



## Challenges and opportunities for broad-scale state-and-transition model development

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### Abstract

State-and-transition models (STMs) provide an intuitive framework for interpreting ecological observations in support of assessment, monitoring, research, and management of rangeland ecosystems. Australian scientists proposed STMs as a non-linear alternative to the equilibrium range succession model after the latter was scrutinized during the 1984 International Rangeland Congress in Adelaide. As the Congress returns to Adelaide 40 years later, the paradigm shift away from linear succession toward a non-linear mental model is self-evident. Yet despite consensus that rangelands often exhibit multiple stable states and irreversible transitions, the broad-scale development of STM products cataloguing alternative states, transitions between states, and differences among states is lacking, thus hindering the ability of natural resource managers and researchers to fully implement the STM paradigm. Renewed efforts by the United States Department of Agriculture are incorporating new ideas to elevate future STM products. We discuss challenges of STM development and present a vision for systematic, broad-scale production of STMs based on the following principles and assertions: spatial context – ecosystem properties or classes to which an STM applies must be well defined to reasonably interpret field observations and predict the behaviour of similar areas; inclusive collaboration – STMs must represent the collective ecological knowledge of field scientists, resource managers, local and indigenous experts, and other observers; reliability – STM developers must curate knowledge and data from reputable sources and implement quality control measures; accessibility – interactive online applications must be designed to easily identify an STM of interest and address specific questions about states, transitions, risks, and opportunities; diverse interpretations – STMs must describe interpretive differences among ecological states (e.g., habitat, fire behaviour, forage, water balance) to reflect diverse management and societal priorities. In addition to these principles and assertions, we discuss a variety of mechanisms to achieve our vision of easy access to reliable ecosystem knowledge in support of rangeland management and research.

### Introduction

The broad-scale development and application of state-and-transition models (STMs) has proven to be inherently challenging. The STM paradigm remains alluring to many because it systematically organizes existing knowledge about ecosystem dynamics into simple box-and-arrow diagrams (Fig. 1), and it has the potential to put reliable scientific information directly into the hands of rangeland managers and other

decision-makers. The basic process of STM development is to 1) define an ecosystem of interest, 2) observe and define the ecological states that occur in that ecosystem, 3) describe the circumstances under which one ecological state transitions to another, and 4) describe the variability in ecosystem attributes and services within each ecological state. STM development is relatively simple when applied to a small area with a few distinct ecosystems, however, the complexity significantly increases when producing STMs for hundreds or thousands of ecosystems across an entire region or continent. Scientists from several countries have made commendable efforts at nationwide STM development in the 35 years since Westoby et al. (1989) proposed the framework as an alternative to the range succession model; yet each attempt has encountered some combination of conceptual, administrative, and technical impediments that stifled broad-scale development and application of STMs (Bestelmeyer et al. 2017). The STM paradigm and its products are seemingly much easier to comprehend and envision than they are to implement and produce.

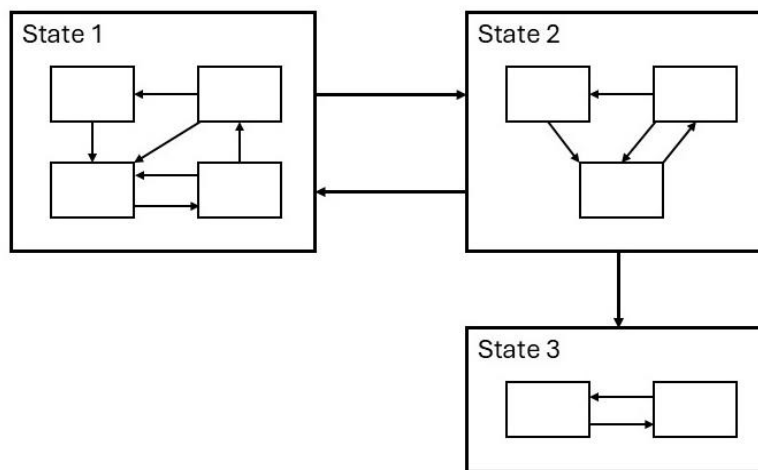


Fig. 1. A generalized STM showing three ecological states, a reversible transition between states one and two, an irreversible transition from states two to three, a lack of transition between states one and three, and community dynamics within each state. The number and nature of states and transitions in STMs varies depending on the ecosystem. To become a complete STM product, these box-and-arrow diagrams should include a legend, photos, tables, figures, and narrative descriptions that describe the variability in attributes and ecosystem services of each state, as well as the primary drivers, triggers, feedbacks, and indicators of each transition.

Despite the many challenges presented by broad-scale STM development and application, the United States (US) Department of Agriculture (USDA) is learning from past efforts and implementing the organizational structure, processes, and systems needed to tackle this complex task for the entire nation. This paper first outlines the challenges associated with broad-scale STM development and application, then outlines specific opportunities that the USDA and partners are pursuing to address each challenge.

## Challenges

Impediments to nationwide STM development can be categorized as conceptual, administrative, technical, and utilitarian.

