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Research article

Land management objectives and activities in the face of projected fire regime change in the Sonoran desert

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ABSTRACT

As a multi-jurisdictional, non-fire-adapted region, the Sonoran Desert Ecoregion is a complex, social-ecological system faced increasingly with no-analogue conditions. A diversity of management objectives and activities form the socioecological landscape of fire management. Different managers have different objectives, resources, and constraints, and each therefore applies different activities. As a result, it can be difficult to predict the regional consequences of changing fire regimes. We interviewed and surveyed managers of 53 million acres of government-managed lands across the Sonoran Desert Ecoregion of Arizona, asking them to describe their management objectives and activities as well as expected changes in the face of projected fire regime change across the region. If current activities were deemed unlikely to meet objectives into the future, this represents a likely adaptation *turning* point, where new activities are required in order to meet objectives. If no potential activity will meet an objective, it may be necessary to select a new objective, indicating an adaptation *tipping* point. Here, we report which current objectives and activities are deemed by managers most likely and least likely to succeed. We also discuss constraints reported by managers from different jurisdictions. We find that agriculture, military, and resource extraction objectives are perceived by managers as most likely to be met, whereas conservation of natural and cultural resources is considered least likely to be achieved. Federal land managers reported higher likelihood of both achieving current objectives and adopting new activities than did non-federal land managers. This study illustrates how rapid global change is affecting the ability of land managers differing in missions, mandates, and resources to achieve their central objectives, as well as the constraints and opportunities they face. Our results indicate that changing environmental conditions are unlikely to affect all management entities equally and for some jurisdictions may result in adaptation turning points or tipping points in natural and cultural resource conservation.

1. Introduction

Resilience is a multi-faceted system characteristic that has been defined in various ways within different streams of literature. The central concept in resilience is that of the stable state, the set of characteristics that describe a given focal system prior to perturbation. Studies of resilience examine factors that influence the amount of change required for an ecosystem to reach a point of no return (a.k.a. "tipping point") at which it transitions to a different type of system (for example, a desert grassland ecosystem to a mesquite-dominated woodland) (Ruesink et al., 2006).

The Sonoran Desert in the southwestern United States is generally considered non-fire-adapted, with native vegetation growth patterns that result in non-continuous fuels and few native fine fuels (Alford et al., 2005; Fuentes-Ramirez et al., 2016). Today, however, the Sonoran Desert faces significant climatic change in the form of steadily increasing temperatures and increasingly patchy rainfall (Abatzoglou and Kolden, 2011; Seager et al., 2007). Increasingly rare and intense precipitation periods, followed by severe drought, can spur biomass production and rapid drying of fine fuels, resulting in elevated fire risk (Gray et al., 2014). Widespread invasion of non-native annual grasses creates a novel layer of continuous fuels that can link native vegetation patches and spread fires ignited by lightning or human activity (McDonald and McPherson, 2013; Moloney et al., 2019). Home to numerous threatened

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and endangered species (Dimmitt et al., 2015), the Sonoran's sensitive plant communities (dominated by cacti and leguminous trees) are not adapted to short fire return intervals, and its native species lack fire recovery mechanisms (Weiss and Overpeck, 2005). Deserts such as the Sonoran may be at risk of self-reinforcing system state change, driven by transformed fire regime. Under such conditions, fire events result in loss of native plants and increased dominance by invasive plant communities which are, in turn, more fire-prone (Rietkerk et al., 1997).

A large majority of this at-risk ecosystem in the US is managed by government at various levels (federal, state, county, local, and Tribal). Such lands are managed to meet established mandates, which underlie management objectives and the activities used in pursuit of those objectives. An "adaptation turning point" identifies the amount or threshold of environmental change that renders current management activities unable able to meet objectives (Kwadijk et al., 2010; Werners, 2013). For example, increased continuity and quantity of flammable fuels under future climate change may make suppression of active ignitions unlikely to adequately meet management objectives, forcing managers to consider fuel reduction and other fire prevention activities. By recognizing turning points, managers can better prepare for the likelihood that they will have to adjust their fire management strategies in order to meet objectives (Kwadijk et al., 2010; Berkhout et al., 2014).

As a case study of adaptation turning and tipping points in a socio-ecological system facing significant environmental change, we examined land management objectives and related activities across government-managed lands within the Sonoran Desert Ecoregion of Arizona. We used a workshop, interviews, and surveys to understand (a) the range of objectives underlying decision-making by managers from different government agencies on the landscape, (b) the range of activities employed to meet each objective, (c) how different managers varied in their confidence that current objectives could be met with current activities under future fire risk, and (d) the extent to which each manager felt that alternative objectives and/or activities could be adopted as needed. Our principal goal was to determine which management entities and objectives are perceived as most vulnerable to fire regime change and thus likely to experience management turning points or tipping points. Our multifaceted case study approach, while yielding data specific to the Sonoran, may provide managers and researchers elsewhere (and particularly in other arid, multijurisdictional, and largely government-managed systems) with insights into the varying effects of significant environmental change within socially complex systems. Furthermore, our findings elucidate links between land management objectives, activities, constraints, and effectiveness under novel disturbance regimes.

