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SPECIAL FEATURE: SUSTAINABILITY ON THE BORDER

Key landscape ecology metrics for assessing climate change adaptation options: rate of change and patchiness of impacts

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Abstract. Under a changing climate, devising strategies to help stakeholders adapt to alterations to ecosystems and their services is of utmost importance. In western North America, diminished snowpack and river flows are causing relatively gradual, homogeneous (system-wide) changes in ecosystems and services. In addition, increased climate variability is also accelerating the incidence of abrupt and patchy disturbances such as fires, floods and droughts. This paper posits that two key variables often considered in landscape ecology—the rate of change and the degree of patchiness of change—can aid in developing climate change adaptation strategies. We use two examples from the "borderland" region of the southwestern United States and northwestern Mexico. In piñon-juniper woodland die-offs that occurred in the southwestern United States during the 2000s, ecosystem services suddenly crashed in some parts of the system while remaining unaffected in other locations. The precise timing and location of die-offs was uncertain. On the other hand, slower, homogeneous change, such as the expected declines in water supply to the Colorado River delta, will likely impact the entire ecosystem, with ecosystem services everywhere in the delta subject to alteration, and all users likely exposed. The rapidity and spatial heterogeneity of faster, patchy climate change exemplified by tree die-off suggests that decision-makers and local stakeholders would be wise to operate under a Rawlsian "veil of ignorance," and implement adaptation strategies that allow ecosystem service users to equitably share the risk of sudden loss of ecosystem services before actual ecosystem changes occur. On the other hand, in the case of slower, homogeneous, system-wide impacts to ecosystem services as exemplified by the Colorado River delta, adaptation strategies can be implemented after the changes begin, but will require a fundamental rethinking of how ecosystems and services are used and valued. In sum, understanding how the rate of change and degree of patchiness of change will constrain adaptive options is a critical consideration in preparing for climate change.

Key words: climate change adaptation; Colorado River delta; ecosystem services; forest die-off; piñon-juniper woodlands.

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Introduction

Anticipating impacts to ecosystems and their services, and devising strategies for adapting to changes in ecosystem services, is one of the foremost challenges of the emerging field of climate change adaptation. To date, most assessments of climate change impacts on biodiversity and ecosystems have focused on homogeneous, gradual ecosystem change (Schroter et al. 2005, Heller and Zavaleta 2009). However, recent research predicts that climate change will also trigger a wide variety of extreme climate events and associated sudden ecosystem disturbances (Stenseth et al. 2002, Breshears et al. 2005, Blacklund et al. 2008) such as extensive wildfires (Bowman et al. 2009), large floods (Milly et al. 2002), and severe forest die-offs (Allen et al. 2010). The impacts of extreme events are likely to be patchy across a landscape (Breshears et al. 2011). Of all the challenges presented by climate change, adapting to sudden, patchy ecosystem crashes may be among the most difficult due to the unpredictability of the timing and location of impacts (Millar et al. 2007).

In this article we use two case studies, which are endpoints on continuous axes of rate of disturbance (from faster to slower) and homogeneity of change (from relatively patchy to relatively homogeneous; Fig. 1). Our first example is the faster, patchy die-off of piñon trees in piñon-juniper woodlands of the Four Corners region (the quadripoint where boundaries of the states of Colorado, New Mexico, Arizona, and Utah meet). The second example is the relatively slower, homogenous impacts of decreasing water flows to Colorado River Delta (Fig. 2). These examples highlight factors likely to constrain the kinds of policy responses available to private and public actors. The purpose of this paper is to assess whether these variables—the rate of change and degree of patchiness/homogeneity of the impacts—should be among the factors considered in a theory of climate change adaptation for large-scale impacts. This perspective draws on key concepts developed from the field of landscape ecology (Turner et al. 1993). Our goal is to help elucidate the factors that are likely to shape and constrain individual and institutional responses to climate change, and that may help researchers across disciplines build and test more robust and functional theories of climate change adaptation.

Our discussion is grounded in our two examples from the "borderlands" region encompassing northwestern Mexico and the southwestern United States. In North America, the US-Mexico borderland region has been called the "front line of on-going climate change" (Harrison 2009). The borderland is experiencing the fastest population growth of both countries, making it critically important to understand climate change impacts and to develop adaptive strategies for increasing societal resilience in the face of climate alterations (Morehouse et al. 2008, Wilder et al. 2010) and impacts on ecosystem services (López-Hoffman et al. 2010).

Terms and Concepts

We evaluate the rapidity of changes relative to the time frame for decision-making, whether by property owners and businesses, or by managers and politicians. As such, we consider *faster* changes to be ecosystem impacts occurring within one to ten years, while *slower* impacts occur over several decades. For the purposes of this general framework, we evaluate the geographic scale and degree of patchiness by the ratio of the scale of disturbance to the scale of the ecosystem; this framework draws on landscape ecology concepts presented by Turner et al. (1993). If disturbed locations cover less area than the total area of the system in question, and the impact affects multiple portions of the total area in a noncontiguous manner, we consider the impact to be *patchy*. Conversely, we consider a situation where the ratio of area of disturbance is equal to, or even greater than, the area of the system in question to be *homogeneous* (Fig. 1). *Adaptation* refers to the ability of individuals, businesses, communities and governments to cope with or adapt to external stresses placed upon livelihoods and well-being (Smit et al. 2000, Adger et al. 2005, Adger 2006). We use *exposure* to describe whether or not an ecosystem service user will experience a change in services. Note, however, that exposure does not necessarily signify *vulnerability*; rather, vulnerability implies potential harm to one's livelihood and/or well-being (Adger 2006). Finally, we consider *resilience* to be the ability of socio-ecological systems to

