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FORESTS UNDERGOING NOVEL DISTURBANCES

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# Disturbances as opportunities: Learning from disturbance-response parallels in social and ecological systems to better adapt to climate change

Brian Buma[1] | Courtney Schultz[2]

[1]Department of Integrative Biology, University of Colorado Denver, Denver, CO, USA

[2]Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins, CO, USA

**Correspondence**
Brian Buma
Email: brian.buma@ucdenver.edu

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## Abstract

1. Disturbances (e.g. fires, floods, windstorms, landslides and tsunamis) are ubiquitous throughout the world. Many social and ecological systems have resilience mechanisms to accommodate and recover from such events. Yet, in an era of directional climate change, adaptation (rather than recovery to the same state) may be the most logical path. In such cases, disturbances, while often unwelcome, may function as opportunities for change.
2. We synthesize the literature on disturbances and adaptation to climate change for both ecological and social systems, attempting to find commonalities and situations where disturbances present adaptation opportunities. We also identify three major characteristics of systems that may drive differential potential for success going forward: their overall richness of actors, their functional overlap in diversity, and their temporal rate of change.
3. Social systems are better positioned to successfully take advantage of disturbance-generated opportunities to adapt when they support collaboration of diverse interests and engage in pre-disturbance response planning to seize opportunities when they arise. Ecological systems are well-positioned for adaptation when they are diverse, populated with species that are tolerant of post-disturbance environments, and when life-history traits are well-matched with the temporal and spatial distribution of those disturbances.
4. Social systems with a lack of planning and inclusive participation and where powerful actors are resistant to change are less able to take advantage of disturbances as adaptational opportunities; ecological systems that are less diverse (spatially and in regards to species composition), especially those dominated by late successional species, are similarly constrained. Overall, we find that disturbances can create opportunities for adaptation when the ecology and social systems are aligned but there are also many situations where this is not true, depending on initial conditions, temporal pace of disturbance and system characteristics.
5. *Policy implications*. Disturbances, while damaging and often catastrophic in the short term, present climate adaptation opportunities because they can spur reorganization towards climatically suitable systems. Policy makers and advocates

  

should carefully consider current social and ecological conditions, specifically how they will reorganize post-disturbance, and explore the options available to prepare and take advantage of (inevitable) future disturbances.

**KEYWORDS**

adaptation, climate change, disturbance, ecology, natural disaster, resilience, social-ecological systems, transformation

## 1 | INTRODUCTION

Disturbances, relatively discrete events that disrupt the dominant system and necessitate recovery, reorganization and/or redevelopment, are globally ubiquitous (e.g. Sommerfeld et al., 2018). As the climate changes and disturbance regimes shift, we need new thinking about disturbances' role in ecosystem and social functioning and adaptation. One facet of disturbances highly relevant to climate change is their ability to create opportunities for reorganization of social and ecological systems—particularly reorganization that leads to, or favours, change towards structures more compatible with emerging climatic realities. Species need to migrate and social systems must deal with emerging ecological management challenges as historic systems become ill-matched to new conditions and stressors.

In this paper, we explore the question of how social and ecological systems might take advantage of disturbance-generated opportunities to change towards more climatically suitable configurations. This change might involve a shift to warmer-climate species or changes to the design of human infrastructure and land management to better withstand disturbances like fire and floods. Social and ecological systems are often tightly interwoven and interdependent, and here we treat them in parallel to focus on where they do and do not align in the context of adaptation. This allows us to explore our question while providing the context of both perspectives as they relate to each other. We then create a typology of linked social and ecological systems that identifies challenges (Figure 1) and opportunities (Figure 2) in the field of disturbance catalysed adaptations (Box 1).

Here we look towards the future: What features of communities (both ecological and social) enable them exploit disturbances to adapt to emerging climate conditions, which are different from the past and contain new challenges (e.g. new disturbance or precipitation regimes)? We use the term 'adapt' and 'adaptation' for the concept of change to a system that is more appropriate to future climates—for example, species which can thrive at higher temperatures, and social systems that are better able to thrive in those climates. Whether disturbances can and will be utilized as an opportunity for adaptation is an open question.