2. Materials and methods

The first step to using an adaptation turning point framework in global change-related research is to present likely environmental change scenarios to land managers (Tompkins et al., 2008). With this information in hand, managers can consider and discuss with researchers the likely impact of each future scenario on their current management objectives and activities (Shackley and Deanwood, 2003). We used the results of previous modeling work (Gray et al., 2014) to map risk of large fires, projected 20 years into the future, across the Sonoran Desert Ecoregion. We created downscaled maps for each government jurisdiction in the study area, and presented those maps to jurisdictional managers, as representatives of management agencies. We placed 10 random points on each map and asked managers, in view of the mapped fire risk, to describe their current management objectives at each of these points, the activities they use to meet those objectives, and the likelihood that those activities will continue to meet objectives given projected fire risk futures (where likelihood was defined by a Likert scale of 1–5, where 1 = very unlikely, 2 = unlikely, 3 = unknown, 4 = likely, and 5 = very likely). If that likelihood was low, we asked managers whether alternative activities could be adopted to meet objectives or, if not, whether new objectives could be adopted (using the same 1–5 Likert scale). To begin this process, we initially met with managers from 11 jurisdictions in a day-long workshop format. These managers provided feedback on the study as a whole as well as supplying the above information for each random point on their own jurisdictional map. Following the workshop, we reached out to the managers of 30 additional jurisdictions to request individual interviews; we eventually secured participation from managers of a total of 25 jurisdictions (Fig. 1, SI Table 1) (where jurisdiction is defined as the day-to-day decision-making body for a given land management unit).

To allow analysis of resulting objective and activity data and comparison across jurisdictions, we identified a set of objective and activity categories, based on our conversations with managers during the workshop, and coded each reported objective and activity by those categories. Two researchers coded the objectives and activities described in each interview so that inter-coder reliability could be assessed (Kurasaki, 2000). To compare associations between the categorical objectives and activities reported by type of management agency (military, non-military federal, state, local, and tribal), we used generalized linear models (in R-package 'glm,' R-Core-Team, 2017) fitted with a logit link function to specify a binomial error distribution (Myers and Montgomery, 1997). We performed pairwise post-hoc comparisons with a Bonferroni correction to account for multiple comparisons (in R-package 'emmeans').

We next examined manager-reported perceived likelihood, measured on the 1–5 Likert scale described above, that current activities will continue to meet current objectives into the future, and also that alternative activities or alternative objectives will be able to be adopted. From these data, we were able to compare levels of manager-reported likelihood that each activity or objective would be successful or continue into the future. Data did not meet assumptions of normality based on quantile-quantile plots (Wood, 2010), so we used nonparametric Kruskal-Wallis tests to examine differences among objectives and activities and employed Dunn's multiple comparisons posthoc tests to determine which pairs of objectives or activities differed significantly (Dinno, 2015). Additionally, since jurisdictions managed by federal agencies (Bureau of Reclamation, Bureau of Land Management, National Park Service, US Fish and Wildlife Service, US Forest Service, and Department of Defense) were so abundant in our dataset compared with other hierarchical categories, we performed simple Student's t tests to determine whether federal vs. non-federal jurisdictions varied in reported likelihood that objectives would be achievable and activities successful. For all analyses, significance was accepted at alpha = 0.05.

Finally, we administered a survey to participating managers to explore how they perceived their organizations' adaptive capacity, including constraints influencing their ability to adopt new activities or objectives and thereby respond to adaptation turning points or tipping points. Survey items focused on organizational innovation and uncertainty, adaptive management practices, and organizational barriers to change (Lockwood et al., 2015; Williams et al., 2009). Responses were recorded on a 7-point Likert scale, such that 1 = Strongly Disagree and 7 = Strongly Agree. The survey was provided to 88 land manager contacts within the study area (i.e., the survey was received by multiple managers in some jurisdictions, but individuals from the same jurisdiction worked together to supply responses). Workshop participants received the survey in paper form, and after the workshop we emailed non-attendees a link to an electronic version of the survey, with three follow-up reminders. Survey responses were kept confidential and identifying characteristics were removed. Likert-scale survey responses were summarized by the percentage of respondents agreeing or disagreeing with each question, although due to limited response rate no additional statistical analyses were attempted. Open-ended responses were analyzed inductively: first grouped using open coding, and then systematically themed and categorized (Bernard, 2017; Corbin and Strauss, 2014).

3. Results

3.1. Objectives and activities reported by participants across agencies

Respondents from 25 jurisdictions, accounting for 79% of the land area in our study extent and managed by federal, state, local, and tribal government agencies (SI Table 1; Fig. 1), participated in this study. Management objectives described in interviews were coded into a total of 10 categories: general fire suppression, conservation, grazing, agricultural, resource extraction, military, recreation, human and infrastructure protection, cultural resource protection, and no objective (Table 1). Generalized linear model results indicated that respondents cited certain management objectives more frequently than others ($\chi^2 = 380.07$, $p < 0.0001$; SI Fig. 1). Overall, objectives related to ecological conservation, fire suppression, and recreation were most commonly mentioned in interviews, while agriculture, military, grazing, and resource extraction objectives were least frequently mentioned (SI Fig. 1). Non-military federal managers reported a particularly high diversity of land management objectives, including agriculture, conservation, cultural resource protection, general fire suppression, grazing, human and infrastructure protection, recreation, and resource extraction (Table 2). Relative to other management entities, non-military federal government managers more frequently mentioned cultural resource protection and general fire suppression objectives; respondents from state entities more often mentioned agriculture-related objectives; and managers from tribal institutions more often reported cultural resource and human infrastructure protection objectives (Table 2). Participants from all agency types reported objectives related to conservation and recreation, while resource extraction was rarely cited as an objective across agencies (Table 2).

