally, the rate of potential autonomous ecological adaptation in many cases is likely to be exceeded by rates of climatic change (Visser 2008).

Riparian Ecosystem Functions, Goods, and Services

Riparian ecosystems have a wide range of ecological, socioeconomic, and cultural functions (Table 1). Many of these functions are important not only locally but also have considerable influence on physical, chemical, and biological components and processes in landscapes, particularly with respect to aquatic ecosystems but also terrestrial and, in some cases, marine ecosystems (Naiman and others 2005). At these larger scales, riparian ecosystem functions include the regulation of climate, water, sediments, nutrients, soils and topography, and food production and transfer among food webs (Table 1). These functions involve the regulation of exchanges of materials and energy between adjacent aquatic and terrestrial ecosystems but can also affect ecosystem components and processes for considerable distances into upland systems, downstream within the catchment, or beyond into coastal and marine systems or other catchments (for example, Johnson and others 1999; Helfield and Naiman 2001). In the case of exchanges facilitated by migrating water birds (Raulings and others 2011), the geographical distances bounding such functions may be immense, for example, intercontinental.

Riparian ecosystems also have significant habitat functions (de Groot and others 2002), both locally and in landscapes, and tend to increase the diversity of species pools at regional scales (Sabo and

Table 1. Major Riparian Ecosystem Functions and Their Associated Components and Processes, and Goods and Services

Ecosystem function	Ecosystem processes and components	Ecosystem goods and services (examples)	Potential mechanisms of climate change effects (examples)	
			Supply-side	Demand-side
Regulation functions				
Gas regulation	Role in biogeochemical cycles	Provision of sinks for potentially harmful solutes	May switch from sinks to sources of harmful solutes with warming and drying	
Climate regulation	Influence of riparian canopy on climate	Reduction of local temperature	Changes to riparian canopy will affect local temperature regimes	Increased importance due to global warming
		Reduction of in-stream temperature	Changes to riparian canopy will affect in-stream temperature regimes	Increased importance due to global warming
		Reduction of in-stream light	Changes to riparian canopy will affect in-stream light regimes	Increased importance due to potential increases in solar irradiance
Disturbance prevention	Dampening of environmental disturbances by riparian vegetation and wetlands	Storm protection, for example, protection of stream banks from erosion	Changes in riparian vegetation will affect susceptibility to damage from storms	Greater importance due to increased frequency and intensity of extreme precipitation events
		Flood mitigation	Changes in riparian vegetation and topography will influence flooding patterns	Greater importance due to increased frequency and intensity of extreme flooding
Water regulation	Influence of riparian topography and vegetation on regulation of runoff and river discharge	Drainage and natural irrigation	Changes in riparian topography and vegetation will affect runoff patterns, flooding patterns and ground water dynamics	Greater importance due to increased frequency of intense precipitation and runoff events

Table 1. continued

Ecosystem function	Ecosystem processes and components	Ecosystem goods and services (examples)	Potential mechanisms of climate change effects (examples)	
			Supply-side	Demand-side
Water supply	Influence of riparian vegetation and soils on filtering of runoff and river discharge	Provision of water suitable for consumptive use	Changes in riparian vegetation, soils and biogeochemistry will affect quantity and quality of stream, flood and ground waters	Greater importance due to increased frequency of intense precipitation and runoff events
Soil retention	Role of vegetation root matrix and soil biota on soil retention	Maintenance of riparian pastures	Changes in water and vegetation will alter capacity of soils to support pasture growth	Greater importance due to increased frequency of intense precipitation and runoff events
		Prevention of erosion	Changes in water and vegetation will alter susceptibility of soils to erosion	
Soil formation	Role of flooding in erosion and deposition, organic matter accumulation, weathering of substrates, role of riparian biota in decomposition	Maintenance of productive soils	Changes in water and vegetation will alter capacity of soils to support pasture growth	May increase in significance under drying climates if surrounding landscape becomes less productive
Nutrient regulation	Role of riparian soils and biota in nutrient storage and recycling	Maintenance of productive ecosystems	Changes to riparian soil and biota will affect nutrient cycling	
Waste treatment	Role of riparian vegetation in removal and breakdown of xenic nutrients and compounds	Pollution control/ detoxification	Changes to riparian vegetation, soils and biogeochemistry may limit capacity to breakdown compounds and act as solute sinks	May increase in significance if human adaptation increases water recycling practices and/or pollution

