Toward a method of collaborative, evidence-based response to desertification

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Abstract. Over generalized narratives about how desertified ecosystems will respond to restoration actions may result in wasted resources, missed opportunities, or accelerated degradation. Evidence-based collaborative adaptive management (CAM) could solve this problem by providing site-specific information that is trusted by users and enables learning opportunities. Although calls for CAM are increasing, many recommendations remain abstract and difficult to operationalize in specific projects. We review some general challenges for managing desertification in rangelands and draw upon recommendations in the recent literature to develop a 6-step method of CAM to address desertification. The method draws upon our ongoing experiences and makes novel connections between CAM concepts and technologies including ecological sites, state-and-transition models, ecological state mapping, and web-based knowledge systems. The development of a broadly-applicable and flexible methodology for CAM could increase the frequency and success of projects and provide sorely needed knowledge to guide locally-tailored responses to desertification.

Keywords: Adaptive management, collaborative science, soil mapping, state-and-transition model.

Introduction

The detection, prevention and reversal of desertification in rangelands are international priorities. In spite of years of effort, however, there are no useful estimates of the extent of desertification, nor coordinated efforts to respond to it (Reynolds *et al.* 2011, Thomas *et al.* 2012). There are several reasons why desertification is difficult to address particularly when compared to other kinds of ecosystem state change (*e.g.* Carpenter 2005). Desertification can involve several ecosystem attributes, high patchiness, and variable timeframes and ecological mechanisms. These difficulties give rise to a “crisis of evidence” (Lamont 2004) regarding the interpretation of desertification and its potential solutions. The crisis is that institutions and individuals lack a site-specific, mechanistic understanding of desertification that can be used in decision making. In the absence of such information, over generalized narratives derived from particular cases fill the information void.

Over generalized narratives or ‘silver bullets’ can be poorly matched to the social and ecological realities of many sites to which they are applied (c.f. the "cookbook" myth of Hilderbrand *et al*. 2005). For example, the transfer of sedentary grazing practices of the United States to the communally-managed rangelands of Africa and Mongolia has accelerated degradation and human suffering in some cases (Bedunah and Angerer 2012) and there is much unexplained variation in the effectiveness of restoration practices across rangelands of the United States that has led to inefficient use of financial resources (Briske 2011).

In some cases, over generalized narratives are actively promoted with a disregard for empirical evidence. A recent example is manifest in the highly publicized assertions of Allan Savory, of the Savory Institute, that grazing rest necessarily *causes* desertification and that concentrated livestock grazing is *required* to restore barren ground to a productive state and sustain it (http://www.ted.com/talks /allan_savory_how_to_green_the_world_s_deserts_and_reverse_climate_change.html). A number of studies clearly demonstrate that these assertions are incorrect for a number of ecosystems and therefore cannot be generally applied (Holechek *et al.* 2000; George *et al.* 2003; Bowker 2007; Briske *et al.* 2008b; Knapp *et al.* 2012; Bestelmeyer *et al.* 2013). Nevertheless, the Savory method is uncritically promoted as the cure-all for desertification (and climate change) by many, including by the Prince of Wales (http://www.savoryinstitute.com /2012/09/uncategorized/hrh-the-prince-of-wales-publicly-supports-allan-savory/).

This case highlights the urgent need for evidence and collaboration to guide both global and local responses to desertification. In order to fulfill this need, we argue that systematic approaches to evidence-based, collaborative adaptive management (CAM) are needed in rangelands, including those at risk of desertification and those that have already been desertified. A systematic approach is needed because successful examples of evidence-based, adaptive management continue to be few and anecdotal, beset by several common limitations (Susskind *et al.* 2012). Increased documentation and critical analysis of site-specific evidence is needed because overgeneralized and evidence-free thinking continues to afflict rangeland management (Briske 2011; Herrick *et al.* 2012; Sayre *et al.* 2012). Furthermore, interventions and restoration actions seldom stem from a clearly-articulated understanding of the processes by which actions will result in the expected outcomes (Michener 1997; Hallett *et al.* 2013). Finally, the approach must be collaborative so that stakeholders have faith in the process and are willing to contribute to and act on the information produced (Roux *et al.* 2006).

In this paper, we propose a method for adaptive management that reflects our evolving experiences with the process and that links several concepts and tools that we feel would be useful for landscape-level CAM projects. We view these ideas as a contribution toward a general set of principles and technologies that could be applied globally, complementing other recent work on the topic (*e.g.* Giardina *et al.* 2007; Duff *et al.* 2009; Pannell *et al.* 2012).

To help frame our proposal, we first describe the specific challenges in managing desertification that our approach was designed to address. We then briefly review some general recommendations that emerge from literature on the science-management interface, including terms such as CAM (Susskind *et al.* 2012), holistic adaptive land management (Herrick *et al.* 2012), resilience thinking and practice (Walker and Salt 2012), resilience-based ecosystem stewardship (Chapin *et al.* 2009), and resilience-based management (Bestelmeyer and Briske 2012). Our goal is to suggest a set of steps that can be implemented by those who may find the existing literature insufficient to get started with CAM-type programs in rangelands threatened with desertification.

Why is desertification so difficult to manage?