Management activities to meet objectives also differed by agency (SI Tables 2–6). For the objective of fire suppression, managers from most agencies described active fire management activities following ignition (Table 5; SI Table 2); fewer managers identified activities related to fire prevention, such as grazing to reduce fine fuel loads, native and non-native vegetation removal, and outreach and education (SI Table 2). To meet conservation objectives, managers from non-military federal, local, military, and tribal agencies frequently cited native species management activities, whereas state agency managers met conservation objectives primarily through invasive species removal efforts (Table 4;

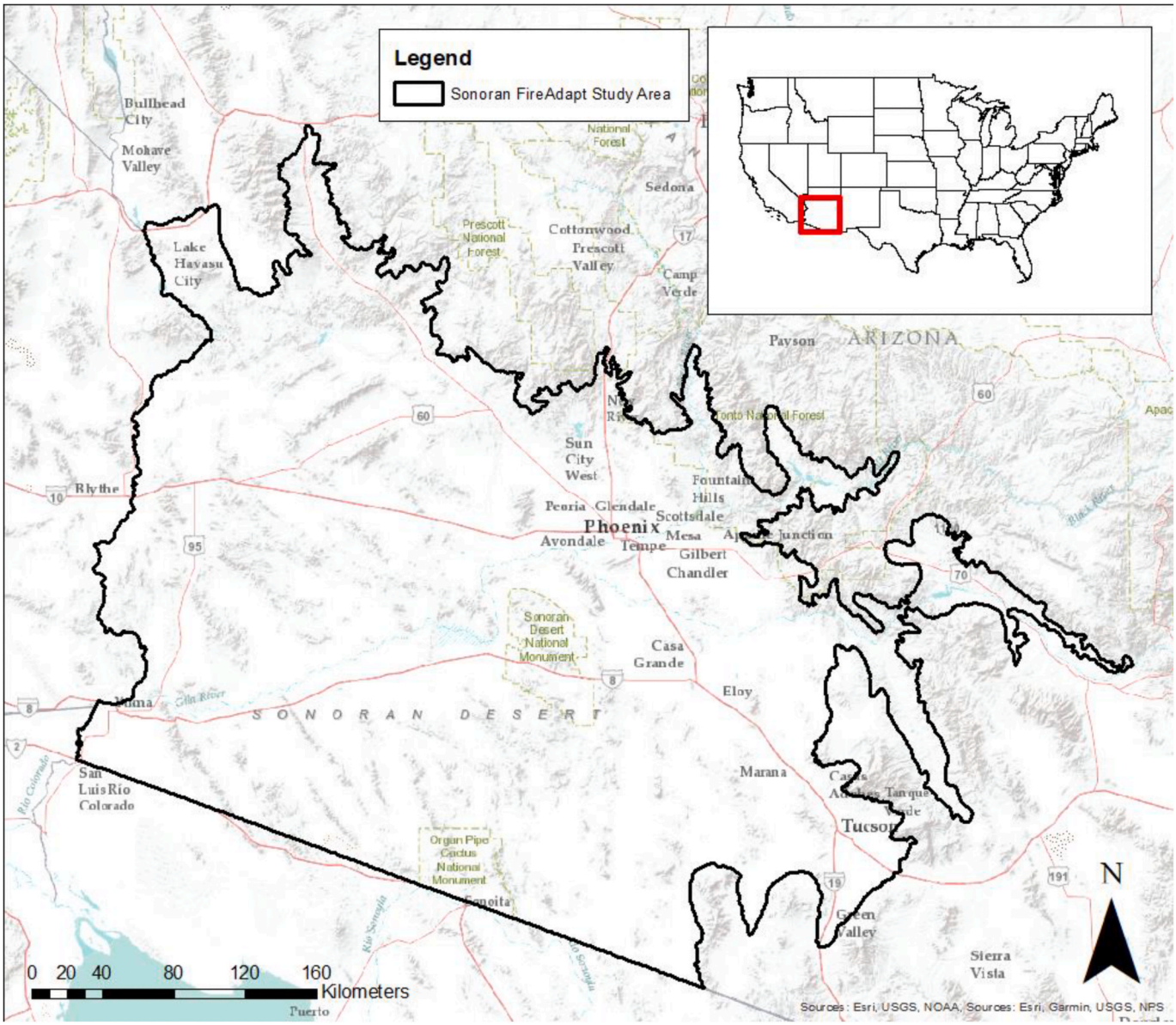

Fig. 1. Map of the Sonoran Desert Ecoregion of Arizona, the focal landscape for this study.

Table 1
Table of management objective and activity categories into which reported objectives and activities were collapsed for analysis.

Management objective categories	Objectives reported by managers and included in this category
Conservation	habitat/species protection, ecological integrity, conservation, wilderness management, restoration, resource management fires
Resource extraction	Mining, minerals exploration and rights, prospecting
Grazing	livestock grazing
Agriculture	all non-grazing agriculture
Fire suppression (general)	fire suppression, roadside fire reduction, lightning strike monitoring
Human/infrastructure protection	infrastructure protection (private and commercial plus roads, powerlines, visitor centers, and campgrounds), human safety (nearby communities), air quality, communications, water management (flood control)
Military	military (training, etc.) and border activities (patrol, enforcing border laws, controlling illegal border activity, border patrol cooperation)
Recreation	hunting, viewshed protection, infrastructure, camping, scenic driving, general recreation
Cultural resource protection	sites and infrastructure, historical sites and buildings, saguaro harvest, traditional uses of area and plants
None	manager lists no management objective for that spatial location or lists a historical (but not current) objective
Management activity categories	**Activities reported by managers and included in this category**
Fire management	general suppression, fire breaks, fuel breaks, access/pre-positioning for fire crews, let burn/monitor, prescribed burns/management fires/ fire regime, fuel load monitoring, road and trail closures, shooting restrictions, burning/fires restrictions/bans, restricting access to culturally important sites, increasing patrols, hazard mitigation
Preventative vegetation/invasives removal for fire	preventative vegetation/invasives removal for fire: general thinning, site-specific fuel removal (around infrastructure and roads), herbicide or manual removal, invasives/grasses removal, mastication, tamarisk removal, general invasive grasses removal, buffer creation, mowing, grazing for fuel management, grazing for invasives/grasses removal
Grazing	leasing for grazing, permits for grazing
Outreach and education	education, public service announcements
Native species management	monitoring for conservation management (invasive/exotic species including feral horses, native vegetation long-term, wildlife populations (like pronghorn and yellow-billed cuckoo), endangered species, birds (eagles, etc.), rare species, riparian habitat), restoration (native species seeding, restoration of general species/habitat, restoration of species for cultural use), maintenance of vegation and native plants (cultural uses, medicinal)
Crops	leasing for crops, irrigation for crops
Resources from partnerships	funding, partnerships/agreements, general, partnering with local fire departments
Leasing and permits	other (not crops or grazing) leasing and permits, improving guidelines and rules for land use
Infrastructure development	general irrigation (not for crops), improved fencing, improved wells/other water infrastructure, firewise campgrounds - infrastructure and training
Soil and watershed protection	erosion prevention/retention for flood control or other reasons
Cultural and social resource protection	maintenance of recreational sites, cultural resources, cultural sites, native plants (for cultural uses, medicinal reasons), preventative maintenance
Recreation	hiking, camping, hunting/shooting, OHV, ORV, general recreation
None	manager lists no current management objective for that point on the map