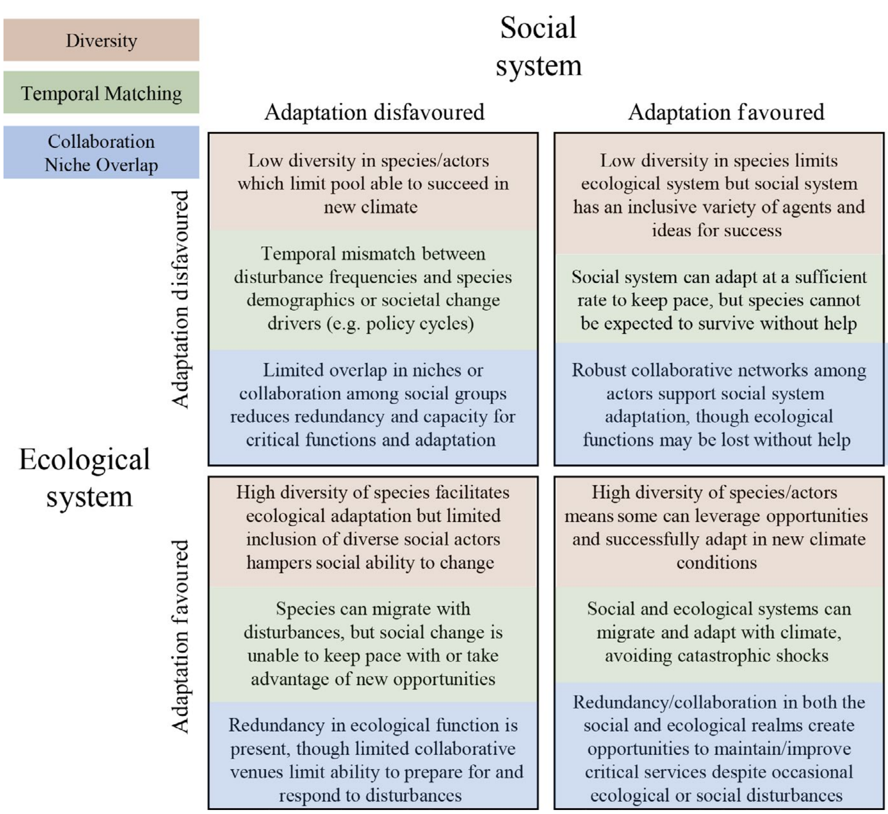


**FIGURE 1** Characteristics of social and ecological systems with respect to disturbance-favouring or disfavouring adaptation to climate change. Each section follows the key axes: Diversity, Temporal Matching, and Collaboration/Niche Overlap

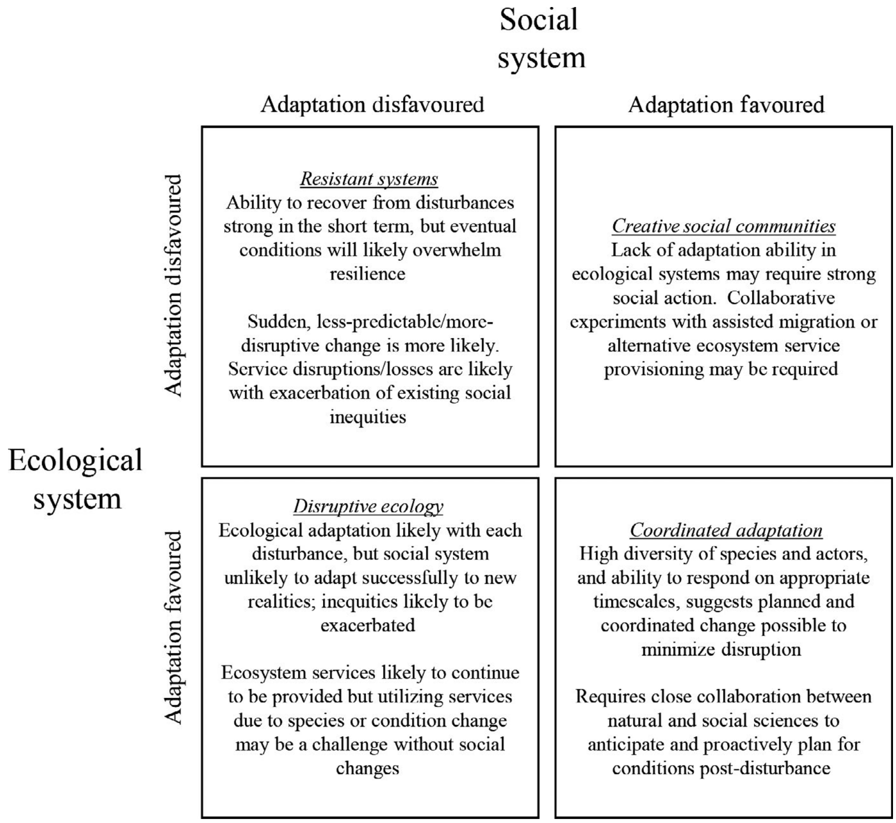


**FIGURE 2** Potential outcomes of disturbance events and changing disturbance regimes. Outcomes are not exhaustive, but rather general trends in what challenges and opportunities management and application may face in the context of the shifting climate and disturbance

**BOX 1 Definitions. Note that individual studies cited herein may use slightly different definitions across fields and contexts**

*Disturbance*: A relatively discrete event to the system that causes disruption to existing processes, such as mortality of biomass or disruption of infrastructure.

