Journal of Environmental Management 240 (2019) 368–373

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Coerced resilience in fire management

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ARTICLE INFO

Keywords:
Coercive social power
Ecological resilience
Fire return interval
Policy
Regime shift
Transformative governance

ABSTRACT

Mechanisms underlying the loss of ecological resilience and a shift to an alternate regime with lower ecosystem service provisioning continues to be a leading debate in ecology, particularly in cases where evidence points to human actions and decision-making as the primary drivers of resilience loss and regime change. In this paper, we introduce the concept of coerced resilience as a way to explore the interplay among social power, ecological resilience, and fire management, and to better understand the unintended and undesired regime changes that often surprise ecosystem managers and governing officials. Philosophically, coercion is the opposite of freedom, and uses influence or force to gain compliance among local actors. The coercive force imposed by societal laws and policies can either enhance or reduce the potential to manage for essential structures and functions of ecological systems and, therefore, can greatly alter resilience. Using a classical fire-dependent regime shift from North America (tallgrass prairie to juniper woodland), and given that coercion is widespread in fire management today, we quantify relative differences in resilience that emerge in a policy-coerced fire system compared to a theoretical, policy-free fire system. Social coercion caused large departures in the fire conditions associated with alternative grassland and juniper woodland states, and the potential for a grassland state to emerge to dominance became increasingly untenable with fire as juniper cover increased. In contrast, both a treeless, grassland regime and a co-dominated grass-tree regime emerged across a wide range of fire conditions in the absence of policy controls. The severe coercive forcing present in fire management in the Great Plains, and corresponding erosion of grassland resilience, points to the need for transformative environmental governance and the rethinking of social power structures in modern fire policies.

1. Introduction

Ecological resilience is the capacity for an ecosystem to absorb change and continue to persist or to self-organize and renew into an essentially similar set of structures and functions following collapse (Angeler and Allen, 2016). The reasons underlying the loss of ecological resilience and a shift to an alternate regime with lower ecosystem service provisioning continues to be a leading debate in ecology (Allen et al., 2016), particularly in cases where evidence points to human actions and decision-making as the primary drivers of resilience loss and regime change (Adger, 2000; Berkes et al., 2000). Ecological regime shifts occur when resilience is exceeded and a new local equilibrium is reached that differs in its structure and function from the previous regime (Holling, 1973). Ecosystem management is an example of an institution seeking to enhance the resilience of ecological systems but where the pathology of governance over ecosystem management strays from resilience principles (Garmestani et al., 2013) and imposes instead tight controls aimed at simplifying the structure-function relationships that are critically important to ecological resilience in complex and adaptive living systems (Holling and Meffe, 1996).

We introduce the concept of coerced resilience as a way to explore the interplay among social power, ecological resilience, and

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https://doi.org/10.1016/j.jenvman.2019.02.073
Received 1 June 2018; Received in revised form 20 January 2019; Accepted 15 February 2019
Available online 04 April 2019

environmental management and better understand the unintended and undesired regime changes that often surprise ecosystem managers and governing officials. Coerced resilience in social-ecological systems integrates elements of social power theory with resilience science. Philosophically, coercion is the opposite of freedom (Gamst, 1991). In social-ecological systems, coercion represents the degree of departure from the capacity for ecological systems, and the ecosystem managers embedded within them, to function freely from external social controls over the system. Social coercion uses influence or force to gain compliance among actors operating within ecosystems (Ripstein, 2004), and thus can reduce or eliminate the potential to manage for essential structures and functions of ecological systems. According to resilience theory, governance structures should be flexible enough to allow managers the opportunity to promote critical ranges of variability in resource systems that are necessary for their resilience (popularly referred to as the Golden Rule for Ecosystem Management; Holling and Meffe, 1996). The coercive force imposed by societal laws and policies represents the degree of control imposed on the natural range of variability that are important to the resilience of an ecological regime and can be demonstrated in models by removing those social constraints and in simulations that elucidate basic theoretical ranges of ecosystem functioning. This does not imply that all governance is coercive; coercion is one of five bases of social power (as initially introduced in French et al., 1959), so coercion represents a specific case where negative influence is leveraged in governance.