Desertification is hard to characterize

The United National Convention to Combat Desertification defines desertification broadly as “the degradation of land in semi-arid and dry sub-humid areas” (http://www.unccd.int). This general definition belies the varied mechanisms and impacts of desertification. Its manifestations can involve several attributes such as changes in net primary production, plant composition, and soil surface properties and it is often not clear in a particular ecosystem how desertification is operationally defined (Warren 2002; Maestre *et al.* 2009; Peters *et al.* 2012). Conflicting interpretations about desertification occur when, for example, long-term natural erosion processes are mistaken for recent anthropogenic impacts (McFadden and McAuliffe 1997) or when remotely-sensed estimates suggesting increased production mask detrimental changes in plant composition (Herrmann and Tappan 2013). The precise nature of the ecological differences between reference (healthy) and desertified states, and therefore management objectives, should be clearly specified and can be informed by various forms of information, including field measurements, historical data, spatial and temporal context, and on-site knowledge and interpretation.

Restoration involves a variety of ecological mechanisms and timeframes.

The term desertification is applied to a broad range of environments and therefore a broad array of ecological mechanisms controlling soil and vegetation change. The environmental conditions and ecological mechanisms together determine whether desertification can be reversed, how it can be reversed, and how quickly. Unfortunately, managers and scientists too often jump to conclusions regarding the ecological mechanisms of both degradation and recovery, leading to flawed prescriptions. For example, brush management efforts typically assume that competitive preemption of water resources is the sole mechanism constraining grass recovery, but recruitment limitation and soil degradation may be primary constraints (Archer *et al.* 2011). If competitive preemption is the dominant constraint to grassland recovery, recovery can be rapid following removal of shrubs. If soil degradation is the dominant constraint, recovery may take decades or never occur (Herrick *et al*. 2006). Conversely, grasslands that are considered to be severely degraded—implying a long or infinite recovery time – may be recovered in a few years to several decades with changes to grazing management and/or following high rainfall events (Valone *et al.* 2002; Li *et al.* 2008; Bestelmeyer *et al.* 2013). Inferences about the ecological mechanisms constraining recovery require local evidence (*e.g.* from process-based indicators) due to important variations in the dominant mechanisms operating across ecosystems.

Desertification is highly patchy

The mechanisms and effects of desertification are highly patchy due to fine-scale variations in land use, soils, and contagious processes (Bestelmeyer *et al.* 2011). Thus, desertification can be difficult to detect and responses can be delayed as a consequence (Pringle *et al*. 2006). Monitoring and the design of restoration actions therefore benefit from fine-scaled spatial information about ecosystem states and physical context (Steele *et al.* 2012).

Desertification is both a social and ecological phenomenon

It is now well understood that desertification must be considered from both biophysical and socio-economic perspectives (Reynolds *et al*. 2007). Because of the vast areas and patchiness involved, restoration in rangelands often requires broad societal change in the interpretation of indicators by: (1) local land users; (2) enterprise or communal management systems; and (3) government and international policies and support programs. These multi-tiered changes require learning, and learning is most effective when participants are directly involved in assessment and testing (Evely *et al.* 2011). Participatory approaches, however, are typically not employed in the assessment of desertification or in the design of responses to it (Reed *et al.* 2008; Addison *et al.* 2012) and is instead often top-down in nature (Briske 2012). Methods for the systematic inclusion of stakeholder participation, especially at local and regional levels are a critical need (Whitfield and Reed 2012).

Guidance on collaborative adaptive management from the literature

The recent literature on CAM and related approaches suggests a suite of key design elements for responding to the complexity of desertification. These recommendations form the basis for our proposal.

Promote participation (Roux *et al.* 2006, Susskind *et al.* 2012). In order for CAM to take root, stakeholders should benefit by both contributing and receiving knowledge. The benefits of receiving knowledge may include increased income, reduced expenses, capital appreciation (*e.g.* land value), sustainability of productive capacity, or increased quality of life, for example associated with local air quality improvements. The benefits of contributing knowledge may include priority access to shared knowledge and increased ability to influence community or government decisions (*e.g.*, restoration priorities).

Develop clear ecological models and identify realistic management options (Bestelmeyer and Briske 2012, Herrick *et al.* 2012). Conceptual models for ecosystem responses are needed to specify realistic expectations as well as to select management and restoration approaches that are likely to yield desired results. Possible ecosystem responses can vary with subtle geographic differences in climate and soil development, as well as the present ecological state of an area.

Focus on trajectories of change rather than a steady state (Chapin *et al.* 2009). Many rangelands have already undergone irreversible societal and biophysical changes; climate change will likely bring more. Thus, a focus on preservation of historical ecosystem and societal attributes must be balanced by a consideration of current constraints and alternative future possibilities. In this regard, a relatively subtle change in thinking can produce very different management goals. For example, the recognition that an ecosystem is irreversibly altered may lead managers to discover new uses and goals for the novel state rather than to attempt costly and ineffective restoration actions (Hobbs *et al.* 2009).

Evaluate a variety of ecosystem services (Chapin *et al.* 2009; Bestelmeyer and Briske 2012). Often, the attributes used to characterize an ecosystem state, or to evaluate an intervention, are based on one or a few ecosystem services of value to a dominant stakeholder (*e.g.*, production of palatable grasses or an endangered species). Measuring attributes that reflect a broader array of ecosystem services allows for the evaluation of synergies and trade-offs and can reduce conflict and unintended consequences.

