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An integrated framework for science-based arid land management

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Abstract

Science is frequently touted as the solution to dryland management problems, yet most management decisions are, by necessity, based primarily on expert knowledge and experience. This paper describes an integrated framework for organizing, synthesizing, and applying our growing understanding of aridland ecosystems using a flexible, multi-objective assessment, monitoring, and management approach. The framework is dual-purpose: (1) to coordinate the use of existing tools, resources, and diffuse knowledge, and (2) to facilitate the integration and application of new knowledge as it is developed. In particular, this framework must facilitate the integration of new knowledge about linkages among landscape units across scales. The framework includes five elements: (1) an ecological site-based approach for categorizing land based on soils and climate, (2) a repository for organizing existing data and knowledge about each ecological site, (3) conceptual models that organize information on the impacts of management and climate variability, and protocols for (4) assessing and (5) monitoring key ecosystem attributes fundamental to a variety of management objectives. Within this framework, basic and applied research are explicitly linked to management of arid and semi-arid ecosystems to more effectively articulate research questions and set research priorities.

Keywords: Adaptive management; Ecological site descriptions; Natural resource management; Rangelands; Thresholds

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1. Introduction

Science-based land management requires the definition of the ecological potential of land, assessment of the current status of land relative to its potential, and monitoring data that document changes in status over time. Land management in the Chihuahuan Desert, for example, is often limited by uncertainty about the ecological potential of currently shrub-dominated areas. Grassland establishment or re-establishment is possible on some sites, while on others, soils and climate favor shrub-dominated communities.

Because land use and land management typically occur at landscape and larger scales (i.e. landscape and geomorphic hierarchies; Peters and Havstad, 2006), a spatially explicit accounting of ecological potential, current status, and change is required. Furthermore, management occurs within the context of climate variability. Determination of causes of change in land status thus requires an ability to assess the relative importance of anthropogenic- vs. climate-driven change and an understanding of how climate might accentuate or mitigate land use impacts. Integrating these spatial and temporal perspectives is a fundamental challenge to assessing and interpreting land use and land cover change (Peters and Havstad, 2006).

Four significant changes over the past several decades have transformed our perspectives on land management. First and foremost is that our understanding of how arid and semi-arid ecosystems function has evolved. Early inventory and monitoring approaches were predicated on the assumption that the tenets of Clementsian succession could be used to reliably predict vegetation change (e.g. Dyksterhuis, 1949). However, by the 1980s, it became clear that this perspective was too narrow and was not uniformly applicable to many arid and semi-arid systems (Lauenroth and Laycock, 1989; Joyce, 1993). This realization led to the development of a 'state-and-transition' perspective that asserts that vegetation on a given site may exist in numerous states, transitions between these states may be driven by management and climate, and transitions back to previous states may not occur without the addition of external inputs (Westoby et al., 1989; Archer and Stokes, 2000). Furthermore, the agronomic, utilitarian emphasis on monitoring a few key forage species has given way to the recognition that monitoring a suite of indicators of ecosystem function is required to ensure ecological sustainability (National Research Council, Committee on Rangeland Classification, 1994). Additionally, the use of total annual precipitation as a predictor of plant production has matured to account for effects of timing, sequencing, inter-annual variability and lag effects (Huxman et al., 2004; Snyder and Tartowski, 2006), and spatial variation and redistribution of precipitation (Gosz et al., 1995; Rango et al., 2006).

The second change is that the number and diversity of management objectives have increased. Recreation and conservation values have been dramatically elevated on land formerly dedicated to livestock production, and pressure to maximize water yield is increasing. Managers require data that can be used flexibly to address these diverse objectives. Changes in land tenure (Knight et al., 2002) have transferred power to interpret and apply these data to new individuals and organizations, including urban retirees and non-governmental conservation organizations.

The third major change is an increased demand for consistent management and monitoring across landscapes, watersheds, and regions. This change is reflected in both Congressional mandates (Pyke and Herrick, 2003) and local demands for agencies to work together. The fourth change is the increased availability of geospatial tools (e.g. geographic

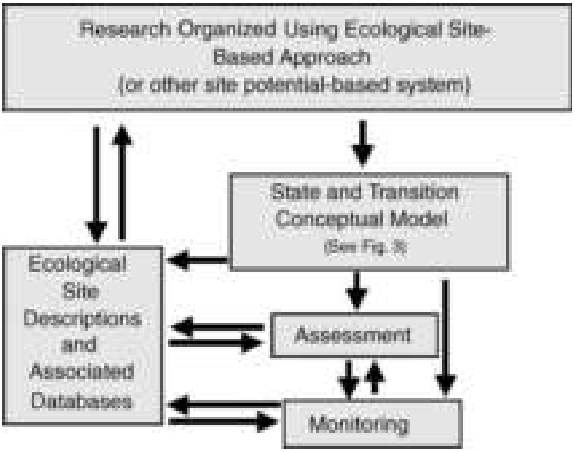

Fig. 1. Framework for organizing, synthesizing, and applying the evolving understanding of aridland ecosystems. The five elements and their relationships to each other are described in the text (modified from Archer and Bowman, 2002).

information systems, global positioning systems, spatial statistics) and remote sensing capabilities that facilitate the development and implementation of dynamic assessment, monitoring, and management systems at watershed and regional scales.