Table 1. continued

Ecosystem function	Ecosystem processes and components	Ecosystem goods and services (examples)	Potential mechanisms of climate change effects (examples)	
			Supply-side	Demand-side
Energy transfer	Role of riparian food webs in energy exchange between aquatic and terrestrial systems	Maintenance of productive ecosystems	Energy exchange between aquatic and terrestrial systems will be affected by changes in riparian biota and habitat	May increase in significance under drying climates if surrounding landscape becomes less productive
Pollination	Role of wind, flooding and riparian biota in dispersal of pollen	Pollination of wild and pasture species, maintenance of wild meta-populations,	Pollination will be affected by changes in riparian biota and habitat	Increasing importance as pathways for migration in response to shifting climate, increasing importance for facilitating potential for genetic adaptation through gene flow
Propagule dispersal	Role of wind, flooding and riparian biota in dispersal of propagules	Dispersal of wild and pasture species, maintenance of egg and seed banks, maintenance of wild meta-populations	Dispersal will be affected by changes in riparian biota and habitat	Increasing importance as pathways for migration in response to shifting climate
Biological control	Influence of trophic–dynamic interactions on populations	Control of pests and diseases	Changes in riparian biota, food webs and habitat will alter spread of pests and diseases	Increasing importance for control of pathways of migration in response to shifting climate
Habitat functions				
Refuge function	Provision of habitat for organisms	Maintenance of harvested and wild terrestrial species	Quality and quantity of refuge habitat will be affected by changes in topography, local climate, nutrients, soils, water, biota, food webs and pests	Increasing importance to terrestrial species under warming and drying climates

Table 1. continued

Ecosystem function	Ecosystem processes and components	Ecosystem goods and services (examples)	Potential mechanisms of climate change effects (examples)	
			Supply-side	Demand-side
Nursery function	Provision of habitat for breeding, for example, water birds, fish	Maintenance of terrestrial and aquatic species	Quality and quantity of breeding habitat will be affected by changes in topography, local climate, nutrients, soils, water, biota, food webs and pests	Increasing importance to terrestrial and aquatic species under warming and drying climates
Corridor function	Provision of habitat for movement of organisms	Maintenance of terrestrial and aquatic species	Movement of organisms through riparian ecosystems will be affected by changes in topography, local climate, nutrients, soils, water, biota, food webs and pests	Increasing importance as pathways for migration in response to shifting climate
Structural function	Influence on in-stream habitats through provision of structure (overhanging roots, canopy, wood, etc.)	Maintenance of aquatic species	Riparian influence on structural aquatic habitat will be affected by changes to topography, vegetation and soils	Increasing importance to aquatic species under warming and drying climates
Production functions				
Food	Provision of edible resources	Hunting, gathering, small-scale subsistence farming and aquaculture	Food production will be affected by changes to regulating and habitat functions	May increase in significance if surrounding landscape becomes drier and less productive
Raw materials	Provision of biomass for human use	Construction and manufacturing Fuel and energy Fodder and fertilizer	Production of raw materials will be affected by changes in regulating and habitat functions and biota	May increase in significance under drying climates if surrounding landscape becomes less productive

Table 1. continued

Ecosystem function	Ecosystem processes and components	Ecosystem goods and services (examples)	Potential mechanisms of climate change effects (examples)	
			Supply-side	**Demand-side**
Genetic resources	Provision of genetic materials	Improved crop resistance to pathogens and pests Gene translocation	Diversity of genetic resources will change with changed riparian biota	
Ornamental resources	Provision of materials (for example, biota) with ornamental use	Resources for crafts, souvenirs, etc.	Diversity of materials will be affected by changes in regulating functions and biota	May increase in significance under drying climates if surrounding landscape becomes less productive
Information functions				
Aesthetic information	Attractive landscape features	Enjoyment of scenery	Scenery will be altered by changes in regulating and habitat functions especially those influencing topography and biota	May increase in significance if surrounding landscape is altered to become less attractive or familiar
Recreation	Provision of landscape with recreational use	Camping, fishing, bird-watching	Recreational utility will be affected by changes in climate, topography, soil, water, and biota	May increase in significance if surrounding landscape becomes less amenable for recreation
Cultural and artistic information	Provision of natural features with cultural value	Use as motive for cultural and artistic activities	Culturally and spiritually valuable features and places may be altered due to changes in topography, vegetation, etc.	May increase in significance if surrounding landscape is significantly altered
Spiritual and historic information	Provision of natural features with spiritual and historic value	Use for religious or historic purposes		
Science and education	Provision of natural features with scientific and educational value	Use for research or education	Scientific and educational opportunities will vary with other changes	Increased significance for adaptive learning and management

