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

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

Adaptation?

Running head: Riparian ecosystems in the 21st Century

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LC: conceived study, performed research, contributed new models, wrote paper

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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, restoration 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.

1 **Keywords:** adaptive capacity; ecosystem services; environmental management; floodplains;

2 human adaptation; vulnerability; water resources

3

1 **Introduction**

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

12 Riparian ecosystems, defined here in their broadest sense as those occurring in semi-
13 terrestrial areas adjacent to water bodies and influenced by freshwaters (Naiman and others
14 2005), have been identified as being particularly susceptible to climate change impacts, at
15 least partially because they are among the world's most transformed and degraded
16 ecosystems (Tockner and Stanford 2002; Rood and others 2008; Perry and others 2012).
17 However, some authors suggest that riparian ecosystems may be relatively resistant to
18 climate change because they have evolved under conditions of high environmental variability
19 and hydrologic extremes (Seavy and others 2009; Catford and others 2012). Either way, there
20 is growing recognition that successful adaptation to climate change of much aquatic and
21 terrestrial biodiversity, as well as human enterprise, may depend on riparian ecosystem
22 functions and their capacity to adapt, or be adapted, to changing conditions (Palmer and
23 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 CO₂ 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 sub-tropical 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). 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 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

1 temperatures. In Australia's Murray-Darling Basin, for example, recent reductions in annual
2 inflows of approximately 15% can be attributed solely to a 1°C rise in temperature (Cai and
3 Cowan 2008). Groundwater hydrology, significant for many riparian ecosystems, is also
4 highly sensitive to changes in precipitation, temperature and evapotranspiration. Potential
5 climate change effects include changes in recharge, discharge and flow direction, the overall
6 impacts of which are anticipated to be detrimental in the majority of cases (Dragoni and
7 Sukhiga 2008).

8 The sensitivity of runoff, stream flow and flood discharges to altered rainfall differs
9 considerably among regions in relation to CO₂ concentrations and temperature, depending on
10 emission scenarios (Goudie 2006; Moradkhani and others 2010). Effects are typically
11 greatest in drier catchments, with declines in annual river runoff of up to 40-70% likely in
12 arid and semi-arid catchments in response to a 1-2°C increase in mean annual temperature
13 and 10% decrease in precipitation (Shiklomanov 1999; Goudie 2006; Jones and others 2006).
14 In and downstream of alpine areas, the sensitivity of riparian hydrologic regimes to climate
15 change is exacerbated by current and projected declines in snow depth and season duration,
16 which commonly lead to reduced spring peak flows and higher winter flows (Lapp and others
17 2005; Goudie 2006; Rood and others 2008). Such effects demonstrate the sensitivity of flow
18 seasonality, as well as volume, to climate change. Indeed, in some regions, shifts in the
19 timing of flow peaks are predicted even where overall hydrograph shapes are insensitive to
20 projected climate changes (for example, Scibek and others 2007).

21 Fluvial and upland geomorphic processes are also major determinants of physical and
22 biogeochemical patterns and processes in riparian ecosystems (Gregory and others 1991) and
23 are similarly sensitive to projected changes in climate stimuli. In particular, changes in
24 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 CO₂ 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; 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). 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 CO₂ 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

1 changes in climatic stimuli. Pathways for autonomous adaptation (that is, ‘adaptation that
2 does not constitute a conscious response to climatic stimuli’; IPCC 2007b) of individual
3 organisms or species include acclimation, morphological or physiological plasticity,
4 behavioral change, genetic adaptation and migration, the outcome of which may be range
5 contraction, expansion or movement (Steffen and others 2009). Shifts in interspecific
6 dependencies (for example, changes in mutualisms) or the composition of assemblages (for
7 example, more salt-tolerant or fire-retardant species) may be regarded as adaptive if resulting
8 novel ecosystems have greater resistance to climate changes or an improved capacity to
9 recover from disturbances associated with climate change (for example, more intense fires;
10 Catford and others 2012).

11 Unlike exposure and sensitivity, adaptive capacity is negatively correlated with vulnerability
12 (Figure 1). In general, a system’s capacity to cope with existing climate variability can be
13 interpreted as an indication of its ability to adapt to climate change in the future (Füssel and
14 Klein 2006). Natural riparian ecosystems may have relatively high adaptive capacity overall
15 because they have evolved under, and are structured by, relatively great environmental
16 variability, much of which is associated with variation in climatic stimuli. Riparian plants, for
17 instance, exhibit a wide array of traits that enable their persistence under variable fluvial
18 disturbance regimes (Dwire and Kauffman 2003). Such adaptations are potential mechanisms
19 for acclimation to increased frequency and severity of extreme events in riparian ecosystems
20 due to climate change, including fires. Additionally, many aquatic and semi-aquatic riparian
21 plants have morphological and physiological plasticity (for example, heterophylly or the
22 ability to elongate roots or shoots) that enable them to respond to water-level fluctuations
23 (Cronk and Fennessy 2001; Horton and Clark 2001). Many riparian biota may also have
24 relatively high adaptive capacity because of their high levels mobility. Diaspores of riparian