The theoretical basis for power and control reveals that coercive power exists in multiple forms in social-ecological systems (French et al., 1959; Raven, 1993). Influence or force to gain compliance among actors in social-ecological systems can be sociopolitical, economic, physical or emotional. All these forms of coercion exist in some manner in fire management today (Sletto, 2009), particularly in grasslands where fire was a frequent occurrence due to Plains Indians' ignitions (Twidwell et al., 2013b). In USA fire management, decades of anti-fire messaging led by government agencies have guided the attitudes and normalized behaviors of the general public (Donovan and Brown, 2007; Stephens and Ruth, 2005), which is a form of increased social forcing toward compliance of fire managers (Dellasala et al., 2004; Twidwell et al., 2016b). Political forcing is widespread and occurs when regulatory agencies or power authorities decide to reject permits needed for private citizens to use fire on their own land, levy certification procedures that increase training and bureaucratic requirements on non-government sector, or impose burning bans that eliminate periods of prescribed fire use (Weir et al., 2016). When prescribed fire practitioners are within designated burning windows and permitted to use fire in management, any fires that get away face some risk of litigation (economic forcing toward compliance) and derisiveness from neighboring citizens has been common (emotional and physical threats meant to force compliance). The end result is a social-ecological system wherein multiple layers of coercive power exist with the intent to limit or eliminate the freedom for private citizens in Great Plains grasslands to use fire to manage their own land.

In this study, we develop a simulation model that depicts a common social-ecological conflict in fire policy and management for a typical tallgrass prairie within the Great Plains of North America. In this system, officials are tasked with imposing external regulations that govern the application of prescribed fire and the occurrence of wildfire, which in turn forces local actors to restrict the occurrence of fire to a legally-bound range of conditions that may constrain their ability to manage or restore pyrogenic ecosystems. A coupled social-ecological-physical model has never been developed in temperate grasslands to address this fundamental knowledge gap. Here, we develop a model that features mechanistic relationships among fuels, fire intensity, and juniper mortality, and based on these relationships, assess the extent to which a simple decision in governance alters these interactions and changes the relative resilience of alternative grass-tree states in a policy-coerced fire system compared to a theoretical, policy-free fire system. The objective of this paper is to quantify the degree of coerced resilience imposed as a result of today's societal governance of fire management in a simulated tallgrass prairie experiencing *Juniperus* encroachment. Grassland transitions to juniper woodland is a well-known regime shift in the Great Plains and thresholds separating grass-woody states have been quantified previously (Twidwell et al., 2013a). Social coercion and forced compliance among ecosystem managers to depart from critical thresholds separating alternative ecological states is a type of social governance that has been unaccounted for in fire management. Doing so disentangles the coercive force resulting from social governance structures relative to the theoretical range of functioning in a system free of social constraints. This is the basis for quantifying coerced resilience and measuring sociopolitical-driven change responsible for changes in the relative capacity for grasslands and juniper woodland alternative regimes to persist in a fire-driven system.

2. Methods

2.1. Model overview

We expand upon a previous threshold model (Twidwell et al., 2013a) that couples semi-physical models of fire behavior with a positive feedback model from grassland fire ecology. The model was developed as a deterministic compartment model based on difference equations ($\Delta t = 1$ year) and programmed in STELLA®. The model consists of three submodels: (1) an individualistic submodel of juniper tree-grass growth relationships, (2) a landscape-level invasion submodel, and (3) a physics-based fire behavior submodel (Fig. 1). The tree submodel represents the growth in height of annual cohorts of trees (from 0 to 5 m), the change in fine fuel load (the biomass of herbaceous understory vegetation) (from 400 to 120 kg ha^{-1}) associated with each cohort, and the loss of cohorts resulting from fire. The landscape sub-