Sources: references in text

Potential mechanisms for climate change effects on the supply of ecosystem goods and services and their importance and/or demand are also indicated. N.B. This table is not intended to be exhaustive, nor universally applicable, but rather provide a framework via which susceptibility of key elements of riparian ecosystems to climate change impacts, and their interactions, can be considered in particular regional settings (adapted from de Groot and others 2002).

others 2005; Clarke and others 2008). With typically cooler air temperatures and higher relative humidity than surrounding uplands (Brosofske and others 1997; Danehy and Kirpes 2000), riparian ecosystems provide refuge, breeding, nursery and feeding habitat, and corridors for movement to many terrestrial and aquatic organisms (Mac Nally and others 2000; Fleishman and others 2003). Riparian ecosystems also influence habitats of adjacent and downstream aquatic ecosystems by regulating light, water temperature and material inputs (for example, sediments, litter, wood; Bunn and others 1999). In addition, many production functions (that is, provision of resources) and information functions (that is, provision of information to humans for spiritual enrichment, mental development and leisure) that are exploited and valued by humans are provided by riparian ecosystems (de Groot and others 2002; Table 1).

Riparian ecosystem functions contribute to the provision of ecosystem goods and services that are disproportionately abundant, with respect to surface area, than those supplied by many, if not most other, ecosystem types (Millennium Ecosystem Assessment 2005; Ten Brink 2009). The diversity and high value of riparian ecosystem functions, goods and services are supported by two key characteristics of (undisturbed) riparian ecosystems: (1) high spatial connectivity, internally and in relation to adjacent ecosystems and (2) high levels of environmental heterogeneity. These attributes both arise from the topographic position of riparian ecosystems and the central role played by variable fluvial disturbance regimes. The capacity of riparian ecosystems to provide many ecosystem functions, goods and services in landscapes reflects levels of lateral (for example, between rivers and their floodplains), longitudinal (that is, between upper and lower reaches), and vertical (that is, between subsurface and surface waters) connectivity, all of which facilitate and regulate the exchange of materials, energy and biota through and within riparian ecosystems (Ballinger and Lake 2006). The high degree of heterogeneity characteristic of riparian ecosystems (for example, Stromberg and others 2007) is significant for the provision of habitat functions and the ecosystem goods and services associated with these (Table 1).

Given their dependence on ecosystem components and processes, many riparian ecosystem functions that are important at local and landscape scales can be considered sensitive to climate change (Table 1). The two key characteristics supporting the capacity of riparian ecosystems to provide functions of importance in landscapes (that is, connectivity and heterogeneity) are particularly susceptible to climate change effects. Levels of lateral, longitudinal, and vertical connectivity between aquatic and terrestrial ecosystems, critical to many regulating functions provided by riparian ecosystems, will be altered directly by changes in precipitation and hydrology and their effects on riparian ecosystem components and processes. Habitat functions with landscape-scale significance are also sensitive to climate change due to altered connectivity. Changes in riparian vegetation structure may alter the suitability of riparian ecosystems as refuge or breeding habitat for terrestrial fauna or affect the capacity of riparian zones to provide corridors for movement of biota between upper and lower reaches of the catchment or vice versa. Aquatic ecosystems will be affected by changes in riparian vegetation that alter the regulation of in-stream light and temperature and the input of sediment, nutrients, and pollutants (for example, Davies 2010).

Climate-change-induced changes in fluvial and other disturbance regimes (for example, fire, tropical cyclones, and so) also have the potential to alter the physical, chemical, and biological heterogeneity of riparian ecosystems. Under a drying climate, and especially where drought becomes more prevalent, examples from other aquatic ecosystems suggest that homogenization is a probable outcome (Lake and others 2010). Diminishment of channels and a proclivity for simple, single-channel stream morphology are likely to result from reductions in flow (Ashmore and Church 2001). If the variability of flooding regimes decreases (for example, where overall flood frequency is reduced and flow regimes become dominated by frequent, large, and intense events), the characteristic patchiness of many riparian ecosystem components, such as soil, nutrients, litter, and vegetation, may also decline because heterogeneity amongst these components tends to be driven primarily by variable patterns of flooding and drying (Stromberg and others 2007). Conversely, increases in the temporal variability of precipitation and runoff anticipated in higher latitudes and some tropical regions, may lead to greater disturbance-driven heterogeneity in some riparian ecosystem components and processes. Such an outcome may have significant implications for biota dependent on relatively predictable hydrologic events (for example, Junk and others 1989).