Our objective is to describe an integrated framework for organizing, synthesizing, and applying our growing knowledge of ecosystems to facilitate development of flexible, multi-objective assessment, monitoring, and management systems for arid and semi-arid ecosystems (Fig. 1). This application framework is designed both to co-ordinate existing tools, resources, and knowledge and to facilitate the integration and application of new knowledge as it is developed. It provides a realistic approach for applying the concepts of adaptive management (Walters, 1986) nationally and internationally.

2. Framework

The application framework includes five elements: (1) an approach for classifying land and applying research results to areas for which they are most likely to be relevant, (2) a repository for archiving, organizing, and facilitating the retrieval of information and knowledge about the ecological potential, plant community dynamics, probable effects of different land use activities for each type of land, and interpretations of the potential of land to support various values, including wildlife habitat, (3) conceptual models of plant community states and drivers of transitions among those states, (4) an assessment protocol that reflects the status of land relative to its potential, and (5) a monitoring system to document changes in the status of key ecosystem attributes. The framework is based on the assumption that sustainability of most land uses depends on the maintenance of three attributes that are the foundation for nearly all land uses: soil and site stability, hydrologic function, and biotic integrity (Fig. 2).

The first two elements of the framework are based on the United States Department of Agriculture–Natural Resources Conservation Service (USDA–NRCS) ecological site system. We selected ecological sites because they are largely consistent with the

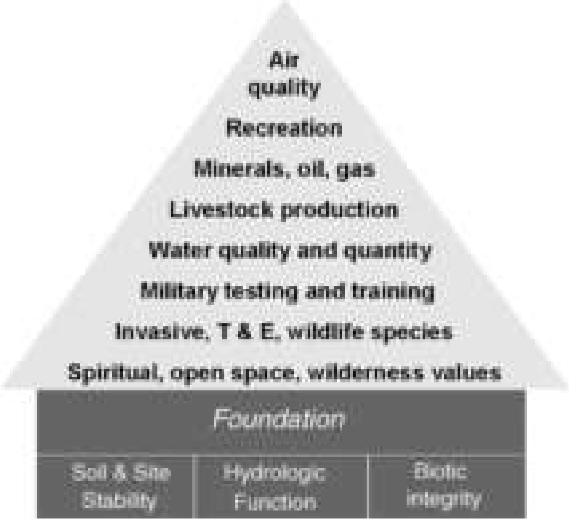

Fig. 2. Three key ecosystem attributes serve as the foundation for most land uses and are addressed by the assessment and monitoring elements of our framework.

requirements of the framework and because, from a practical perspective, the ecological site system is already being applied throughout much of the western United States. As currently implemented, however, the system has a number of weaknesses. Another objective of this paper is to identify limitations of all five elements and to suggest strategies for overcoming these limitations in light of information presented in other papers in this special issue.

2.1. Classification system

Numerous ecologically based spatial frameworks for land classification are currently available (McMahon et al., 2001), many of which are based on current or potential vegetation cover and composition. Approaches based on current vegetation may have value for specific goals (e.g. predicting wildfire risk) but they are generally of little use for land management, particularly in areas that have been extensively modified by historic cultivation, erosion, grazing, logging, off-road vehicle use, changes in fire regime, or species (plant or animal) introductions or removals. Research reports that include only a description of current vegetation are of little use to managers. A site may have similar vegetation, but the research may not be relevant to the manager if soils or climate differ significantly. For example, creosotebush (*Larrea tridentata*) dominates large areas of the southwestern United States, northern Mexico, and parts of Argentina. Some soils in certain climate regions currently dominated by creosotebush have the potential to support grasslands, while others do not (Gardner, 1951).

Classification systems that reflect potential vegetation are generally based on climate alone, a combination of climate and soils, or a combination of climate, soils, and current vegetation (Ladislav, 1997). Classification systems based on climate alone (e.g. Holdridge, 1967) are applied at regional or biome scales and are of little utility for management because of the large number of potential plant communities that can occur within a climate zone. Management requires knowledge of which potential plant communities can be established and persist at a particular location in the landscape. In the short term (years to decades), potential vegetation depends on climate, current soil structure and fertility, topography, and current vegetation. In the long term (decades to centuries), the ecological potential depends only on climate, relatively static soil properties (e.g. texture and depth; Tugel et al., 2005), and topography. The short-term potential can be modified by external inputs and manipulations including species additions and removals. Because resource availability varies both spatially and temporally (e.g. rainfall), classifications based on current or short-term potential tend to become quickly outdated. Consequently, we recommend use of classification systems based on long-term ecological potential as determined by climate, soil, and topographic setting. This approach has the additional advantage of being directly compatible with soil erosion risk classification systems (e.g. Warren et al., 1989; Helms, 1992).