SI Table 3). Managers from most agency types considered fire management a necessary activity to manage for recreation, in addition to direct maintenance of recreational areas (e.g., campgrounds, hiking trails) and recreational permitting (Table 4; SI Table 5). Both non-military federal managers and tribes managed land for cultural resources. Tribal government managers focused on cultural and social resource protection, which included identifying and maintaining areas of cultural importance, and native species management of culturally important plants. Non-military federal government managers, on the other hand, emphasized active fire management and preventative vegetation removal around structures or areas of cultural importance. Non-military federal and tribal participants also identified active fire management as a critical activity to meet agricultural objectives (Table 4; SI Table 6). Probably due to low sample size, activities to meet objectives related to grazing, military, and resource extraction did not differ among agency types.

3.2. Perceived likelihood that activities and objectives will continue under future conditions

On average, reported Likert-scale (1–5) levels of perceived likelihood that objectives could continue under future conditions hovered around the central value of 3, meaning "unknown" in Likert-scale likelihood assessments and thus indicating uncertainty on the part of managers (Table 3, Fig. 2). However, there were differences in reported likelihood that objectives would continue into the future (Kruskal-Wallis $X^2 = 104.67$; $p < 0.0001$) (Fig. 2a), with agriculture, military, and resource extraction objectives considered significantly more likely to be achieved than conservation or cultural resource protection objectives (Fig. 2a). Likewise, there were significant differences in the likelihood that management activities would achieve objectives (Kruskal-Wallis $X^2 = 52.13$; $p < 0.0001$) (Fig. 2b), with crops, grazing, and vegetation management for fire prevention considered significantly more likely to succeed than cultural and social resource protection or native species management (Fig. 2b). Across all activities, managers of federal jurisdictions reported higher perceived likelihood of achieving results than did non-federal managers (mean Likert-scale likelihood 3.42 vs. 3.13) ($t = 4.58$; $p < 0.0001$). Managers of federal jurisdictions also reported higher likelihood of adopting new activities than did non-federal managers (mean Likert-scale likelihood 3.89 vs. 3.51) ($t = 5.23$; $p < 0.0001$).

3.3. Survey analysis: indicators of adaptive capacity

A total of 32 respondents (a response rate of 36.4%) representing 11 management agencies responded to the survey (SI Table 7) examining perceived capacity to adopt new approaches in response to adaptation turning and tipping points. Survey respondents described multiple drivers of change in objectives and strategies that had occurred previously for their jurisdictions. Change due to increases or reductions in funding availability was the most frequently cited of these drivers ($n = 5$) (SI Table 8). Notably, only one respondent identified past fire, specifically, as a driver of change in objectives and strategies. Respondents also identified multiple barriers to changing management strategies or objectives when needed. The most cited of these barriers was inadequate funding ($n = 11$), followed by inadequate time ($n = 6$), inadequate staffing ($n = 5$), and political or policy context, such as NEPA constraints or other policies ($n = 5$) (SI Table 9).

A majority of respondents (75–100%) agreed with statements indicating that their organizations were able to innovate and manage uncertainty (SI Table 10). We also explored perceptions of organizational constraints to making change, including time, finances, public opinion, neighboring land managers, and the financial leeway to make mistakes. Most respondents (72%) did not believe that their organizations have enough resources to manage fire and fuels either on a day-to-day basis or

Table 2
Summary table of management objectives (row headings) reported by land management agencies (column headings) and corresponding X^2 and p-values for statistical analyses of each objective. Within the Management agency columns, values represent the proportion of total manager-reported objectives comprised by each objective, reflecting the relative investment of land management entities in those objectives. Statistically significant differences (alpha ≤0.05) among management agencies in the reporting of objectives are emboldened.

		Management Agency					Statistical Results	
		Federal non-military	Local	Military	Tribal	State	χ^2	p-value
Management objective	Agriculture	0	0	0	0.1	0.2	**28.58**	**<0.01**
	Conservation	0.21	0.23	0.07	0.14	0.2	8.52	0.07
	Cultural Resource Protection	0.13	0	0	0.24	0	**38.66**	**<0.01**
	Fire Suppression General	0.26	0.03	0	0.08	0	**59.95**	**<0.01**
	Grazing	0.04	0.07	0	0	0.33	**22.56**	**<0.01**
	Human/Infrastructure Protection	0.02	0.2	0.17	0.22	0	**51.45**	**<0.01**
	Military	0	0	0.5	0	0	**124.82**	**<0.01**
	None	0.01	0.24	0.02	0.04	0	**54.95**	**<0.01**
	Recreation	0.3	0.24	0.22	0.2	0.27	4.15	0.39
	Resource Extraction	0.03	0	0.02	0	0	6.41	0.17

during fire incidents (SI Table 11). A large majority (89%) also agreed that while their organization may be open to trying different approaches, funding availability is a constraint to making changes. Responses varied more widely as to the perceived role of public opinion and neighboring land management units in constraining needed change, as well as the role of time and the financial flexibility to try different options or make mistakes, with percent agreement with these statements ranging from 57 to 64% (SI Table 11).

