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REVIEW PAPER

When Ecosystem Services Crash: Preparing for Big, Fast, Patchy Climate Change

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Abstract Assessments of adaptation options generally focus on incremental, homogeneous ecosystem responses to climate even though climate change impacts can be big, fast, and patchy across a region. Regional drought-induced tree die-off in semiarid woodlands highlights how an ecosystem crash fundamentally alters most ecosystem services and poses management challenges. Building on previous research showing how choice of location is linked to adaptive capacity and vulnerability, we developed a framework showing how the options for retaining desired ecosystem services in the face of sudden crashes depend on how portable the service is and whether the stakeholder is flexible with regard to the location where they receive their services. Stakeholders using portable services, or stakeholders who can move to other locations to obtain services, may be more resilient to ecosystem crashes. Our framework suggests that entering into cooperative networks with regionally distributed stakeholders is key to building resilience to big, fast, patchy crashes.

Keywords Climate change · Drought · Ecosystem services · Forest tree die-off

INTRODUCTION

Climate change is projected to trigger a wide variety of abrupt ecosystem disturbances (Alley et al. 2003; Breshears and Allen 2002; IPCC 2007; Overpeck and Cole 2006). Of particular concern is the potential for large abrupt disturbances such as extensive wildfires (Bowman et al. 2009; Flannigan et al. 2009; Westerling et al. 2006), large floods (Milly et al. 2002; Overpeck and Cole 2006), tropical storm landfall (Boose et al. 1994; Overpeck and Cole 2006), and severe droughts (Allen et al. 2010; Wilcox 2010). Through these ecosystem disturbances, climate change is projected to trigger dramatic changes in the services society derives from ecosystems (MA 2005). A changing climate will sporadically set off ecosystem crashes that are big, fast, and patchy—substantial and large scale, rapid relative to regeneration time frames, and regionally heterogeneous (Blacklund et al. 2008; Breshears et al. 2005; Scheffer et al. 2002; Stenseth et al. 2002). These sudden ecosystem crashes will result in extensive losses of ecosystem services, yet to date most assessments of adaptation to climate change have focused on incremental, homogeneous ecosystem changes (Blacklund et al. 2008; Heller and Zavaleta 2008). Because ecosystem crashes often cannot be predicted, and because in many cases it is not feasible to make ecosystems resistant to crashes, it will fall upon *stakeholders* to adapt to sudden changes in ecosystem services. Of all the challenges presented by climate change, developing adaptive responses to sudden ecosystem crashes may be among the most difficult (Millar et al. 2007). Crafting strategies to adapt to big, fast, and patchy ecosystem crashes will be difficult because both the timing as well as the specific location of sudden crashes is largely unpredictable at present. In a more general context of social vulnerability, adaptive capacity is linked to flexibility of choice in location—stakeholders who are tied to particular locations may be more vulnerable to climate change (e.g., Leary et al. 2008). With respect to the potential impacts of crashes in ecosystems goods and services, additional consideration is needed to understand the relationship between location, ecosystem services, and societal adaptive capacity. In particular, it is crucial to understand how dependency on certain *types* of ecosystem services may shape stakeholder flexibility in choice of location and in turn their adaptive capacity.

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Understanding societal dependence on ecosystems has been the focus of the Millennium Ecosystem Assessment (MA)—an international effort to assess the drivers of global change, elucidate the importance of ecosystems and their services, and suggest adaptive strategies for enhancing stakeholder resilience in the face of global change (MA 2003). The MA developed a conceptual approach for evaluating the complex interactions between ecosystems, the services they provide, and human well-being. Although the MA approach has been used to assess the consequences of abrupt spatial boundaries for the management of ecosystem services (López-Hoffman et al. 2009), notably it has not yet been used to illustrate how temporally abrupt and spatially patchy ecosystem changes will alter ecosystem services and impact the communities that depend on them.

