187

A tool for guided state and transition model development based on ecological theory

. Bestelmeyer, B.T[1]; Williamson, J.C[1]; and McCord, S.E[1]

*USDA-ARS Jornada Experimental Range, Las Cruces, NM, USA

Key words: ecosystem dynamics; land degradation assessment; monitoring

Abstract

State-and-transition models (STMs) are ideally suited to provide management and restoration guidance as well as site-specific benchmarks for land degradation monitoring and measurement, monitoring, reporting, and verification for ecosystem service markets. STMs, however, have been difficult to produce with sufficient consistency, utility, and accessibility to serve these functions. To address these problems, we developed the State Transition Classifier and State Transition Atlas tools that guide users through the production of STMs featuring 1) guidance for defining land units based on the maximum spatial extent of an STM, 2) menus for attributing each STM component (i.e. states and elements of transition narratives) with standard, logic-based classes, 3) guidance for structuring STM narrative portions in an efficient and consistent way, 4) guidance for inclusion and interpretation of quantitative indicators and benchmarks, and 5) an online storage and display solution (the Atlas). These tools support collaborative development of STMs at a variety of scales and can be adapted to different classification systems used on rangelands globally. The Classifier and Atlas can facilitate a broad understanding of rangeland ecosystem dynamics by developers, users, and the public at large.

Introduction

Evaluation of land degradation supporting land health and sustainable development goals is an ongoing global challenge (Cowie et al. 2018). There is vast heterogeneity in potential ecosystem conditions and their responses to global change drivers. Unrecognized heterogeneity can lead to incorrect assessment of land degradation and counterproductive responses. For example, afforestation of naturally treeless grasslands, based on the assumption that open ecosystems were deforested at some time in the past, is symptomatic of misidentified land potential (Briske et al. 2024). Furthermore, misidentification of ecological constraints to recovery in true instances of ecosystem transition can accelerate, rather than reverse, land degradation. For example, use of fire or physical removal of woody plants to recover historical grassland degradation in some circumstances can trigger increased soil erosion and worsen land degradation (Karban et al. 2022).

State and transition models (STMs) provide a means to organize scientific information about causes and management of ecosystem transitions according to variations in land potential (e.g. via ecoregions or ecological sites). STMs are used globally for evaluating, mapping, and managing ecosystem services

(Eastburn et al. 2017; Han et al. 2022; Jones et al. 2023; Peinetti et al. 2019; Sato and Lindenmayer 2021). By classifying land areas to discrete states based on ecosystem processes, STMs provide mappable benchmarks for land evaluation. STMs can house qualitative and quantitative information about the consequences of state transitions for ecosystem services. Thus, STMs can play central roles in the measurement, monitoring, reporting, and verification of carbon storage and other processes for ecosystem service markets and climate commitments. Furthermore, STMs can guide restoration investments. Restoration successes and failures can be predicted by variation in soil, climate, and the characteristics of existing vegetation states (Brudvig and Catano 2024).

While many STMs have been developed, the unorganized body of models has several critical limitations, including 1) lack of consistency and accuracy, 2) lack of spatial coverage, 3) vague or incorrect application to specific land areas, and, consequently, 4) limited utility for decision making. Systematic development of STMs is a requirement for databasing STM information and helps to create logical consistency and scientific credibility.

We developed two tools, the State Transition Classifier and State Transition Atlas. The Classifier is a web-based tool to develop STMs using a consistent model structure and choice lists for each STM component. The Atlas is a global database for building and storing STMs linked to spatial data and related information for different ecoregions that is useable by the public.

Methods and Tools

The guided STM format, called the State Transition Classifier, was developed from literature review using terminology for STM components including states, triggers, resilience management (actions affecting the ability of triggers to cause a transition), feedbacks reinforcing alternative state after transitions occur, and restoration practices to overcome specific feedbacks (Bestelmeyer et al. 2017; Suding and Hobbs 2009). Each component is associated with a drop-down list of potential categories, also derived from the STM literature. When logically constructed, this format creates an STM "class" or syndrome. Options for descriptive narratives and data tables are also included for most components to provide region-specific details.

Two web applications were developed. The State Transition Classifier (https://webapps.jornada.nmsu.edu/transition-classifier) is accessible to anyone interested in exploring STM development through an interactive interface. This application encourages users to catalog the changes that can occur within an ecosystem of interest. It displays transitions graphically and lets users assign Classifier categories to diagram components using point-and-click features. Once a set of transitions has been created, users are able to connect these transitions to form a complete STM. Classifier attributes are incorporated into STM diagrams and providing a concise visual summary of the mechanisms that lead to (and potentially reverse) ecosystem transitions.