*Resilience*: The ability of a given system to be disturbed and yet return to a similar state, function, or regime.

*Adaptation*: The ability of a system to accommodate new disturbances and disturbance regimes through change while still retaining its essential identity. *Transformation* is an extension of adaptation, where a system redefines itself (i.e. becomes a new system) in the face of changing conditions; here, that is generally climate change.

*Inertia*: Resistance to change despite disturbance.

## 2 | LOOKING BEYOND RESILIENCE

While originally defined as a quasi-mathematical concept related to disturbance and recovery to the same state (Holling, 1973), the concept of 'resilience' has been adopted and developed in multiple fields. Despite some ambiguity in definition, 'resilience' persists as an organizing concept for multiple disciplines, and definitions are converging towards a conceptualization that involves not only adaptation and innovation, but sometimes transformation and significant systemic reorganization of system properties (Davidson et al., 2016; Leverkus, Murillo, Dona, & Pausas, 2019; Schoennagel et al., 2017).

In the field of ecology, resilience is traditionally understood as the ability of a given system to be disturbed and yet return to a similar state, function, or regime (Gunderson, 2000; Holling, 1973). Resilience is often also an aspirational goal of for ecosystem managers (Bone, Moseley, Vinyeta, & Bixler, 2016; Folke et al., 2004). Yet the value of resilience is challenged in the context of a changing climate (Harris, Hobbs, Higgs, & Aronson, 2006; Higuera et al., 2019). There is recognition that, in some areas, historical communities may not be viable in future climates (Jackson & Hobbs, 2009); there are few avenues available for many species: adapt, evolve or die (Aitken, Yeaman, Holliday, Wang, & Curtis-McLane, 2008). This is creating unique difficulties for applied systems (e.g. US National Parks, Baron et al., 2009), where the question becomes one of preservation, adaptation or some mix of the two. Resilience, in the strict sense of recovery to a similar state, may be the maladaptive path when climate is changing so rapidly as to make historical communities non-viable (Jackson & Hobbs, 2009). As a result, concepts of resilience increasingly incorporate notions of adaptation and transformation (Hobbs, Higgs, & Hall, 2013). For example, in forest management, Schoennagel et al. (2017) distinguish between specified resilience, or return to a similar state post-disturbance; adaptive resilience, which involves altering properties, reorganization of structures, and adaptability within a given management system; and transformative resilience, which involves planned (e.g. socially directed) change to a functionally new system state.

This expanding perspective of resilience to include adaptation/transformation is mirrored in the social science literature. As the concept of resilience has developed over time within the social-ecological systems, urban planning and community development literature (among others; Davidson et al., 2016), generally there has been convergence towards a concept that incorporates adaptation and embraces the good and bad of stability and change (Djalante, Holley, & Thomalla, 2011; Moser, Meerow, Arnott, & Jack-Scott, 2019). As with highly resilient but undesirable ecological systems (e.g. landscapes dominated by invasive species), resilience in social systems is not always a positive. Social system resilience can translate to the persistence of undesirable social norms and inequities in terms of access to collaborative venues, public services or safe and affordable housing (Olsson, Jerneck, Thoren, Persson, & O'Byrne, 2015). Because social change to mitigate social inequities is a normative goal underlying many social sciences, scholars across multiple disciplines are exploring characteristics that allow communities adapt over time (Djalante et al., 2011). Ideally, communities resilient to disturbances are those that can absorb and recover from an impact through learning and change (Berke & Smith, 2010), then adapt towards a more sustainable system (potentially including social change; Adger, Hughes, Folke, Carpenter, & Rockström, 2005). In the face of environmental shocks and social disasters like the 2018 fire in Paradise, California or the effects of hurricanes such as Katrina (2005) or Maria (2017), post-disturbance social adaptation and change—in ways that promote well-being—is an increasingly important question.

## 2.1 | The problem of inertia

Disturbances, by definition, disrupt the dominant ecosystem. Why might this disruption be useful for adaptation? Ecosystems often exhibit significant stability, or inertia, even in the presence of disturbances (Calder & Shuman, 2017). For example, in fire-prone systems, thick bark in many tree species prevents fire mortality. In systems where fire causes extensive mortality, serotiny is a common trait (Buma, Brown, Donato, Fontaine, & Johnstone, 2013). The disruption of disturbances may catalyse adaptation by providing an opportunity for reorganization along more climatically suitable directions (Johnstone & Chapin, 2003).