Here we address the critical, and to date, largely unaddressed gap between big, fast, patchy climate-induced ecosystem crashes and the development of adaptive options for increasing stakeholder resilience to sudden loss of ecosystem services. To explore this issue, we use the MA's four categories of ecosystem services to illustrate how the recent drought-induced tree die-off of piñon pine woodlands across the southwestern US altered the capacity of ecosystems to support human well-being. Our analysis draws on published literature about changes in piñon pine ecosystem function and media accounts of how stakeholders are being impacted and are responding to abrupt changes. Building on this example, we suggest that the adaptive options for increasing stakeholder resilience to sudden loss of ecosystem services will depend on the degree to which services are tied a to particular location. Our intent is to provide an example—one that explicitly considers the relationship among location, type of ecosystem service, and adaptive capacity in the context of an ecosystem crash—that will stimulate additional future research to more quantitatively assess this concept.

Big, Fast, Patchy Climate Change Impacts: Drought-Induced Tree Die-Off in Semiarid Woodlands

Drought can trigger an ecosystem crash via widespread tree die-off, either directly from effects of water stress and/or indirectly from associated pests such as bark beetles or pathogens such as fungi that are more damaging when trees are water stressed (McDowell et al. 2008). Such die-off events have recently been documented on every wooded continent globally (Allen et al. 2010) and produce pronounced ecosystem changes (Adams et al. 2010; Raffa et al. 2008). One of the most extensively documented examples of a sudden ecosystem crash in response to climate change is the drought-induced tree die-off in piñon-juniper woodlands in the US southwest accompanying a drought that occurred around 2000 (Breshears et al. 2005, 2009; Shaw et al. 2005). Historically, semiarid woodlands, such as the extensive piñon-juniper forests, have been sensitive to climate, responding rapidly to severe drought with widespread tree die-offs (Allen and Breshears 1998; Breshears et al. 2005; Brown et al. 2001). During past droughts, piñon-juniper mortality occurred most predominantly in the driest areas of the species' distribution, resulting in an ecotone shift between vegetation types (Allen and Breshears 1998). However, the severe drought that began in 2000 was notable because it not only triggered tree mortality in dry areas but in wetter, cooler locations as well (Breshears et al. 2005; Shaw et al. 2005). During the drought, piñon pine mortality was 90% or greater at some upper elevation, cooler sites, although quite patchy across the region (Breshears et al. 2005). Tree mortality was substantial enough to alter key ecosystem characteristics (Fig. 1), including site greenness (measured by the satellite index for Normalized Difference Vegetation Index, NDVI). Mortality extended across the region and to other woody and herbaceous species as well (Breshears et al. 2005; Gitlin et al. 2006; Shaw et al. 2005). The piñon trees appear to have been ultimately killed by bark beetles (Shaw et al. 2005), but the underlying driver of mortality was water stress caused by regional-scale drought and exacerbated by warmer temperatures (Adams et al. 2009; Breshears et al. 2005, 2009; McDowell et al. 2008).

Ecosystem changes in the southwestern US piñon-juniper woodlands are notable for several reasons. First, the events have been "big"—in 2000, die-off occurred throughout the region (Fig. 1) and in resulted in >90% mortality at some locations. Second, the events have been "fast"—most of the mortality in the die-off occurred within one to 2 years (2002–2003). This is particularly notable in semiarid woodlands where trees grow slowly, and mature forest canopy overstory structures can require more than a century to mature. Third, the events have been "patchy" at the regional scale—in the 2000 crash, the die-off occurred throughout the region with some areas experiencing nearly complete loss of overstory piñons, while other locations experienced few tree deaths (Breshears et al. 2005). Finally, the piñon pine die-off can be considered a "crash," in the sense that it will take decades at best for a similar vegetation with a mature canopy overstory to develop, and such large mortality events can even result in altered trajectories of vegetation, where even decades after mortality, the former dominant tree species have generally not reestablished (Allen and Breshears 1998).