4. Discussion

Fire regime change can impact biodiversity, economic systems, recreation, and human health and safety (Bowman et al., 2011; Williams et al., 2009). These fundamental effects make land management in the face of fire regime change particularly challenging, since fire affects a wide swath of resources, crosses boundaries, and responds to both social and ecological drivers (Schultz and Moseley, 2019). Understanding the social context within which fire regime change emerges is essential to identifying responses that permit land managers to adapt effectively to novel conditions (Moser et al., 2010). Collaboration and information flow across boundaries are essential in order to develop and carry out meaningful responses to fire regime change in multijurisdictional landscapes (Steele et al., 2014; Schultz and Moseley, 2019), and such collaborative efforts require networking, resources, and shared vision (Howes et al., 2015; Scarlett and McKinney, 2016). Cross-boundary responses to fire regime change, however, can be impeded by differences among organizations in resources, information, and objectives (Fischer and Jasny, 2017). Continued environmental change requires continued adaptation (Stein et al., 2013) and thus organizational flexibility in activities and resources (Camacho and Glicksman, 2016). It is increasingly evident that the degree to which managing institutions are adaptive and flexible in their decision-making is critical to wildfire resilience in

Table 3
Mean perceived likelihood that objectives can be achieved and current activities will be effective, by management agency type, in light of projected fire regime shifts. Data were provided by managers on a Likert scale from 1 to 5 (1 = very unlikely; 2 = unlikely; 3 = unknown; 4 = likely; 5 = very likely). Mean values below 3 (i.e., unlikely) and above 4 (likely) are emboldened to emphasize areas of pessimism and optimism, respectively.

a. OBJECTIVES	Federal	Local	Military	Tribal	State
Agriculture	**2.00**			**5.00**	**5.00**
Conservation	3.09	3.00	3.78	**2.79**	3.00
Cultural Resource Protection	3.24			**2.53**	
Fire Suppression General	3.64	**5.00**		**2.63**	
Grazing	3.59	3.00			3.20
Human/Infrastructure Protection	3.47	3.40	3.57	3.16	
Military	3.00		3.80		
Recreation	3.34	3.44	3.77	**2.00**	3.64
Resource Extraction	3.78		**4.00**		
AVERAGE	3.24	3.57	3.78	3.02	3.71
b. ACTIVITIES	**Federal**	**Local**	**Military**	**Tribal**	**State**
Crops					**5.00**
Cultural and social resource protection	3.09		**4.00**	**2.33**	
Fire management	3.43	**4.22**	3.25	3.38	3.50
Grazing	3.96	3.00			3.20
Infrastructure development	3.00	3.00			**4.00**
Leasing and Permits	**4.00**		**4.00**		
Native Species Management	3.31	3.00	**4.29**	**2.93**	
Outreach and education	3.53	3.00			**4.00**
Preventative vegetation/invasives removal for fire	3.28	3.00	3.42	**2.50**	3.25
Recreation	3.30	3.33	3.79	**2.00**	3.50
Resources from partnerships	3.35	3.20			
Soil and watershed protection		3.00			
Vegetation/invasives management for fire	**4.00**				
AVERAGE	3.48	3.20	3.79	2.63	3.78

Table 4
Generalized linear model (GLM) with binomial error distribution results exploring relationships between management activities (column headings) and objectives (row headings). Significant p-values (≤0.05) indicate a statistically significant relationship between the categorical objectives and activities reported by management agencies. Dashed lines within cells indicate that there was no corresponding management activity cited for a particular objective.

		Management activity categories										
		Fire management	Native species management	Infrastructure development	Outreach and education	Preventative vegetation removal	Grazing	Resources from partners	Soil and watershed protection	Recreation	Crops	Leasing and permits
Management objective categories	Fire suppression	$\chi^2 = 8.72$; $p = 0.01$	$\chi^2 = 0.4$; $p = 0.82$	–	$\chi^2 = 2.65$; $p = 0.27$	$\chi^2 = 0.96$; $p = 0.62$	$\chi^2 = 1.4$; $p = 0.50$	$\chi^2 = 1.25$; $p = 0.54$	–	–	–	–
	Conservation	$\chi^2 = 11.65$; $p = 0.02$	$\chi^2 = 26.22$; $p < 0.01$	–	$\chi^2 = 1.43$; $p = 0.84$	$\chi^2 = 16.57$; $P < 0.01$	–	$\chi^2 = 7.5$; $p = 0.11$	$\chi^2 = 11.17$; $p = 0.02$	–	–	–
	Cultural resource protection	$\chi^2 = 6.95$; $p < 0.01$	$\chi^2 = 3.84$; $p = 0.05$	–	–	$\chi^2 = 7.64$; $P < 0.01$	–	–	–	–	–	–
	Agriculture	$\chi^2 = 11.46$; $p < 0.01$	–	–	–	–	–	–	–	–	$\chi^2 = 11.46$; $p < 0.01$	–
	Grazing	–	–	–	–	$\chi^2 = 1.11$; $P = 0.57$	$\chi^2 = 2.28$; $p = 0.32$	–	–	–	–	–
	Recreation	$\chi^2 = 13.36$; $p < 0.01$	$\chi^2 = 7.26$; $p = 0.12$	–	–	$\chi^2 = 5.34$; $P = 0.25$	–	$\chi^2 = 12.9$; $p = 0.01$	–	$\chi^2 = 13.58$; $p < 0.01$	–	–
	Military	–	–	–	–	–	–	–	–	–	–	–
	Resource extraction	–	–	–	–	–	–	$\chi^2 = 0.76$; $p = 0.38$	–	–	–	$\chi^2 = 1.5$; $p = 0.22$
	Human/ infrastructure protections	$\chi^2 = 20.76$; $p < 0.01$	–	$\chi^2 = 6.3$; $p = 0.10$	$\chi^2 = 6.3$; $p = 0.10$	$\chi^2 = 11.65$; $p < 0.10$	–	$\chi^2 = 4.1$; $p = 0.25$	–	–	–	–