Effects of climate change on the provision of goods and services by riparian ecosystems are likely to result from changes to the ecosystem components, processes and functions with which they are associated, and complex feedback loops among these (Table 1). Although the direction and magnitude of these effects will vary spatially, depending on exposure to climate change and the sensitivity of local riparian ecosystem components and processes, negative effects on the supply of ecosystem goods and services associated with freshwater systems are widely anticipated in the absence of adaptation (for example, Gleick 2003; Bates and others 2008; Dragoni and Sukhiga 2008; Palmer and others 2008; Vörösmarty and others 2010). In regions where declines in precipitation and runoff are projected, there are clear risks to the capacity of riparian ecosystems to supply the many important ecosystem goods and services that are shaped by hydrologic connectivity (Table 1). In regions where increased precipitation and runoff are projected, such riparian ecosystem goods and services also face risks due to increased variability in precipitation and runoff and shifts in the seasonal timing of flows (Bates and others 2008).

Changes to the role and significance of riparian ecosystem functions, as well as human demand for riparian ecosystem goods and services, are also probable outcomes of climate change. In many cases, riparian ecosystem functions, goods, and services can be expected to become more important, particularly at a landscape scale (Table 1). Rising temperatures in aquatic and terrestrial ecosystems, for example, increase the importance of the role of riparian vegetation in providing thermal refuges for biota (Davies 2010). Similarly, the provision of corridors for the movement of biota may become increasingly crucial as organisms seek pathways for migration in response to shifting climatic conditions. With respect to goods and services provided to human systems, demand for potable water is likely to intensify under drying climates (Bates and others 2008). Additionally, the protection afforded by riparian vegetation from effects associated with storms and floods (for example, mitigation of erosion) will be even more important where such events increase in frequency and intensity.

PATHWAYS FOR PLANNED ADAPTATION OF RIPARIAN ECOSYSTEMS

Human adaptation to climate change can be autonomous or planned, proactive or reactive, and can involve physical, on-the-ground actions and a range of socio-economic, political, or cultural changes, collectively referred to here as 'governance'. Goals of human adaptation, which may be explicit or implicit, typically are to reduce exposure or minimize sensitivity to climate change or to increase adaptive capacity, or some combination of these (Table 2). Drivers for human adaptation concern the minimization of risks associated with changing climatic conditions, especially the frequency and severity of extreme events, or to capitalize on opportunities these provide (Füssell 2007). Adaptation measures that address only socio-economic risks or opportunities can be maladaptive for natural ecosystems and biodiversity (Hulme 2005), reinforcing the need for planned, proactive adaptation of conservation and natural resources management practices. Many such adaptation approaches have been implemented and proposed (for example, Steffen and others 2009; Hansen and Hoffman 2011) that broadly encompass: (1) adaptation of existing management approaches; (2) hard adaptation measures; (3) retreat; (4) ecological engineering; and (5) a range of governance approaches. Each is summarized here with respect to riparian ecosystems (Table 2).

Adaptation of Existing Management Approaches

Many existing approaches to riparian management can be seen as adaptive if conducted in a framework of risk and uncertainty. Management of non-climatic threats (for example, pollution control, flow restoration, riparian fencing, and so on) can reduce the vulnerability of ecosystem components and processes to climate change and simultaneously build adaptive capacity (Table 2). Restoration activities (for example, riparian re-vegetation) are critical for reducing sensitivity and building adaptive capacity, particularly where restoration targets concern the protection, restitution or enhancement of riparian ecosystem functions and services such as temperature regulation of in-stream habitats (Davies 2010; Seavy and others 2009). Under the uncertain and transformational conditions imposed by climate change, riparian restoration might be particularly adaptive if, rather than driven by targets tied to antecedent reference conditions, restoration goals are more 'open-ended', emphasizing minimal levels of intervention and allowing for a range of future trajectories of ecological change that account for autogenic (for example, succession) and allogenic processes (for example, propagule dispersal; Hughes and others 2012). Prioritization of investments made in threat management and restoration should account for risks to capital, including infrastructure and social