The ecological site approach used by the USDA–NRCS is one such system. An 'ecological site' is defined as 'a kind of land with specific physical characteristics which differs from other kinds of land in its ability to produce distinctive kinds and amounts of vegetation and in its response to management' (Natural Resource Conservation Service, 1997). The ecological site approach relies on soil surveys for the identification of local landscape units and the Major Land Resource Area system to group units with similar climate. The ecological site approach is the only potential-based approach based on soils and climate that has been widely applied by land managers in the United States. Information regarding soil, climate, and vegetation characteristics of most ecological sites has already been collected (see Section 2.2). Because it is soil- and climate-based, the approach is generally compatible with the Terrestrial Ecosystem Unit Inventory (TEUI) system recently adopted by the United States Forest Service (USFS). The primary difference between the two systems is that TEUI includes current vegetation, in addition to soils and climate, as factors contributing to ecological potential. Consequently, an NRCS ecological site may be sub-divided in the TEUI system based on current vegetation. Also, soils with similar vegetation may also be combined in the TEUI system in certain situations.

The NRCS ecological site approach currently has five significant limitations. The first problem is that the definition of ecological sites is often based on previously established range sites (Natural Resource Conservation Service, 1997) rather than a systematic classification system. While site potential was fundamental to the range site system, the specific criteria used to define range sites varied from locale to locale throughout the United States. The second limitation is that if the approach is applied too dogmatically, important and functionally significant variability within ecological sites may be overlooked (Bestelmeyer et al., 2004). While many patterns and processes are relatively similar within and among many ecological sites, variability in soil surface texture, soil depth, and climate within an ecological site can have dramatic effects on plant community dynamics and resistance to stressors. Both of these limitations could be addressed through an inter-agency effort to transform the ecological site approach into a systematic, integrated soil–climate–landscape ecological land classification system. Closer integration with the National Co-operative Soil Survey is also needed, and the amount of information on dynamic soil properties included in soil surveys should be increased. Integration with other spatial frameworks (e.g. West et al., in press) could also help address these limitations. Some ecological sites will need to be divided or redefined, while others simply need to be more clearly correlated to soil survey map unit components. Remote sensing and GIS technologies, together with more detailed soil and topographic information collected in the area of interest, can be used to improve the quality of interpretations.

The third limitation is that while ecological sites are defined by what is *possible* in the long term, the approach by itself provides little information about what is *practical* in the short term. This limitation can be addressed by incorporating state-and-transition conceptual models into ecological site descriptions (ESDs) (see Section 2.3).

The fourth limitation is that even though ecological sites are groups of soil–landscape units with the same potential, the system does not explicitly account for the importance of linkages and feedbacks between soils, plants, and animals, and among landscape elements (Ludwig et al., 1997, 2000; Bestelmeyer et al., 2006; Peters and Havstad, 2006). For example, while playas are defined by the fact that they receive runoff, the timing and amount of runoff varies depending on hydrologic condition of upslope contributing areas. State and transition (S&T) models have the potential to partially address the fourth limitation. However, it is virtually impossible to fully account for dynamic linkages and feedbacks within a static classification system. For example, the spatial scale of hydrologic conductivity varies as a function of storm characteristics, antecedent soil moisture, ground cover, and soil structure. Despite this limitation, the classification system does help focus attention on the need to factor these types of relationships into decision making and interpretation.

The fifth and potentially most challenging limitation is that ecological potential cannot be precisely defined due to the nearly infinite number of soil, environmental, and climate combinations, the unpredictability of climate and weather patterns, the continuing evolution of plants, animals, and microbes, and the diversity of dynamic interactions described above. The range sites which serve as the basis for ecological sites were often based on relict areas believed to have been relatively unaffected by human activity. Addressing this last limitation will require the integration of diverse information sources. For example, data on the natural range of variability of plant species and communities on different soils and across climate gradients, experimental data on limitations to plant growth and reproduction in the context of changes in atmospheric chemistry (e.g. CO_2 enrichment, N deposition), and effects of animals and microbes on plant–soil interactions (see Lucero et al., 2006), may be included.

It should be noted that these limitations are not unique to the NRCS classification system; rather, they reflect limited knowledge in general. Research during the past 50 years has dramatically transformed our understanding of arid and semi-arid ecosystems; future research will further increase our understanding of critical processes that control soil, vegetation, and animal population dynamics. It is thus important that a working classification scheme has a structural flexibility that will allow it to accommodate new knowledge and perspectives as they become available.