Consider human perceptions in addition to ecosystem attributes (Reynolds *et al.* 2007). The information gathered and available is often focused solely on biophysical attributes and processes. Human perceptions recorded via social science techniques or even open discussions can reveal the operation of important societal processes that mediate the interpretation of ecosystem attributes and govern management actions.

Establish clear goals (Susskind *et al.* 2012). This may require that conflicting goals among stakeholders are prioritized. In many rangeland settings, there may be common goals for ecosystem conditions that simultaneously support a variety of ecosystem services (*e.g.*, adequate grass cover to support livestock forage, control erosion, and promote wildlife). In other settings (cropland conversion) resolution of conflicts will require landscape-level planning.

Collaborate on research questions and methods (Susskind *et al.* 2012). All participants should be involved in framing the critical problems to be tested via adaptive management, selecting the variables to be measured, and contributing to the interpretation of new data. This level of preparation increases the likelihood that new information will be trusted and used.

Create knowledge systems that are durable, accessible, and expandable (Karl *et al.* 2012). This requires the blending of both science and local knowledge and investments in making the information readily available to users (*e.g.*, via internet and cellular technologies). It also requires an institutional commitment to maintain the integrity of the information and expand it.

Implement mechanisms for modifying management (Susskind *et al.* 2012). The goal of CAM should not be just to monitor, but to create the potential for adaptation. CAM emphasizes the importance of sharing knowledge about lessons learned through multiple land managers and across a broad variety of conditions to facilitate local improvements in management approaches. In regulatory settings or when a government supports a restoration action, there should be protocols in place for modifying policies and investments.

A method of evidence-based, collaborative adaptive management

The approach we outline below draws upon the preceding recommendations to address the challenges posed by desertification. Our proposal is based on our developing experiences in employing these ideas with land managers in the U.S., Mongolia, and Africa and draws upon several concepts and technologies that we expect will aid the implementation of CAM but that have not yet been connected to it. Below, we outline six practical steps and specific products resulting from them (Fig. 1, Table 1).

Identify focal landscapes and designate team members

Collaborating stakeholders identify and prioritize natural resource problems and restoration goals for a project area, typically a specific landscape sharing a common institution (*e.g.*, a land management office) or "community of practice" defined by shared interests (Roux *et al.* 2006). The boundaries of the project area are defined and a common vision and general strategies for the kinds of interventions sought are identified. For example, Morton *et al.* (2010) describe their efforts to work with land owners of the Grand River Grasslands region in the central U.S. to address the relationship between red cedar (*Juniperus virginiana*) encroachment, prescribed fire, and attitudes toward the use of fire. An essential component of this phase is to establish team leaders or "boundary spanners" (Briske 2012) and active representation from different stakeholder groups.

Obtain and organize existing information

Available information about a study region is gathered, made available, and synthesized. Information sources are

Table 1. Steps, tasks, and products proposed for a standard collaborative adaptive landscape management approach in rangelands.

Step	Tasks	Products
1. Designate focal landscape and team	Prioritize management issues, establish team leader, assemble team members representing stakeholders and information providers	Formalized work group, initial proposal document with timeline and resource requirements.
2. Obtain and organize existing information	Create GIS with existing layers; obtain relevant inventory, monitoring data, and historical information, and local knowledge within project area; literature on change processes within region or similar ecosystems	Digital workspace/portal to make information available; synthetic general conceptual models
3. Develop ecological site description (ESD) and state-and-transition models (STMs)	Conduct workshop to develop STMs and define properties of ecological sites; field evaluation of concepts via integrated plot data; develop and database ESD documents	Published workshop results, draft dichotomous keys to ecological sites, draft ESD documents and correlations to soil map units
4. Develop map products	Design and execute strategies for mapping ecological sites and states (may vary in scale of mapping, type of imagery used depending on types of states/scale of heterogeneity); incorporate output from models of landscape processes (e.g., hydrology, animal movement, downscaled climate change projections).	Ecological state map for project area (existing states), mapped climate change scenarios and resource concerns.
5. Use ESDs and maps for planning within focal landscapes	Interpret state maps and create derived management maps to guide management strategies; field validate map classes/interpretations; apply management actions	Derived maps with recommended actions, initial monitoring plan for review.
6. Monitoring and adaptive management	For each management unit, use STMs to define expected responses over specific timeframes and appropriate indicators; implement monitoring and data management protocols; update ESDs and management as necessary	Monitoring protocols in place, databases developed with clear links to further management actions