Impacts on Ecosystem Services and Stakeholders

The ecosystem changes triggered by drought-induced vegetation die-off will alter the capacity of piñon-juniper woodlands to provide services to society. In this section,

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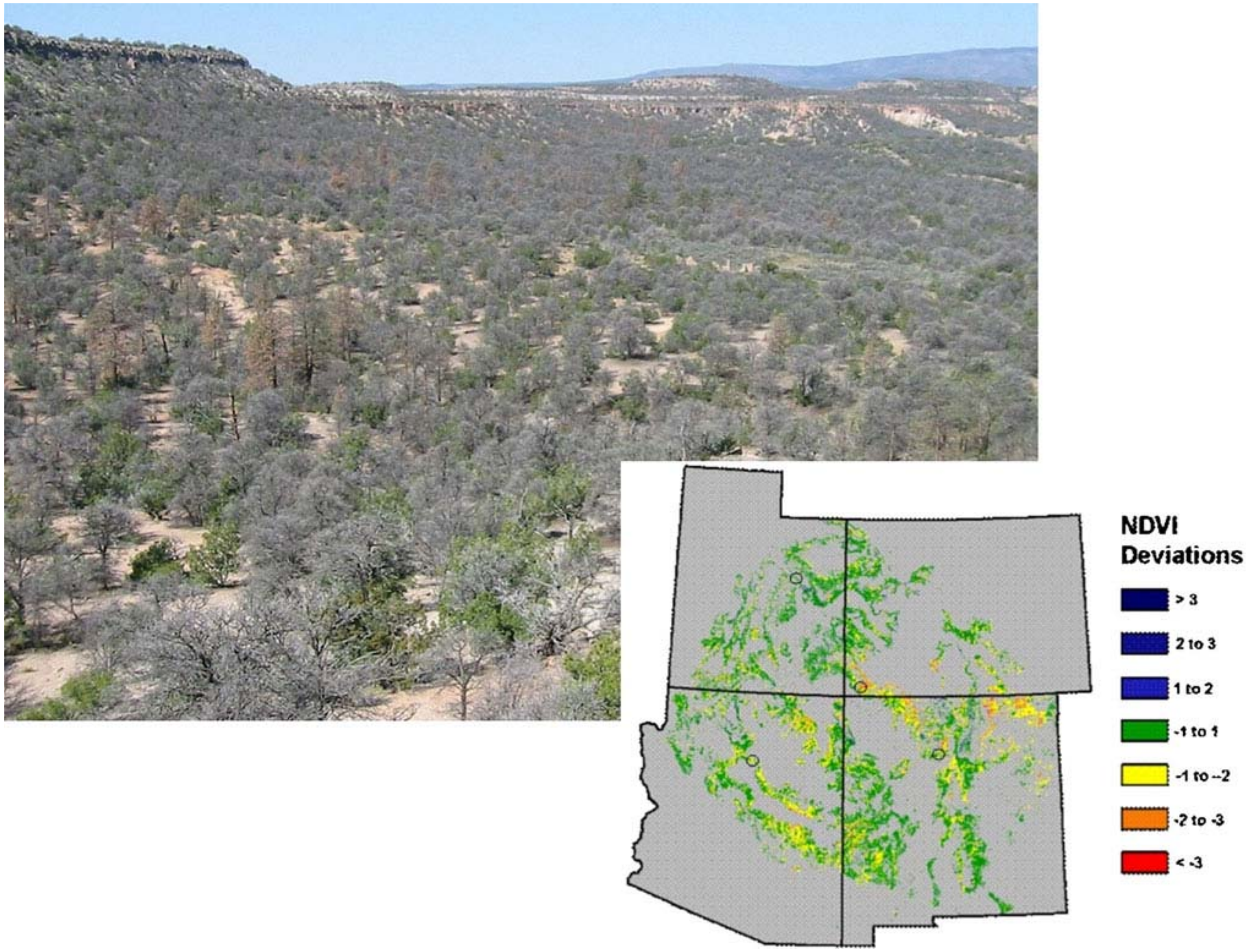