2.2. *Data repositories*

A concern commonly expressed by both land managers and scientists is that existing data and knowledge are too infrequently applied to management. Two of the primary reasons are that information is not easily accessible and that it is too difficult to determine which research is applicable to a particular piece of land. ESDs (Table 1) provide one option for organizing information for management in the proposed framework.

Table 1
Elements of a typical ecological site description[a]

Element	Notes
Characteristics	
Physiographic features	Landform slope, elevation, aspect, and other features affecting long-term site potential
Climatic features	Averages and potential for extreme events, where relevant
Representative soil features	Parent material, texture and depth, other relatively static properties
Plant communities	
Ecological dynamics	General overview of current knowledge
State and transition model	e.g. Fig. 3
State descriptions	Communities and dynamics within states
Transition descriptions	Factors and processes associated with state changes
Interpretations	
Animal use	Often includes forage suitability by species and month, and initial stocking rates for livestock
Hydrology	This information is based on the soil survey
Other	May include information relevant to any other uses, such as wood products or recreation
Supporting information	
Sources used	Information and data sources
Relationship to other sites	How to distinguish from other sites; spatial linkages could be described here

[a] Currently under revision by Natural Resources Conservation Service.

ESDs serve as a repository for information describing the ecological potential, range of variability, and dynamics of each ecological site (Section 2.1). Managers can use this information to assess current status relative to potential, to establish realistic, practical management objectives, and to identify appropriate monitoring indicators. The determination of what is practical is commonly based on the current status of the plant community and dynamic soil properties, and on financial resources available for management inputs and manipulations. ESDs currently exist for most ecological sites and are increasingly available through the NRCS Ecological Site Information System (ESIS). While it is not a formal relational database, ESIS serves as a repository for data and other information contained in ESDs. The NRCS is currently in the process of updating and improving this on-line system. In the meantime, ESDs are available through many NRCS and Bureau of Land Management (BLM) state and local offices.

Most ESDs are based on previously developed range site descriptions (RSDs; Natural Resource Conservation Service, 1997). Whereas RSDs emphasized interpretive information for livestock production and wildlife habitat, ESDs include more information concerning ecological processes and dynamics (through incorporation of a S&T model) and a ‘reference sheet’ for making rangeland health assessments (see below).

ESDs share the strengths and weaknesses of the ecological site system described above. Because both are ultimately based on soils and climate, they share a consistent foundation and can be easily extended to other ecosystems and land uses, including cultivated and forested land (Brown et al., 1999; Herrick et al., 2002). Because ESDs integrate and re-interpret multi-year and multi-location data originally collected to develop RSDs, they provide access to a wealth of data that would be impossible to collect given current budget and personnel constraints.

This wealth of data is, however, also at the root of one of the primary limitations of ESDs: most of the vegetation data describe only what was believed to be the historic climax plant community. Data on other plant communities (states) and the transitions leading to them tend to be rather limited. This limitation is being addressed in the process of developing S&T models described in Section 2.3. In the future, data from independent studies and from inventory and monitoring protocols including the NRCS National Resources Inventory (NRI) can be incorporated into ESDs. Other data sets include some developed by the USFS and those being used to develop the National Vegetation Classification Standard (http://biology.usgs.gov/npsveg/nvcs.html). Use of much of the plot data included in these data sets is, however, often limited by lack of associated soil information needed to assign the data to a particular ecological site.

Another limitation of ESDs is that the quality of the RSDs that form the basis for current ESDs varies widely. Furthermore, inconsistencies exist in methods used to measure variables in ESDs (e.g. production and cover based on clipping or double-sampling, foliar vs. basal cover). A concerted commitment to standardization by ESD developers, scientists, and managers is required to address this limitation.

A final limitation of ESDs is that they lack sufficient information necessary to make interpretations for specific land uses and values (e.g. wildlife management). This limitation could be cost-effectively addressed by linking ESDs to other databases (e.g. those associated with habitat type classification systems) in which much of the information required to make these interpretations already exists. These linkages could be facilitated through the use of standard names for the plant communities associated with each ecological site (see Section 2.3). The National Vegetation Classification Standard could be used in many cases. However, because this classification is based solely on composition, it sometimes groups functionally distinct plant communities into a single ‘association’, which is the finest division in this classification. This problem is exacerbated when higher (coarser) classification levels are used (e.g. alliance or formation).

2.3. Conceptual models

Conceptual models are often used to represent our understanding of ecosystem dynamics, including effects of different management actions, and are therefore a key component of the proposed framework. Integrating conceptual models into ESDs provides managers with a tool that can be used to interpret information present in the database and appropriately apply that information to specific management problems. The S&T model is a particular type of conceptual model currently being incorporated into ESDs.