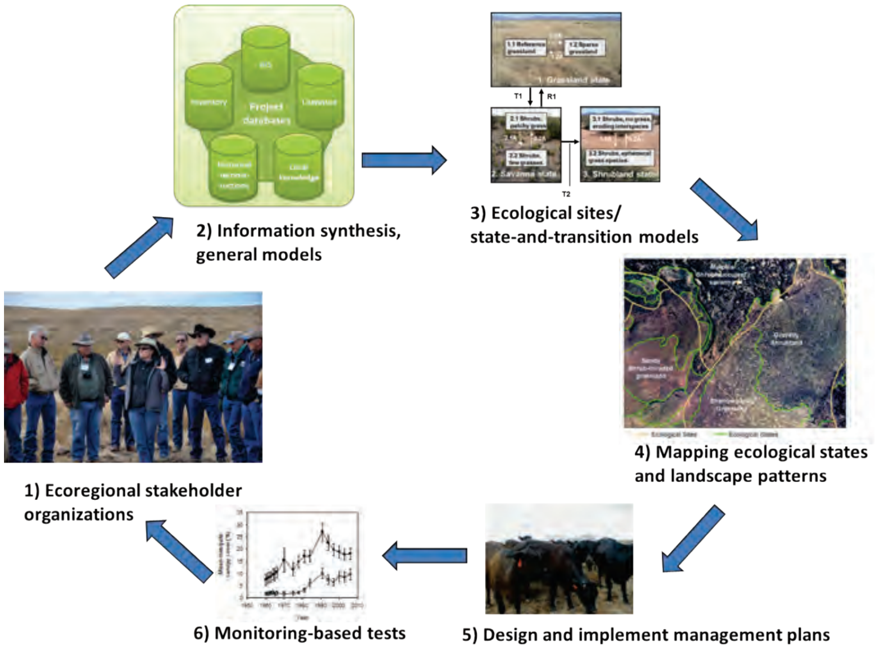

Figure 1. A schematic of the proposed method of evidence-based adaptive management.

now vast, including published literature, Geographic Information System (GIS) layers, existing inventory and monitoring data, historical reconstructions, and local knowledge. Global databases describing the outcomes of management actions, such as the Global Restoration Network (http://www.globalrestoration network.org/ database/), the Conservation Registry (www.conservationregistry.org), and the World Overview of Conservation Approaches and Technologies (https://www.wocat.net/) can provide ideas derived from similar environmental settings. Geo-semantic searching can be used to obtain literature from specific geographic areas or matched to specific environmental settings anywhere on Earth (Karl *et al.* In press). Participatory mapping exercises, interviews, and workshops (Reed *et al.* 2008; Morton *et al.* 2010) can be centered on logically organizing this information to produce general conceptual models of ecosystem change and restoration options for a region (Miller 2005).

Develop ecological site concepts and state-and-transition models

Land classes called ‘ecological sites’ are used in rangelands and forests as a means to differentiate land areas according to the soil and climatic factors that control vegetation composition (Brown and MacLeod 2011). Distinct ecological sites feature different climates, soil profiles, and topography which subdivide landscapes according to differences in historical reference conditions and likely responses to intervention.

Following the U.S. scheme, each ecological site is associated with a detailed state-and-transition model (STM) that describes the possible ecosystem states, the mechanisms of transitions, and the mechanisms preventing or promoting recovery of desired states (Briske *et al.* 2008a). Alternative ecosystem states represent differences in structure and function that are stable over management-relevant timescales without energy-intensive interventions, whereas state variants called “community phases” represent transient or reversible changes in vegetation and soils occurring within states. The mechanisms of transition between states or community phases in STMs logically link to management and restoration approaches presented as narratives. The narratives reflect all sources of available information and diverse stakeholder perspectives.

Generalized conceptual models specify important soil variations and mechanisms of state change; therefore, they serve as a basis for developing ecological site concepts (i.e. rationales for subdividing the landscape) and STMs of fine spatial resolution (Bestelmeyer *et al.* 2010; Moseley *et al.* 2010). Formal workshops and interviews capture a broad range of knowledge about ecological sites and also create a sense of shared ownership of these tools (Knapp *et al.* 2011). Guidelines for recognizing ecological sites and states are used to develop “Ecological Site Description” (ESD) documents that communicate the ecological indicators for each state, indicators of the resilience of particular states, and the ecosystem services provided by states. ESDs can then be used to: (1) specify goals, restoration practices, and hypotheses for specific parts of a landscape; and (2) structure and interpret tests with regard to the different states of particular ecological sites. The results of these tests can be archived and drawn upon to recognize the conditions in which particular interventions are effective and how they should be designed. Thus, the information contained in ecological site and STM narratives can evolve over time.

Databases managed by federal land management agencies in the U.S. provide mechanism for archiving and dissemination of information. Ecological sites directly link to digital soil maps of the U.S. National Cooperative Soil Survey, providing a spatially-explicit database system connecting ecological site information to specific land areas (*e.g.* see the SoilWeb browser; http://casoilresource.lawr.ucdavis.edu/drupal/node/902). Similar tools are being developed in other parts of the world (Herrick *et al.* 2013). For example, GlobalSoilMap.net is developing web-accessible, digital soil maps and related interpretations with 30-90 m resolution in several areas of the world (Sanchez *et al.* 2009).

Develop map products

Spatial data on ecological sites and states are essential to connect predictions to areas on the ground. Aerial photography and other GIS layers (*e.g.* digital elevation models, soil maps) can be used to produce maps of ecological sites and states and community phases by hand or using automated procedures (Steele *et al.* 2012). Because the ecological state or phase of a map unit is often difficult to ascertain from remotely-sensed data, the “state maps” should be used to structure rapid field assessments, based on indicators in ESDs, to verify state identity. The potential for spatial interactions with adjacent states (*e.g.*, off-site effects) can also be evaluated using imagery, field observations, and process-based logic or models. The mapping effort delineates land units according to their responses as predicted in STMs, rather than to arbitrary vegetation classes. The map units can also be used to store data about restoration actions in a GIS database.