1 plants, for example, often have traits that facilitate their dispersal by several vectors including
2 wind, water and animals (Nilsson and others 1991). High levels of connectivity within and
3 between riparian ecosystems provide pathways for the movement of propagules and
4 individuals as climatic conditions shift within catchments (for example, from lower to upper
5 reaches with rising temperatures) or, where dispersal is facilitated by wind or water birds,
6 between regions (Raulings and others 2011). The characteristic heterogeneity of many
7 riparian ecosystems (for example, Stromberg and others 2007) also increases the probability
8 that dispersing organisms will find appropriate habitats for recolonization. Furthermore,
9 riparian biotic assemblages are typically dynamic, demonstrating considerable capacity to
10 shift in composition and structure in response to fluvial disturbances (for example, Junk and
11 others 1989; Capon 2003). Autonomous transitions to more fire-retardant or salt-tolerant
12 vegetation are therefore possible in riparian areas where climate change effects include
13 greater fire frequency or elevated salinity (Nielsen and Brock 2009).

14 A critical influence on the adaptive capacity of natural ecosystems with respect to climate
15 change is exposure and sensitivity to non-climatic threats because the effects of these may
16 limit the scope of adaptations to climate change that organisms or ecosystems might
17 otherwise be able to express. Riparian ecosystems often are sites of intensive human activity
18 and have been much transformed and degraded (Tockner and Stanford 2002). Thus, the
19 capacity of riparian ecosystems to adapt autonomously to climate change is much constrained
20 (Palmer and others 2008). Altered hydrologic regimes, fragmentation and encroachment onto
21 riparian lands by agriculture and human settlements all reduce connectivity and heterogeneity
22 of riparian ecosystems and are likely to aggravate the exposure and sensitivity of their
23 ecosystem components and processes to climate change (Palmer and others 2008). The time
24 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 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

1 corridors for movement to many terrestrial and aquatic organisms (Mac Nally and others
2 2000; Fleishman and others 2003). Riparian ecosystems also influence habitats of adjacent
3 and downstream aquatic ecosystems by regulating light, water temperature and material
4 inputs (for example, sediments, litter, wood; Bunn and others 1999). In addition, many
5 production functions (that is, provision of resources) and information functions (that is,
6 provision of information to humans for spiritual enrichment, mental development and leisure)
7 that are exploited and valued by humans are provided by riparian ecosystems (de Groot and
8 others 2002; Table 1).

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

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

16 Climate-change-induced changes in fluvial and other disturbance regimes (for example, fire,
17 tropical cyclones, and so) also have the potential to alter the physical, chemical and
18 biological heterogeneity of riparian ecosystems. Under a drying climate, and especially where
19 drought becomes more prevalent, examples from other aquatic ecosystems suggest that
20 homogenization is a probable outcome (Lake and others 2010). Diminishment of channels
21 and a proclivity for simple, single-channel stream morphology are likely to result from
22 reductions in flow (Ashmore and Church 2001). If the variability of flooding regimes
23 decreases (for example, where overall flood frequency is reduced and flow regimes become
24 dominated by frequent, large and intense events), the characteristic patchiness of many

1 riparian ecosystem components, such as soil, nutrients, litter and vegetation, may also decline
2 because heterogeneity amongst these components tends to be driven primarily by variable
3 patterns of flooding and drying (Stromberg and others 2007). Conversely, increases in the
4 temporal variability of precipitation and runoff anticipated in higher latitudes and some
5 tropical regions, may lead to greater disturbance-driven heterogeneity in some riparian
6 ecosystem components and processes. Such an outcome may have significant implications
7 for biota dependent on relatively predictable hydrologic events (for example, Junk and others
8 1989).

9 Effects of climate change on the provision of goods and services by riparian ecosystems are
10 likely to result from changes to the ecosystem components, processes and functions with
11 which they are associated, and complex feedback loops among these (Table 1). Although the
12 direction and magnitude of these effects will vary spatially, depending on exposure to climate
13 change and the sensitivity of local riparian ecosystem components and processes, negative
14 effects on the supply of ecosystem goods and services associated with freshwater systems
15 are widely anticipated in the absence of adaptation (for example, Gleick 2003; Bates and
16 others 2008; Dragoni and Sukhiga 2008; Palmer and others 2008; Vörösmarty and others
17 2010). In regions where declines in precipitation and runoff are projected, there are clear
18 risks to the capacity of riparian ecosystems to supply the many important ecosystem goods
19 and services that are shaped by hydrologic connectivity (Table 1). In regions where increased
20 precipitation and runoff are projected, such riparian ecosystem goods and services also face
21 risks due to increased variability in precipitation and runoff and shifts in the seasonal timing
22 of flows (Bates and others 2008).

23 Changes to the role and significance of riparian ecosystem functions, as well as human
24 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 2010) 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 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 2010). 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 interventionist 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,

1 spontaneous adaptation triggered by ecological, market or welfare changes and not
2 constituting a conscious response to climatic stimuli; IPCC 2001). Education and
3 communication strategies to engender public and political support for adaptation are central
4 to these approaches (for example, Steffen and others 2009). With respect to riparian
5 ecosystems, promoting an increased awareness of the significance of the ecosystem
6 functions, goods and services they provide is fundamental (Table 2).