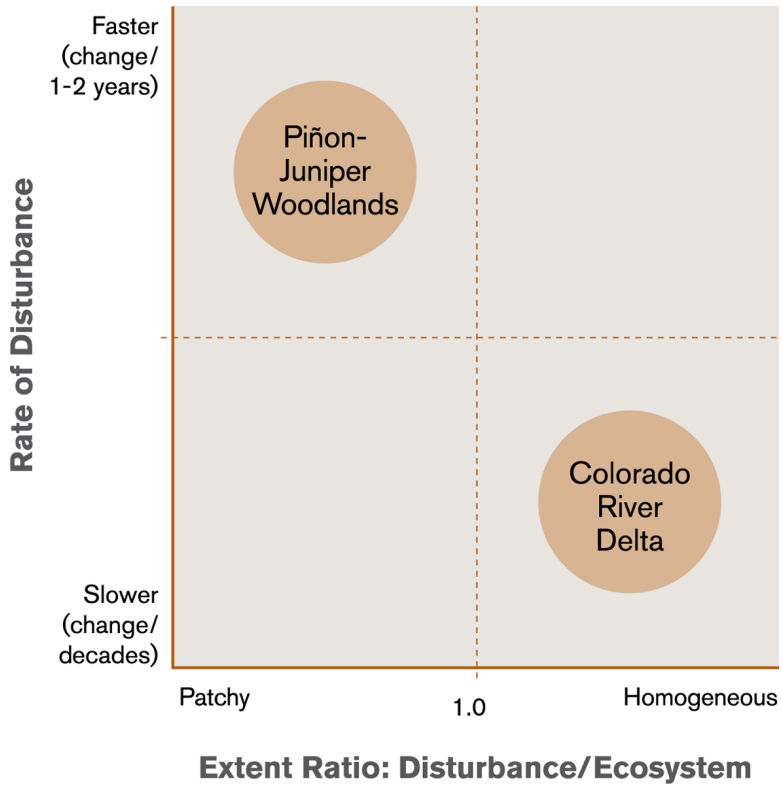

Fig. 1. Framework for evaluating climate change regimes in terms of how quickly or gradually they occur and how spatially homogeneous or patchy they are. Fast changes are ecosystem impacts occurring within one to two years, while slower impacts occur over multiple decades. The degree of patchiness/homogeneity is evaluated by the ratio of the scale of disturbance to the scale of the ecosystem service of interest. If affected (disturbed) locations cover less area than the total area of the system in question, the impact is relatively patchy. When the area of disturbance is greater than the area of the system in question, the impact is homogeneous.

self-organize and to build capacity to learn and adapt, undergoing change while still retaining some—but not necessarily all—of the same ecosystem functions and services (Folke et al. 2005).

We use the term *ecosystem services* to mean all the benefits human society derives from ecosystems (Daily 1997, Millennium Ecosystem Assessment 2003, 2005). In this sense, ecosystem services include goods from altered agricultural landscapes, as well as the benefits from "natural" or semi-natural systems. This approach is critical to evaluating trade-offs between allocating scarce land and water to different kinds of ecosystems and services, such as allocating water to agricultural systems for crop production versus to "natural" and semi-natural systems for recreation, fishing and wildlife habitat. To this end, we use the Millennium Ecosystem Assessment (2003, 2005) categories for four types of ecosystem services: *provisioning services* are material benefits to humans, such as fiber, food, or timber; processes such as pollination, flood, and disease control are *regulating services*; nutrient cycling and soil formation are examples of *supporting services*; and *cultural services* are those aspects of species and ecosystems that provide humans with recreational, spiritual, or religious experiences.

Climate Change in the Southwestern United States and Northwestern Mexico

In the past decade, climate change in the southwestern United States and northwestern Mexico has by several metrics surpassed changes

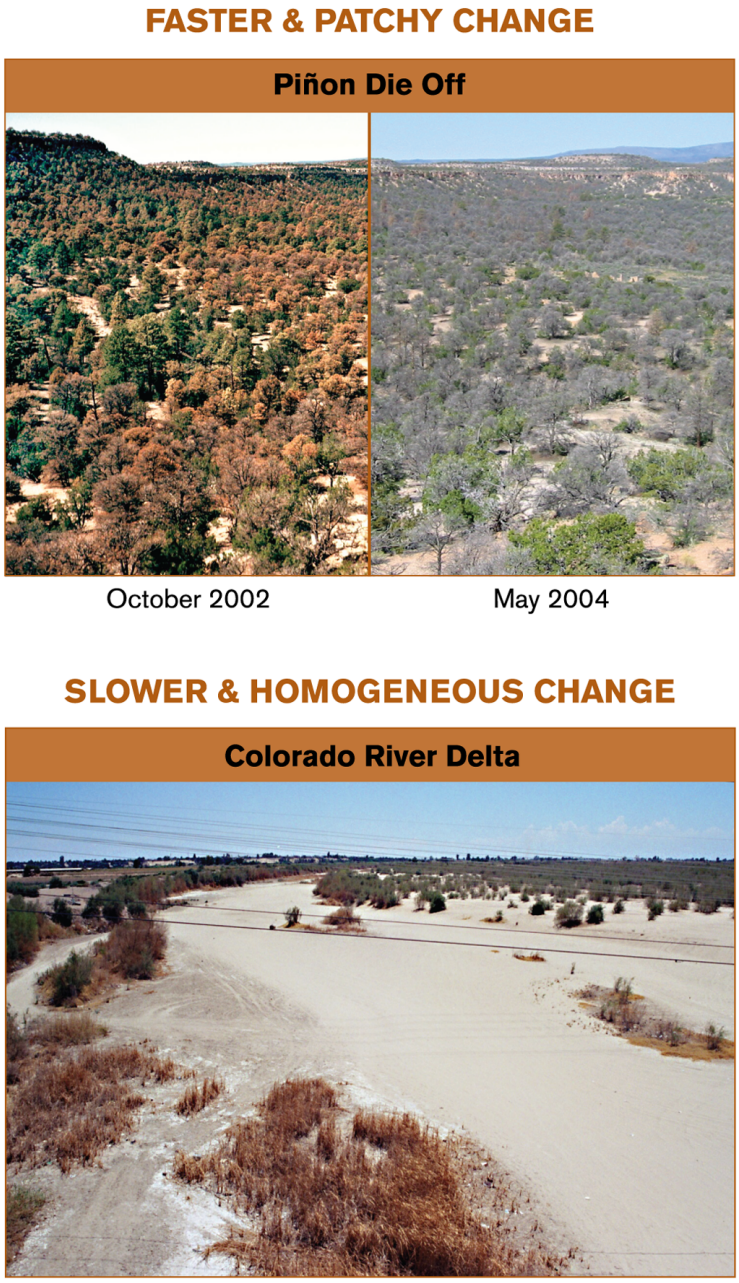

Fig. 2: Top: Landscape transformation associated with a drought-induced die-off of piñon pine, near Los Alamos, NM, USA. Piñon pine trees, evergreen when alive, exhibiting reddish-brown foliage indicating mortality (October 2002); after they have lost their needles, exposed gray trunks of standing dead tree carcasses remain (May 2004; photos by C.D. Allen; from Breshears et al. 2009). Bottom: The Colorado River delta below Morelos Dam (Photo by K. Flessa).