increasingly transformed social-ecological systems (Abrams et al., 2015).

In our interviews, 52% of respondents, representing all types of jurisdictions (local, state, federal non-military, military, and tribal) reported a need to change activities to meet objectives, indicating adaptation turning points. Meanwhile, 32% of respondents, again representing all types of jurisdictions, expected to change objectives, a more fundamental management shift and an indication of adaptation tipping points. It remains unclear how resilient both ecological and management systems will be to anticipated environmental changes (Elmqvist et al., 2003; Millar et al., 2007; Nelson et al., 2007). Current and projected patterns of environmental change in the Sonoran Desert include significant changes in both abiotic conditions (e.g., temperature and moisture availability) and in biotic conditions via species range shifts, single-species extinctions, and phenology shifts (Araújo and Luoto, 2007; Parmesan, 2006). In much of the arid West, warming temperatures foster invasive species spread, elevate flammability of biomass, and reduce recruitment of native species (Jardine et al., 2013; Shafer et al., 2001; Westerling et al., 2006), leading to periodic high-fire years following high-precipitation seasons (Gray et al., 2014). Fire regime change can force management changes and thus alter socioecological landscapes. Management may also help boost resilience and prevent or mitigate these changes by restoring sites that have been disturbed (Perrings and Walker, 1997).

Fire management activities, both preventative and post-ignition, were cited as tools necessary to meet nearly every objective mentioned by managers. While fire management typically took the form of active fire suppression following ignitions, some managers also mentioned preventative efforts such as non-native vegetation removal and outreach and education, indicating adaptation to the changing fire dynamics of the Sonoran. Across the study region, a shift from reactive fire suppression to broader-scale preventative fire management may require greater resource allocation across all management agency types.

4.1. Adaptation turning points and tipping points across the socioecological system

Adaptation turning points in our study were indicated by low perceived likelihood by managers that a given activity could continue into the future and (correspondingly) a high likelihood that a shift to a new activity would be necessary in order to meet objectives. Adaptation tipping points were indicated by low perceived likelihood that current objectives would continue under any activity. Turning points and tipping points varied by management agency type. Tribal agency managers identified the highest number of current activities perceived as unlikely to achieve objectives and thus linked to turning points; such activities included cultural resource protection, native species management, vegetation removal for fire prevention, and recreation (SI Table 3). Tribal managers also identified tipping points, as objectives unlikely to be achieved under any activities. These included conservation, cultural resource protection, fire suppression, and recreation (SI Table 3). Among other agency types, federal non-military managers were least certain that activities including infrastructure development, cultural protection, recreation, and native species management would continue to meet objectives, and were most confident in leasing and permits as well as vegetation removal for fire prevention. Federal non-military managers identified a tipping point for the objective of agriculture, which they expected could not be achieved under future conditions (SI Table 3). By contrast, state-level managers reported notably high confidence that crops, infrastructure development, and outreach activities would continue under future conditions, and that agriculture as an objective would continue to be achieved (SI Table 3). Local managers identified fire management as an activity likely to meet objectives, and fire suppression as an objective that would likely be achieved in the future (SI Table 3). The most optimistic management agency type, the military, reported that native species management, cultural

Table 5
Dunn's test results comparing manager-reported levels of likelihood that management objectives (top panel) would continue and that management activities (bottom panel) would meet objectives. Significant p-values (≤0.05) indicate significant differences in manager-reported likelihood between the two compared objective or activity categories.

Management objective categories						
	Conservation	Economic	Fire	Human resources	Military	Recreation
Conservation		$Z = -5.09$; $p < 0.0001$	$Z = -6.24$; $p < 0.0001$	$Z = -0.77$; $p = 0.47$	$Z = -4.50$; $p < 0.0001$	$Z = -3.38$; $p = 0.0015$
Economic			$Z = 0.83$; $p = 0.51$	$Z = 4.47$; $p < 0.0001$	$Z = -0.05$; $p = 0.96$	$Z = 2.80$; $p = 0.0085$
Fire				$Z = 5.27$; $p < 0.0001$	$Z = -0.78$; $p = 0.50$	$Z = 2.93$; $p = 0.0063$
Human resources					$Z = -3.97$; $p = 0.0002$	$Z = -2.50$; $p = 0.019$
Military						$Z = 2.49$; $p = 0.017$
Recreation						

Management activity categories					
	Conservation	Economic	Fire	Human resources	Recreation
Conservation		$Z = -4.06$; $p = 0.0002$	$Z = -1.95$; $p = 0.072$	$Z = 1.78$; $p = 0.095$	$Z = -0.68$; $p = 0.49$
Economic			$Z = 3.25$; $p = 0.0023$	$Z = 5.44$; $p < 0.0001$	$Z = 3.72$; $p = 0.0005$
Fire				$Z = 4.05$; $p = 0.0002$	$Z = 1.30$; $p = 0.22$
Human resources					$Z = -2.56$; $p = 0.018$
Recreation					

resource protection, and leasing and permits activities would continue, and that resource extraction and general military objectives would be achieved under future conditions (SI Table 3).