7 To survive, prosper and remain sustainable under a changing climate, individual land-holders
8 that are dependent on riparian ecosystem goods and services (for example, graziers, farmers
9 and fishers) need to adapt to changes in riparian ecosystems. Several factors can influence the
10 extent to which such adaptation occurs including a range of motivating factors and barriers to
11 adaptation (Campbell and Stafford-Smith 2000; Ford and others 2006; Leonard and Pelling
12 2010). Social networks play an important role in motivating individuals to participate in
13 adaptation processes (Marshall and others 2007; Guerrero and others 2010). Individual
14 adaptive capacity is significantly correlated with the extent to which landholders are both
15 formally and informally networked (Marshall and others 2007, 2010). Farmers, fishers or
16 graziers that are well connected to formal sources of information (for example, extension
17 officers, industry representatives, researchers or other government officials) are more likely
18 to have the capacity to adapt. Networks engender interest in adapting and provide
19 opportunities to develop more positive perceptions of risks associated with adaptation and the
20 necessary skills to change and emotional support to undertake change.

21 From an institutional perspective, changes to property rights regimes are likely to be
22 particularly important for riparian ecosystems, both for minimizing existing stressors and for
23 building ecosystem resilience. Water licenses, land zoning and tenure for conservation are
24 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

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

- 11 1. Adaptation planning should consider all riparian ecosystem functions, goods and
12 services and involve all stakeholders, not just direct consumers or managers of water
13 (for example, Gleick 2003).
- 14 2. The overall goal of planned adaptation of riparian ecosystems should be to build
15 adaptive capacity and to facilitate integrated autonomous adaptation of natural and
16 human systems so as to reduce the risk of failure and perverse effects (for example,
17 Hulme 2005). Specific riparian ecosystem components and processes with high and
18 multi-faceted values that are identified as being particularly vulnerable to climate
19 change may require the application of more immediate, interventional strategies (for
20 example, species translocations).
- 21 3. Adaptation planning must be underpinned by effective systems for gathering and
22 interpreting information to inform vulnerability and risk assessments to prioritize

1 how, where and when to act (for example, triggers for ratcheting up levels of
2 intervention; Palmer and others 2009).

3 4. Although many adaptation actions are conducted at small scales, effective adaptation
4 planning for riparian ecosystems needs to be conducted in a landscape context, with
5 consideration of catchment processes, and prioritization for restoration given to the
6 most vulnerable riparian areas and those that promote connectivity (for example,
7 Palmer and others 2007, 2009; Davies 2010).

8 5. Adaptation planning should prioritize ‘no- or low-regret’ measures with clear and
9 multiple benefits even in the absence of further climate change, particularly those that
10 enhance connectivity and maintain heterogeneity of riparian ecosystems (for example,
11 management of existing stressors, restoration and retro-fitting of engineered
12 structures).

13 6. Reversible measures (that is, actions that are easy to stop, remove or retrofit) should
14 be given priority and irreversible actions, or those likely to create path-dependency,
15 avoided or treated with caution. Allowing development in riparian zones is likely to
16 be difficult to retreat from in the future, socio-economically and politically, even if
17 certain thresholds are reached, and may encourage an expectation of ever more
18 extreme hard-engineering measures.

19 7. Construction and management of hard-adaptation actions should be planned in the
20 context of large, overly pessimistic security margins with periodic reviews (for
21 example, through relicensing) and short-time horizons where possible (Hallegatte
22 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.

References

- 1 Arnell, NW. 1999. The effect of climate change on hydrological regimes in Europe: a
2 continental prospective. *Global Environmental Change* 9: 5-23.
- 3 Ashmore P, Church M. 2001. The impact of climate change on rivers and river processes in
4 Canada. *Geological Survey of Canada Bulletin* 555.
- 5 Ballinger A, Lake PS. 2006. Energy and nutrient fluxes from rivers and streams into
6 terrestrial food webs. *Marine and Freshwater Research* 57: 15-28.
- 7 Barnett JA, O'Neill S. 2010. Maladaptation. *Global Environmental Change* 20: 211-213.
- 8 Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (Eds). 2008. *Climate Change and Water*.
9 Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat,
10 Geneva, 210pp.
- 11 Bernhardt ES, Palmer MA, Allan JD, Alexander G, Barnas K, Brooks S, Carr J, Clayton S,
12 Dahm C, Follstad-Shah J, Galat D, Gloss S, Goodwin P, Hart D, Hassett B, Jenkinson R,
13 Katz S, Kondolf GM, Lake PS, Lave R, Meyer JL, O'Donnell TK, Pagano L, Powell B,
14 Sudduth E. 2005. Synthesizing U.S. river restoration efforts. *Science* 308: 636-37.
- 15 Brooks SS, Lake PS. 2007. River restoration in Victoria, Australia: change is in the wind, and
16 none too soon. *Restoration Ecology* 15: 584-591.
- 17 Brosofske KD, Chen J, Naiman RJ, Franklin JF. 1997. Harvesting effects on microclimatic
18 gradients from small streams to uplands in western Washington. *Ecological Applications* 7:
19 118-1200.
- 20 Bunn SE, Davies PM, Mosisch T D. 1999. Ecosystem measures of river health and their
21 response to riparian and catchment degradation. *Freshwater Biology* 41: 333-345.