### Conceptual challenges

The most significant conceptual challenge to broad-scale development efforts in many parts of the world is defining the reference domain to which each STM applies. STM development across broad regions requires a systematic ecosystem classification based on the environmental features that determine ecosystem

potential and dynamics (Bestelmeyer et al. 2009). Climate, soils, physiography, hydrology, and other attributes vary across the landscape and determine the ability of each site to provide ecosystem services (i.e., site potential) and respond to natural and anthropogenic disturbances (i.e., ecosystem dynamics). For example, a peat bog may be adjacent to a well-drained sandy hillslope. Despite sharing a similar climate, these two sites have very different soils, hydrology, geomorphology, disturbance regimes, and ecosystem services associated with their distinct landscape context. These ecosystems are inherently different; thus, the STMs must reflect differences in states, transitions, and the interpretations thereof. Early efforts to produce broad-scale STMs in Australia and Argentina stalled, in part, due to a general lack of soil and other site attribute data at management-relevant scales (Bestelmeyer et al. 2017). Another conceptual challenge suggested by the STM literature is the need to systematically incorporate useful information about ecological processes and resilience into STMs, since the site-specific data needed to do so is generally lacking (Stringham et al. 2003; Briske et al. 2008).

### ***Administrative challenges***

In countries where detailed soil and site information is sufficient for systematic classification of ecosystems, administrative challenges represent the next barrier to nationwide STM development (Bestelmeyer et al. 2017). Organizational structure is necessary to develop 1) a coordinated network of experts with experience across all regions of the country, 2) coordinators responsible for bringing the experts and data together to produce useable products, and 3) clear STM product standards that include robust quality control and assurance processes. Of course, this level of organization requires sustained support and funding from institutions and individuals that value comprehensive, reliable ecosystem knowledge in support of ecosystem-based resource management. A one-time investment to develop a national STM reference library is at odds with the incremental nature of scientific knowledge generation. Instead, a sustained commitment must be procured to establish and maintain an organizational structure capable of developing and updating STMs over time as new knowledge is generated (Karl and Talbot 2016).

### ***Technical challenges***

Given administrative support and an ecological classification system, technical challenges abound when implementing a broad-scale STM development program. Most of the technical challenges stem from data management needs and training technical staff. Data systems must facilitate the efficient capture, organization, and summarization of soils, vegetation, climate, disturbance, and many other observational data types from reputable sources across all regions and ecosystem classes. While field data collection methods can be standardized for future STM refinements, first draft STMs often rely on the use of existing datasets, which can vary greatly in quality, methods, scale, and other variables. Capturing, organizing, and preprocessing new and existing data can be a monumental undertaking. Efficient workflows and processes must be designed for streamlined analysis and synthesis. Significant training is required for technical experts to learn the STM paradigm, apply standards consistently across all regions, and analyse and summarize data into useful STM products. Perhaps the greatest training challenge is for field ecologists and data analysts to become effective STM development coordinators, capable of utilizing a network of contributors with diverse experiences and perspectives in a truly collaborative process (Bruegger et al. 2016). Moderating meetings, active listening, social skills, and concise writing are critical communication skills necessary to successfully integrate our collective knowledge of ecosystem potential and dynamics into authoritative STM products.

### ***Utilitarian challenges***

The ultimate utilitarian challenge is to create STM products that are so informative and intuitive that a person would be foolish not to use them. Unfortunately, STM developers can become so enthusiastic about

the science of STM development that they lose focus on the customers' fundamental need to interpret STMs for the purpose of making land management decisions in the real world. Decision-makers use STMs to assess trade-offs in ecosystem services among different ecological states as they consider the costs and benefits of managing in favour of one ecological state over another (Miller et al. 2011). Because many end users have their own work to do, it can be difficult to engage them directly to understand what information is most relevant to them, at what scales, and in what delivery format. Once customer needs are identified, new challenges arise. Software applications must be developed to deliver the STMs in an intuitive, accessible, reliable format that offers quick access to specific answers to the most common questions. A successful software application would also encourage the collection of user feedback as a method to further validate the concepts within the STM. Finally, the arithmetic of developing tables, graphs, photos, and narratives for many ecosystem services occurring on multiple ecological states and across hundreds or thousands of different ecosystems adds up to an enormous workload that requires competent teams with diverse expertise.

### **Opportunities**

The USDA Natural Resources Conservation Service (NRCS) is poised to address each of the conceptual, administrative, technical, and utilitarian challenges facing STM development in the US today.

#### ***Conceptual opportunities***

The US benefits from more than 125 years of soil survey. The US soil survey produced the spatial and edaphic data needed to develop the "range site" classification system in the mid-twentieth century. Once NRCS began adding STMs to range site descriptions in the late 1990s, the name of the classification was changed to ecological sites (ES), and the scope of ES development expanded to include all native landscapes, with the inclusion of all intensively managed lands in 2010. The ES classification system provides an ideal reference domain for STMs because ESs define the soil and site attributes that determine site potential and dynamics of ecosystems at human operative scales (Moseley et al. 2010). Shortly after the STM paradigm was adopted by NRCS, a complementary concept of dynamic soil properties (DSPs) emerged within the agency (Tugel et al. 2008). The premise of DSPs is that some soil properties change in measurable ways when an ecosystem changes to a different state. The number of DSP projects in the US has steadily increased in the past 15 years, creating new insights about soil-plant feedback process and resilience that can be incorporated into STMs as the literature suggests (Stringham et al. 2003; Briske et al. 2008).