Spatial and temporal constraints can contribute to this inertia. The opportunity to establish is a requisite for migration and local community adaptation. Locally dominant species generally have an advantage in reproduction due to higher seed source availability and persistence of surviving individuals (Bisbing, Buma, Oakes, Krapek, & Bidlack, 2019). Furthermore, disturbance-catalysed opportunities for establishment must occur within the dispersal constraints of new species (the species must exist with the regional species pool). Temporally, opportunities must coincide with the life-history characteristics of the species (Renwick & Rocca, 2015). Species that mature quickly benefit from more frequent disturbance rates, late successional species benefit from slower disturbance rates (Buma et al., 2013; Liang, Duveneck, Gustafson, Serra-Diaz, & Thompson, 2018; Vanderwel & Purves, 2014). Community composition may be an important constraint if certain pollinators or seed dispersal vectors are required or if herbivore populations crash due to climatic variability (e.g. Van Bogaert et al., 2011). Finally, if opportunity and seed are available, climatic conditions need to be suitable for germination, growth and reproduction. All these mechanisms may delay shifts to more climate-suitable species by favouring pre-existing species over new migrants (Johnstone & Chapin, 2006).

Inertia exists in social systems as well. While ecological disturbances may act as 'focusing events' or 'critical junctures' if plans are laid ahead of time (Lindenmayer, Likens, & Franklin, 2010), governance institutions are typically slow to change, designed to create stability rather than adaptability, and shaped by historical pathways that limit future trajectories (Huber-Stearns, Schultz, & Cheng, 2019; Ulibarri & Scott, 2019). There are myriad factors that further contribute to social inertia and limit adaptive change. For instance, while disturbances can reshape political coalitions which might lead to change, that process may reveal deep divides across political coalitions that hinder adaptation (e.g. Müller, 2011). Disturbances can increase uncertainty and obviate hard-won social agreements about appropriate land management. On some collaborative forest restoration projects in the US, disturbances drove collaborators to revisit management agreements, delaying planning and implementation (Schultz et al., 2018). Potential policy solutions may not even occur if changes take so long that the window of opportunity provided by a disturbance event begins to close and fade into memory.

Another challenge is that the responses to disturbance may not necessarily increase long-term system resilience and may even be maladaptive (Anderson et al., 2018). Policy actors can 'wait in the wings' to use disturbances to pursue preferred policy solutions designed to favour some interest groups with no consideration for adaptation. For instance, the Forest Service and key political actors have used wildfires to pursue a goal of reducing legal requirements regarding environmental impact assessment and vulnerability to legal challenges, despite a lack of evidence that planning and litigation delays are the key factors limiting the agency's ability to reduce hazardous fuels (Schultz, Jedd, & Beam, 2012; Vaughn & Cortner, 2005). More recently, the Trump administration used fire events to promote more intensive timber management that prioritizes the removal of merchantable timber volume in places where there are industry partners and markets to do so. While timber removal is a common response to fire events, implementation may not clearly be connected to fire hazard reduction and may exacerbate the problem (Müller et al., 2019). Priority locations for fuels reduction often do not spatially overlap with the places having the most valuable timber volume, and actually reducing fire hazard often means leaving larger, economically valuable trees on the landscape and focusing on the removal of non-marketable trees and brush (Fears & Eilperin, 2019). This is an example of a disturbance catalysed opportunity exploited in non-adaptive ways.

In fact, while disturbances can help facilitate social change, the most common outcome post-disturbance for social systems is a return to the status quo, with an emphasis on 'getting back to normal' as quickly as possible. Mockrin, Stewart, Radeloff, and Hammer (2016) looked at community responses to three large fires in Colorado between 2010 and 2012 and found that land-use changes did not occur. Building restrictions were relaxed in some cases, although in one municipality mitigation standards for home and vegetation were improved. A statewide taskforce considered, but eventually declined, implementing statewide fire mitigation standards, determining that this was better left to local governments. In their summary, Mockrin et al. (2016) expected community exposure to be largely similar to before the fires and noted that while the fires resulted in some adaptation, they primarily resulted in reinvestment in building in hazard-prone areas. Others have found that responses after disturbances often are most damaging for poor and marginalized groups (e.g. Davies, Haugo, Robertson, & Levin, 2018) and exacerbate existing inequalities—resources are often directed to people and places that have power and capacity to make their political voices heard (Mockrin et al., 2016; Nohrstedt & Weible, 2010; Tompkins & Adger, 2004). Emergency management is often disconnected from integrated planning processes that might identify needs and opportunities for improving community response, with the result that emergencies are not capitalized upon as opportunities for change. In other cases, political leaders may focus on quicker responses rather than investing in longer-term resilience, as a higher priority for their constituents. Communities may also determine that proactive adaptation to minimize damage when the levees break in floods or structures are lost along the wildland urban interface, such as disruptive land-use or building-code changes, are too contentious. Political leaders also face disincentives to invest in changes likely to pay future dividends in terms of community well-being after their time in office (Berke & Smith, 2010). Thus, multiple factors result in social inertia in the face of disturbance, although as we discuss below, there are some examples of disturbances spurring change.