elsewhere in North America, excepting the Arctic (Solomon et al. 2007). Temperatures in the Upper Colorado River Basin were 1°C warmer than the 20th century average, and this warming has diminished late-season snowpack, driving reductions in Colorado River flow (Barnett et al. 2008). The decreased snowpack, coupled with the most severe drought since 1900, have caused the

Colorado's Lake Powell and Lake Mead reservoirs to shrink from nearly full capacity in 1990 to 50% capacity by 2004 (Overpeck and Udall 2010). The Intergovernmental Panel on Climate Change (IPCC) projects that the area extending from the southwestern United States to central and western Mexico is likely to undergo significant precipitation decreases through the remainder of the 21st century (Solomon et al. 2007). By the end of the century, annual precipitation is projected to decrease 5–10%, with the greatest declines occurring during winter months (Christensen et al. 2007, Seager et al. 2007). Regional mean temperatures are projected to increase 3.0–3.5°C by 2099. This increase will not be evenly distributed through the year; rather, summer high temperatures will increase more than summer average temperatures, indicating greater variability in temperature extremes (Christensen et al. 2007, Overpeck and Udall 2010). In addition, potential changes in drought frequency accompanied by warmer temperatures (and associated changes in vapor pressure deficit) can result in what has been coined "global-change-type drought" (Breshears et al. 2005), which may pose substantial physiological challenges for organisms, among other impacts (McDowell et al. 2008).

A report comparing a number of studies that explicitly calculate runoff indicates a multi-study average streamflow decrease in the Colorado basin of between 6–20% by 2050 as compared to 20th century conditions (Ray et al. 2008). Under conditions of decreased streamflow, the reliability of the water supply becomes increasingly dependent on reservoir storage. By 2057, with a 20% reduction of annual Colorado river flow, the annual probability of Colorado River reservoir storage (an amount of water equivalent to a 3–5 year water supply) being depleted would increase tenfold relative to the risk in 2008 (Rajagopalan et al. 2009).

Further, the above scenarios do not take into account the possibility of a "mega-drought." Historical tree-ring records show that climate in western North America is variable (Hughes and Diaz 2008) and that droughts lasting decades repeatedly have gripped the region (Woodhouse et al. 2006, Meko et al. 2007). As western North America currently endures its worst drought since 1900, it is important to realize that even this drought is relatively mild compared to what is possible in the future if a mega-drought and even hotter temperatures coincide.

In addition to climate-change-related alterations in snowpack and river flow, the region, like others globally, has already experienced drought-related forest die-off events that may be being exacerbated by warmer conditions (Allen et al. 2010). Recent piñon pine mortality in the US Four Corners region has been linked to a combination of record warm temperatures and drought (Breshears et al. 2005), which are interrelated with changes in vapor pressure deficit (Weiss et al. 2009, Williams et al. 2013).

Other vegetation die-off events have occurred historically in this semiarid, drought-prone region (see e.g., Allen and Breshears 1998). However, in a regional, multi-species study, the background rate of tree mortality (mortality for reasons other than a die-off event) is documented to have increased—a trend that was attributed to warmer temperatures after ruling out other possibilities (van Mantgem et al. 2009). Further, recent regional-scale forest die-off has been strongly linked to warmer temperatures (Williams et al. 2013), and could portend more large die-off events under warmer temperatures in the future, consistent with recent experimental results (Adams et al. 2009). Due to mounting evidence, recent regional assessments of climate change impacts emphasize how climate change is driving the accelerated rate of drought-induced die-offs (CCSP 2008). In addition to drought, the exceptional warming trends and associated snowpack declines have led to an acceleration of other disturbances in the region, such as increases in the frequency of large wildfires (Westerling et al. 2006, Williams et al. 2013). Collectively, a large proportion of US Southwest woodlands and forests have been impacted by die-off or wildfire in recent decades (Williams et al. 2010).

Contrasting Spatiotemporal Examples of Climate Change-Driven Ecosystem Changes

The two examples from the borderlands, piñon-juniper forests in the Four Corners region of the southwestern United States and the Colorado River delta ecosystem in Mexico, were

chosen for two key reasons. First, these examples are indicative of the kinds of climate change impacts on ecosystems that we should expect in this region in the near future (Overpeck and Udall 2010). In particular, they underscore that in semiarid and arid areas such as the southwestern United States and northwestern Mexico, many climate change impacts on ecosystem services will be mediated by ecohydrological factors such as reduced instream flows and long-term drought (Safriel and Adeel 2005). In the piñon-juniper die-off example, short, severe drought under warmer conditions has created conditions that enable swift ecosystem changes, while in the Colorado River delta example, longer-term drought of variable severity is expected to reduce instream flows over the next several decades. Second, these examples illustrate different end-points along temporal and spatial axes of how climate change will act on ecosystems (Fig. 1). Within one or two years, piñon mortality in the region spanned more than 12,000 km^2, and the change has been "patchy" at the landscape scale, with some areas experiencing a nearly complete loss of piñon trees, while other locations experience only a few tree deaths (Breshears et al. 2005; Fig. 3). Between 1997 and 2008, tree mortality related to drought and associated bark beetles impacted more than 7.5% of Southwest forests and woodlands (Williams et al. 2010). This is a large impact considering the slow growth rates of these trees. The exact locations of areas of high piñon mortality were unpredictable when they occurred, and apparently relate to a combination of climate-driver and water-balance issues (Weiss et al. 2009, Peterman et al. 2013) but remain challenging to predict.

In the Colorado River delta, the rate of ecosystem disturbance—the reduction of water supply to the delta—is expected occur across several decades (Zamora-Arroyo and Flessa 2009), slower than the forest die-off example. Additionally, the ratio of the geographic area of disturbance to the area of the system in question is greater in the Colorado River delta example than in the piñon-juniper example. In the delta example, the area of disturbance—the entire Colorado River basin—is much greater than the area of the delta itself.