Fig. 1 Depiction of drought-induced tree die-off of piñon pine, an example of an ecosystem crash. The *grey* standing trees died following severe drought coupled with warmer temperatures. The die-off occurred regionally (*inset*) as evident in remotely sensed measurements of greenness (NDVI), with *yellow*, *orange*, and *red* indicating progressive reductions in greenness; circles correspond to field verification sites (modified from Breshears et al. 2005, 2009; photo: C. D. Allen)

we use the MA classification of ecosystem services to highlight how drought-induced tree die-off affects stakeholders in the US southwest. Our discussion is organized around the MA's four categories: *provisioning services*, material benefits to humans, such as water or food; *regulating services*, processes such as pollination, flood, and disease control that regulate other ecological processes; *cultural services*, the aspects of nature that provide humans with recreational, spiritual, or religious experiences; and *supporting services*, processes such as nutrient cycling and soil formation that are necessary to support biodiversity (MA 2003). According to the MA framework, changes in supporting services in turn impact the other types of services (Fig. 2).

Supporting services will be modified because reductions in tree cover will alter water, energy, biogeochemical, and plant-animal dynamics (Breshears 2006). These changes potentially include: an increase in the amount of radiation reaching the ground surface; a large increase in herbaceous vegetation; changes in mycorrhizae communities; altered habitat quality for wildlife; and modified piñon pine production rates (Breshears et al. 2005; Floyd 2003; Gehring et al. 1988; Rich et al. 2008; Royer et al. 2010).

Primary productivity is altered following die-off, as reflected in reduced tree inventories (Shaw et al. 2005) and indices of vegetation greenness (Normalized Difference Vegetation Index, Breshears et al. 2005; Rich et al. 2008) after the 2000 drought. Although overall greenness has returned to pre-drought levels following the 2000 drought (Rich et al. 2008), this recovery is due to increases in herbaceous rather than woody plant cover, and therefore, does not correspond to a return to pre-drought vegetation characteristics. Soil formation can be impacted by potential changes in erosion, which are tied to the degree to which an increase in herbaceous vegetation persists following die-off.

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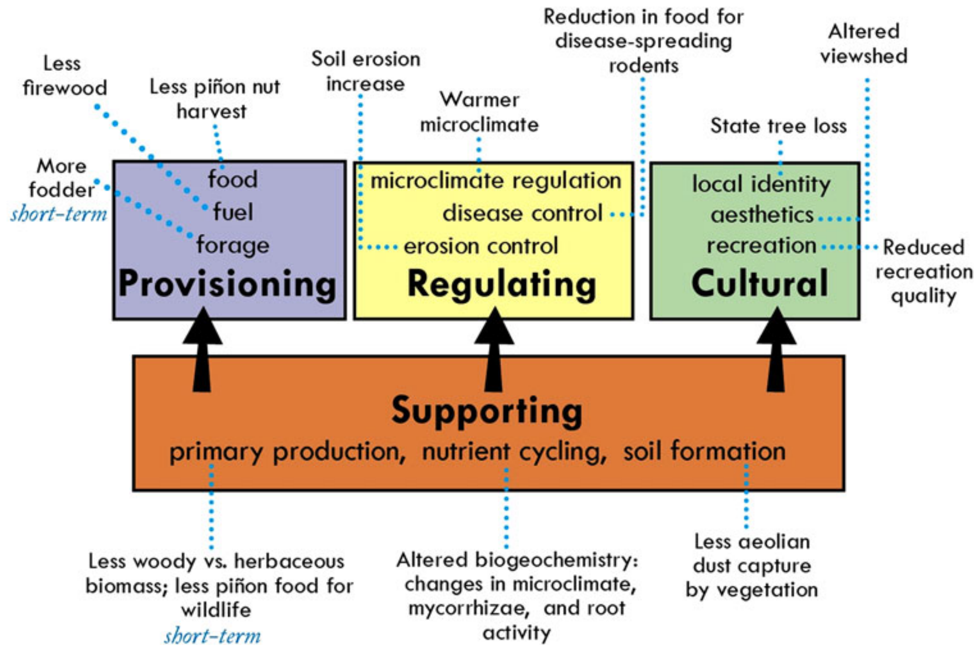