S&T conceptual models (Bestelmeyer et al., 2003; Stringham et al., 2003) are simply descriptions of our current understanding of ecosystem dynamics within particular regions and soil types. Because they are conceptual, draft versions can be developed quickly and are easily modified to reflect evolving understanding. These models can be used to focus research and data collection to further refine the models. This iterative approach to development and testing also allows these conceptual models to be used to guide the development of quantitative models. The approach is sufficiently flexible to represent community fluctuation in response to changes in resource availability (e.g. precipitation), changes caused by disturbance, recovery from disturbance (directional or cyclic), and

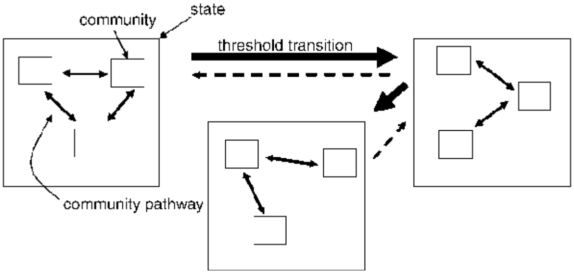

Fig. 3. Schematic of the organizational structure of a state and transition model (modified from Stringham et al., 2003). Large boxes are states connected by relatively irreversible threshold transitions. Small boxes (plant communities) within states are connected by relatively reversible pathways. Single-state systems are possible where no thresholds have been identified.

dynamics associated with species life-history traits (Westoby et al., 1989; Briske et al., 2003). S&T models consist of two basic components (Fig. 3): embedded boxes representing plant communities connected by relatively reversible transitions and large boxes representing ecological states (groups of plant communities) among which certain transitions are unlikely to occur over time frames relevant to management or which are difficult to achieve without aggressive management intervention (i.e. threshold transitions). Transitions within states include fluctuation, successional changes, and shifts among communities that can 'exist simultaneously under the same set of conditions' (Beisner et al., 2003). Interacting drivers, including management practices that promote transitions between states, are described in a legend specific to each model. In some ecosystems, transitions to alternate states have not been identified. These systems would thus be represented as a single state (large box) with dynamics reflected in transitions among plant communities within that state.

S&T models can be used to develop management strategies, choose appropriate assessment and monitoring approaches, and focus research and modeling efforts on key ecosystem properties and processes (Fig. 1). When applied in conjunction with land classification systems based on ecological potential (soils and climate), this approach has the potential to forge explicit linkages between ecosystem science and management (Fig. 1), increase the ability of ecologists to focus their research on questions directly relevant to management, and help managers prioritize their efforts and activities in time and space. Most importantly, explicit propositions in the model can be disproved using research and management experiments.

The S&T model in Fig. 4 is typical of several that have been developed for fine-textured soils in the Chihuahuan Desert. This particular model includes five states that differ in vegetation composition and spatial structure, soil organic matter content, and soil structure. Two interacting processes dominate the dynamics of the system portrayed in this model: (1) replacement of a highly productive grass community (Tobosa [*Pleuraphis mutica*] grassland state) by a low productivity grass community (Burrograss [*Scleropogon brevifolius*] grassland state) or by shrub-dominated communities (shrubland and mixed shrub–grassland states), and (2) changes in infiltration and runoff at both patch and landscape scales. Runoff increases at both scales as the Tobosa grassland transitions to the other states. Once these transitions have occurred, recovery to Tobosa grassland is limited by reduced soil water availability. In some cases, loss of soil organic matter inputs and

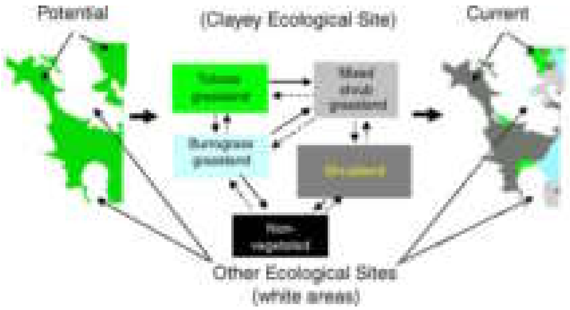

Fig. 4. State and transition model for the clayey ecological site (R042XB023NM; Sylvester et al., 2002) showing dynamics in an approximately 10-km^2 area in south-central New Mexico. Map colors correspond to states in the state and transition model. Multiple plant communities occurring in some states are not illustrated.

degradation of soil structure associated with compaction caused by livestock grazing reduce infiltration to the point that all plants die, leading to the non-vegetated state.

By emphasizing the importance of water redistribution for site dynamics, the model focuses research and management on areas for which changes in vegetation patch structure and soil structure degradation result in increased runoff. This conceptualization also suggests that a particular suite of indicators will be most useful to managers in recognizing change. The model illustrates the futility of re-seeding devegetated areas without addressing runoff (e.g. using low contour dikes as described by Rango et al. (2002)).