For illustrative purposes, we contrast faster, patchy versus slower, homogeneous examples of climate-change-driven ecosystem impacts. In reality, however, these types of impacts are neither mutually exclusive nor fixed. A given area could experience underlying slower, homogeneous changes while at the same time experiencing a faster, patchy change. For example, in 2011, while in the midst of gradually declining water supplies, the Cienega de Santa Clara, a wetland within the delta, experienced a sudden wildfire. Further, there is recent evidence that snowpack levels and river flows in the western United States are declining more rapidly than expected, suggesting the slower changes may not be as gradual as previously expected (Hidalgo et al. 2009). Finally, as the rate of occurrence of faster, patchy climate change regimes accelerates, the impacts could overlap in space and time, to the point that they will no longer be spatially patchy, nor will they be so uncommon and sudden.

Faster, Patchy Ecosystem Change: Drought-Induced Tree Die-off in the Four Corners

The drought-induced die-off of piñon trees in the mixed species piñon-juniper woodlands of the US Four Corners region is perhaps the most extensively documented example of a sudden ecosystem change in response to climate change. Although piñon-juniper woodlands have historically been sensitive to drought (Romme et al. 2009), the response to a recent drought event appears to have been especially pronounced (Breshears et al. 2005).

In the past drought, piñon mortality was most pronounced in the driest areas of the species' distribution (Allen and Breshears 1998). However, the severe drought that began in 2000 was notable because it triggered tree mortality not only at lower elevations that are usually drier and warmer, but also at higher elevations that are usually wetter and cooler (Breshears et al. 2005). During the drought event, piñon mortality was 90% or greater at some upper elevation, cool sites, and quite patchy across the Four Corners (Breshears et al. 2005; Fig. 3). The piñon trees appear in many cases to have ultimately been killed by bark beetles (Shaw et al. 2005), but the underlying driver of mortality was water stress caused by regional-scale drought and exacerbat-

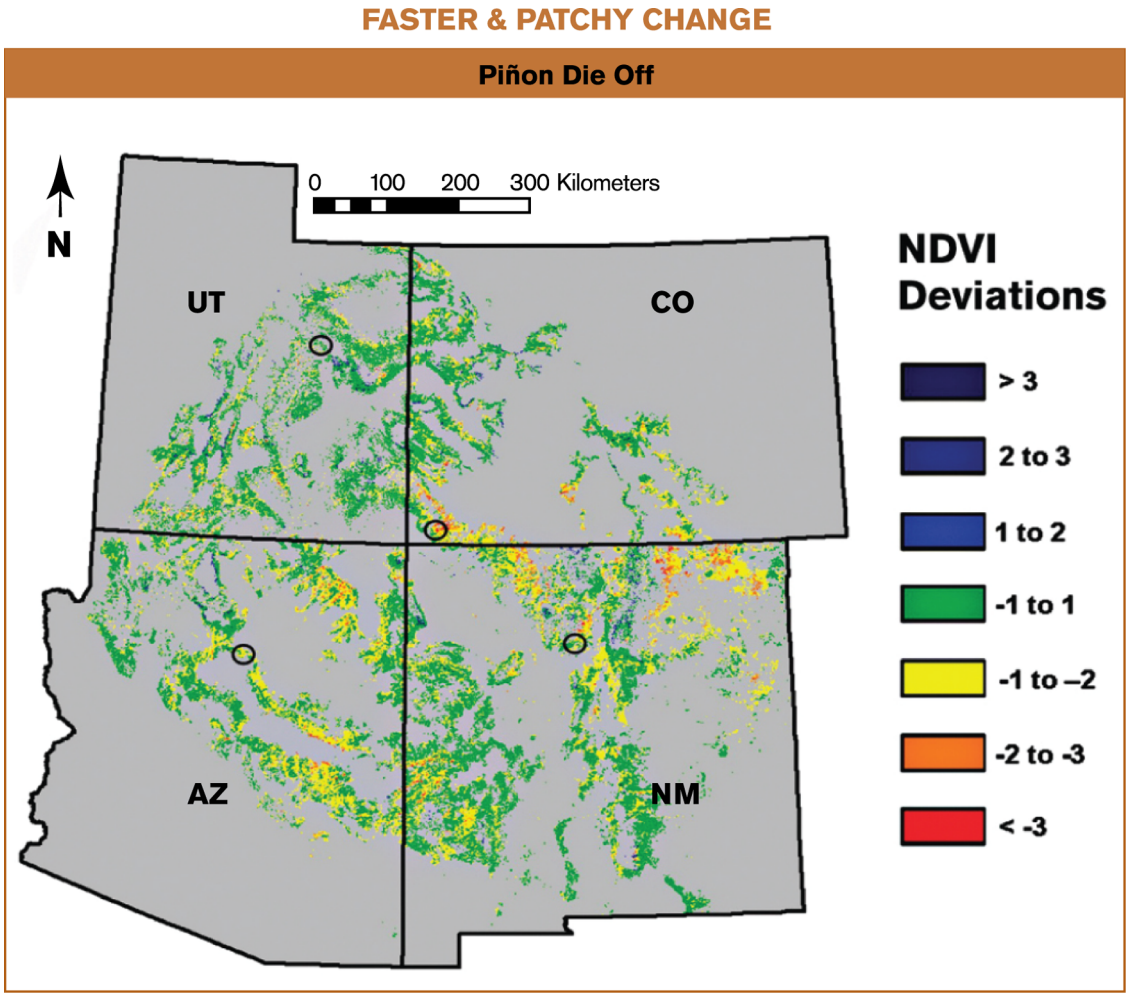

Fig. 3. Regional patchiness in piñon tree die-off across the Four Corners states of Arizona (AZ), New Mexico (NM), Colorado (CO) and Utah (UT) as evident in remotely sensed greenness (Normalized Difference Vegetation Index: NDVI) of piñon-juniper woodlands. On the color scale green and blue denote equal or increased NDVI greenness relative to the pre-drought baseline period of 1989–1999. Yellow, orange and red indicate intensifying reductions in greenness due to significant tree mortality in the drought period 2002–2003 (modified from Breshears et al. 2005, 2011).

ed by warmer temperatures (Breshears et al. 2005, Adams et al. 2009, Williams et al. 2013). The ecosystem changes in piñon-juniper woodlands triggered by drought can be considered an ecosystem "crash" (Breshears et al. 2008) in the sense that the tree die-off has been pervasive across the elevation distribution at a given location and it will take decades at best for a mature canopy overstory to re-develop (Allen and Breshears 1998).