Overall, our participants considered agriculture, military, and resource extraction objectives particularly likely to be achieved. In part, this may be because these objectives are less directly connected to fire than, for example, endangered species conservation. However, interviewees mentioned both military exercises and prospecting as sources of accidental ignitions, and described the need to employ fire prevention when fine fuels are dense. Based on interviews, these objectives are also supported by greater access to resources, in the form of funding, materials, personnel, and time. By contrast, conservation and cultural resource protection objectives were perceived as the least likely to be achieved and thus most likely to face adaptation tipping points. Cultural resource protection includes protection from fire of buildings and historic sites as well as locations of traditional plant harvest, which in the non-fire-adapted Sonoran can be lost as a result of fire regime change. Such resources are particularly vulnerable because they are non-renewable; once lost, they are lost either forever or for a very long period of time. Additionally, such resources are fixed in place and cannot be relocated in the event of a burn. Conservation objectives include protection of sensitive species, native species assemblages, and ecosystem integrity. Because fire regime change in the Sonoran represents a novel disturbance regime to which native species are ill-adapted, effective approaches to support conservation of those species can be difficult to identify; traditional management measures may not work in highly changed systems exhibiting no-analogue conditions (Seastedt et al., 2008).

Both direct fire management and recreation were considered intermediate by our participants in terms of the likelihood that objectives would be achieved and the likelihood that activities would be successful. Respondents indicated that fire management as an objective is not likely to be abandoned in the face of fire regime change; it may simply require new approaches as regime shift pushes systems past previous thresholds and reaches adaptation turning points. Recreation can be an economic activity or an agency mandate. Our interviewees did discuss adaptation turning point impacts to recreation from fire regime shift (for example, likely future management changes stemming from increased ignition risk due to recreational shooting; increased frequency of area closures due to fire hazard; campfire bans) but did not identify recreation as an objective or activity that would likely be abandoned entirely in the face of fire regime change.

Resource availability is not the whole story when it comes to resilience. As top-down entities, federal agencies are ultimately subject to mandates and resources established by the US Congress. As a result, there may be strong institutional barriers to shifting objectives, resulting in a higher threshold maintaining a system in its current stable state. Additionally, federal agencies may have access to a wider array of techniques from across the country as a whole, rather than being limited to those management activities currently in operation within the state. In combination, these factors suggest that federal managers are less likely to encounter adaptation tipping points than are non-federal managers.

4.2. Barriers and routes to adaptation

Our survey explored managers' perceptions of constraints on their ability to change management strategies and objectives. We found that while managers have observed their organization change course, and generally perceive their capacity to innovate and conduct adaptive management as high, they also perceive significant barriers to making needed change. Interestingly, the barriers to change identified by respondents were primarily policy and organizational-driven (funding, mandates, laws and policy) rather than individual (i.e., self-perceived competence to make changes) or environmental (i.e., increased variability in environmental conditions as a barrier to a restoration objective). However, in addition to funding shifts, respondents frequently recounted times that their organizations made a needed change due to a catalyst, such as a large fire, a lawsuit, a new leader, or new information. Managers in the Sonoran Desert will likely adapt to changing conditions via a combination of national, regional, or organizational-level initiatives that fund and encourage a needed change, as well as on-the-ground effective leadership, information, and staff capacity.

As described above, fire is a cross-boundary challenge. Individual ignitions cross boundaries, as do risk factors such as spread of invasive species (Ager et al., 2018). Effective landscape-scale management of fuels and fires therefore requires collaboration and coordination across boundaries (Charnley et al., 2016). Some of the barriers identified by our study participants—such as insufficient resources and funding, as well as regulatory limits—may prevent them from collaborating effectively with neighboring jurisdictions to reduce broadscale fire risk or to suppress active fires and prevent damage to neighboring resources. On the other hand, collaboration and cooperation can extend the availability and distribution of resources beyond individual jurisdictions and allow managers across the landscape to leverage diverse experiences, tools, technology, and knowledge (Olsson et al., 2004; Weible et al., 2018; Koebele 2019). Since this study was focused within jurisdictions, the factors that might facilitate or increase cross-boundary collaboration in this system were not explicitly examined, but this area remains ripe for future exploration and development in Sonoran Desert resilience