Table 2. Key Options for Planned Adaptation for the Maintenance, Restoration and Enhancement of Riparian Ecosystem Components, Processes, Functions, Goods and Services

Adaptation option	Target(s)	Adaptation goal			Potential for multiple benefits	Potential for perverse outcomes	Irreversibility	Opportunity costs
		Reduce exposure	Minimize sensitivity	Increase adaptive capacity				
Adaptation of existing management approaches								
Management of existing stressors in climate change risk framework	Management target(s)	Y	Y	Y	High	Low	Low	Low
Riparian restoration, for example, re-vegetation	Vegetation, whole ecosystem	Y	Y	Y	High	Low	Low	Moderate
Expansion of protected area network	Whole ecosystem, landscape	N	Y	Y	High	Low	Moderate	Moderate
Hard adaptation approaches								
Construction of new structures, for example, barrages, sea walls, weirs	Fluvial processes and associated goods and services	Y	Y	N	Low–moderate	High	High	Moderate–high
Construction of new channel bank/bed armoring	Fluvial processes and associated goods and services	Y	Y	N	Low–moderate	High	High	Moderate–high
Meso- or micro-climate management infrastructure, for example, sprinkler systems	Local climate	Y	Y	N	Low–moderate	Moderate	Low–moderate	Low–moderate
Artificial habitats, for example, roosting structures	Specific taxa	N	Y	Y	Moderate	Moderate	Low–moderate	Low–moderate

Table 2. continued

Adaptation option	Target(s)	Adaptation goal			Potential for multiple benefits	Potential for perverse outcomes	Irreversibility	Opportunity costs
		Reduce exposure	Minimize sensitivity	Increase adaptive capacity				
Retrofitting of existing structures to increase connectivity or habitat functions	Specific taxa, biotic community	N	Y	Y	High	Moderate	Moderate	Low–moderate
Adaptation of management of existing structures in climate change risk framework	Management target(s)	Y	Y	Y	Moderate–high	Low–high	Low	Low
Retreat								
Removal of existing structures	Whole ecosystem, landscape, ecosystem goods and services	N	Y	Y	High	Moderate	Moderate–high	Moderate
Prevention or minimization of development	Whole ecosystem, landscape, ecosystem goods and services	N	Y	Y	High	Low	Low	Moderate–high
Ecological engineering								
Managed introduction of species or genotypes suited to new or predicted future conditions	Biotic community, whole ecosystem, ecosystem goods and services	Y	Y	Y	Moderate–high	Moderate–high	Moderate–high	Moderate–high
Over-restoration of riparian vegetation	Vegetation, whole ecosystem, landscape	Y	Y	Y	High	Moderate	Moderate–high	Moderate
Species translocation and 'banks'	Specific taxa	Y	Y	N	Low	Moderate–high	Moderate–high	Moderate–high

Table 2. continued

Adaptation option	Target(s)	Adaptation goal			Potential for multiple benefits	Potential for perverse outcomes	Irreversibility	Opportunity costs
		Reduce exposure	Minimize sensitivity	Increase adaptive capacity				
Governance								
Education and communication on riparian ecosystem functions, goods and services	Human community, land and water policy makers and managers, decision-makers	N	Y	Y	Moderate–high	Low	Low	Low
Improved social networks involving information access	Human community	Y	Y	Y	Moderate–high	Low	Low	Low
Changes to property rights, for example, land tenure, water rights, etc.	Human community	Y	Y	Y	High	Moderate	High	Moderate–high
Adaptive management practices, including information gathering and interpretation in climate change risk framework	Management target(s)	Y	Y	Y	High	Low	Low	Low

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For each adaptation option, key management targets and adaptation goals with respect to reducing exposure and/or sensitivity to climate changes and increasing adaptive capacity are identified. The potential for adaptation options to have effects beyond the intended target(s) is also suggested, both in terms of positive (that is, multiple benefits) and negative consequences (that is, perverse outcomes). The final columns indicate probable levels of irreversibility of adaptation options, referring to the ease of their removal (for example, physically, legally and/or economically) once implemented, and opportunity costs, defined here as the costs associated with the options sacrificed in choosing that particular option (for example, the existing or potential alternative benefits that have been lost by implementing the selected adaptation option).

capital, from exposure to climate change (for example, sea-level rise).