The piñon-juniper die-off following the drought of the 2000s in the Four Corners region serves to illustrate how climate change may have sudden, patchy impacts on supporting, provisioning, regulating and cultural ecosystem services (Fig. 4). This example recaps a previous discussion of forest die-off impacts on ecosystem services (Breshears et al. 2011), expanding the discussion to treat ecosystem services in a broader management context.

Primary productivity, a *supporting service*, was altered following the die-off, as reflected by reduced tree inventories (Shaw et al. 2005) and indices of vegetation greenness such as the

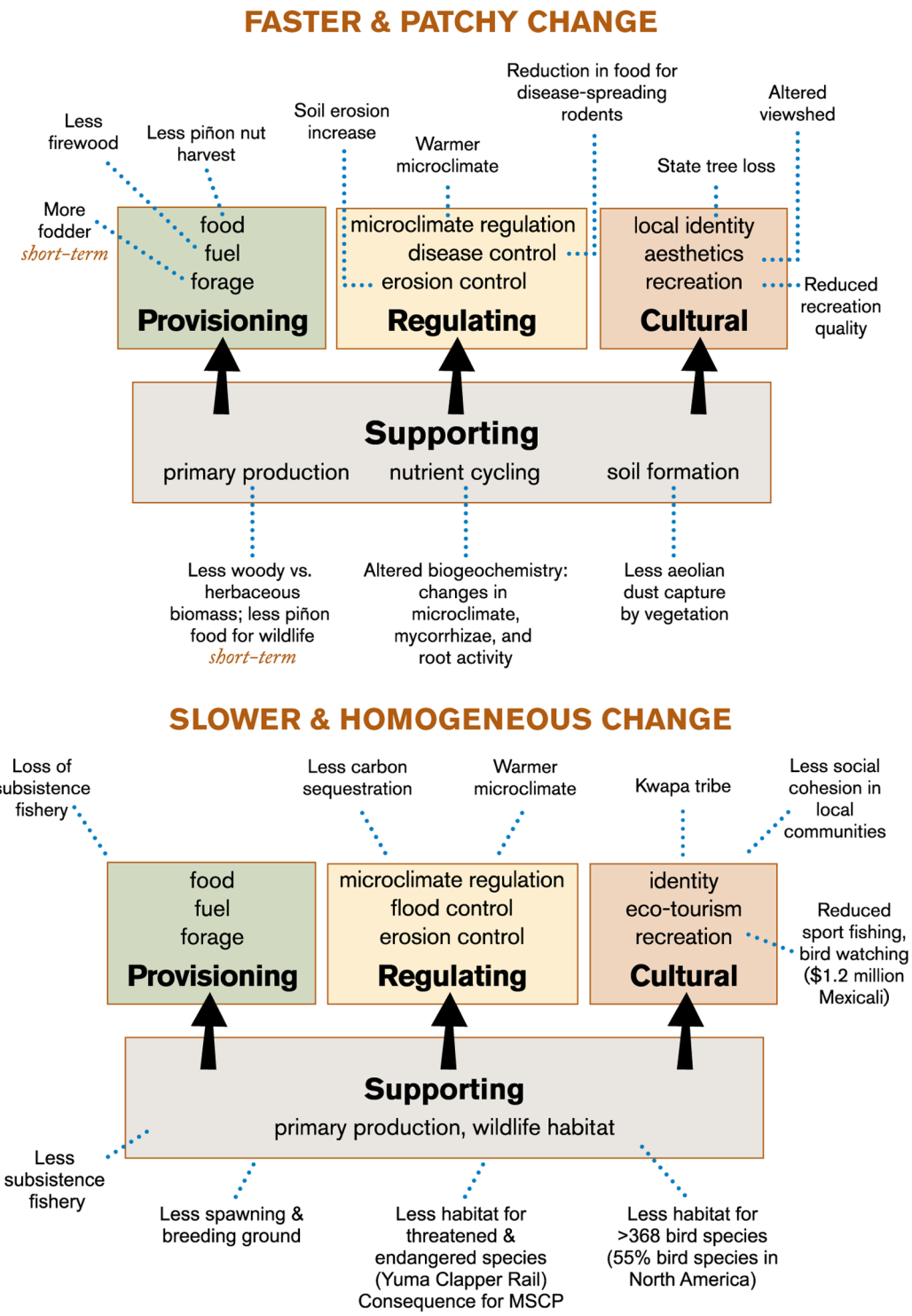

Fig. 4. Top: Changes in ecosystem services in the US Four Corners region following piñon-juniper die-off (modified from Breshears et al. 2011). Bottom: Expected changes in ecosystem services in the Colorado River delta if instream flows are not dedicated to riparian areas. The ecosystem services categories for both panels are based on the Millennium Ecosystem Assessment (2003).

Normalized Difference Vegetation Index (Rich et al. 2008). Although overall greenness has returned to pre-drought levels following the drought of the 2000s (Rich et al. 2008), the recovery was due to increases in herbaceous rather than woody plant cover, and does not signify a return to pre-drought vegetation characteristics. In addition, reductions in tree cover likely altered water, energy, biogeochemical, and plant-animal dynamics, and in turn, other ecosystem services: herbaceous vegetation probably increased over the short term; mycorrhizae communities likely changed; and habitat quality and piñon food sources for wildlife possibly were altered (Murphy et al. 1998, Breshears 2006, Royer et al. 2010).

The *provisioning services* modified following the tree die-off include piñon nuts and firewood. Extensive tree die-off greatly reduces piñon nut production, which occurs only during infrequent, synchronous masting events by mature trees, given the large number of trees lost in such die-off events and the multiple decades needed for new seedlings to reach maturity. Following a massive die-off, it could be several decades before pre-drought nut production levels are once again attained (it should be noted that piñon nuts also provide cultural services; locally grown piñon nuts are so important to New Mexico that under a state law passed in 1987 pine nuts cannot be called "piñon" unless grown in the state). In addition to nuts, piñon trees are also valued for their slow-burning and fragrant firewood. Although there was a short-term increase in the availability of piñon firewood immediately following the die-off, there is likely to be a large reduction in firewood availability over the next several decades. In contrast, there may be a short-term increase in forage for livestock as overstory trees die, provided reductions in competition for water are not offset by increased evaporative loss associated with changes in understory microclimate (Rich et al. 2008, Royer et al. 2010).