## 3 | WHEN DO DISTURBANCES CREATE OPPORTUNITIES FOR ADAPTATION?

While inertia may a challenge, disturbances can create the initial opportunities for adaptation by disrupting the dominant and historical community (ecological or social). We identified three major axes associated with the ability to adapt to new climatic conditions post-disturbance: 'Diversity', which facilitates ecological adaptation by ensuring appropriate species are in the regional pool and aids social adaptation by ensuring an array of actors to inform transitions as the climate shifts; 'Collaboration or Functional Overlap', which provides foundational structures and functions to ensure critical services are maintained if species are lost and that actors can develop effective institutions to promote change; and 'Temporal Matching', which ensures that properties of the system itself, such as the demographics of species or the process of a governance system can take advantage of opportunities as they arise (Figure 1). In the following section, we outline the arguments for those classifications.

### 3.1 | Ecological response

Disturbances can facilitate ecological adaptation (Thom, Rammer, & Seidl, 2017), for example by enhancing species' migratory opportunities (Brice, Cazelles, Legendre, & Fortin, 2019; Landhäusser, Deshaies, & Lieffers, 2010; Mori, Isbell, & Seidl, 2018; Wang et al., 2019) assuming species are present to take advantage. This may mean transformation, such as from forest to shrublands, as well as species substitution within the current dominant ecosystem (e.g. Serra-Diaz & Franklin, 2019). Some species are well-adapted to take that opportunity, such as fire-specialist species like *Pinus contorta*, whose distribution is moving north with successive fire events (Johnstone & Chapin, 2003). Other shade-intolerant species are able to take advantage of finer-scale gap disturbances within forests (Leithead, Anand, & Silva, 2010). Less intensive disturbances may increase resistance to climate change-related stressors like drought, increasing community stability (at least in the short term; Bradford & Bell, 2017). In general, higher diversity (in both species richness, relative abundances and spatial heterogeneity) often facilitates resilience and adaptation (Oliver et al., 2015).

It is worth mentioning interactions with social systems in this regard. Anthropogenic disturbances (i.e. forest management) often facilitate adaptation in a sense, because timber harvest often favours or explicitly translocates fast-growing species adapted to warmer and drier conditions (frequently early successional species). While these changes may not be directly targeted towards climate change itself, they can function in parallel, with harvesting or reforestation efforts often favouring the types of species likely to succeed in future climates. For example, Danneyrolles et al. (2019) document widespread changes in community types across >130,000 km$^2$ of Canadian boreal forest associated with land-use history, changes that favour species likely to fare better under future climate conditions. Similarly, Wang et al. (2019) found that harvest activities will likely ameliorate many of the negative effects of climate change on management-relevant species by favouring transitions to warm/dry tolerant species. While this provides a proof of concept regarding social factors shaping fundamental ecosystem adaptation via disturbance, we also note there is essentially no evidence that favours active management in more wild systems where management often has a negative impact (e.g. fire suppression).

The role of biodiversity in maintaining short-term ecosystem functioning despite climate change has been historically debated, with arguments for and against the relative importance of biodiversity versus external factors (see Mooney, 2002). In the long-term, however, as ecosystems need to adapt or transform, higher biodiversity is generally accepted to be important, equating to a higher variety of species that might persist in future conditions either at a specific location (Oliver et al., 2015) or within a spatial landscape that provides adaptive/transformative capacity to the surrounding areas (Isbell, Tilman, Polasky, & Loreau, 2015). Higher biodiversity equates to redundancy in ecosystem service provision in many (but not all) cases, providing continuity through time despite individual species being lost as the climate shifts. There are still considerable debates about the relative importance of individual species, and the potential idiosyncratic nature of keystone species. At broad scales, however, higher biodiversity appears to favour continuity in functioning despite change in composition.