The Classifier is meant to be a temporary repository of ecological information. It is a place where users can think through ideas about STMs in a non-committal way. Transitions created with the tool are saved in an IndexedDB database on the user's device so that users can return to their work at a later time. Aside from exporting STMs from the tool as JSON documents and graphics (Fig. 1), however, users have no way to share the STMs they create with a broader audience.

We developed a second web application to extend the functionality of the Classifier and facilitate more effective information sharing. With the State Transition Atlas, users can create and characterize ecosystem transitions just as with the Classifier application. In addition, the Atlas provides a place where uses can

archive STMs indefinitely, map regions where STMs are applicable, and share STMs with a global audience. Users must register with the Atlas project to publish information to the platform. Published STMs can be either public (i.e., accessible to everyone) or private (accessible only to a group of invited users). Users invited to the platform can be assigned read-only, read-write, or administrative access. Whereas the Classifier is a single-page web application served as a static website, the Atlas requires more sophisticated system architecture. It includes a website, server application, and supporting document database. STM documents exported from the Classifier can be imported seamlessly into the Atlas application. The structure of the Atlas enables future integration with monitoring and other key rangeland management datasets (McCord et al. 2023) to support streamlined assessment and management decision making.

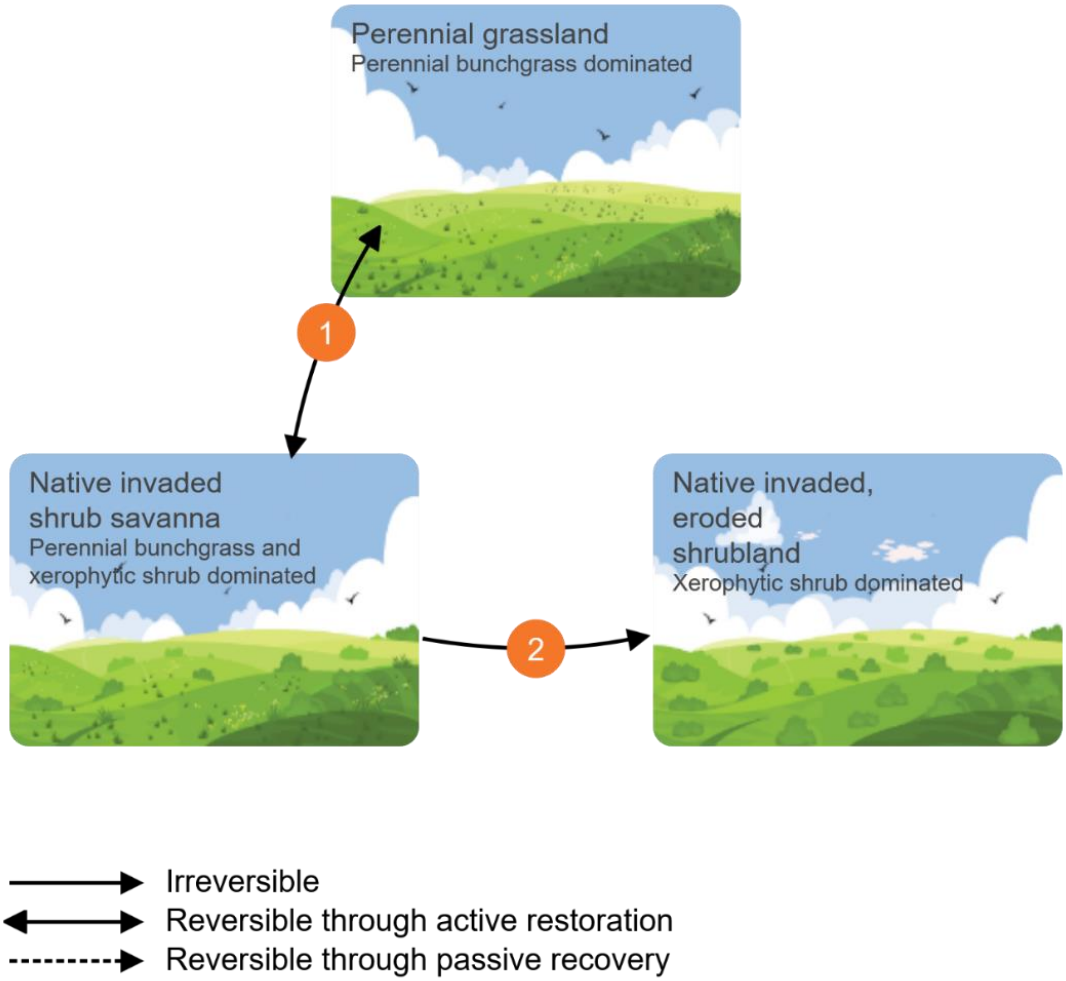

Figure 1. A simplified example of the Ecosystem Transition Sandbox graphical format. State and transition details can be added.