Fig. 2 Changes in ecosystem services following piñon pine die-off and consequent impacts on stakeholders. The categories of ecosystem services are based on MA (2003)

Nutrient cycling related to carbon, nitrogen, and phosphorous has almost certainly been impacted numerous ways. Microclimate should be hotter, likely producing greater soil evaporation rates (Breshears 2006; Royer et al. 2010). Microclimate differences in temperature and soil moisture (due to changes in precipitation interception) are expected to alter decomposition rates (Murphy et al. 1998). Tree mycorrhizae effects on soil biogeochemistry will be impacted by extensive tree mortality (Mueller and Gehring 2006). If high soil erosion rates are triggered, this is expected to result in impacts to important biogeochemical cycles, including carbon loss associated with erosion and volatilization (Breshears and Allen 2002).

The *provisioning services* modified following tree die-off include piñon nuts and firewood. Extensive tree die-off reduces piñon nut production. Because mature trees grow nuts only during infrequent large-scale synchronous masting events (Floyd 2003), it could be several decades following a massive die-off before pre-drought nut production is again possible. For many people in New Mexico, buying piñon nuts from elsewhere simply will not do. A famed Albuquerque candy makers says “I’ll never use anything but New Mexico piñon in my candy. I won’t go to the Chinese pine nut or the Nevada pine nut because it isn’t right. That would be like selling Native American jewelry that was made in Hong Kong” (Carlton 2006). Locally grown piñon is so important to New Mexicans 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 regionally for firewood because they are relatively slow burning and aromatic. Although there may be a short-term increase in piñon firewood immediately following die-off, a substantial reduction in availability over the next several decades is likely because the trees are slow growing. Conversely, a post-drought increase in herbaceous vegetation after tree die-off (Rich et al. 2008) could be positive from ranchers’ perspective.

Several types of *regulating services* are impacted by die-off: thermal regulation, disease spread, and erosion control. Extensive mortality fundamentally alters the land surface microclimate, affecting people as well as wildlife and ecological processes. Even a reduction of tree cover from ∼40 to ∼25% can produce dramatic changes in the amount of solar radiation incident on the land surface that influence microclimate for humans and other biota and can result in increased losses of water via soil evaporation (Breshears 2006; Royer et al. 2010). Although some forestry practices focus on increasing water yield via tree thinning, such vegetation changes in piñon-juniper woodlands have been shown to be negligible (Zou et al. 2010). Forest die-off might affect water quality regulation: if high erosion rates are triggered, as appears to have occurred previously with a smaller die-off event (Allen and Breshears 1998), water quality in some watersheds dominated by piñon-juniper woodlands could decline (although conversely herbaceous cover might increase; Rich et al. 2008).

On the other hand, hantavirus disease regulation may be positively impacted by the piñon-juniper die-off. Areas of high hantavirus exposure are often associated with piñon nut caches of the deer mouse *Peromyscus* sp. The deer mouse is the principle disease vector in the southwest (Dizney et al. 2010; Luis et al. 2010). Although more information is needed to fully understand how the spread of hantavirus will change, it is quite possible that disease

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transmission may be slowed by long-term reductions in pine nut availability.

Cultural services are greatly impacted by the vegetation die-off. Piñon pine is the state tree for New Mexico. Use of piñon has been integral in Native American and Hispanic cultures for centuries, and has become important to Anglo newcomers as well (Floyd 2003; Lanner 1981). During the 2000 drought, many homeowners were impacted by the die-off when tree deaths reduced privacy from nearby homes and removal of dead tree fire hazards raised expenses. Loss of the symbolic trees around their homes has alarmed many New Mexicans. An urban wildlife specialist for the city of Santa Fe said that during the die-off she "had people crying on the phone" over the loss of their piñon trees (Carlton 2006). Indeed tree loss was so pervasive that a local resident wrote a book of poetry and art titled "What to do with a dead piñon" (Wellman 2004).