#### ***Administrative opportunities***

Even as the ES paradigm was evolving to include STMs in the US, nationwide STM development failed to accelerate due to a lack of organizational structure. Several western US states made marked progress in STM development in the first decade of the twenty-first century, yet from a national standpoint, the products were not consistent nor the coverage complete. In 2009, NRCS made administrative changes by establishing a national ES leadership team within the Soil and Plant Science Division (SPSD) to oversee nationwide STM development. Dozens of new ES specialists were hired by the SPSD to coordinate STM development work in all regions of the country. As part of the SPSD, ES specialists have sustainable funding and administrative support and have built upon the many strengths of soil survey, including access to soils experts, established networks of local technical expertise, a long history of nationwide standards, and established product quality review processes. With proper ES staffing in the SPSD, the first nationwide standard for STM development was implemented in the US in 2015 (USDA-NRCS 2014) by an initiative to develop provisional STMs for every ES in the country. Today, over 90 percent of the major soils in the US have a provisional STM product published online, and NRCS is on pace for complete nationwide

coverage of provisional STM products in 2025. Many lessons were learned during this first nationwide STM effort, improvements are being made to the STM quality review processes, and new field projects have been designed to collect data for STM revisions.

### ***Technical opportunities***

Provisional STMs for the US can be accessed online via the Ecosystem Dynamics Interpretive Tool (EDIT; Bestelmeyer et al. 2016). EDIT is an STM database that houses tabular, photographic, and narrative data describing ranges in characteristics of ESs, states, transitions, and the variability in ecosystem attributes and services within each state. These ranges are summarized from observational data that is stored and analysed outside of EDIT. Since STMs must be derived from the best available information, and since vegetation plot data and experiential knowledge can take many forms, it is virtually impossible to design a single database or workflow to capture, organize, and summarize the best available information across all regions of the country. Therefore, NRCS has developed standards for determining when and how ecological plot data must be entered into the corporate soils database (the National Soils Information System: NASIS), and how to cite other data, publications, or expertise used to develop the STM. Entering vegetation plot data into NASIS should create countless analysis opportunities within the proper soil, ecological, and spatial context. One recent example is the use of NASIS vegetation plot data to forecast changes in the spatial distribution of several berry species important to indigenous Alaskan communities under different climate change scenarios (Hamilton et al. 2024). Standardized data analysis workflows are being developed to streamline STM development, which requires specialized training. NRCS and partners have developed several online training modules and instructor-led courses to expose new staff and partners to the fundamentals of STM development. Developing STM expertise, data management systems, and efficient workflows are just a few of the many opportunities to address technical challenges of nationwide STM development.

### ***Utilitarian opportunities***

Understanding how people use STMs is the key to creating a meaningful product. In 2024, NRCS established a national ES team to identify, prioritize, and address STM customer needs within the agency, as well as an interagency ES focus team with the US Forest Service, Bureau of Land Management, US Geological Survey, and Agricultural Research Service. These two new teams foster open and regular communication about how to best meet STM user needs. For example, the Bureau of Land Management would like to use STMs for landscape-scale assessment, planning, and wildfire response, but the ES scale is too detailed for these purposes. Therefore, NRCS has begun developing STMs for ES groups (ESGs) as a complementary product to the STMs already produced at the ES scale (Bestelmeyer et al. 2016). ESGs reduce the number of STMs by approximately one order of magnitude, which addresses the workload problem of developing interpretive information for many ecosystem services across multiple ecological states. With fewer total STMs, it should be easier to draft interpretations for states at the ESG scale and then apply the interpretation to similar STMs at the ES scale, for use in the short-term at least. The EDIT database includes a catalogue of STMs at the ESG scale, but unfortunately, EDIT is not designed to deliver interpretations for ecological states in a simple, intuitive format at the ESG or ES scale. As NRCS invests more resources in IT development, there may be an opportunity to redesign the EDIT data model to include tables, photos, graphs, and other functionality that better communicates interpretations of ecosystem services by ecological state (e.g., wildlife habitat, fire behaviour, water balance). The Grazing land Resource Analysis System is a software application that imports annual forage production values from EDIT directly into the conservation planning software used by NRCS planners. Similar upgrades to EDIT functionality promise to greatly improve the use of STMs.

## Conclusions

Ecosystems are infinitely complex, and organizational development is complicated. It has taken several decades to work through the conceptual, administrative, technical, and utilitarian challenges facing broad-scale STM development, and now all the pieces are all in place to produce high quality STM products for the entire US. Perhaps other countries that value accessible, reliable ecosystem knowledge will benefit from these lessons learned in the 35 years of systematic STM development in the US.

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