- 1 Cai W, Cowan T. 2008. Evidence of impacts from rising temperature on inflows to the
2 Murray-Darling Basin. *Geophysical Research Letters* 35: L07701.
- 3 Campbell BD, Stafford-Smith DM. 2000. A synthesis of recent global change research on
4 pasture and rangeland production: reduced uncertainties and their management implications.
5 *Agriculture, Ecosystems and Environment* 82: 39-55.
- 6 Capon SJ. 2003. Plant community responses to wetting and drying in a large arid floodplain.
7 *River Research and Applications* 19: 509-20.
- 8 Catford JA, Naiman RJ, Chambers LE, Roberts J, Douglas M, Davies P. 2012. Predicting
9 novel riparian ecosystems in a changing climate. *Ecosystems*. DOI 10.1007/s10021-012-
10 9566-7.
- 11 Chambers LE, Hughes L, Weston MA. 2005. Climate change and its impact on Australia's
12 avifauna. *Emu* 105: 1-20.
- 13 Chang SW, Clement TP, Simpson MJ, Lee K. 2011. Does sea-level rise have an impact on
14 saltwater intrusion? *Advances in Water Resources* 34: 1283-1291.
- 15 Clarke AR, Mac Nally R, Bond N, Lake PS. 2008. Macroinvertebrate diversity in headwater
16 streams: a review. *Freshwater Biology* 53: 1707-1721.
- 17 Cronk JK, Fennessy MS. 2001. - *Wetland plants: biology and ecology*. CRC Press, Lewis
18 Publisher, Boca Raton, 462pp.
- 19 Danehy RJ, Kirpes BJ. 2000. Relative humidity gradients across riparian areas in eastern
20 Oregon and Washington forests. *Northwest Science* 74: 223-223.

- 1 Davies PM. 2010. Climate change implications for river restoration in global biodiversity
2 hotspots. *Restoration Ecology* 18: 261-268.
- 3 de Groot RS, Wilson MA, Boumans, RMJ. 2002. A typology for the classification,
4 description and valuation of ecosystem functions, goods and services. *Ecological Economics*
5 41: 393-408.
- 6 Dragoni W, Sukhiga BS. 2008. Climate change and groundwater: a short review. *Geological*
7 *Society, London, Special Publications* 288: 1-12.
- 8 Dwire KA, Kauffman JB. 2003. Fire and riparian ecosystems in landscapes of the western
9 USA. *Forest Ecology and Management* 178: 61-74.
- 10 Favis-Mortlock DR, Guerra AJT. 1999. The implications of general circulation model
11 estimates of rainfall for future erosion: a case study from Brazil. *Catena* 37: 329-354.
- 12 Fleishman E, McDonal N, Mac Nally R, Murphy DD, Walters J, Floyd T. 2003. Effects of
13 floristics, physiognomy, and non-native vegetation on riparian bird communities in a Mojave
14 Desert watershed. *Journal of Animal Ecology* 72: 484-490.
- 15 Ford JD, Smit B, Wandel J. 2006. Vulnerability to climate change in the Arctic: a case study
16 from Arctic Bay, Canada. *Global Environmental Change* 16: 145-160.
- 17 Freeman C, Lock MA, Reynolds B. 1993. Climatic change and the release of immobilized
18 nutrients from Welsh riparian wetland soils. *Ecological Engineering* 2: 367-373.
- 19 Fuller RA, McDonald-Madden E, Wilson KA, Carwardine J, Grantham HS, Watson JEM,
20 Klein CJ, Green DC and Possingham HP. 2010. Replacing underperforming protected areas
21 achieves better conservation outcomes. *Nature* 466: 365-367.

- 1 Füssell H, Klein RJT. 2006. Climate change vulnerability assessments: an evolution of
2 conceptual thinking. *Climatic Change* 75: 301-329.
- 3 Füssell H. 2007. Adaptation planning for climate change: concepts, assessment, approaches,
4 and key lessons. *Sustainability Science* 2: 265-275.
- 5 Gleick PH. 2003. Global freshwater resources: soft-path solutions for the 21st Century.
6 *Science* 302: 1524-1528.
- 7 Goudie AS. 2006. Global warming and fluvial geomorphology. *Geomorphology* 79: 384-394.
- 8 Grady KC, Ferrier SM, Kolb TE, Hart SC, Allan GJ, Whitham TG. 2011. Genetic variation
9 in productivity of foundation riparian species at the edge of their distribution: implications
10 for restoration and assisted migration in a warming world. *Global Change Biology* 17: 3724-
11 2725.
- 12 Gregory SV, Swanson W, McKee WA, Cummins KW. 1991. An ecosystem perspective of
13 riparian zones. *BioScience* 41: 540-551.
- 14 Guerrero AM, Knight AT, Grantham HS, Cowling RM, Wilson KA. 2010. Predicting
15 willingness-to-sell and its utility for assessing conservation opportunity for expanding
16 protected area networks. *Conservation Letters* 3: 332-339.
- 17 Hallegatte S. 2009. Strategies to adapt to an uncertain climate change. *Global Environmental*
18 *Change* 19: 240-247.
- 19 Hansen LJ, Hoffman JR. 2011. *Climate Savvy: Adapting Conservation and Resource*
20 *Management to a Changing World*. Island Press, Washington.