Use ESDs and maps for planning within focal landscapes

Information in ESDs, via the spatial information from state maps, is used to specify the target states or community phases for specific land areas and the management interventions needed to achieve them. The selection of targets and interventions depends upon the ecosystem services desired and either the risk of degradation or the nature of restoration thresholds that must be overcome to achieve the target state. For example, in the Sandy ecological site of the northern Chihuahuan desert, the reference state was dominated historically by black grama (*Bouteloua eriopoda*) grassland. In grazed public lands of Dona Ana county, New Mexico, these rare states (Fig. 2) can be preserved with annual and seasonal adjustments to stocking rates (Nelson 1934) and recovered from very low cover values with multi-year rest (Bestelmeyer *et al.* 2013). Altered grassland states, dominated by bunchgrasses that are subordinate in the reference state, might recover black grama over the long-term if remnant plants exist, but can also be managed for the high cover and drought resilience of subordinate grass species, possibly even seeded in high rainfall years (Peters *et al.* 2012). Shrublands states can also be managed for ephemeral bunchgrass cover but are unlikely to be restored to grassland with any reasonable effort; therefore adaptation to shrub dominance is called for, perhaps including urban or energy development or creative new uses for wild shrublands (such as for biofuels). In this way, the scientific and local knowledge synthesized in STMs about different states can be used to produce derived “management maps” that represent in spatially-explicit fashion the potential ecosystem services possible from facets of land and testable propositions for attaining those services.

Monitoring and adaptive management

Monitoring stratified to different map units can test for the effectiveness practices to achieve desired outcomes. Stratification by ecological site and ecological state allows context-dependent tests of interventions. In designing the monitoring, there should be careful consideration of the

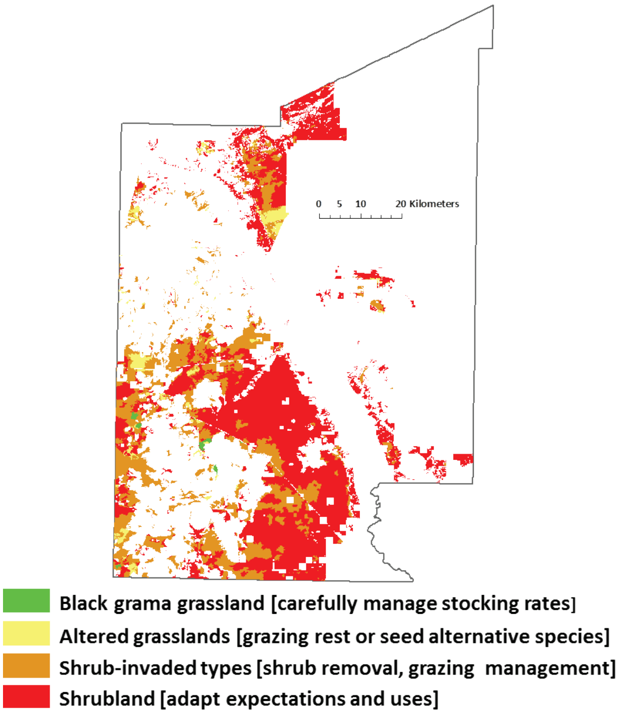

Figure 2. The distribution of the sandy ecological site (coarse-loamy, nongravelly Aridisols) occurring on public lands of Dona Ana County, New Mexico, USA (based on USDA-NRCS SSURGO data (http://soils.usda.gov/survey/geography/ssurgo). Each representative was classified to states of an STM using aerial photography coupled to ground surveys. The general restoration or adaptation strategies for each state are highlighted in brackets.

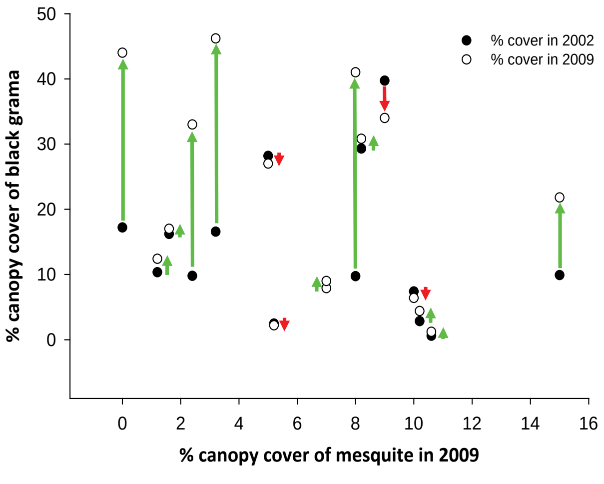

Figure 3. Monitoring data were used to test the assumption that mesquite shrub (*Prosopis glandulosa*) cover would constrain the recovery of black grama grass cover in lightly grazed settings at the Jornada Basin Long-Term Ecological Research site (http://www.lternet.edu/sites/jrn). The initial data were gathered in a dry period (2002) and the response data gathered after years of above average rainfall (2009). Mesquite cover changed little over this period. The results indicate that increases (green) and decreases (red) in black grama cover were not consistently related to mesquite cover.

response attributes and timelines for detectable change, based ideally on information in the ESDs.