For many species and systems, however, the effects of disturbances are less clear. This often involves a temporal mismatch between disturbances and the rate of climate change. First, if disturbances occur relatively infrequently, the effects of the shifting disturbance regimes may be minimal compared to shifting climatic variables (Boisvert-Marsh, Périé, & de Blois, 2019). In other words, the velocity of climate change may be too fast and opportunities out of sync with life-history constraints. Second, disturbances that occur too frequently for establishment, growth, maturity and then reproduction to occur can inhibit survival and migration, as can disturbances that favour competing species (Moran & Ormond, 2015). In general, species less tolerant of post-disturbance environments are unlikely to migrate as quickly due to their need for ecosystem development time post-disturbance, and thus may be lost (Scheller & Mladenoff, 2005). This occurs because either the rate of climatic change outpaces the ability of the species to disperse or the time period between opportunities to migrate is longer than the climatic window of opportunity (Renwick & Rocca, 2015). In these cases where adaptation is not favoured, when change eventually occurs, it is likely to be threshold-type change, rapid and fundamental (e.g. forest loss; McDowell et al., 2016).

### 3.2 | Social response

In social systems, disturbances are often disasters, with profound consequences for human life and well-being. Birkmann and Fernando (2008) note that major disasters, like the 2004 Indian Ocean tsunami, can result in broader policy and governance changes; though in that case, changes were observed only in some places and were either maladaptive or effective depending on the social and ecological contexts. Generally, disturbances are more likely to catalyse learning and adaptation when collaborative forums with a diversity of participants are in place (Armitage, Berkes, Dale, Kocho-Schellenberg, & Patton, 2011). Such groups can undertake pre-disturbance planning and focus on long-term risk reduction goals, overcoming challenges associated with powerful political actors or temporal mismatches.

While there are often difficulties in changing formal policy (see the discussion of inertia, above), other adaptational pathways may emerge. Both Nelson (2007) and Abrams, Huber-Stearns, Bone, Grummon, and Moseley (2017) identify minimal formal changes to governance in response to extensive bark beetle outbreaks, largely because of the influence of economic interests and bureaucratic institutions that favoured the status quo. However, insect outbreaks led to the creation of regional, multi-party collaborative groups that brought together diverse interests, explored potential solutions and raised external funds to protect human safety and infrastructure (British Columbia, Colorado and Southern California; Abrams et al., 2017; Peterson & Wellstead, 2014). These efforts demonstrate an increased reliance on networked institutions to facilitate response to disturbances when more formal changes to policies or other governance institutions may be stymied by powerful interests, bureaucratic inertia or a lack of political momentum to redesign policy approaches.

Governance processes may also be redesigned to address new challenges. For instance, Rutherford and Schultz (2019) found that collaborative, multi-jurisdictional forums, formed decades prior to connect actors for fire planning can prove useful for addressing increased fire as a result of climate change. Collaborative partnerships around forest and watershed management also have undergone substantial changes as a result of lessons learned after large fires and subsequent flooding that caused dramatic problems for water quality and infrastructure. Huber-Stearns et al. (2019) found that watershed partnerships, which invest new sources of funding in forest restoration efforts, emerged as the result of a confluence of several factors: problem-solving by high-level policy actors (i.e. government leaders working with the US Forest Service) to engage water utilities in forest restoration on the Colorado Front Range; partners working through existing collaborative forums around forest management; and the focusing events of major fires that led to sedimentation and extensive damage to reservoirs. Often the temporal mismatch between the pace of disturbance and the rate of governance change can be problematic because policy change can become more difficult and less relevant as the time from a disturbance event increases. Yet enduring collaborative coalitions, as were present on the Colorado Front Range, can maintain focus on solving long-term challenges even years after a major event (Huber-Stearns et al., 2019).

Some of the most explicit examples of disturbances creating opportunities for adaptation, and people taking advantage, involve floods. Researchers with the Pew Charitable Trusts (2019) show that adaptive funding programs and policies can be put into place soon after major flood events. They note that community-based planning and strong communication are important to identify locally specific problem drivers and solutions, present solutions to policy makers, and ensure community members are aware of available resources. Local flood mitigation policies often work in concert with state support in the form of tax incentives, cost-sharing, or selective assistance to communities that have taken specific actions. The authors suggest that disturbances should be used as opportunities to change policy because they focus residents' attention on adaptation needs.

Disturbances can lead to responses that may not be adaptive or even be undesirable. Invasive species can take over ecosystems, for example, Anderson et al. (2018) note past floods resulted in built infrastructure which sometimes exacerbates subsequent floods. In the case of forest management, multi-decadal suppression policy in response to fires in the early 20th century has led to more intense fires (Millar & Stephenson, 2015). Understanding trends of disturbance likelihoods (e.g. increased fires in a given area) is a necessary pre-requisite for successful adaptation planning that takes advantage of disturbances when they occur, but also grapples with the potential future legacies of maladaptive changes.