The *regulating services* of thermal regulation, control of disease spread, and erosion control were likely impacted by the die-off. Extensive tree mortality fundamentally alters the land surface microclimate, affecting people as well as wildlife and ecological processes (Royer et al. 2010). A reduction of tree cover from ~40% to ~25% can result in pronounced changes in the amount of solar radiation incident on the land surface, influencing microclimate for humans and wildlife (Breshears 2006, Royer et al. 2010). Further, forest die-off, if also associated with understory vegetation loss, can trigger higher soil-erosion rates (Allen and Breshears 1998, Allen 2007; but see Rich et al. 2008), possibly affecting water quality in watersheds previously dominated by piñon-juniper woodlands. On the other hand, the impacts on hantavirus disease regulation may be positive, as areas of high virus exposure are often associated with piñon nut caches of *Peromyscus* sp. (deer mice), the principle hantavirus vector in the area (Dizney et al. 2010, Luis et al. 2010). It is quite possible that disease transmission may be slowed by long-term reductions in pine nut availability, although more information is needed to fully understand changes in disease transmission.

Cultural services were greatly impacted by the vegetation die-off. The piñon tree has been integral to local Native American and Hispanic cultures for centuries, and has become important to Anglo newcomers as well (Lanner 1981). For example, it is the New Mexico state tree (Lanner 1981, Floyd 2003). During the drought of the 2000s, many homeowners experienced loss of privacy from reduced tree cover around their homes, while facing the additional expense of having to remove the dead trees that had become fire hazards. The loss of the symbolic trees alarmed many New Mexicans. According to an urban wildlife specialist in Santa Fe, people were "crying on the phone" over the loss of their trees (Carlton 2006). Indeed tree loss was such a big concern that a local resident wrote a book of poetry and art titled "What to do with a dead piñon" (Wellman 2004).

Slower, Homogenous Climate Change: The Colorado River Delta

The Colorado River delta was once considered "the Nile delta of America," supporting nearly 800,000 hectares (2 million acres) of wetlands and wildlife, and providing local people and Indigenous tribes with abundant ecosystem services such as food and raw materials for shelter, clothing and cultural ceremonies (Sykes 1937). Today, it is widely recognized that wetlands and

estuaries provide incalculable benefits to society in terms of habitat for the spawning, development and subsistence of commercially important fisheries, habitat for migratory and resident birds, recreation and tourism opportunities, filtration of pollutants and shoreline protection, among other services (Daily 1997, Millennium Ecosystem Assessment 2005, Zedler and Kercher 2005).

Due to the construction of upstream dams, the Colorado delta is now less than 10% of its original size (Hinojosa-Huerta et al. 2004). The "Law of the River"—the collection of interstate agreements and international treaties that govern the distribution of Colorado River water—does not consider "nature" or instream flow to be a recognized water user. Even these remnants of the delta now survive almost entirely on "inefficiencies" in the system—inadvertently released water, or "waste" water that is not used by agriculture and cities—amounting to less than 1% of the water that historically reached it (Zamora-Arroyo and Flessa 2009). Despite the reduction in inflows, remnant wetlands still support ecosystem services for local and Indigenous people and US and Mexican visitors to the area (Lellouch et al. 2007).

The current drought conditions across western North America, and reductions in snowpack, are expected to diminish water flows in the Colorado River basin. To deal with these expected future decreases in water supply, water managers and users in the United States and Mexico are implementing urban and agricultural water conservation projects. However, water conservation efforts may ultimately lead to an "efficiency paradox" as the "inefficiencies" in the system (i.e., leaking canals, agricultural return flows) that actually maintain the delta wetlands are eliminated (Jenkins 2007). Based on a review of all water sources for the delta, incidental water flows on which the delta currently depends will likely disappear in the coming decades (Zamora-Arroyo and Flessa, 2009). And, without dedicated water sources for the delta, declining incidental flows will likely spell further diminishment of ecosystem services (Fig. 4).

The delta provides many *supporting services* by serving as a critical stopover on the Pacific migratory bird flyway. At least 368 bird species breed, winter, or migrate through the area, representing 55% of the total bird species in North America (Hinojosa-Huerta et al. 2007). During the winter, the delta is home to over 400,000 migratory water birds, and it is the permanent home of over 70% of the total population of the Yuma clapper rail, a marsh bird protected in both the United States and Mexico (Hinojosa-Huerta et al. 2004). Because many birds, particularly clapper rails, are sensitive to changes in wetland vegetation (Hinojosa-Huerta et al. 2004, Conway and Sulzman 2007), and delta wetland vegetation contracts as water flows decline and salinity increases (Glenn et al. 1996, Glenn et al. 2001), the Colorado River delta's supporting services to migratory birds are liable to decline as future water supplies dwindle (Hinojosa-Huerta 2006).

The Colorado River once delivered its entire annual flow of freshwater to the Upper Gulf of California, creating an enormous estuary that extended 70 kilometers (44 miles) south, and with it, a vibrant and productive fishery—constituting *provisioning ecosystem services*—in the delta and Upper Gulf of California (Carbajal et al. 1997, Kowaleski et al. 2000). Although only a trickle of water now reaches the estuary in most years, during floods in the 1980s and 1990s in which significant amounts of freshwater flowed through the delta to the Upper Gulf of California, breeding and nursery grounds for diverse and economically important marine shrimp, finfish, and shellfish fisheries rebounded (Calderon-Aguilera and Flessa 2009). For example, six years after the 1993 flood (approximately 130 $m^3 \cdot s^{-1}$ of water flows), fish landings of *Cynoscion othonopterus* (Gulf corvina) increased approximately 100% to almost 4000 metric tons (Calderon-Aguilera and Flessa 2009). Calderon-Aguilera and Flessa (2009) suggest that as little as 25 $m^3 \cdot s^{-1}$ of freshwater delivery to the delta, paired with ecosystem-based management of fishing systems, could benefit commercial and sport fishers, shrimp production, and tourism, for example, resulting in 1000 metric tons of Gulf corvina landings. However, even this relatively small volume of flow is unlikely without dedicated water sources for the delta.