The interpretation of the monitoring data should be discussed among stakeholders because the effects of intervention are influenced by short-term climate variability and other events such that the results are sometimes not straightforward to interpret. Furthermore, interpretations of a given result may be affected by manager perceptions, so interviews or surveys can provide information that would ultimately explain management responses to the new information. The limitations of the data obtained at any given time should be recognized and interpretations can evolve with additional data, hence the need for chronological archiving of observations.

For example, a recent monitoring exercise was used to examine grassland recovery in response to years of high rainfall and reduced grazing use across a range of shrub cover values. We learned that black grama grass recovery following high rainfall years can be substantial in areas with high shrub cover, as long as grass cover is not too low (Fig. 3). This result contrasts with the earlier belief that shrubs constrain grass responses and calls into question the expectations of some shrub control actions. The learning accomplished through monitoring can be used to change the criteria for recognizing ecological sites and states, as well as the practices applied to them. This learning can also feed global management-effects databases discussed earlier.

Implementing evidence-based collaborative adaptive management

Several policies could promote project-level implementations of our proposal. First, government (or even private) investments in restoration actions could include a mandateory monitoring component. This recommendation is already being advocated in the US via the Conservation Effects Assessment Program and is realistic considering the magnitude of public investment in restoration. Second, government agencies responsible for ecosystem or soil mapping (*e.g.*, the USDA Natural Resources Conservation Service in the US) could be directed to link mapping and interpretive products (ESDs) directly to restoration practices and to facilitate project-level use of these tools. Agencies could also help to manage data resulting from tests and update ESDs. Third, funding for, and partnerships with, universities, non-governmental science organizations, and government science agencies could be used to attract the expertise needed to organize adaptive management projects. Existing funding sources, such as the USDA Agricultural and Food Research Initiative, could direct resources toward these efforts.

Careful attention to information management is critical. Projects in the US would start with national databases housing soil maps that link the constituent soil map unit components to ecological sites. Soil mapping coupled to ecological site classifications and STMs (housed within a national ecological site database) would be used by project staff to map ecological sites and states in project areas. Practices are selected based on the STMs, monitoring is used to test for their effects, and STMs and ecological site classifications are updated in the national databases. Coordinators at the state or regional level within the agencies managing the databases would have responsibility for incorporating information produced from projects into the national databases. In this view, federal or state government agencies are needed to ensure the durability and integrity of information, but the inspiration, organization, and technical expertise for projects is necessarily a community-level effort.

Conclusion

As global change accelerates in the coming decades, management interventions and restoration will play an increasingly important role in sustaining ecosystem services (Aronson and Alexander 2013). Strategies that may have adequately served this role in the past may not be adequate for inexorably changing environments (Harris et al. 2006). Learning and adaptation will therefore be required. A method of evidence-based CAM could harness the power of site-specificity, community, and science to promote learning and adaptation and to avoid the pitfalls of rigid, overgeneralized thinking. The development of a broadly-applicable and flexible methodology for CAM, taking advantage of concepts such as ecological sites and STMs, and technologies such as mapping and web-accessible databases, could increase the frequency and success of projects and provide sorely needed knowledge to guide responses to desertification.

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References

Addison J, Friedel M, Brown C, Davies J, Waldron S (2012) A critical review of degradation assumptions applied to Mongolia's Gobi Desert. *Rangeland Journal* **34,** 125-137.

Archer SA, Davies KW, Fulbright TE, McDaniel KC, Wilcox BP, Predick KI (2011) Brush management as a rangeland conservation tool: a critical evaluation. pp 105-170.m In: D D Briske, editor. Conservation benefits of rangeland practices: assessment, recommendations, and knowledge gaps. Allen Press, Lawrence, KS.

Aronson J, Alexander S (2013) Ecosystem restoration is now a global priority: Time to roll up our sleeves. *Restoration Ecology* **21,** 293-296.

Bedunah DJ, Angerer JP (2012) Rangeland degradation, poverty, and conflict: How can rangeland scientists contribute to effective responses and solutions? *Rangeland Ecology and Management* **65,** 606-612.

Bestelmeyer BT, Briske DD (2012) Grand challenges for resilience-based management of rangelands. *Rangeland Ecology and Management* **65,** 654-663.

Bestelmeyer BT, Duniway MC, James DK, Burkett LM, Havstad KM (2013) A test of critical thresholds and their indicators in a desertification-prone ecosystem: more resilience than we thought. *Ecology Letters* **16,** 339-345.

Bestelmeyer BT, Goolsby DP, Archer SR (2011) Spatial perspectives in state-and-transition models: a missing link to land management? *Journal of Applied Ecology* **48,** 746-757.

Bestelmeyer BT, Moseley K, Shaver PL, Sanchez H, Briske DD, Fernandez-Gimenez ME (2010) Practical guidance for developing state-and-transition models. *Rangelands* **32,** 23-30.

Bowker MA (2007) Biological soil crust rehabilitation in theory and practice: An underexploited opportunity. *Restoration Ecology* **15,** 13-23.

Briske DD, editor (2011) Conservation benefits of rangeland practices: Assessment, recommendations, and knowledge gaps. United States Department of Agriculture, Natural Resources Conservation Service.

Briske DD (2012) Translational Science Partnerships: Key to Environmental Stewardship. *Bioscience* **62,** 449-450.

Briske DD, Bestelmeyer BT, Stringham TK, Shaver PL (2008a) Recommendations for development of resilience-based state-and-transition models. *Rangeland Ecology and Management* **61,** 359-367.