Application of S&T models to management is limited primarily by the fact that our understanding of the dynamic interactions between soil, vegetation, climate, and animals is incomplete. Historic legacies (Fredrickson et al., 2006; Peters and Havstad, 2006) further confound our understanding of these dynamics. Furthermore, the data necessary to define current state and trend within a model are frequently unavailable at scales relevant to management. A third limitation is that it is difficult to represent all factors that can affect site dynamics. Spatial linkages, feedbacks, and lag effects are particularly difficult to capture because of the virtually infinite number of possible interactions and because such linkages have not been widely studied or quantified. Finally, because the models are developed for individual ecological sites, they are most relevant to modal (soil and climate) conditions; two or more models must often be considered at soil or climate-defined ecotones.

These models, like all other models, are only as good as the knowledge used to develop them and the data used to apply them. One advantage of these models over more mathematical models, however, is that they are fully transparent. This fact allows managers to adapt the model to specifically represent their particular context and circumstances, to apply their local knowledge and experience, and serve as a basis from which to develop their own dynamic simulation models with off-the-shelf, user-friendly software (e.g. STELLA, 2004). Similarly, scientists can readily test assumptions and refine models based on research results.

In summary, S&T models are powerful tools for organizing and communicating current knowledge concerning management effects on ecosystem dynamics. They can also be readily adapted to integrate new knowledge as it becomes available. When integrated with appropriate assessment protocols, S&T models help focus management and monitoring activities on parts of the landscape that are most likely to change within a management timeframe.

2.4. Assessment protocol

Application of S&T models requires a holistic assessment of the functional status of the ecosystem. Many land assessment protocols are available, but most focus on the status of the system relative to its potential to provide a particular good or service, or rely on a single indicator (e.g. similarity to the historic climax plant community).

A new qualitative, standardized assessment protocol was designed to generate site-specific evaluations of three key ecosystem attributes that are the foundation for nearly all land management objectives: soil and site stability, hydrologic function, and biotic integrity (Fig. 2; Pellant et al., 1999, 2005; Pyke et al., 2002). Development of the protocol 'Interpreting Indicators of Rangeland Health' was initiated in response to two national level reviews (National Research Council, Committee on Rangeland Classification, 1994; Society for Range Management and Task Group on Unity in Concepts and Terminology, 1995) and has been led by an interagency team consisting of representatives from the USDA Agricultural Research Service, BLM, NRCS, and United States Geological Survey, with input from university personnel, consultants, and other interested organizations (Pellant et al., 1999).

Assessments are comprised of 17 indicators which are evaluated relative to site-specific 'reference sheets' (Table 2) accompanying ESDs (Section 2.2). The reference sheets provide a semi-quantitative description of each indicator relative to its ecological potential. Various combinations of indicators are then used to evaluate the status of each of the three foundational attributes (Fig. 2).

Limitations of the assessment protocol are discussed in the technical manual (Pellant et al., 1999) and in a subsequent manuscript (Pyke et al., 2002). Like nearly all qualitative protocols, this method is inappropriate for most monitoring applications because qualitative indicators generally lack the precision necessary to detect small changes. Because the indicators are relativistic and subjective, they should be assessed by individuals familiar with the ecosystem that understand the effects of variable soils, weather, and climate on the ecological potential of the site. Version 4.0 of the assessment protocol has been designed to minimize disagreement among practitioners (Pellant et al., 2005). Evaluations can be corroborated and checked by comparing measurements of selected indicators (e.g. bare ground) to reference-sheet ratings.

An additional limitation of this protocol is that it does not address linkages among landscape units that may affect the status of a particular location. For example, the presence of a gully would be reflected in a more negative rating of an area, but there is currently no protocol for characterizing landscape-level changes that lead to gully formation or its impact on downslope sites. This limitation is currently being addressed (see Bestelmeyer et al., 2006; Monger and Bestelmeyer, 2006; Peters and Havstad, 2006). Peters and Havstad (2006) proposed a framework encompassing five key elements that interact to connect units of varying spatial scales.

A final limitation of this assessment protocol is that many of the indicators were developed for use in ground surveys and cannot be assessed using airborne remote sensing technologies. Two approaches are being pursued to address this limitation. In the short term, ground-based evaluations of each of the three attributes can be

Table 2
Draft reference sheet for Clayey ecological site (R042XB023NM) for qualitative assessments[a]