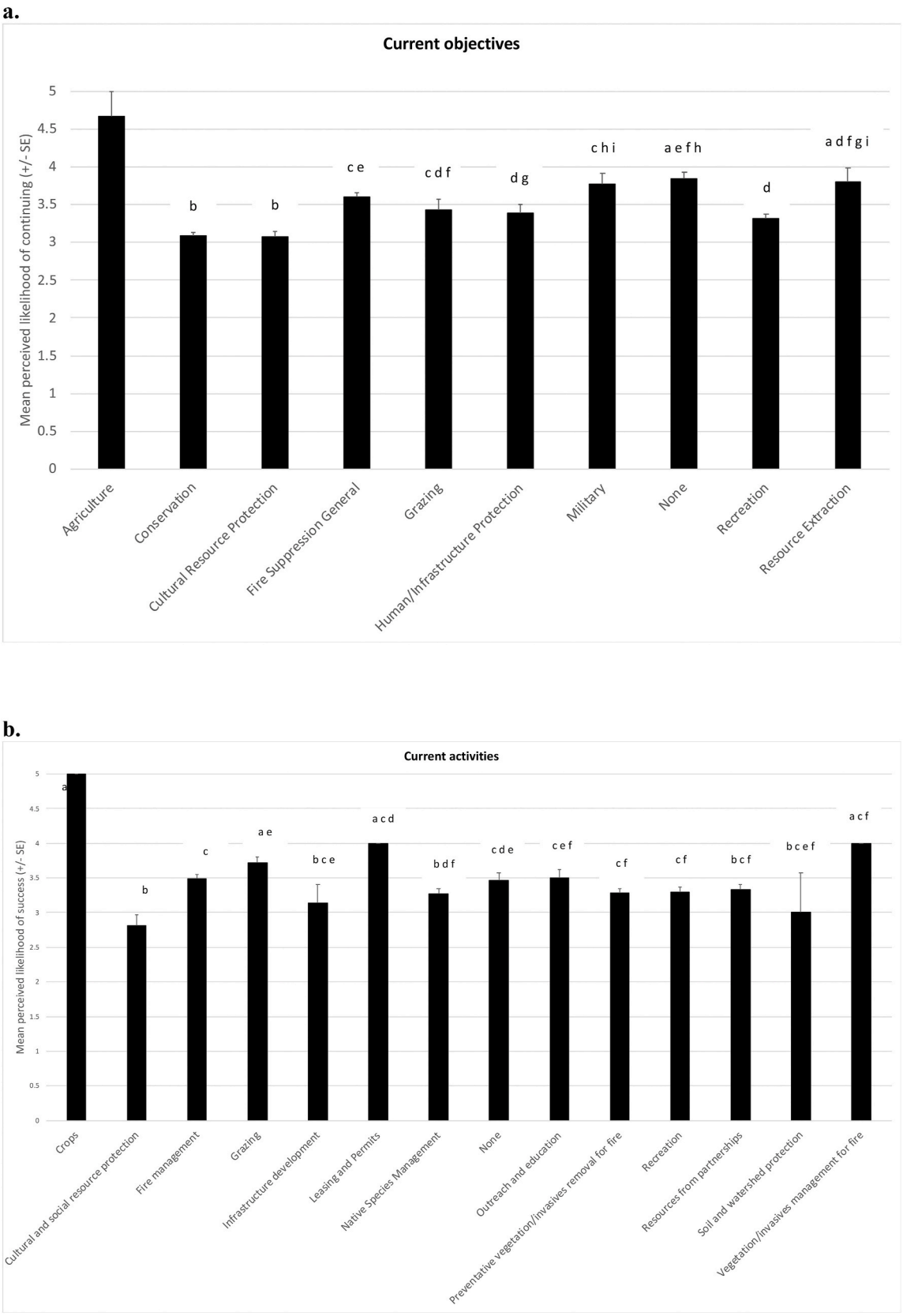

Fig. 2. Manager-reported likelihood that (a) objectives will continue into the future, and that (b) management activities will achieve objectives. Error bars indicate standard error. Bars superseded by different letters indicates significant differences by Dunn's test for multiple comparisons. Likelihood was reported on a Likert scale, with the central value of 3 indicating "unknown."

studies (Charnley et al., 2014).

4.3. Conclusions

Fire regimes and human communities are linked through socio-ecological feedbacks. Across landscapes, fire regime change can have varying degrees of impact on human communities and institutions, which may rely on historical ecosystem products and services and may be ill-equipped to deal with the impacts of altered fire regimes on human infrastructure, health, and safety (e.g., Busenberg, 2004; Cissel et al., 1999; Conedera et al., 2009). Meanwhile, land use and management decision-making can drive ignitions as well as fuels buildup, continuity, and flammability (Littell et al., 2009; Mann et al., 2016; Stephens and Ruth, 2005). These bidirectional influences may vary by agency at any given location, since agency dictates the missions, mandates, resources, and constraints of human activities within an area (Epanchin-Niell et al., 2010; Fischer and Charnley, 2012; Sayer et al., 2013). Our findings illustrated the complexity of these social-ecological feedbacks: it is evident that fire regime change will not impact this ecoregion homogeneously, but rather interacts with a complex management landscape and is likely to exert more significant impacts in some management units than in others. Similar conditions are likely to be found in other arid, multijurisdictional, largely-government managed landscapes: managers with high availability of resources and a diversity of potential or available management activities will likely continue to retain current objectives in the face of environmental change, whereas managers with few resources and few management options may encounter tipping points and be forced to switch objectives.

In the case of our study system, Tribal jurisdictions faced particular challenges in achieving objectives in the future, and, across all jurisdictions, objectives related to conservation of natural and cultural resources were considered least likely to be achieved. Based on our surveys, factors such as scarcity of resources and few available management options likely contributed to these findings. By contrast, military land managers reported optimism that their objectives would continue into the future. The military in the US is typically well-resourced with funding, personnel, and technology, and for strategic reasons the resources on military lands are often considered to be high-priority and to receive the protections they require (for example, fire suppression efforts). As this contrast among jurisdictions illustrates, efforts to generate and direct resources (personnel, funding, tools, and new management approaches) toward areas of vulnerability may be important to prevent undesirable state change as Sonoran Desert ecosystems increasingly face tipping points.

Credit author statement

Clare E. Aslan, Conceptualization, Writing – original draft preparation, Visualization, Formal analysis, Supervision. Sara Souther, Methodology, Formal analysis, Visualization, Investigation. Sasha Stortz, Methodology, Investigation. Martha Sample, Investigation, Writing – review & editing. Manette Sandor, Formal analysis, Visualization, Writing – review & editing. Carrie Levine, Formal analysis, Writing – review & editing. Leah Samberg, Conceptualization, Investigation. Miranda Gray, Visualization, Investigation. Brett Dickson, Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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