Protected areas may become relatively more important in the context of climate change adaptation to reduce sensitivity and build adaptive capacity of ecosystems and biodiversity (Steffen and others 2009; Hansen and Hoffman 2011). A focus on the protection of existing and potential climate refuges, or ecosystems known to be resistant to extreme climatic events, is especially adaptive. Landscape-level planning is likely to be effective for protected area networks, including corridors and prioritization of off-reserve conservation measures (for example, Steffen and others 2009; Wilby and others 2010). More novel, transformative approaches may involve some degree of spatial or temporal flexibility in protected area status (for example, gazetting reserves in locations identified as likely to be significant in the future; Fuller and others 2010). Given the structural and functional significance of riparian ecosystems, their incorporation into protected-area networks may have many benefits for biodiversity. Protection of remaining free-flowing streams and their riparian ecosystems under 'wild' or 'heritage rivers' programs, for instance, may have many benefits for autonomous ecological adaptation at a landscape scale (Palmer and others 2007; Pittock and Finlayson 2011).

Hard Adaptation Approaches

Hard approaches to adaptation involve the use of physical infrastructure to control or minimize a system's exposure and sensitivity to climate change (Table 2). Hard measures for riparian ecosystems can include the construction of barrages, sea walls, weirs and armoring (Pittock and Lankford 2010). Such measures are often intended to protect ecosystem goods and services (for example, water resources) or human settlements and infrastructure, in which case they are designed to replace natural ecosystem services (for example, flood protection) that are thought to be inadequate under actual or projected climatic conditions. Some hard approaches explicitly address ecological objectives. Engineering interventions such as water delivery channels and regulating structures that aim to use less water to conserve more riparian biodiversity are being implemented in some places including Australia's Murray-Darling Basin (Pittock and others 2012). Use of infrastructure to adjust local meso- or microclimates (for example, sprinkler systems or shade cloth to lower extreme temperatures) or the introduction of artificial habitats (for example, roosting structures) are other hard approaches.

Hard approaches to climate-change adaptation seek to 'hold the line' rather than to facilitate autonomous adaptation. Hard-engineering measures risk failure when modest thresholds are exceeded (for example, breaching of levee banks) and can be maladaptive at larger scales. They may result in a wide range of unintended and perverse consequences (for example, redirection of erosive outcomes) that may be difficult to reverse and that may be associated with high opportunity costs (Barnett and O'Neill 2010; Nelson 2010). Where hard-engineering measures are employed, an adaptive approach might entail periodic review of works (for example, through relicensing) to enable regular appraisal of costs and benefits and identification of necessary remedial actions (Pittock and Hartmann 2011). The renovation of infrastructure required to keep it safe under a changing climate provides an opportunity to retrofit technology to reduce environmental effects (for example, by introducing habitat diversity to hard surfaces or using fish-ladders to increase connectivity; Pittock and Hartmann 2011). The management and operation of hard-engineering structures such as dams can be adapted to provide greater ecological benefits such as the allocation of environmental flow releases or dilution flows.

Retreat

Retreat involves the partial or complete removal of hard-engineering structures. A retreat strategy aims to facilitate autonomous ecological adaptation by providing space and time for ecosystem components and processes to respond to climate change and to reduce their sensitivity to these by removing other stressors associated with the perverse effects of existing infrastructure (Table 2). Two examples relevant here are the restoration of floodplains to provide room to safely manage flood peaks, along with many other co-benefits (Pittock 2009), and the removal of redundant or deteriorating dams to increase connectivity in rivers and riparian ecosystems (Stanley and Doyle 2003).

Ecological Engineering

A wide range of ecological engineering approaches have been proposed as adaptation measures to climate change, many of which have relevance to riparian ecosystems. These include the managed introduction of species or genotypes more suited to altered conditions, either from ex situ populations or from genetically modified stock (for example, Grady and others 2011; Sgrò and others 2011). These strategies build the adaptive capacity of populations or increase the resilience of biological communities to climate change locally (Steffen and others 2009). Ecological engineering approaches may enhance ecosystem functions (for example, through the 'over restoration' of riparian vegetation to increase the provision of shade to in-stream habitats; Davies 2010). Such approaches seek to accommodate and direct change whereas hard-engineering approaches usually intend to prevent or minimize change (Table 2). More extreme ex situ conservation actions (for example, species translocation and species banks) may be required to conserve species or ecosystems with requirements beyond the limits of less interventionalist adaptation (Steffen and others 2009). Planned species translocations may be more effective for conserving species with limited dispersal capabilities than approaches that aim to facilitate migration by increasing connectivity (Hulme 2005).