Discussion

The Classifier and Atlas have undergone preliminary testing and refinement and will undoubtedly be refined further. Regarding the Atlas, the governance of a body of STMs that can be produced by multiple users is a challenging problem. Even with the structure provided by these tools, logically inconsistent and conflicting models can be produced by different users. Thus, we are developing a strategy involving the

production of global STM "syndromes" based on ecological mechanisms in the scientific literature as a first step for the Atlas, followed by national-scale application of the syndromes and adding details and benchmarks as a second step carried out by vetted, inclusive, collaborative groups. Participatory development of STM information is essential for their practical use in managing communal natural resources (Knapp et al. 2011). Separating development of syndromes as a first step from details and benchmarks as a second step in effect separates arguments about the ecological mechanisms underpinning STMs from values and experiences in local to national land management. This approach, we hope, will simplify the production of STMs and accelerate their use for the science-supported monitoring and evaluation of rangelands. We expect that such revised approaches to STM development will improve the accessibility, consistency, and quality of information to pastoralists and the institutions seeking to promote rangeland resilience.

Acknowledgements
This research was supported by appropriated funds to the USDA Agricultural Research Service and is also a product of the Jornada Basin Long-Term Ecological Research Program.

References

Bestelmeyer, B.T., Ash, A., Brown, J.R., Densambuu, B., Fernández-Giménez, M., Johanson, J., Levi, M., Lopez, D., Peinetti, R., Rumpff, L. and Shaver, P. 2017. State and transition models: Theory, applications, and challenges. In: D.D. Briske (Ed.), *Rangeland Systems: Processes, Management and Challenges*. Springer International Publishing, Cham, pp. 303-345.

Briske, D.D., Vetter, S., Coetsee, C. and Turner, M.D. 2024. Rangeland afforestation is not a natural climate solution. *Frontiers in Ecology and the Environment*, 22(5): e2727.

Brudvig, L.A. and Catano, C.P. 2024. Prediction and uncertainty in restoration science. *Restoration Ecology*, 32(8): e13380.

Cowie, A.L., Orr, B.J., Castillo Sanchez, V.M., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S., Tengberg, A.E., Walter, S. and Welton, S. 2018. Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science & Policy*, 79: 25-35.

Eastburn, D.J., O'Geen, A.T., Tate, K.W. and Roche, L.M. 2017. Multiple ecosystem services in a working landscape. *PLoS ONE*, 12(3): e0166595.

Han, P., Zhao, X., Dong, Z., Yan, Y., Niu, J. and Zhang, Q. 2022. A new approach for the classification of grassland utilization in Inner Mongolia -- based on ecological sites and state-and-transition models. *Ecological Indicators*, 137: 108733.

Jones, C.S., Thomas, F.M., Michael, D.R., Fraser, H., Gould, E., Begley, J., Wilson, J., Vesk, P.A. and Rumpff, L. 2023. What state of the world are we in? Targeted monitoring to detect transitions in vegetation restoration projects. *Ecological Applications*, 33(1): e2728.

Karban, C.C., Miller, M.E., Herrick, J.E. and Barger, N.N. 2022. Consequences of Piñon-Juniper Woodland Fuel Reduction: Prescribed Fire Increases Soil Erosion While Mastication Does Not. *Ecosystems*, 25(1): 122-135.

Knapp, C.N., Fernandez-Gimenez, M., Kachergis, E. and Rudeen, A. 2011. Using participatory workshops to integrate state-and-transition models created with local knowledge and ecological data. *Rangeland Ecology & Management*, 64(2): 158-170.

McCord, S.E., Webb, N.P., Bestelmeyer, B.T., Bonefont, K., Brehm, J.R., Brown, J., Courtright, E.M., Dietrich, C., Duniway, M.C., Edwards, B., Fraser, C., Herrick, J.E., Knight, A.C., Metz, L., Van Zee, J.W. and Tweedie, C. 2023. The Landscape Data Commons: A system for standardizing, accessing, and applying large environmental datasets for agroecosystem research and management. *Agricultural & Environmental Letters*, 8(2): e20120.

Peinetti, H.R., Bestelmeyer, B.T., Chirino, C.C., Kin, A.G. and Frank Buss, M.E. 2019. Generalized and Specific State-and-Transition Models to Guide Management and Restoration of Caldenal Forests. *Rangeland Ecology & Management*, 72(2): 230-236.

Sato, C.F. and Lindenmayer, D.B. 2021. The use of state-and-transition models in assessing management success. *Conservation Science and Practice*, 3(10): e519.

Suding, K.N. and Hobbs, R.J. 2009. Threshold models in restoration and conservation: a developing framework. *Trends in Ecology & Evolution*, 24(5): 271-279.