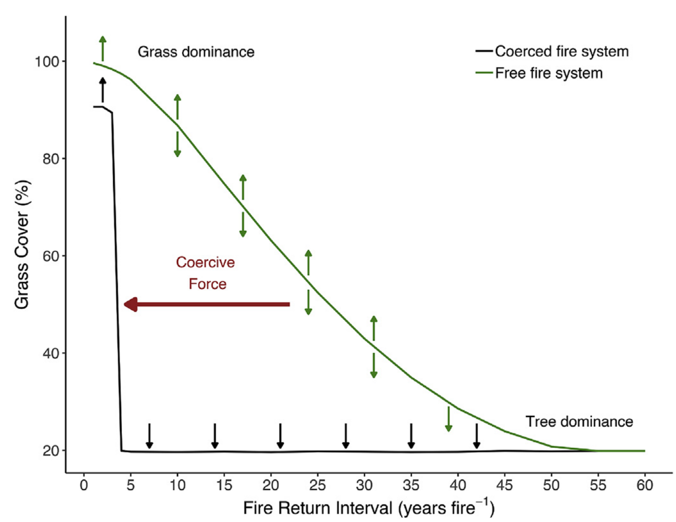

Fig. 1. Coerced resilience in fire management for a simulated tallgrass prairie. Shown here are resilience curves (defined as the relative change in conditions that a tallgrass prairie can absorb before transitioning to an alternative, juniper woodland state) in the presence (policy-coerced) and absence (policy-free) of external social governance over fire. Grass cover represents a relative dynamic equilibrium that emerges at the end-of-model for a given temporal probability of fire occurrence (see Methods). Coercive force represents the relative difference in the resilience of tallgrass prairie to changes in fire that are imposed through social coercion and external governance over fire. Black and green arrows represent conditions that foster dominance of a grassland state (up arrows), tree state (down arrows), or co-dominated grass:tree state (up-down arrows) for a coerced and free fire system, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

model represents the effects of each cohort on canopy cover (from 0 to 80%) and corresponding changes to fine fuel load at the landscape level, and the loss of canopy cover associated with each cohort resulting from fire. The fire sub-model represents two of the most widely applied models in fire science in the U.S. and combines Albini's adjustment of Rothermel's rate of fire spread model (Albini, 1976; Rothermel, 1972) with Byram's fireline intensity model (Byram, 1959), which have been used previously to quantify a process-based fire threshold of juniper mortality (Twidwell et al., 2013a). Details of the three submodels are provided in the Supplemental Materials.

2.2. Experimental design for simulations

We used our model to explore the dynamics of grassland transitions to juniper woodland resulting from interactions among (1) fire intensity, (2) fire return interval, and (3) the level of canopy cover at the time of fire occurrence. We simulated two governance scenarios representing the presence and absence, respectively, of modern external sociopolitical constraints on fire occurrence. In the absence of sociopolitical constraints, actors are free to target more extreme conditions, so we use our simulation model to experiment and compare the outcomes that are possible when actors are free to target conditions that polarize the narrow conditions permitted via policy-induced coercion today. Twidwell et al. (2016) provides the basis for establishing the likely range of fuel and weather conditions that are possible in tallgrass prairie. In addition, Twidwell et al. (2016) reviewed the policies governing prescribed fire in tallgrass prairie, and identified wind speed and herbaceous fuel moisture as the two parameters most altered in relation to Rothermel's rate of fire spread model. Wind speed was held constant in this model because of its disproportionate impact on rate of fire spread in tallgrass prairie (Twidwell et al., 2016b), so the two scenarios used in this design differed as a result of policy constraints imposed on herbaceous fuel moisture content ($FFM \geq 0.13$ for all fire occurrences in the policy-coerced scenario; $FFM = 0.02$ in the policy-free fire scenario; *FFM* refers to 1-h dead fuel moisture in Rothermel's model). For each scenario, we simulated 16 fire occurrence intervals (representing fire return intervals of 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 years). Independent simulations were run to compare output for each fire return interval across a gradient of juniper canopy cover (0, 5, 10, 20, 30, 40, 50, 60, 70, and 80%). This resulted in 320 total simulations (2 scenarios x 16 fire return intervals x 10 canopy cover levels).

We initialized each simulation with no trees ($TS_0 = 0$ and $T_{cover0} = 0$) and 400 kg ha^{-1} of fine fuel ($FL_0 = 400$), a common upper bound value used in previous models of herbaceous biomass tallgrass prairie (Fuhlendorf et al., 2008; Twidwell et al., 2009; Twidwell et al., 2016b). The relative dominance of grasslands and juniper woodlands was then simulated across a range of fire conditions. Our simulation effectively allows fire intensity and fire return interval to interact, which is a novel approach that has not been developed in previous models for this system. It has been conventional to focus primarily on fire return interval alone, so this model is the first to account for critical fire intensity thresholds in the system that are now known be foundational to fire-induced collapse of mature juniper stands (Twidwell et al., 2013a). We monitored subsequent system dynamics for 225 years, which was long enough for the system to reach a static or dynamic equilibrium (exhibit constant or cyclically repeating values of landscape-level canopy cover, T_T_{Cover}) under all scenarios simulated. We summarized results of each simulation in terms of percent canopy cover during the year prior to execution of the last fire, which we interpreted as an indicator of the degree of grass-tree dominance resulting from interactions among fire intensity, fire return interval, and initial juniper cover for contrasting policy-coerced and policy-free fire scenarios.