Generally, adaptive responses to disturbances by social systems are often limited, especially in places lacking pre-event collaboration and planning. Change is often stymied by the desire to 'return to normal' as quickly as possible, resisted by powerful, entrenched actors or inhibited by existing policies. Yet opportunities exist where institutions are flexible, inclusive of diverse actors, and collaborative—especially if planning for future disturbances occurs ahead of time to deal with persistent temporal mismatches between the pace of governance and disturbance processes (Kates, Travis, & Wilbanks, 2012; Lindenmayer et al., 2010). Adaptation also requires action at multiple levels of government, in order to solve problems that might require locally tailored solutions with support from higher-level policy makers (Djalante et al., 2011; Ulibarri & Scott, 2019).

## 4 | CLASSIFYING OPPORTUNITIES

We propose a typology of ecological and social adaptiveness, mediated by the connectedness between the social and ecological components within a system. For instance, in situations where both the social and the ecological systems are ill-equipped to utilize opportunities for transformation, disturbances may be highly disruptive (Figure 1). On the Tongass National Forest climate warming has caused extensive mortality for an economically significant species (Buma et al., 2017) without concomitant disturbances that could favour species migration (Krapek, Hennon, D'Amore, & Buma, 2017); as a result, the ecological community has lost diversity (Oakes, Hennon, O'Hara, & Dirzo, 2014). Similarly, changes in the social and political system have been limited, remaining strongly timber-focused despite a decline of 80% in harvest rates (Berg et al., 2014) primarily driven by global economic trends and competition from less remote locations. As a result, the timber industry, both as a powerful political player and in places one of the only sources of economic productivity, may work against adaptation even when it is necessary. In the Tongass, the recent rise of the tourism industry—often opposed to the historical intensive forestry management due to the visual impact of clear-cuts and the pollution of pulp mills—represents a social disruption that may facilitate adaptation in the future (NPR, 2017). A recent push to repeal the Roadless Rule and open hundreds of thousands of hectares to logging despite protests from a variety of local groups, however, demonstrates the hold that logging still has on the social system of the region, particularly among actors connected to current political leaders. We see this is an example of more 'resistant systems', where adaptation can be difficult and disruptive (Figure 2).

We can also imagine social and ecological systems that are primed for adaptive change. In these cases, climate change and disturbances can be an opportunity for 'coordinated adaptation', in the sense that disturbances might be less disruptive when they are planned for and not too extreme. For example, after several highly damaging fires in the US Southwest pine forests, local communities are proactively adapting (both socially and ecologically) to climate change. With support from local, state and federal government partners, community-level organizations and bridging organizations like the Rio Grande Water Fund (riograndwaterfund.org) and the Four Forests Restoration Initiative (4fri.org) are planning and implementing fuels reduction and other activities to reduce fuels and restore natural fire regimes. The ecological system is diverse, and future-climate adapted ecological communities may emerge (Sánchez Meador, Waring, & Kalies, 2015). Although there are difficulties reconciling visions among stakeholders of what the future forest should look like (prioritizing ecological conservation, future fire regimes, habitat, basal area for timber, and identifying forest products industry partners to implement work, etc.; Sánchez Meador et al., 2015), the expectation of future disturbance events—and adapting to them—is a core tenant of the discussion (Urgenson et al., 2017).

This stands in contrast to communities with less capacity to adapt but where ecosystems are changing rapidly—what we term cases of 'disruptive ecology'. For example, increased fires in along urban edges present a difficult environmental challenge, particularly when social systems and infrastructure are extensive and lack the ability to adapt as quickly as climate change proceeds. In these instances, temporal matching and collaboration at large scales present a tremendous challenge. For large cities in California urban areas, where fires are increasingly damaging, significant governance changes are needed. The potential strategies, like redesigning infrastructure, moving communities or subsets of communities, reducing inequalities in disturbance exposure, facilitating equitable access to infrastructure updates post-disturbance, and improving communication/collaboration strategies all present daunting challenges.

In situations where ecological adaptation is unlikely, but the social system has adaptive capacity, there is both more opportunity and more necessity for proactive change. At the extreme, an example would be communities that need to relocate due to rising sea levels (Bronen & Chapin, 2013). There are examples of 'creative social communities' that are working to undertake such challenges (although we recognize that this is an idealized characterization of what is likely to be a highly challenging and disruptive situation replete with uncertainty). As an example, some local communities on barrier islands in the Gulf of Mexico, like Isle De Jean Charles in Louisiana, are planning to migrate as a community with governmental aid, indicating that both community characteristics and supportive government institutions are important factors in difficult situations (isledejeancharles.la.gov). In another case, forest-adjacent communities may be able to stay in place but are threatened by disruption due to loss of timber-relevant species. For those, adaptive shifts to other industries (Kirilenko & Sedjo, 2007) or proactive assisted migration (Williams & Dumroese, 2013) will likely be necessary, though with non-trivial ecological risk and short-term changes that may be highly disruptive for pre-existing social and ecological systems (Kates et al., 2012). In these cases, the climate-threatened ecological system is forcing action. Particularly where transformation is difficult but plausible, building community capacity to promote diverse participation in collaborative forums that can work on difficult problems over time will be critical.