A Conceptual Framework for Identifying Options

Given the fundamental changes in ecosystem services that will accompany such big, fast, patchy climate-induced ecosystem crashes like that of the drought-induced woodland die-off, what options are there for stakeholders to protect themselves against the loss of services? The challenge of sudden ecosystem crashes is that the location and the timing of impact is uncertain. Here, we offer some suggestions for building adaptive capacity in the face of this uncertainty.

We build upon the understanding that adaptive capacity is linked to flexibility of choice in location and that stakeholders who are tied to particular locations may be more vulnerable to climate change. We developed a framework showing how the adaptive options for retaining ecosystem services following a patchy ecosystem crash depend on how tied both services and stakeholders are to location. Stakeholders who are limited to obtaining services from a specific location—that is the stakeholder is "location-centric"—should have few options if that location is hit by an ecosystem crash. On the other hand, stakeholders who are "location flexible"—who can import "portable services" from another location, or who can move to another location to obtain "non-portable services"—should have more options for adapting to sudden ecosystem changes.

In the piñon-juniper die-off example, piñon pine nuts are an example of a portable service whereas a viewshed is an example of a non-portable service. We use these two types of ecosystem services to contrast the adaptive options of location-centric versus location-flexible stakeholders (Fig. 3). We begin with a non-portable viewshed. Homeowners are typically not flexible with regards to