It is important to comment here that policy restrictions imposed on the range of variability of fire relate to a number of social-ecological considerations. The calculations in this simulation could be expanded in future studies to include stochastic behaviors and how those influence governance and decision-making. Moreover, policy itself is non-stationary and this simulation approach lends itself to scenario analyses that take into consideration multiple plausible future conditions (e.g. Twidwell et al., 2018) that go beyond the objectives of this study.

3. Results

Social coercion caused large departures in the fire conditions associated with alternative grassland and juniper woodland states, and reveal relative differences in the resilience of grassland in the presence and absence of external policy controls over fire (Fig. 1). The tipping point associated with grassland regime dominance changed from a fire return interval of 10 years fire^{-1} to 3 years fire^{-1} for policy-free and policy-coerced scenarios, respectively (Fig. 1). A greater magnitude of change was observed for the tipping point of the juniper woodland regime, which did not emerge and become dominant until long fire return intervals in the policy free scenario (> 40 years fire^{-1}), whereas the juniper regime emerged when fire return interval was an order of magnitude lower as a result of policy coercion (at ≥ 4 years fire^{-1}). A co-dominated grass-tree state, representing a relative form of dynamic equilibrium, emerged in the absence of policy constraints at fire return intervals between 10 and 30 years fire^{-1} (Fig. 1). Grassland and juniper woodland states were unable to coexist under current policy coercion.

Management for a grassland regime became increasingly untenable as juniper cover increased in the coerced fire system. A juniper-dominant regime occurred across all potential ranges of fire return intervals when fire was withheld until juniper cover reached 50% or greater in the simulation model (Fig. 2). In the policy-coerced governance scenario, a treeless, grassland regime occurred only at short fire return intervals (1–3 yrs fire^{-1}) and prior to the establishment of juniper (Fig. 2). At intermediate levels of juniper cover, short fire return intervals (1–3 yrs fire^{-1}) maintained a relative dynamic equilibrium of grass-tree dominance whereas fire return intervals ≥ 4 years fire^{-1} eventually transitioned to a juniper-dominant regime (Fig. 2). In the simulated scenario without policy constraints, the initial juniper cover did not dictate the range of possible future ecological states (Fig. 2). Relative dominance of grasses and trees became solely dependent on fire return interval and its interaction with surface fireline intensity.

4. Discussion

Simplifying fire in nature is expected to erode the resilience of many pyrogenic systems (Twidwell et al., 2016a) and this study shows the degree to which coercion imposed by today's social governance of fire alters resilience in a simulated tallgrass prairie experiencing woody encroachment. Modern societal attempts to minimize the magnitude and occurrence of fire events have imposed such severe coercive forcing that this simulated tallgrass prairie landscape exhibited minimal ecological resilience to changes in fire occurrence. Here, ecological resilience is quantified as a measure of the ability for tallgrass prairie to withstand changes in fire occurrence, as a result of policy coercion, and avoid collapse and reorganization into an alternative ecological state (juniper woodland). Any change from historical fire return intervals (< 3 years fire^{-1}; Frost, 1998; Guyette et al., 2012) led eventually to grassland collapse and a shift to an alternative woody-dominated state under current policy coercion. In contrast, grassland dominance theoretically emerges over juniper woodland across a broad range of potential fire conditions in the absence of contemporary social command-and-control (Fig. 1), demonstrating that tallgrass prairie exhibits a robust degree of resilience when critical ranges of variability of fire are in place. The implication is that external policy controls have led to the erosion of resilience in tallgrass prairie, thereby necessitating more intensive fire management (in the form of recurrent fires at short intervals and prior to the establishment and spread of adult trees) than would be required in the absence of external policy interference.