Regulating services, specifically local and global climate regulation, will be impacted by reduced water flows and vegetation die-off. Similar to the piñon die-off, extensive tree mortality due to lack

of water flows could potentially change the microclimate, affecting people, wildlife and ecosystem function in the delta region, where summertime temperatures already exceed 46°C (115°F). Although the carbon sequestration capacity of the Colorado River has not been studied, work elsewhere has shown that wetlands are particularly effective at sequestering carbon, but degraded and dried out wetlands are not as effective at carbon sequestration (Zedler and Kercher 2005). Conversely, degraded wetlands release the greenhouse gases methane and carbon dioxide, thereby exacerbating climate change; further, the release of these gases also increases exponentially with increasing temperatures (Zedler and Kercher 2005).

Currently the delta provides many hunting, tourism, and recreational activities—all of which are *cultural ecosystem services*. Annual revenues from tourism are estimated at US $1.2 million in the entire Mexicali Valley, and US $300,000 along the Río Hardy alone (Zamora-Arroyo and Lellouch 2007). Tourism, and the economic benefits it brings, has been linked to increased social cohesion in the region's small towns and communities (Zamora-Arroyo and Lellouch 2007). Further, willingness-to-pay surveys conducted by the Mexican government's National Institute of Ecology indicate a growing recognition of the need to protect delta habitats for recreation and biodiversity; however, the estimated willingness to pay for conservation in the delta pales in comparison to the value of agricultural production in the Mexicali Valley and across the border in the Yuma, Arizona irrigation districts (Rivera and Carrillo-Guerrero 2006). These cultural benefits will likely diminish if water inflows to the delta disappear in the coming decades.

Uncertainty, Exposure, and Vulnerability

The examples of piñon pine die-off and the Colorado River delta dry-out can serve as archetypes to help characterize how the rate of disturbance and degree of patchiness will shape uncertainty about timing and location of impacts, exposure of ecosystem services users, and the vulnerability of those users to climate-driven change (Fig. 5).

Uncertainty about impacts

The two examples differ greatly in terms of degree of certainty about the timing and location of impacts to ecosystem services. In the faster, patchy ecosystem change of the piñon-juniper woodlands example, ecosystem services crashed in certain parts of the system, but remained unaffected in other locations. The uncertainty in this situation lay in when and where the vegetation die-off and concomitant crashes in ecosystem services would occur. Despite recent progress on determining the spatial patterns of climate and soil moisture that may have driven the patterns of tree mortality (Weiss et al. 2009, Peterman et al. 2013, Williams et al. 2013), considerable uncertainty remains in precisely forecasting future such patterns of die-off, and this in turn constrains adaptation options.

In contrast, in a slower, homogeneous change such as declining water supplies to the Colorado River delta, the entire ecosystem will be impacted and ecosystem services everywhere are likely to be altered. For example, the Río Hardy is an important river for sport fishing (Zamora-Arroyo and Lellouch 2007). As water flows decline, fish stocks all along that river will also decline, not just in certain fishing spots. Over the short term, these types of alterations are likely to entail degradation in the amount (and quality) of ecosystem services rather than a complete loss. The source of uncertainty in this situation is not in the timing or location of impacts, but rather the degree to which ecosystem services are altered.

Exposure

The two examples differ in terms of the exposure of ecosystem services users to changes in services. In the piñon-juniper example, because the tree die-off is patchy across the landscape, not all users in the Four Corners region will experience a change in services. However, those who are exposed will experience a fundamental change—quite possibly a near-complete loss—in services in their location, such as a sudden reduction in piñon nut harvests, or a loss of trees around homes. On the other hand, in the Colorado River delta, all users of a particular type of service will experience alterations in services. In the Río Hardy example, all sport fishers will experience declining catches, not just those who fish in specific spots.

CHARACTERISTICS OF CLIMATE CHANGE-DRIVEN ECOSYSTEM CHANGE

	Faster & Patchy	Slower & Homogeneous
Impacts	Parts of system will maintain Ecosystem Services Where: Uncertain When: Uncertain	Altered Ecosystem Services everywhere in system Where: Everywhere When: Gradual (but may be thresholds)
Exposure	Not all Ecosystem Services users exposed	All Ecosystem Services users exposed
Options	Flexibility in where to get Ecosystem Services Rapidity requires proactive strategies	No location flexibility May be time to react as change progresses

Fig. 5. Characteristics of climate change-driven ecosystem change in terms of impacts on ecosystem services, user exposure and adaptive options.

Vulnerability

When assessing the vulnerability of ecosystem service users to changes in services, two considerations are important. First, exposure to altered ecosystem services does not necessarily signify vulnerability. Second, vulnerability may depend on the type of ecosystem service and the degree of user dependence on the service.

Vulnerability to climate change impacts implies harm to a person's livelihood and/or well-being (Adger 2006). People can be exposed to the same change in ecosystem services but differ in whether their livelihoods are harmed or benefited by the change. For example, following the piñon die-off of the 2000s, many homeowners in Santa Fe, New Mexico felt harmed by the loss of privacy around their homes and by the unexpected expense of having to remove dead trees—suddenly a fire hazard—from their property (Carlton 2006). On the other hand, anecdotal reports suggest that the landscaping and gardening business boomed from the increased demand for services clearing dead brush (Carlton 2006). Similarly, in the Colorado River delta, both subsistence and sport fishers may be equally exposed to fishery declines, but subsistence fishers may be more vulnerable given that these declines for them mean the loss of a food source.

In addition to recognizing that all users with the same exposure are not equally vulnerable, it is important to consider that the degree of vulnerability may depend on the type of ecosystem service being used. In the general context of social vulnerability to climate change, vulnerability may be linked to flexibility about choice of location (Leary et al. 2008). In the piñon-juniper example, users who are tied to particular locations, and who depend on non-portable services (homeowners who value the viewsheds around their home), may be more vulnerable to loss of services than people who are flexible about where they obtain services (tourists who can visit other viewsheds) or users of portable services (such as piñon nuts and firewood) that can be transported across a landscape (Breshears et al. 2011).