- 1 Helfield JM, Naiman RJ. 2001. Effects of salmon-derived nitrogen on riparian forest growth
2 and implications for stream productivity. *Ecology* 82: 2403–2409.
- 3 Horton JL, Clark JL. 2001. Water table decline alters growth and survival of *Salix gooddingii*
4 and *Tamarix chinensis* seedlings. *Forest Ecology and Management* 140: 239–247.
- 5 Hughes FMR, Adams WM, Stroh PA. 2012. When is open-endedness desirable in restoration
6 projects? *Restoration Ecology* 20: 291-295.
- 7 Hulme PE. 2005. Adapting to climate change: is there scope for ecological management in
8 the face of a global threat? *Journal of Applied Ecology* 42: 784-794.
- 9 Hupp CR, Osterkamp WR. 1996. Riparian vegetation and fluvial geomorphic processes.
10 *Geomorphology* 14: 277-295.
- 11 Hutchins MG, Johnson AC, Deflandre-Vlandas A, Comber S, Posen P, Boorman D. 2010.
12 Which offers more scope to suppress river phytoplankton blooms: reducing nutrient pollution
13 or riparian shading? *Science of the Total Environment* 408: 5065-5077.
- 14 IPCC. 2001. Third Assessment Report (TAR). Intergovernmental Panel on Climate Change.
- 15 IPCC. 2007a. Climate Change 2007: Synthesis Report. Cambridge University Press,
16 Cambridge, UK and New York, NY, USA.
- 17 IPCC. 2007b. Climate Change 2007: Working Group II: Impacts, Adaptation and
18 Vulnerability. Cambridge University Press, Cambridge, UK and New York, NY, USA.
- 19 Johnson AKL, Ebert SP, Murray AE. 1999. Distribution of coastal freshwater wetlands and
20 riparian forests in the Herbert River catchment and implications for management of

- 1 catchments adjacent to the Great Barrier Reef Marine Park. *Environmental Conservation* 26:
2 229-335.
- 3 Jones RN, Chiew FHS, Boughton WC, Zhang L. 2006. Estimating the sensitivity of mean
4 annual runoff to climate change using selected hydrological models. *Advances in Water*
5 *Resources* 29: 1419-1429.
- 6 Junk WJ, Bayley PB, Sparks RE. 1989. The Flood Pulse Concept in river-floodplain systems.
7 *Canadian Special Publication of Fisheries and Aquatic Science* 106: 110–127.
- 8 Kingsford RT, Norman FI. 2002. Australian waterbirds – products of the continent’s ecology.
9 *Emu* 102: 47-69.
- 10 Kingsford R, Biggs H, Pollard S. 2011. Strategic adaptive management in freshwater
11 protected areas and their rivers. *Biological Conservation* 144: 1194-1203.
- 12 Lake PS, Thomson JR, Lada H, Mac Nally R, Reid D, Stanaway J, Taylor AC. 2010.
13 Diversity and distribution of macroinvertebrates in lentic habitats in massively altered
14 landscapes in south-eastern Australia. *Diversity and Distributions* 16: 713-724.
- 15 Lapp S, Byrne J, Townshend I, Kienzle S. 2005. Climate warming impacts on snowpack
16 accumulation in an alpine watershed. *International Journal of Climatology* 25: 521-536.
- 17 Leonard L, Pelling M. 2010. Civil society response to industrial contamination of
18 groundwater in Durban, South Africa. *Environment and Urbanization*. 22: 579-595.
- 19 Mac Nally R, Cunningham SC, Baker PJ, Horner GJ, Thomson JR. 2011. Dynamics of
20 Murray-Darling floodplain forests under multiple stressors: The past, present, and future of
21 an Australian icon. *Water Resources Research* 47: W00G05.

- 1 Mac Nally R, Soderquist TR, Tzaros C. 2000. The conservation value of mesic gullies in dry
2 forest landscapes: avian assemblages in the box-ironbark ecosystem of southern Australia.
3 *Biological Conservation* 93: 293-302.
- 4 Marshall NA. 2010. Understanding social resilience to climate variability in primary
5 enterprises and industries. *Global Environmental Change – Human and Policy Dimensions*
6 20: 36-43.
- 7 Marshall NA, Fenton DM, Marshall PA, Sutton SG. 2007. How resource-dependency can
8 influence social resilience within a primary resource industry. *Rural Sociology* 72: 359-390.
- 9 Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Biodiversity*
10 *Synthesis*. Pp. 1-64, Island Press, Washington DC.
- 11 Moradkhani H, Baird RG, Wherry SA. 2010. Assessment of climate change impact on
12 floodplain and hydrologic ecotones. *Journal of Hydrology* 395: 264-278.
- 13 Najjar RG. 1999. The water balance of the Susquehanna River Basin and its response to
14 climate change. *Journal of Hydrology* 219: 7–19.
- 15 Naiman RJ, Décamps H, McClain ME. 2005. *Riparia: ecology, conservation and*
16 *management of streamside communities*. Academic Press.
- 17 Nanson GC, Tooth S. 1999. Arid-zone rivers as indicators of climate change.
18 *Paleoenvironmental reconstruction in arid lands*. Oxford and IBH, New Delhi and Calcutta:
19 75-216.
- 20 Nearing MA. 2001. Potential changes in rainfall erosivity in the U.S. with climate change
21 during the 21st century. *Journal of Soil and Water Conservation* 56 : 229-232.