Scientists continue to shed new light on the absence of ecological

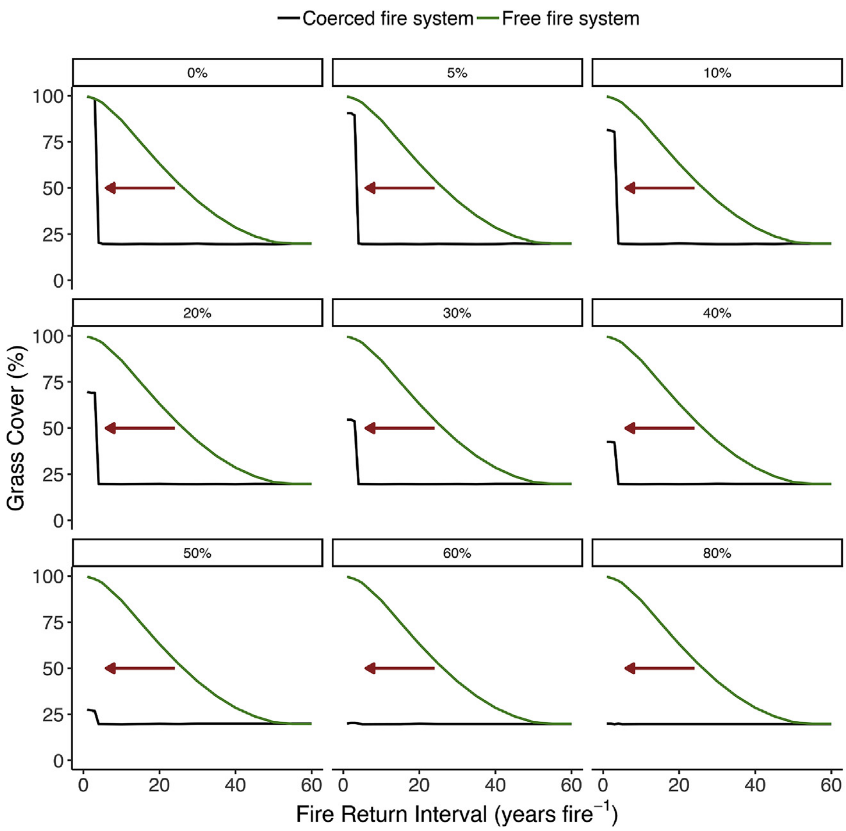

Fig. 2. Relative differences in resilience of tallgrass prairie across a range of starting levels of juniper abundance (% cover; given in each figure panel) changes for each simulated fire return interval in the presence (policy coercion; black lines) and absence (policy free; green lines) of externally imposed policy controls. Coercive force is shown as red arrows. A grass cover value of approximately 20% represents the amount of grass cover remaining following a transition from grassland dominance to an alternative juniper woodland state; a treeless state corresponds to a cover value of 100% grass cover. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

considerations in fire policy and the corresponding implications for biodiversity, productivity, and structure-function relationships in ecosystems. Current fire policy in the U.S., and elsewhere, has institutionalized a command-and-control ideology meant to freeze complex, adaptive grassland and forest ecosystems in a single, equilibrial state (Holling, 1986). A command-and-control approach has been rationalized as being necessary to protect human developments, personal security, and old-age harvestable resources; yet, the irony of fire policy and management is that efforts to eliminate and minimize the range of variability of fire in nature has eroded ecological resilience and heightened, not reduced, vulnerability to human infrastructures and resources (Donovan et al., 2017; Stephens et al., 2016). This would be a fundamental prediction, given modern ecological theory. Ecosystems exist in multiple alternative ecological regimes and exhibit a complex array of adaptive and emergent behaviors when exposed to external controls.