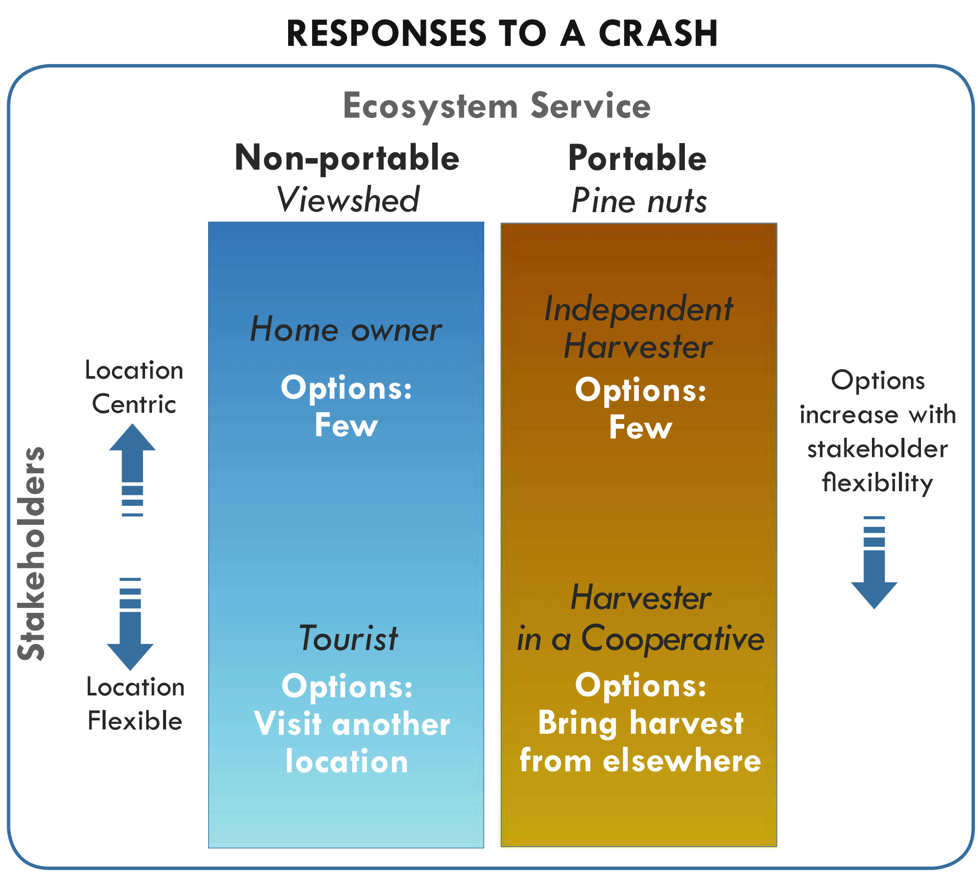

Fig. 3 A framework of options for maintaining access to ecosystem services following sudden crashes. Adaptive options depend on whether the service is portable or the stakeholder is flexible regarding where they receive services. Viewsheds and pine nuts provide examples of non-portable and portable services, respectively. Within each service type, stakeholders may be either location-centric or location-flexible regarding the source of their services. Options for building resilience increase with stakeholder flexibility regarding location of source of service

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viewsheds—if the viewshed surrounding their home is altered by tree die-off, they cannot move to another location to obtain the services. Tourists, on the other hand, are flexible; if a particular location is impacted by tree die-off, they can simply choose to move to another location. Similarly, piñon pine nut harvesters who only gather nuts in one spot (such as their own property) will have few options if that location is hit by an ecosystem crash. In contrast, harvesters who belong to cooperatives which allow them to harvest in other locations will be able to continue gathering pine nuts even if their own land is subjected to a crash (Fig. 3). This simple example highlights how explicitly considering whether services are portable or not plays into the consequences of a big, fast, patchy ecosystem crash. We suggest that stakeholders can build adaptive capacity in the face of uncertainty by being more location flexible in obtaining ecosystem services. Going further, we suggest pursuing innovative collaborations that are location flexible in obtaining ecosystem services. Future research is needed to investigate this idea empirically by comparing options between homeowners and cooperatives and the economic prospects of independent versus networked harvesters.

Adaptive Capacity, Scale, and Resilience

Our example has focused on how individuals, households, and communities in the Southwest may be vulnerable to ecosystem crashes through a loss of critical ecosystem services. In focusing attention on local-scale adaptation options, we build on the already rich literature in the social sciences that describes how coupled social-ecological systems cope with, manage or adjust to changing conditions, often at local scales (Kelly and Adger 2002; Yohe and Tol 2002). The social dimensions of adaptive capacity can be influenced by factors such as access to resources (e.g., financial, technological), and institutional arrangements, including networks of political influence, economic ties, and kinship (Smit and Wandel 2006). These factors, while expressed locally, are often determined by larger scale factors of politics, economics, and culture (Blaikie et al. 1994). Thus, while we argue that the greatest capacity for adaptation, and thus greatest resilience, appears to occur in circumstances where stakeholders are flexible and well-networked, we recognize that flexibility and networking are facilitated or constrained by larger social and economic factors operating at regional scales. A full analysis of the vulnerability or resilience of a system in response to big, fast, patchy changes would need to nest local dynamics in a broader analysis of cross-scale dynamics (Turner et al. 2003). Similarly, policies designed to enhance resilience in the face of big, fast, patchy changes must be adaptive, flexible, and address governance at multiple levels (Folke et al. 2002). For example, regional-scale ecosystem management should insure that target ecosystems are well-distributed.

The framework we have developed—differentiating ecosystem services that are portable from those that are not, as well as differentiating whether or not stakeholders are flexible about where they obtain services—enables us to identify a broader suite of options for building resilience to the big, fast, patchy impacts anticipated to accompany climate change. Notably, our framework highlights that networks and cooperatives may be an important means of addressing big, fast, patchy climate change for stakeholders wishing to maintain access to ecosystem services following a sudden ecosystem crash. Finally, we suggest that the most effective schemes for enhancing adaptive capacity in the face of climate change will be those that address the sustainability of coupled social and ecological systems.

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