- 1 Nearing MA, Pruski FF, O'Neal MR. 2004. Expected climate change impacts on soil erosion
2 rates : A review. *Journal of Soil and Water Conservation* 59: 43-50.
- 3 Nelson DR. 2010. *Adaptation and resilience : responding to a changing climate*. Wiley
4 *Interdisciplinary Reviews: Climate Change* 2(1): 113-120.
- 5 Nielsen DL, Brock MA. 2009. Modified water régime and salinity as a consequence of
6 climate change: prospects for wetlands of Southern Australia. *Climatic Change* 95: 523-533.
- 7 Nilsson C, Jansson R, Kuglerová L, Lind L, Ström L. 2012. Boreal riparian vegetation under
8 climate change. *Ecosystems* DOI: 10/1007/s10021-012-9622-3.
- 9 Nilsson C, Svedmark M. 2002. Basic principles and ecological consequences of changing
10 water regimes : riparian plant communities. *Environmental Management* 30: 468-480.
- 11 Nilsson C, Gardfjell M, Grelsson G. 1991. Importance of hydrochory in structuring plant
12 communities along rivers. *Canadian Journal of Botany* 69: 2631-2633.
- 13 Pahl-Wostl C. 2007. Transitions towards adaptive management of water facing climate and
14 global change. *Water Resources Management* 21: 49-62.
- 15 Palmer MA, Allan JD, Meyer J, Bernhardt ES. 2007. River restoration in the twenty-first
16 century: data and experimentally knowledge to inform future efforts. *Restoration Ecology* 15:
17 472-481.
- 18 Palmer MA, Reidy Liermann CA, Nilsson C, Flörke M, Alcamo J, Lake PS, Bond N. 2008.
19 *Climate change and the world's river basins: anticipating management options*. *Frontiers in*
20 *Ecology and the Environment* 6: 81-89.

- 1 Palmer MA, Lettenmaier DP, Poff NL, Postel SL, Richter B, Warner R. 2009. Climate
2 change and river ecosystems: protection and adaptation options. *Environmental Management*
3 44: 1053-1068.
- 4 Pannell DJ. 2008. Public benefits, private benefits, and policy intervention for land-use
5 change for environmental benefits. *Land Economics* 84: 225-240.
- 6 Perry LG, Andersen DC, Reynolds LV, Mark Nelson S, Shafroth PB. 2012. Vulnerability of
7 riparian ecosystems to elevated CO₂ and climate change in arid and semiarid western North
8 America. *Global Change Biology* 18: 821-842.
- 9 Pittock J, Finlayson CM. 2011. Australia's Murray Darling Basin: freshwater ecosystem
10 conservation options in an era of climate change. *Marine and Freshwater Research* 62, 232–
11 243.
- 12 Pittock J, Finlayson CM, Howitt JA. 2012. Beguiling and risk: “Environmental works and
13 measures” for wetlands conservation under a changing climate. *Hydrobiologia*. DOI
14 10.1007/s10750-012-1292-9.
- 15 Pittock J, Hartmann J. 2011. Taking a second look: climate change, periodic re-licensing and
16 better management of old dams. *Marine and Freshwater Research* 62: 312-320.
- 17 Pittock J, Lankford BA. 2010. Environmental water requirements: Demand management in
18 an era of water scarcity. *Journal of Integrative Environmental Sciences* 7: 75 – 93.
- 19 Pittock J. 2009. Lessons for climate change adaptation from better management of rivers.
20 *Climate and Development* 1: 194-211.

- 1 Poff NL, Zimmerman JKH. 2010. Ecological responses to altered flow regimes: a literature
2 review to inform the science and management of environmental flows. *Freshwater Biology*
3 55: 194-205.
- 4 Power MD, Sun A, Parker M, Ietrich WE, Wootton JT. 1995. Hydraulic food-chain models:
5 an approach to the study of food-web dynamics in large rivers. *BioScience* 45: 159-167.
- 6 Raulings E, Morris K, Thompson R, Mac Nally R. 2011. Do birds of a feather disperse plants
7 together? *Freshwater Biology* 56: 1390-1402.
- 8 Richardson DM, Holmes PM, Esler KJ, Galatowitsch SM, Stromberg JC, Kirkman SP, Pysek
9 P and Hobbs RJ. 2007. Riparian vegetation: degradation, alien plant invasions, and
10 restoration prospects. *Diversity and Distributions* 13: 126-139.
- 11 Rood SB, Pan J, Gill KM, Franks CG, Samuelson GM, Shepherd A. 2008. Declining summer
12 flows of Rocky Mountain rivers: changing seasonal hydrology and probable impacts on
13 floodplain forests. *Journal of Hydrology* 349: 397– 410.
- 14 Sabo JL, Sponseller R, Dixon M, Gade K, Harms T, Heffernan J, Jani A, Katz G, Soykan C,
15 Watts J, Welter J. 2005. Riparian zones increase regional species richness by harboring
16 different, not more species. *Ecology* 86: 56-62.
- 17 Scibek J, Allen DM, Cannon AJ, Whitfield PH. 2007. Ground-water-surface water
18 interaction under scenarios of climate change using a high-resolution transient groundwater
19 model. *Journal of Hydrology* 333: 165-181.
- 20 Seavy, NE, Gardali, T, Golet, GH, Griggs, FT, Howell, CA, Kelsey, R., Small, SL, Viers, JH,
21 Weigana, JF. 2009. Why climate change makes riparian restoration more important than ever:
22 recommendations for practice and research. *Ecological Restoration* 27: 330-338.