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1. Number and extent of rills: There should not be any rills on this site.
2. Presence of water flow patterns: Water flow patterns will be generated by high-intensity storms due to the fine-textured soils on this site. However, high grass basal cover and low slope should limit patterns to less than 3 ft in length.
3. Number and height of erosional pedestals or terracettes: Pedestals should not be present due to high basal cover and low slope (1–5%); small terracettes (<1 in high) can be present on this site at the downslope edge of vegetation patches in areas with higher slope ($>3\%$).
4. Bare ground from ecological site description or other studies (rock, litter, standing dead, lichen, moss, plant canopy are not bare ground): Less than 45%.
5. Number of gullies and erosion associated with gullies: None.
6. Extent of wind scoured, blowouts and/or depositional areas: None.
7. Amount of litter movement (describe size and distance expected to travel): Fine litter (leaves and grass stems) may move up to 3 ft following intense storms. Coarse, woody litter should not move more than a few inches on this site due to high basal cover and low slope.
8. Soil surface (top few mm) resistance to erosion (stability values are averages—most sites will show a range of values): The soil surface should be resistant to erosion with stability values averaging 4–6. Lower values are associated with extended drought and possibly high $CaCO_3$ soils.
9. Soil surface structure and soil OM content (include type and strength of structure, and A-horizon color and thickness): The most common soil is the Stellar series. The A horizon is 0–2 in thick. It is a loam with a moderate medium platy strength of structure. The color of the A horizon is brown, (7.5 YR 3–5/4) and the soil OM is approximately 1%.
10. Effect of plant community composition (relative proportion of different functional groups) and spatial distribution on infiltration and runoff: High cover of stoloniferous grasses should increase infiltration by maintaining good soil structure. Plant bases should slow runoff, allowing more time for infiltration to occur.
11. Presence and thickness of compaction layer (usually none; describe soil profile features which may be mistaken for compaction on this site): No compaction layers should be on this site, however, argillic horizons are common with this soil and could be mistaken as a compaction layer.
12. Functional/structural groups (list in order of descending dominance by above-ground production or live foliar cover (specify) using symbols: $\gg, >, =$ indicate much greater than, greater than, and equal to; place dominants, subdominants and 'others' on separate lines):

Dominants: warm-season perennial rhizomatous grasses (e.g. tobosa (*Pleuraphis mutica*)).

Sub-dominants: warm-season perennial stoloniferous grasses (e.g. burrograss (*Scleropogon brevifolius*)) $\Leftrightarrow$ warm-season perennial bunchgrasses (e.g. *Aristida spp.* and *Sporobolus spp.*).

Other: annual forbs, perennial forbs, woody shrubs, succulents.

13. Amount of plant mortality and decadence (include which functional groups are expected to show mortality or decadence): Limited mortality and decadence of all functional groups expected following extreme drought. Alkali sacaton (*Sporobolus airoides*) and ring muhly (*Mulhenbergia torreyi*) can show decadence in the center of the plants at any time.
14. Average percent litter cover (15–50%) and depth (3/4 in). Low end of range during extended droughts; high end following periods with high production.
15. Expected annual production (this is total above-ground production, not just forage production): The amount of annual production for this site should be approximately 200 lbs/acre in unfavorable precipitation years and 600 lbs/acre in favorable precipitation years (as per ESD).
16. Potential invasive (including noxious) species (native and non-native). List species which characterize degraded states and which, after a threshold is crossed, 'can, and often do, continue to increase regardless of the management of the site and may eventually dominate the site'. Tarbush, mesquite and creosotebush can be potential invasive species on this site.
17. Perennial plant reproductive capability: All functional groups should be capable of producing through seed and/or vegetatively during nearly all years with near-average precipitation. Reproductive capability may be limited during droughts.

Applies to reference (tobosa) state in Fig. 4.

Indicators. For each indicator, describe the potential for the site. Where possible, (1) use numbers, (2) include expected range of values for above- and below-average years for each community and natural disturbance regimes within the reference state, when appropriate, and (3) cite data.

[a] 1 in = 2.54 cm; 1 ft = 30.48 cm; 1 lb = 0.45 kg; 1 acre = 0.41 ha.

extrapolated using remote sensing and supervised classification systems. This correlation-based approach can be quite successful at particular points in time for a particular area. However, the empirical relationships are rarely consistent through time and space. A longer term strategy involves the development of unique rangeland health indicators that can be detected using remote sensing (e.g. Ludwig et al., 2000, 2002). Identifying these indicators has been a long-standing challenge (e.g. Pickup, 1989; Pickup et al., 1998), but new airborne and satellite sensor arrays (e.g. Booth and Tueller, 2003) together with new analytical software show promise for resolving this shortcoming. For example, scientists at the Jornada Experimental Range are using eCognition to develop spatial pattern indicators at multiple spatial scales (Laliberte et al., 2004). Compared to traditional pixel-based image classification, the eCognition software (Definiens, 2003) is based on an object-oriented multi-scale image segmentation and classification approach (Benz et al., 2004).

2.5. *Monitoring protocol*

The final element of the framework is monitoring. Monitoring and assessment data are used in conjunction with S&T models to anticipate threshold transitions and to document changes in response to management. Both types of information are necessary for adaptive management. Like assessment protocols, most existing monitoring protocols focus on the status of the system relative to its potential to provide a particular good or service, or rely solely on vegetation cover and composition. They rarely consider the spatial pattern of vegetation or soil properties, both of which can be important indicators of threshold transitions.