Governance

Governance adaptation strategies are concerned with directing human responses to climate change including managed or planned responses as well as autonomous responses (that is, spontaneous adaptation triggered by ecological, market or welfare changes and not constituting a conscious response to climatic stimuli; IPCC 2001). Education and communication strategies to engender public and political support for adaptation are central to these approaches (for example, Steffen and others 2009). With respect to riparian ecosystems, promoting an increased awareness of the significance of the ecosystem functions, goods and services they provide is fundamental (Table 2).

To survive, prosper, and remain sustainable under a changing climate, individual land-holders that are dependent on riparian ecosystem goods and services (for example, graziers, farmers, and fishers) need to adapt to changes in riparian ecosystems. Several factors can influence the extent to which such adaptation occurs including a range of motivating factors and barriers to adaptation (Campbell and Stafford-Smith 2000; Ford and others 2006; Leonard and Pelling 2010). Social networks play an important role in motivating individuals to participate in adaptation processes (Marshall and others 2007; Guerrero and others 2010). Individual adaptive capacity is significantly correlated with the extent to which landholders are both formally and informally networked (Marshall and others 2007; Marshall 2010). Farmers, fishers, or graziers that are well connected to formal sources of information (for example, extension officers, industry representatives, researchers, or other government officials) are more likely to have the capacity to adapt. Networks engender interest in adapting and provide opportunities to develop more positive perceptions of risks associated with adaptation and the necessary skills to change and emotional support to undertake change.

From an institutional perspective, changes to property rights regimes are likely to be particularly important for riparian ecosystems, both for minimizing existing stressors and for building ecosystem resilience. Water licenses, land zoning, and tenure for conservation are core considerations (Pannell 2008). Economic approaches (for example, flexible water markets or incentive systems) can promote more efficient, equitable, and sustainable use and distribution of critical resources (Gleick 2003). Changes to the organizational structure of institutions involving the distribution of centralized control may be similarly adaptive, with regional and local institutions (for example, river basin or watershed catchment management groups) being important for facilitating adaptive management of riparian ecosystems (Gleick 2003; Pittock 2009). Greater integration across sectors and collaboration among organizations in planning and management will be vital, particularly with respect to land use and development planning at a basin or watershed scale (Palmer and others 2008). A shift in the focus of management from 'controlling' to 'learning' through the adoption of a strategic adaptive management approach, is widely acknowledged as critical for gaining adaptive capacity amongst socio-ecological systems (Pahl-Wostl 2007; Kingsford and others 2011).

Capacity for Planned Adaptation

Effective planned adaptation for riparian ecosystems is likely to be favored by several factors other than a relatively high capacity for autonomous ecological adaptation (sensu Füssell 2007). There are strong existing social and political drivers for the protection of riparian ecosystem functions, goods, and services, particularly in relation to water resources, but also for recreational, cultural, aesthetic, and other information functions (Table 1). Conflicts around such issues, exacerbated by high levels of exposure and sensitivity of riparian ecosystems to climate change, have created an imperative for action (Palmer and others 2007, 2009). The risks associated with climate change present an opportunity to manage such conflicts using approaches that might not have been socially or politically acceptable in the past (for example, retreat approaches, flexible water markets, or retrofitting of engineering structures; Pittock and Hartmann 2011; Perry and others 2012). Increasing recognition of the importance of riparian ecosystem functions, goods, and services under a changing climate promotes an awareness of the benefits of prioritizing riparian zones as foci for adaptation in landscapes (for example, Palmer and others 2009; Seavy and others 2009; Davies 2010).

The means for planning, implementing, and maintaining managed adaptation strategies for the protection, restoration, and enhancement of riparian ecosystem components, processes, and functions are relatively well established due to the concentration of human activities in riparian areas and their dependence on riparian ecosystem goods and services. The presence of water resources infrastructure can provide an opportunity to conduct ecological triage with respect to the allocation of scarce flows during prolonged droughts. Riparian ecosystems are a major focus for conservation and restoration throughout the world (Bernhardt and others 2005; Brooks and Lake 2007) and many institutions and social networks are explicitly concerned with riparian management issues. The challenge of climate change adaptation is for these existing arrangements to become more integrative, responsive, and flexible and so avoid path-dependency and perverse outcomes (Pittock 2009).

