



# State-and-transition models in geomorphology



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## ABSTRACT

State-and-transition models (STM) are used to describe, model, interpret, and predict when landscapes will undergo a qualitative state change. Although rangeland ecologists pioneered STMs, geomorphological STM-type models were developed prior to and independently of ecological STMs. This study categorized 47 geomorphological STMs according to whether they were: based on single or multiple study areas; primarily for description and interpretation or predictive and prescriptive use; explicitly concerned with complex system dynamics; and the role of biogeomorphic interactions in the model. Each STM was represented as a graph and the structure identified. Spectral radii were calculated to measure the complexity of each STM. Although STMs are associated with conceptual frameworks that recognize the possibility of nonequilibrium, alternative states, and path dependency, results show that an explicit concern with complexity does not necessarily lead to the identification of more states and transitions, or a more complex transition pattern. The purpose for which a STM was created, as well as the number of study sites it can be applied to, also had little bearing on the models' complexity. This review suggests that geomorphic STMs, rather than being used to fit explanations about landscape evolution into predefined theoretical categories, are veridical representations of empirical observations. Although STMs are particularly useful for grasping the biogeomorphological dynamics of landscapes, this review indicates their utility is not limited to biogeomorphology or to systems with a strong ecological imprint. Time scales involved in geomorphic change can make it difficult to observe a large number of states and transitions, which may constrain what types of STM structure can be identified, as the number of observed states and transitions required to develop particular graph structures varies widely.

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## 1. Introduction

There is a well-established consensus among geomorphologists, ecologists, and other biophysical scientists which holds that understanding the dynamics of landscape change demands knowledge of the recursive, multi-scale interactions among abiotic and biotic states and processes. What complicates efforts to interpret landscape adjustments is the fact that landscape states and biophysical processes operate and interact at multiple, sometimes disparate, spatial and temporal scales, either naturally or through human interventions (e.g., Ashmore, 2015; Bestelmeyer et al., 2015; Lane and Richards, 1997; Okin et al., 2015; Van Dyke, 2015; Wainwright et al., 2011). Recognizing this, researchers have devised a number of conceptual strategies to delineate the relationships among processes and states to predict geomorphic transitions. Some of these have been straightforward, relying on linear sequence of stages to explain landscape adjustments. For example, models depicting channel evolution, biogeomorphic succession, or the

cyclical stages implicated in landscape evolution have represented change as a single-path, predictable process (e.g., Corenblit et al., 2009; Schumm et al., 1984; Simon and Rinaldi, 2006). Other researchers have incorporated greater complexity into their models to present a fuller picture of geomorphic dynamics. These models represent landscapes as complex networks that support multiple states and transitional pathways — although some transitions occur linearly, others can arise due to nonlinear, spatially disaggregated relationships among the landscape's structural and functional components (e.g., Rountree et al., 2000; Gurnell and Petts, 2002; Hesp, 2002; Bestelmeyer et al., 2003; Wyrick and Pasternack, 2014).

State in general refers to the condition or configuration (i.e., morphology) of a system. Geomorphic state transitions occur when changes in form-process dynamics produce a qualitatively different landform, landscape unit, or geomorphic environment. For instance, a simple increase or decrease in coastal erosion rates would not qualify as a state transition. However, if the system shifted from a stable or net accretional to an eroding condition — or vice versa — it would count as a state transition. In this scenario, other zones or landforms (e.g., nearshore, beach, dunes, marshes) may undergo state transitions due to changing erosion-deposition process regimes.

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Over the past 30 years, rangeland ecologists and other biophysical scientists have increasingly turned to state-and transition models (STMs) to represent and analyze state changes in ecological systems (Bestelmeyer et al., 2003; Twidwell et al., 2013; Westoby et al., 1989). They consist of box-and-arrow diagrams coupled with expository narratives that offer detailed accounts of possible landscape states and the underlying biophysical dynamics that drive state transitions. These models are underpinned by in-depth fieldwork and expert knowledge of landscape dynamics, and lend themselves to qualitative or quantitative interpretation using graph and network analysis; interaction, transition, or adjacency matrices; or causal models (Phillips, 2011a; Phillips et al., 2015; Thompson et al., 2016). STMs have quickly become an essential tool for resource management agencies in the United States and around the world (Twidwell et al., 2013). As such, it is imperative to understand the role state-transition thinking has played in geomorphology. Accordingly, this study reviews the application of STMs in geomorphology by describing the range of geomorphic models that have either been identified by their authors as STMs or have clear structural and epistemological affinities with STMs. In conducting a meta-analysis of published models, our intention is to demonstrate that state-transition frameworks are tools that have commonly been used by geomorphologists; scrutinize the capacity of STMs to represent a range of simple and complex forms of adjustment in geomorphic systems; characterize the graph structures associated with our case studies; determine the number of observations of states and transitions needed to produce specific graph structures; and argue for the expanded use of STMs by geomorphologists to facilitate interdisciplinary collaborations.