- 1 Sgrò CM, Lowe AJ, Hoffmann AA. 2011. Building evolutionary resilience for conserving
2 biodiversity under climate change. *Evolutionary Applications* 4: 326-337.
- 3 Shiklomanov IA. 1999. Climate change, hydrology and water resources: the work of the
4 IPCC, 1988–1994. In: van Dam JC (Ed.), *Impacts of climate change and climate variability*
5 *on hydrological regimes*. Cambridge University Press, Cambridge. Pp. 82-20.
- 6 Stanley E, Doyle MW. 2003. Trading off: the ecological effects of dam removal. *Frontiers in*
7 *Ecology and the Environment* 1: 15-22.
- 8 Steffen W, Burbidge AA, Hughes L, Kitchin R, Lindenmayer D, Musgrave W, Stafford
9 Smith M, Werner PA. 2009. *Australia's Biodiversity and Climate Change*. CSIRO
10 Publishing, Collingwood.
- 11 Stromberg J, Beuchamp VB, Dixon MD, Lite SJ, Paradzick C. 2007. Importance of low-flow
12 and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-
13 western United States. *Freshwater Biology* 52: 651-679.
- 14 Sun G, McNulty SG, Moore J, Bunch C, Ni J. 2002. Potential impacts of climate change on
15 rainfall erosivity and water availability in China in the next 100 years. *International Soil*
16 *Conservation Conference*, Beijing, China, May, 2002.
- 17 Ten Brink P. 2009. *TEEB—the economics of ecosystems and biodiversity for national and*
18 *international policy makers—summary: responding to the value of nature*. Wesseling,
19 Germany: Welzel + Hardt.
- 20 Thomson JR, Bond NR, Cunningham SC, Metzeling L, Reich P, Thompson RM, MacNally
21 R. 2012. The influence of climatic variation and vegetation on stream biota: lessons from the
22 Big Dry in southeastern Australia. *Global Change Biology* 18: 1582-1596.

- 1 Tockner K, Stanford JA. 2002. Riverine flood plains: present state and future trends.
2 Environmental Conservation 29: 308-330.
- 3 Turton S. 2012. Securing landscape resilience to tropical cyclones in Australia's Wet tropics
4 under a changing climate: lessons from cyclones Larry (and Yasi). Geographical Research
5 50: 15-30.
- 6 Vicuna S, Dracup JA. 2007. The evolution of climate change impact studies on hydrology
7 and water resources in California. Climate Change 82: 327-350.
- 8 Visser ME. 2008. Keeping up with a warming world; assessing the rate of adaptation to
9 climate change. Proceedings of the Royal Society B: Biological Sciences 275: 649-659.
- 10 Vörösmarty C.J, McIntyre PB, Gessner MO, Dudgeon D, Prusevich, Green P, Glidden S,
11 Bunn SE, Sullivan CA, Reidy Liermann C, Davies PM. 2010. Global threats to human water
12 security and river biodiversity. Nature 467: 555-561.
- 13 Walker JT, Geron CD, Vose JM, Swank WT. 2002. Nitrogen trace gas emissions from a
14 riparian ecosystem in southern Appalachia. Chemosphere 49: 1389-1398.
- 15 Wilby RL, Orr H, Watts G, Battarbee RW, Berry PM, Chadd R, Dugdale SJ, Dubar MJ,
16 Elliott JA, Extence C, Hannah DM, Holmes N, Johnson AC, Knights B, Milner NJ, Ormerod
17 SJ, Solomon D, Timlett R., Whitehead PJ, Wood PJ. 2010. Evidence needed to manage
18 freshwater ecosystems in a changing climate: Turning adaptation principles into practice.
19 Science of the Total Environment 408: 4150-4164.
- 20 Yang D, Kanae S, Oki T, Koike T, Musiake K. 2003. Global potential soil erosion with
21 reference to land use and climate changes. Hydrological Processes 17: 2913-2928.

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

2

Ecosystem function	Ecosystem processes and components	Ecosystem goods and services (examples)	Potential mechanisms of climate change effects (examples)*	
			Supply-side	Demand-side
<i>Regulation functions</i>				
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
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 xenobiotics 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
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
<i>Habitat functions</i>				
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,	Increasing importance to terrestrial species under warming and drying climates

Nursery function	Provision of habitat for breeding, for example, water birds, fish	Maintenance of terrestrial and aquatic species	biota, food webs and pests 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
<i>Production functions</i>				
Food	Provision of edible resources	Hunting, gathering, small-scale subsistence farming & 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
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
<i>Information functions</i>				
Aesthetic information	Attractive landscape features	Enjoyment of scenery	Scenery will be altered by changes in regulating and habitat functions especially	May increase in significance if surrounding landscape is altered to become less attractive or

			those influencing topography and biota	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

1 * Sources: references in text.