Many options for planned adaptation of and for riparian ecosystems can be considered no-regret or low-regret options, most with benefits across multiple sectors and scales (Füssell 2007; Hallegatte 2009). Excluding cattle from riparian zones has direct and indirect benefits for biodiversity and can have an important influence on riparian ecosystem functions such as the efficiency with which nitrogen is diverted from upper soil layers into the atmosphere rather than the stream (Walker and others 2002). Restoration of riparian ecosystems can be more cost effective than reducing nutrient pollution for suppressing river phytoplankton blooms (Hutchins and others 2010).

Guiding Principles for Planned Adaptation of Riparian Ecosystems to Climate Change

There is no 'one size fits all' prescription for planned adaptation of riparian ecosystems and the choice of effective adaptation strategies will depend on many climatic, biophysical, cultural, socio-economic, historic, and political factors (Füssell 2007). Adaptation actions are undertaken by many actors, across diverse sectors and at several scales, with a broad spectrum of objectives and targets. Adaptation actions are rarely conducted in isolation and comprise part of a broader strategy involving hard and soft measures. Given the significance of riparian ecosystem functions, goods and services and their relationship to environmental connectivity and heterogeneity, some guiding principles for adaptation decision making emerge that are likely to improve cost-effectiveness and minimize maladaptation risks (sensu Füssell 2007; Hallegatte 2009).

1. Adaptation planning should consider all riparian ecosystem functions, goods and services and involve all stakeholders, not just direct consumers or managers of water (for example, Gleick 2003).
2. The overall goal of planned adaptation of riparian ecosystems should be to build adaptive capacity and to facilitate integrated autonomous adaptation of natural and human systems so as to reduce the risk of failure and perverse effects (for example, Hulme 2005). Specific riparian ecosystem components and processes with high and multifaceted values that are identified as being particularly vulnerable to climate change may require the application of more immediate, interventional strategies (for example, species translocations).
3. Adaptation planning must be underpinned by effective systems for gathering and interpreting information to inform vulnerability and risk assessments to prioritize how, where and when to act (for example, triggers for ratcheting up levels of intervention; Palmer and others 2009).
4. Although many adaptation actions are conducted at small scales, effective adaptation planning for riparian ecosystems needs to be conducted in a landscape context, with consideration of catchment processes, and prioritization for restoration given to the most vulnerable riparian areas and those that promote connectivity (for example, Palmer and others 2007, 2009; Davies 2010).
5. Adaptation planning should prioritize 'no- or low-regret' measures with clear and multiple benefits even in the absence of further climate change, particularly those that enhance connectivity and maintain heterogeneity of riparian ecosystems (for example, management of existing stressors, restoration and retro-fitting of engineered structures).
6. Reversible measures (that is, actions that are easy to stop, remove or retrofit) should be given

priority and irreversible actions, or those likely to create path-dependency, avoided or treated with caution. Allowing development in riparian zones is likely to be difficult to retreat from in the future, socio-economically and politically, even if certain thresholds are reached, and may encourage an expectation of ever more extreme hard-engineering measures.

7. Construction and management of hard-adaptation actions should be planned in the context of large, overly pessimistic security margins with periodic reviews (for example, through relicensing) and short-time horizons where possible (Hallegatte 2009).
8. Soft measures, especially education and communication, should be incorporated into planned adaptation strategies because successful complex adaptive systems are characterized by distributed control and self-organization (for example, Gleick 2003; Pahl-Wostl 2007).

CONCLUSION

High levels of exposure and sensitivity to direct and indirect effects of climate change suggest that, in the absence of adaptation, riparian ecosystems may be very susceptible to climate change impacts. Despite substantial regional variation in climate change and its effects on riparian ecosystems, it is likely that in most cases these impacts will alter overall ecosystem functions and compromise the supply of goods and services used by humans. The increasing importance of riparian ecosystem functions and growing demand for these goods and services due to climate change provide significant socio-economic and political impetus for human adaptation of and for riparian ecosystems. Considerable means and opportunities for effective human adaptation actions exist because of the concentration of human activities and institutions in and around riparian zones. Given the high potential for autonomous adaptation of riparian biota, riparian ecosystems, as integrated socio-ecological systems, should therefore have a relatively high overall adaptive capacity. Arguably, the greatest threat to riparian ecosystems in the 21st century, and the main component of their vulnerability to climate change, is the implementation of irreversible approaches to adaptation that favor a limited range of ecosystem components and processes and have a high potential for perverse outcomes. Climate change presents a crisis from which arises an opportunity to correct situations in which such imbalances in riparian management have occurred in the past.

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