### 1.1. Ecological state transition models

Rangeland ecologists developed STMs after recognizing the limitations of classical ecological or range succession models to explain vegetation change. The latter proposed that a rangeland — in the absence of grazing — adjusts toward a single climax state (Westoby et al., 1989). Theoretical and empirical work has demonstrated that rangeland sites may exhibit multiple vegetation states owing to complex, multivariate interactions among existing landscape features and abiotic and biotic processes (see Westoby et al., 1989; Bestelmeyer et al., 2003; Peters et al., 2015; for overviews of STMs, see also Hobbs, 1994; Briske et al., 2008; Van Dyke, 2015). The adoption of STMs has emerged from a growing body of empirical work that has demonstrated the profound impacts nonlinear ecological dynamics have had on ecosystem management practices, both within the United States and globally. Agencies within the U.S. Department of Agriculture use Ecological Site Descriptions (ESDs), which include STMs, to assist with the identification, monitoring, evaluation, and management of rangelands (Twidwell et al., 2013). While STMs have been viewed as increasingly authoritative tools within a variety of institutional settings, they have also grown in popularity among ecologists and other academic researchers because they are useful for cataloguing and synthesizing large quantities of information about landscape dynamics, which in turn can inform management and restoration decision making (e.g., van der Wal, 2006; Hernstrom et al., 2007; Czembor and Vesik, 2009; Zweig and Kitchens, 2009; Creutzburg et al., 2015).

Before highlighting the ways in which STMs have been applied to the analysis of geomorphic systems, we take a closer look at an example STM from the U.S. Natural Resources Conservation Service to clarify the epistemological underpinnings of state-transition thinking and provide a better understanding of the data used to inform their development. Ecological sites are classified based on physiographic factors such as soil properties, slope, climate, and geomorphology, and on the vegetation assemblages they support (Bestelmeyer et al., 2003; Caudle et al., 2013). Essentially, ecological sites describe the relationship between environmental factors and plant community composition (Caudle et al., 2013, p. 12). Ecological site descriptions include STMs that describe

what ecological states (mainly defined in terms of vegetation communities) are possible on a given site, as well as the drivers of state transitions (e.g., overgrazing, drought, mismanagement, other human interventions that impact form-process dynamics). States, transitions, and their drivers are defined using inventories of soil and vegetation, long-term monitoring data, historical data and paleoenvironmental reconstructions, site dynamics revealed by recent monitoring, and expert and local knowledge (Caudle et al., 2013; Knapp and Fernandez-Gimenez, 2009; Knapp et al., 2011).

Fig. 1 is a provisional STM for the Shallow Droughty ecological site, located in northwestern Montana (LRU 43A-A, NRCS, 2009). This ecological site consists of three states — Taller Bunchgrass State, Altered Bunchgrass State, and Invaded State, with the former two states encompassing two distinct community types. States differ from one another in terms of characteristic vegetation structure and composition, and the rates of biogeomorphic processes (Bestelmeyer et al., 2003; Briske et al., 2008). Two types of transitions are possible — within-state and between-state. Within-state transitions occur when a shift from one vegetation community to another occurs, but with no change in the dominant species. An undesirable within-state transition can be reversed through modest adjustments to resource management. Between-state transitions are threshold-crossing events that negatively impact ecological resilience and cannot be reversed in a short time without significant management interventions (cf. Lawley et al., 2013). In this example, overgrazing, soil erosion, and the introduction of weedy propagules catalyze transitions away from the reference community (Taller Bunchgrass State), whereas proper weed and grazing management or range seeding can produce a transition from the Altered Bunchgrass State or Invaded State back to the Taller Bunchgrass State. Although the STM diagram is a high-level representation of ecological sites, full ESDs includes explanatory narratives which explain the dynamics of communities and states and assist resource managers in analyzing where and when qualitative changes in landscape states are likely to occur. Ecologists have typically used STMs to integrate ecological theory and observations into ecosystem management and restoration, or as tools to model or predict ecological changes (Bestelmeyer et al., 2009; Zweig and Kitchens, 2009).

Predictive applications have mainly focused on individual states and transitions with a view toward predicting conditions under which different states will emerge, or on identifying management practices that can promote desirable or inhibit undesirable state changes. More recently, however, STMs have been applied to examine the dynamics and complexity of potential state transitions as well as the spatial patterning of different states (e.g., Bestelmeyer et al., 2009; Phillips, 2011a, 2011b).

### 1.2. Geomorphological STMs

While there are relatively few examples of geomorphology studies that explicitly use state-transition frameworks that are characterized as such (exceptions: Phillips, 2011a, 2014; Van Dyke, 2016), a brief look at historical scholarship reveals that a number of geomorphologists have conceptualized landscape dynamics and evolution in terms of states and transitions. For example, Raymond Dugrand, a French geographer, deduced state changes in soils and vegetation communities in scrublands driven in part by erosion and pedogenesis in 1964 (Dugrand, 1964). Wainwright (1994) introduced Dugrand's ideas to a larger audience of geomorphologists. Smart's (1988) model of fluvio-karst landscape changes exhibits state transitions. Geomorphic channel evolution models (CEMs) appeared at least as early as 1984 (Schumm et al., 1984; Simon, 1989; Van Dyke, 2013). These models decompose the evolution of river morphodynamics into stages, each characterized by distinctive form-process relationships. Early CEMs emphasized a linear succession-like sequence of stages rather than acknowledging that multiple evolutionary pathways may exist depending on the interrelations among disturbance,

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