2

3 Potential mechanisms for climate change effects on the supply of ecosystem goods and services and their importance and/or demand are

4 also indicated. N.B. This table is not intended to be exhaustive, nor universally applicable, but rather provide a framework via which

5 susceptibility of key elements of riparian ecosystems to climate change impacts, and their interactions, can be considered in particular

6 regional settings. (Adapted from de Groot and others 2002).

1 Table 2. Key Options for Planned Adaptation for the Maintenance, Restoration and Enhancement of Riparian Ecosystem Components,
2 Processes, Functions, Goods and Services
3

Adaptation option	Target(s)	Adaptation goal			Potential for multiple benefits	Potential for perverse outcomes	Irreversibility	Opportunity costs
		Reduce exposure	Minimize sensitivity	Increase adaptive capacity				
<i>Adaptation of existing management approaches</i>								
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
<i>Hard adaptation approaches</i>								
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
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	Management target(s)	Y	Y	Y	Moderate – High	Low – High	Low	Low

change risk framework								
<i>Retreat</i>								
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
<i>Ecological engineering</i>								
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
<i>Governance</i>								
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

- 1 For each adaptation option, key management targets and adaptation goals with respect to reducing exposure and/or sensitivity to climate
- 2 changes and increasing adaptive capacity are identified. The potential for adaptation options to have effects beyond the intended target(s)

1 is also suggested, both in terms of positive (that is, multiple benefits) and negative consequences (that is, perverse outcomes). The final
2 columns indicate probable levels of irreversibility of adaptation options, referring to the ease of their removal (for example, physically,
3 legally and/or economically) once implemented, and opportunity costs, defined here as the costs associated with the options sacrificed in
4 choosing that particular option (for example, the existing or potential alternative benefits that have been lost by implementing the
5 selected adaptation option).

6

1 FIGURE LEGEND

2

3 Figure 1. Conceptual framework for assessing vulnerability to climate change showing relationships between exposure, sensitivity and

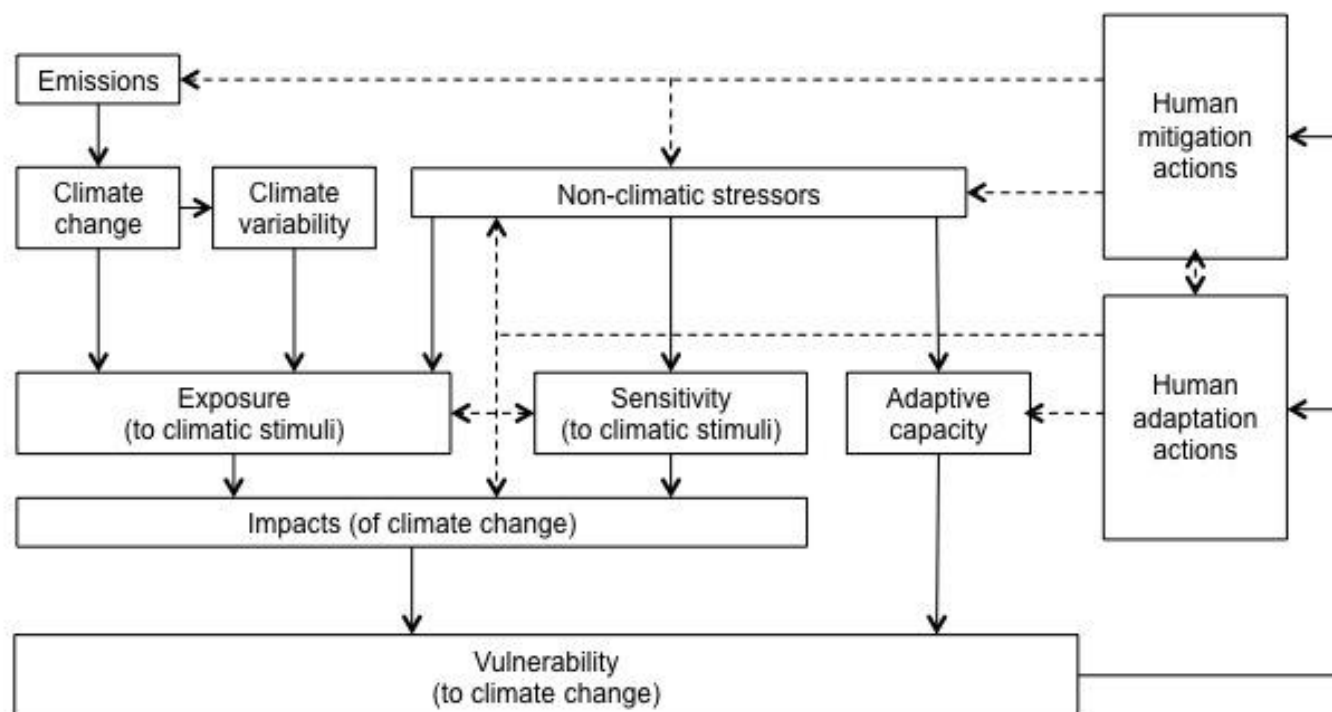
4 adaptive capacity, and climate change impacts and vulnerability. Dashed lines indicate the effects of human actions, including the

5 potential for human climate change adaptation and mitigation actions to influence exposure, sensitivity and adaptive capacity, both

6 directly and indirectly through their influence on emissions and non-climatic stressors (adapted from Füssel and Klein 2005)

7

1 Figure 1.



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