Globally, scientists have documented critical dependencies of rare and endangered species to variation in the intensity, severity, timing, spatial pattern, and temporal occurrence of fire, and the inability to manage for these species under current policy guidelines (Hutto, 2008; Smucker et al., 2005; Van Wilgen, 2013). Van Wilgen (2013) coined the phrase, “The Failure of Safe Prescribed Burning,” to describe the inability for prescribed fire policy to conserve floral and faunal specialists today. This premise is consistent with one of the primary dogmas of grassland fire ecology and the assumption that low intensity fires are sufficient to maintain grassland dominance, as long as they applied with sufficient temporal frequency. This assertion only held in this model simulation if fire management preceded the establishment of juniper trees. Evidence suggests most fire stewards wait to incorporate fire management until a resource problem becomes identified (e.g. when juniper encroachment has reached a level of abundance that incurs social-ecological damages; Roberts et al., 2018). Only one ecoregion in the entire Great Plains of North America, the Flint Hills, operates within this range, and social pressures are mounting to force the Flint Hills to alter existing fire practices (Leis et al., 2017). This study extends the implications of “the failure of safe prescribed burning” to quantify the heightened susceptibility of a regime shift as a result of policy-driven coercion, which has implications for the entirety of grassland-dependent ecosystem services. “Let it burn” policies have been proposed and implemented in some contexts (Dombeck et al., 2004; Romme and Despain, 1989), given the inability to exclude wildfires from nature and the recognition of the criticality of some ecosystem functions to a broader range of fire behavior and severity; however, implementation of these policies are controversial, they do not currently exist anywhere in Great Plains ecosystems, and their return interval would be quite different from indigenous-driven fire frequencies that allowed grassland dominance to emerge across the interior of North America (Twidwell et al., 2013b).

An alternative vision for fire management is to coexist with fire (Jensen and McPherson, 2008; Moritz et al., 2014), which calls for policy to more closely align with modern ecological theory and recognize critical ranges of variability needed to manage for resilience and prevent a shift to an alternative ecological regime that can undermine long-term sustainability priorities (Hutto et al., 2016). It is in humanity's best interest to recognize and avoid tendencies in modern policies and practices that erode ecological resilience and make transitions to an alternative state more likely (Allen et al., 2014; Holling and Meffe, 1996). Such shifts are often hysteretic, meaning the “path out” differs from the “path back”, and require considerably greater capital and energy to attempt to restore a semblance of the original state than was required for prevention (Scheffer et al., 2001). As evident from this simulation model, hysteresis is dependent on social coercion over critical ranges of functioning in systems, and should be a critical consideration for fire management going forward.

We consider the concept of coerced resilience to hold great promise for transformative governance and avoid policies that foster transitions to alternative, undesirable ecological regimes (Chaffin et al., 2016). Authorities in power with little knowledge of what constitutes resilience in ecological systems, or civic responsibility to aid in its management, might be expected to exert greater coercive force (Ripstein, 2004). Developed countries have incurred great expenses to develop formal institutions and policies aimed at minimizing the extremes of fire and imposing greater control over its range of variability (Dellasala et al., 2004; Hawbaker et al., 2013). Governing authorities generally have little knowledge of the fundamental biology of pyrogenic ecosystems and the role of fire as a stabilizing feedback that has led to the emergence of many of the world's globally expansive vegetation types. For example, political appointees, foresters, and fire department officials are the primary groups that hold direct control and authority over contemporary human use of fire for grassland management in the Great Plains. Rarely do professionals in these disciplines acquire training or advanced knowledge in grassland fire ecology, resilience science, or the anthropogenic history of fire use in grasslands, and the fiscal responsibilities of these decision authorities are linked to alternative land use types. Groups that actually manage grasslands have minimal control or influence over fire governance; instead, social control over a primary stabilizing feedback responsible for the emergence of grassland resources is held by government entities with contrasting land use ethics that receive funding to manage non-grassland resources. This is where incentivizing polycentric systems of governance has been proposed as more suitable for fostering the adaptive capacity needed to deal with cross-scale social-ecological change and foster a more desirable social-ecological condition that sustains local benefits and livelihoods into the future (Bixler, 2014).

Acknowledgements

Multiple funding sources contributed to this research and we are grateful to the Nebraska Game & Parks Commission (W-125-R-1), the U.S. Strategic Environmental Research and Development Program (SERDP; W912HQ-15-C-0018), the August T. Larsson Foundation of the Swedish University of Agricultural Sciences and the Swedish Research Councils Formas (2014-1193) and VR (2014-5828), USDA Natural Resource Conservation Service (Conservation Innovation Grant 68-3A75-5-180), USDA-CSREES National Needs Fellowship 2009-38420-05631, Rob and Bessie Welder Wildlife Foundation, and the Tom Slick Foundation. We thank Lynn Drawe, Terry Blankenship, Selma Glasscock, Baldemar Martinez, Nick Garza, Robert Moen, Colin Rosser and many others for their assistance in conducting experimental treatments and vegetation sampling that were foundational to this simulation model.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2019.02.073.

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