Briske DD, Derner JD, Brown JR, Fuhlendorf SD, Teague WR, Havstad KM, Gillen RL, Ash AJ, Willms WD (2008b) Rotational grazing on rangelands: Reconciliation of perception and experimental evidence. *Rangeland Ecology and Management* **61,** 3-17.

Brown J, MacLeod N (2011) A site-based approach to delivering rangeland ecosystem services. *Rangeland Journal* **33,** 99-108.

Carpenter SR (2005) Eutrophication of aquatic ecosystems: Bistability and soil phosphorus. *Proceedings of the National Academy of Sciences of the United States of America* **102,** 10002-10005.

Chapin FS, Kofinas GP, Folke C (2009) Principles of ecosystem stewardship: Resilience-based natural resource management in a changing world. Springer-Verlag New York.

Duff G, Garnett D, Jacklyn P, Landsberg J, Ludwig J, Morrison J, Novelly P, Walker D, Whitehead P (2009) A collaborative design to adaptively manage for landscape sustainability in north Australia: lessons from a decade of cooperative research. *Landscape Ecology* **24,** 1135-1143.

Evely AC, Pinard M, Reed MS, Fazey I (2011) High levels of participation in conservation projects enhance learning. *Conservation Letters* **4,** 116-126.

George DB, Roundy BA, St Clair LL, Johansen JR, Schaalje GB, Webb BL (2003) The effects of microbiotic soil crusts on soil water loss. *Arid Land Research and Management* **17,** 113-125.

Giardina CP, Litton CM, Thaxton JM, Cordell S, Hadway LJ, Sandquist DR (2007) Science driven restoration: A candle in a demon haunted world - Response to Cabin (2007). *Restoration Ecology* **15,** 171-176.

Hallett LM, Diver S, Eitzel MV, Olson JJ, Ramage BS, Sardinas H, Statman-Weil Z, Suding KN (2013) Do we practice what we preach? Goal setting for ecological restoration. *Restoration Ecology* **21,** 312-319.

Harris JA, Hobbs RJ, Higgs E, Aronson J (2006) Ecological restoration and global climate change. *Restoration Ecology* **14,** 170-176.

Herrick JE, Duniway MC, Pyke DA, Bestelmeyer BT, Wills SA, Brown JR, Karl JW, Havstad KM (2012) A holistic strategy for adaptive land management. *Journal of Soil and Water Conservation* **67,** 105a-113a.

Herrick JE, Havstad KM, Rango A (2006) Remediation research in the Jornada Basin: Past and future. Pp. 278–304. In:K.M Havstad, WH Schlesinger and LF Huenneke, editors. Structure and function of a Chihuahuan Desert ecosystem: The Jornada Basin LTER. Oxford University Press, New York, NY.

Herrick JE, Urama KC, Karl JW, Boos J, Johnson MVV, Shepherd KD, Hempel J, Bestelmeyer BT, Davies J, Guerra JL, Kosnik C, Kimiti DW, Ekai AL, Muller K, Norfleet L, Ozor N, Reinsch T, Sarukhan J, West LT (2013) The global Land-Potential Knowledge System (LandPKS): Supporting evidence-based, site-specific land use and management through cloud computing, mobile applications, and crowdsourcing. *Journal of Soil and Water Conservation* **68,** 5A-12A.

Herrmann SM, Tappan GG (2013) Vegetation impoverishment despite greening: A case study from central Senegal. *Journal of Arid Environments* **90,** 55-66.

Hilderbrand RH, Watts AC, Randle AM (2005) The myths of restoration ecology. *Ecology and Society* **10**:19. [online] URL: http://www.ecologyandsociety.org/vol10/iss11/art19/.

Hobbs RJ, Higgs E, Harris JA (2009) Novel ecosystems: implications for conservation and restoration. *Trends in Ecology and Evolution* **24,** 599-605.

Holechek JL, Hilton G, Molinar F, Galt D, Valdez R (2000) Short-duration grazing: The facts in 1999. *Rangelands* **22,** 18-22.

Karl JW, Herrick JE, Browning DM (2012) A strategy for rangeland management based on best available knowledge and information. *Rangeland Ecology and Management* **65,** 638-646.

Karl JW, Herrick JE, RUnnasch RS, Gillan JK, Ellis RC, Lutters WG, Martin LJ In press. Geo-semantic searching: discovering ecologically-relevant knowledge from published studies. Bioscience.

Knapp AK, Hoover DL, Blair JM, Buis G, Burkepile DE, Chamberlain A, Collins SL, Fynn RWS, Kirkman KP, Smith MD, Blake D, Govender N, O'Neal P, Schreck T, Zinn A (2012) A test of two mechanisms proposed to optimize grassland aboveground primary productivity in response to grazing. *Journal of Plant Ecology* **5,** 357-365.

Knapp CN, Fernandez-Gimenez M, Kachergis E, Rudeen A (2011) Using participatory workshops to integrate state-and-transition models created with local knowledge and ecological data. *Rangeland Ecology and Management* **64,** 158-170.

Lamont P (2004) Spiritualism and a mid-Victorian crisis of evidence. *The Historical Journal* **47,** 897-920.

Li YH, Wang W, Liu ZL, Jiang S (2008) Grazing gradient versus restoration succession of *Leymus chinensis* (Trin.) Tzvel. grassland in Inner Mongolia. *Restoration Ecology* **16,** 572-583.