## 5 | FUTURE RESEARCH DIRECTIONS

Climate change is shifting several, interlocking aspects of ecological and social communities simultaneously—and as a result, proactive planning is both important and difficult. Future research should explore how social systems respond to the opportunities that disturbances present and aim to support proactive social and environmental change when it is inevitable (e.g. Urgenson et al., 2017), especially in the context of climate change uncertainty (Kates et al., 2012). While there is considerable literature looking at factors that support adaptive capacity in systems, we suggest that there is ample room for research looking across several key topics related to these significant but (historically) infrequent events: pre-disturbance conditions that allow differing communities to pivot to more adapted systems post-disturbances; how this varies with disturbance type, scope, frequency and severity; and how adaptive opportunities may be more or less accessible for different aspects and specific populations within social and ecological systems (as we explore in Figure 2). There are also interesting questions for further research regarding what kinds of adaptation may be more feasible in response to different disturbances (Ulibarri & Scott, 2019).

For ecosystems, at broad scales, the observations that (a) disturbances facilitate migration in some ecosystems, (b) disturbances are not randomly distributed on the landscape and (c) certain spatial locations are disproportionately important for migration suggests that disturbance ecology investigations relevant to community adaptation might prioritize specific, migration critical areas—for example, riparian corridors in the Amazon (Killeen & Solorzano, 2008) or the Appalachian range in North America (Bowers & McKnight, 2012). The decision on how, or if, to manage disturbances in those disproportionately significant areas would be better informed if the role of disturbances in adaptation was better understood and their social contexts specifically included in the research.

At the local scale, there is a rich body of literature on the effects of climate change on individual species, as well as work exploring the emergence of novel communities. Disturbance-facilitated change will likely hasten these novel assemblages. Restoration ecology, with its long interest in invasive species, is a valuable source of data regarding the effects of emerging dynamics within these new communities (e.g. Cordell, Ostertag, Michaud, & Warman, 2016; Hobbs et al., 2013). Shifting distributions of native species can have similar effects as non-native species (Nackley, West, Skowno, & Bond, 2017), and as such the analogues are valuable. Of need are investigations that incorporate expectations of disturbance and migration of plant-pollinator systems and other communities with strong inter-species dependencies, not well studied to date. In managed systems and for targeted species, assisted migration is an option, with well-appreciated risks and ongoing, and appropriate, debates about its use (St-Laurent, Hagerman, & Kozak, 2018).

## 6 | CONCLUSIONS: TAKING ADVANTAGE OF OPPORTUNITIES TOGETHER

As disturbances increase in frequency across much of the world, the question of how social and ecological systems respond to disturbance will be ubiquitous across multiple disciplines. Disturbances provide an opportunity to break through system inertia, catalysing significant adaptive change in the context of climate change for both ecological and social systems—but it is equally clear that there are barriers to that adaptation. Ecologically, opportunities arise when species are present and competitive in the post-disturbance environment; socially, the best opportunities are associated with collaborative communities with pre-existing plans (Lindenmayer et al., 2010) or stated goals for adaptation (Figure 2). For species not well suited to taking advantage of disturbance or social systems with a strong interest in maintaining the status quo (e.g. recovering rather than adapting), disturbances are less valuable as catalysts for change and may be detrimental in terms of long-term resilience.

These observations provide important guidance on where research and effort are needed. Ecologically, species expected to be detrimentally impacted by disturbances (rather than favoured) are clear candidates for social intervention (e.g. assisted migration). Socially, communities in areas that are likely to be increasingly affected by disturbances should focus on linking pre-disturbance adaptation planning, emergency response and diverse actors in collaboration. We cannot overlook the fact that disturbances can be humanitarian disasters, and that even proactive transformation can be highly traumatic. Yet this reality only underscores the need for forward-thinking planning in terms of policy, ensuring that collaborative networks are developed, priorities determined and contingencies explored before the next disturbance.

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### AUTHORS' CONTRIBUTIONS

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### DATA AVAILABILITY STATEMENT

No data have been archived because this Review article does not present new datasets.

### ORCID

*Brian Buma* https://orcid.org/0000-0003-2402-7737
*Courtney Schultz* https://orcid.org/0000-0002-9972-7802

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