Options and Policy Implications: Two Suggestions for Moving Forward

Under a changing climate, the rate of change and degree of spatial heterogeneity of change will constrain the adaptive options open to individuals and institutions. Due to the rapidity of faster, patchy ecosystem change, we expect that the primary challenge will be forming a timely response. In such situations, we suggest that decision-makers and local stakeholders

would be wise to act *before* ecosystem changes occur. On the other hand, slower, homogeneous, system-wide impacts to ecosystem services will require a fundamental rethinking of how ecosystems and services are used and valued.

Faster, patchy changes and proactive cooperative networks

Under faster, patchy ecosystem changes, all actors (private and public, individuals and institutions) are effectively operating under what the legal philosopher John Rawls termed the "veil of ignorance" (Rawls 1971). Prior to the ecosystem disturbance, no one knows who might be harmed or when. In situations where the future outcomes are unknown, Rawls suggests that society benefits when a priori decisions about the distribution of rights and resources equally favor all members (Rawls 1971).

In response to fast, patchy ecosystem changes, Breshears et al. (2011) envision a Rawlsian solution—the pro-active formation of cooperative networks where all members equally share the potential risk of sudden loss of ecosystem services. In such an arrangement, "location centric" ecosystem service users—such as nut harvesters who might ordinarily be constrained to harvesting on their own property—could pursue cooperative arrangements with other harvesters to share the risk of losing ecosystem services (Breshears et al. 2011). A harvester who entered into a cooperative agreement prior to a drought-induced ecosystem crash would be assured of sharing in the harvest from other locations, even if their own property is subject to forest die-off.

Similar cooperative arrangements already exist in the western United States, such as "swing allotments," which provide ranchers grazing relief following a drought or fire on their land, or "grass banks," where cattle can graze while the US Forest Service undertakes restoration improvements on ranchers' home allotments (Edwards 2005, White and Conley 2007). Developing adaptive strategies for sharing the risk of losing the diverse ecosystem services impacted by fast climate change may require new institutional structures and governance arrangements. Both the swing allotment and grass bank examples demonstrate the potential of local groups in devising and promoting new innovative arrangements, and in negotiating with state and federal land-management agencies to realize these ideas (Edwards 2005). Although there are uncertainties and costs to either creating new governance arrangements or staying with the status quo and letting costs fall where they may, the piñon-juniper woodland case and emerging concepts of collaborative governance suggest that local, state, and federal land managers would be well-served by exploring partnerships with ecosystem service users to devise and implement the proactive strategies necessary to adapt to faster, patchy climate change.

Slower, homogeneous changes and fundamental rethinking

Slower, homogeneous, system-wide changes such as those occurring in the Colorado River delta will require fundamental rethinking about how ecosystem services are valued and managed. In the delta, the critical issue is water allocation; decisions about allocating basin water to agriculture and urban areas versus instream flows are fundamentally decisions about the relative importance of agricultural and urban ecosystem services versus services from natural and semi-natural riparian areas. Previous generations of users and managers have deferred the hard decisions about allocating water to some ecosystem services versus others. Now, because of the current drought and the impending long-term water shortages due to climate change, further postponing these decisions risks far more substantial harm in the delta. Moreover, in contrast to patchy changes, in which not all users are exposed, system-wide changes such as those seen in the delta require community-wide engagement from all ecosystem services users and stakeholders (users, scientists, managers, and decision-makers).

While the idea of "fundamentally rethinking" water allocation in the Colorado River basin as a strategy for adapting to climate change may sound far-fetched, recent efforts in the delta suggest that progress is possible. The ongoing drought in the western United States has opened the possibility of dedicating instream flows of water for the Colorado River delta (Zamora-Arroyo and Flessa 2009, Carrillo-Guerrero et al. 2013). Prior to the drought, conservationists and water managers were at loggerheads, and it

seemed improbable that either the Mexican or the US government would dedicate valuable water to the delta. The drought is forcing both water managers and conservationists to develop creative solutions for dealing with water shortages in the Colorado River basin; among them are agreements to seek alternative water sources for the delta. In fact, a water trust created by NGOs (non-governmental organizations) recently secured 1.7 million cubic meters of water per year from purchases in the Mexicali Valley (Zamora-Arroyo et al. 2008, Zamora-Arroyo and Flessa 2009) and has signed a 50-year agreement with the government of the Mexican state of Baja California to send reclaimed water from an urban water treatment plant to the delta.

Conclusion

Under a changing climate, devising strategies to help stakeholders adapt to alterations to ecosystems and their services is of utmost importance. This paper posits that two key variables often considered in landscape ecology—the rate of change and the degree of patchiness of change—can aid in developing climate change adaptation strategies. Here, we have used two examples from the US-Mexico borderland region to highlight how these two key variables might constrain the kinds of policy responses available to private and public actors.

Although the necessary responses are different for the two examples presented here—we suggest that faster, patchy changes will require proactive cooperative networks, and slower, homogeneous changes will require fundamental rethinking—in both circumstances climate change will require new understandings and arrangements. The new generation of climate change models currently being developed likely will enable better predictions and understandings of potential ecosystem changes. Climate science and ecological modeling, in concert with social science research and wise decision-making, should allow for prospective strategizing rather than reflexive and expensive after-the-fact adjustments.

We encourage property owners and managers facing faster, patchy ecosystem changes to consider strategies that allow all stakeholders to share risk. In the arid regions of the US-Mexico borderlands, there is precedent for local stakeholders devising and promoting changes in management practices that allow users to share risk (Edwards 2005, White and Conley 2007). In the Colorado River delta example, however, fundamental widespread changes in ecosystem services require not just local adjustments but collective shifts in overarching policies and priorities.

The option of waiting for changes to strike in the long-run may lead to notably higher costs in terms of time, money, and social conflict if users rely on lawsuits to sort out rights and responsibilities to ecosystem goods and services. At the same time, planning and coordination are also costly activities. This paper suggests, although cannot prove, that fundamental changes in policy driven by collective voluntary agreements may produce more ecologically sustainable and more socially equitable and cost-effective responses to climate change. The example of the Colorado River delta suggests that climate change, and related water scarcity, may be just the kind of policy driver that will help to make prospective planning for foreseeable changes a more compelling and desirable option compared to backward-looking conflicts over rights. More generally, an appreciation for how the rate of change and degree of patchiness of change will constrain adaptive options is critical in preparing for the impacts of climate change.

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