Maestre FT, Bowker MA, Puche MD, Hinojosa MB, Martinez I, Garcia-Palacios P, Castillo AP, Soliveres S, Luzuriaga AL, Sanchez AM, Carreira JA, Gallardo A, Escudero A (2009) Shrub encroachment can reverse desertification in semi-arid Mediterranean grasslands. *Ecology Letters* **12,** 930-941.

McFadden LD, McAuliffe JR (1997) Lithologically influenced geomorphic responses to Holocene climatic changes in the Southern Colorado Plateau, Arizona: A soil-geomorphic and ecologic perspective. *Geomorphology* **19,** 303-332.

Michener WK (1997) Quantitatively evaluating restoration experiments: Research design, statistical analysis, and data management considerations. *Restoration Ecology* **5,** 324-337.

Miller ME (2005) The structure and functioning of dryland ecosystems—conceptual models to inform long-term ecological monitoring. United States Geological Survey, Reston, VA.

Morton LW, Regen E, Engle DM, Miller JR, Harr NR (2010) Perceptions of landowners concerning conservation, grazing, fire, and eastern redcedar management in tallgrass prairie. *Rangeland Ecology and Management* **63,** 645-654.

Moseley K, Shaver PL, Sanchez H, Bestelmeyer BT (2010) Ecological site development: A gentle introduction. *Rangelands* **32,** 16-22.

Nelson EW (1934) The influence of precipitation and grazing upon black grama grass range. U.S. Department of Agriculture, Washington, DC.

Pannell DJ, Roberts AM, Park G, Alexander J, Curatolo A, Marsh SP (2012) Integrated assessment of public investment in land-use change to protect environmental assets in Australia. *Land Use Policy* **29,** 377-387.

Peters DPC, Yao J, Sala OE, Anderson JP (2012) Directional climate change and potential reversal of desertification in arid and semiarid ecosystems. *Global Change Biology* **18,** 151-163.

Pringle HJR, Watson IW, Tinley KL (2006) Landscape improvement, or ongoing degradation - reconciling apparent contradictions from the and rangelands of Western Australia. *Landscape Ecology* **21,** 1267-1279.

Reed MS, Dougill AJ, Baker TR (2008) Participatory indicator development: What can ecologists and local communities learn from each other? *Ecological Applications* **18,** 1253-1269.

Reynolds JF, Grainger A, Smith DMS, Bastin G, Garcia-Barrios L, Fernandez RJ, Janssen MA, Jurgens N, Scholes RJ, Veldkamp A, Verstraete MM, Von Maltitz G, Zdruli P (2011). Scientific concepts for an integrated analysis of desertification. *Land Degradation and Development* **22,** 166-183.

Reynolds JF, Stafford Smith DM, Lambin EF, Turner BL, Mortimore M, Batterbury SPJ, Downing TE, Dowlatabadi H, Fernandez RJ, Herrick JE, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre FT, Ayarza M, Walker B (2007) Global desertification: Building a science for dryland development. *Science* **316,** 847-851.

Roux DJ, Rogers KH, Biggs HC, Ashton PJ, Sergeant A (2006) Bridging the science–management divide: moving from unidirectional knowledge transfer to knowledge interfacing and sharing. . *Ecology and Society* **11(1)**, 4. [online] URL: http://www.ecologyandsociety.org/vol11/iss11/art14/.

Sanchez PA, Ahamed S, Carre F, Hartemink AE, Hempel J, Huising J, Lagacherie P, McBratney AB, McKenzie NJ, Mendonca-Santos MD, Minasny B, Montanarella L, Okoth P, Palm CA, J. Sachs D, Shepherd KD, Vagen TG, Vanlauwe B, Walsh MG, Winowiecki LA, Zhang GL (2009). Digital soil map of the world. *Science* **325,** 680-681.

Sayre NF, deBuys W, Bestelmeyer BT, Havstad KM (2012) "The Range Problem" After a Century of Rangeland Science: New Research Themes for Altered Landscapes. *Rangeland Ecology and Management* **65,** 545-552.

Steele CM, Bestelmeyer BT, Burkett LM, Smith PL, Yanoff S (2012) Spatially explicit representation of state-and-transition models. *Rangeland Ecology and Management* **65,** 213-222.

Susskind L, Camacho AE, Schenk T (2012) A critical assessment of collaborative adaptive management in practice. *Journal of Applied Ecology* **49,** 47-51.

Thomas RJ, Akhtar-Schuster M, Stringer LC, Marques MJ, Escadafal R, Abraham E, Enne G (2012) Fertile ground? Options for a science-policy platform for land. *Environmental Science and Policy* **16,** 122-135.

Valone TJ, Meyer M, Brown JH, Chew RM (2002) Timescale of perennial grass recovery in desertified arid grasslands following livestock removal. *Conservation Biology* **16,** 995-1002.

Walker B, Salt D (2012) Resilience practice: Building capacity to absorb disturbance and maintain function. Island Press.

Warren A (2002) Land degradation is contextual. *Land Degradation & Development* **13,** 449-459.

Whitfield S, Reed MS (2012) Participatory environmental assessment in drylands: Introducing a new approach. *Journal of Arid Environments* **77,** 1-10.