A monitoring approach has recently been developed that addresses both spatial pattern and critical soil properties (Herrick et al., 2005). The monitoring approach was developed by Jornada Experimental Range (USDA Agricultural Research Service) scientists in co-operation with personnel representing the BLM, Department of Defense, Environmental Protection Agency, INIFAP (Mexican natural resource research organization), Nature Conservancy, NRCS, and New Mexico State University. The methods provided in this manual can be used to generate indicators of the three fundamental attributes that are evaluated using the qualitative assessment protocol (Section 2.4): soil and site stability, hydrologic function, and biotic integrity (Pyke et al., 2002). In addition to monitoring these attributes, the methods provided can be used to generate indicators that are relevant to a broad range of specific management objectives and concerns (e.g. wildlife habitat, fire, recreational impacts). The manual includes standardized descriptions of traditional (e.g. line-point intercept for monitoring cover, tree density using the USFS Forest Resource Inventory approach) and new methods (e.g. soil stability kit for monitoring soil erodibility). Our objective was to develop an approach that is sufficiently flexible to address multiple objectives while increasing data consistency among different monitoring programs.

The approach integrates both long- and short-term indicators. Long-term indicators, including plant basal cover, invasive species density, and soil erodibility, are used to determine trend. Short-term indicators, such as residual cover following grazing, are used to guide application of a management plan. A short 'quick start' volume describes basic methods and a supplementary volume describes additional methods, replication requirements, and monitoring program design (Herrick et al., 2005).

A unique feature of this manual is that it formally integrates soil indicators (e.g. compaction, infiltration, aggregate stability) with vegetation indicators, including vegetation spatial structure. Research at the Jornada Experimental Range (Bestelmeyer et al., 2006; Schlesinger et al., 1990) and elsewhere has clearly demonstrated that vegetation structure is a key indicator of ecosystem function. For example, size of inter-canopy gaps controls soil susceptibility to wind erosion (Okin and Gillette, 2001; Okin et al., 2006) and can affect resistance to exotic species invasions.

Like all plot-based protocols, the approach is limited in its ability to detect changes at the landscape scale. Even patch- and patch mosaic-scale changes (Peters and Havstad, 2006) may go undetected if transects are inappropriately located or the wrong size. S&T models (Section 2.3) may be useful for locating transects in areas that have a high probability of change (Bestelmeyer et al., 2004; Herrick et al., 2002).

3. Current applications

The five elements of the framework described in this paper are currently being used at the Jornada Experimental Range to identify research questions, set research priorities, and link research to management. At the national scale, core monitoring measurements are being incorporated into the NRCS NRI for rangelands (Spaeth et al., 2003). Benefit-cost and statistical analyses of data from pilot studies have been used to make the NRI progressively more cost-effective relative to its broadly defined objectives (Fig. 5). The framework has also been incorporated into the development of some of the Nature Conservancy's planning tools. The assessment protocol is being applied at various locations throughout the United States by the BLM, NRCS, private consultants, and non-profit conservation organizations. The protocol is also being translated into Spanish for application in Mexico and is currently being tested in China (K.M. Havstad, personal communication). The monitoring protocol will be available in Spanish and Mongolian.

4. Summary and conclusions

The framework described here has the potential to significantly increase the extent to which aridland management is based on science. This management framework addresses many of the issues raised by the research framework of Peters and Havstad (2006).

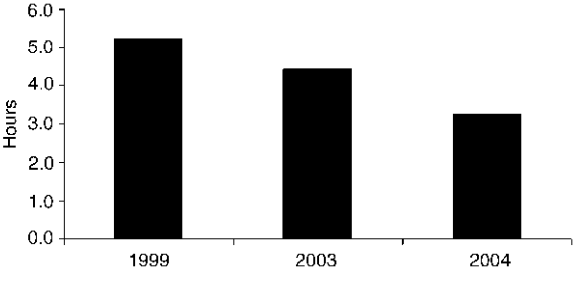

Fig. 5. Average time required (h) for a two-person team to complete field measurements at a Natural Resources Conservation Service National Resources Inventory point using framework monitoring methods (Herrick et al., 2005).

By making research data and other information more accessible to land managers, this management framework can increase the probability that research will be applied (Sections 2.1 and 2.2). By focusing research on critical land management issues, S&T models can increase research relevance (Section 2.3). By applying assessment and monitoring protocols that are consistent with a broad range of management objectives, managers can reduce costs while increasing their ability to adapt management based on an understanding of changes in fundamental ecosystem properties and processes (Sections 2.4. and 2.5). All elements of the framework exist. Implementation throughout the United States will require a multi-agency commitment to improving the quality of the ecological site system and a commitment by scientists to ensuring the geographic relevance of their research is clearly reported. Although some of the components of this framework (e.g. ESDs) are not currently available in other countries, the principles and many of the methodologies are applicable to arid and semi-arid systems worldwide.

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