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State transitions in geomorphic responses to environmental change

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ABSTRACT

The fundamental geomorphic responses to environmental change are qualitative changes in system states. This study is concerned with the complexity of state transition models (STM), and synchronization. The latter includes literal and inferential synchronization, the extent to which observations or relationships at one time period can be applied to others. Complexity concerns the extent to which STM structure may tend to amplify effects of change. Three metrics—spectral radius, Laplacian spectral radius, and algebraic connectivity—were applied to several generic geomorphic STMs, and to three real-world examples: the San Antonio River delta, soil transitions in a coastal plain agricultural landscape, and high-latitude thermokarst systems. While the Laplacian spectral radius was of limited use, spectral radius and algebraic complexity provide significant, independent information. The former is more sensitive to the intensity of cycles within the transition graph structure, and to the overall complexity of the STM. Spectral radius is an effective general index of graph complexity, and especially the likelihood of amplification and intensification of changes in environmental boundary conditions, or of the propagation of local disturbances within the system. The spectral radius analyses here illustrate that more information does not necessarily decrease uncertainty, as increased information often results in the expansion of state transition networks from simpler linear sequential and cyclic to more complex structures. Algebraic connectivity applied to landscape-scale STMs provides a measure of the likelihood of complex response, with synchronization inversely related to complex response.

1. Introduction

The most fundamental landscape responses to environmental change are not quantitative changes in rates of, e.g., erosion, deposition, or shoreline retreat. Rather, the most important changes are qualitative changes in system states. In a coastal environment, for instance, changes to marsh surface accretion rates are less important than transitions of tidal to marsh to, say, open water or to supratidal marsh. This study is concerned with models of such state transitions—specifically, the extent to which networks of geomorphic state transitions may be prone to complex responses to environmental change.

Specifically, this study addresses the complexity of networks of state transitions, stability of patterns of geomorphic change, and synchronization of geomorphic responses to change. Complexity in this case concerns the extent to which the structure of networks of (potential) geomorphic transitions may tend to amplify effects of change. The concern with synchronization is chiefly with respect to the extent to which state transitions are contemporaneous or lagged at the landscape scale, an issue related directly to the geomorphic concept of complex response (Schumm, 1973, 1977).

A state transition is a change that results in a qualitatively different landform, geomorphic environment, or landscape unit. Thus, for instance, an increase or decrease in shoreline erosion rates would not constitute a state transition. However, a change from an eroding to a stable or accreting condition would be a state transition, as would the changes among nearshore, beach, dune, backbarrier, and marsh environments.

There exist a number of conceptual, analytical, and interpretive models of state transitions in landscape response to environmental changes and disturbances. These may take some standard or canonical forms, including linear sequential, cyclical, radiation, cross, mesh, and random patterns. This study will examine properties of these standard forms and compare them to three field examples with respect to network complexity, stability, and synchronization. Rather than analysis or prediction of state transitions at fixed locations, the concern here is with landscape-scale responses to environmental change reflected in the spatial pattern of geomorphic system states and the nature of change propagation. The use of ecological state transition models (STMs) has recently been extended into this type of application (Perry and Enright, 2002; Bestelmeyer et al., 2009, 2011), and Phillips (2011a) explored the use of graph theory for this type of analysis in geomorphic and pedologic systems.

Here complexity is concerned with the extent to which changes (whether due to internal development or interactions, or external disturbances or changes in boundary conditions) tend to be amplified by the pattern of transitions. This reflects, for example, the likelihood that a localized disturbance may produce responses elsewhere in the landscape, and the uncertainty with respect to predicting those responses. Network complexity also reflects whether a landscape-scale environmental change is

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likely to produce homogeneous or heterogeneous responses within the landscape.

The index of stability analyzed in this study reflects the spatial resolution or time step necessary to observe stability. The more unstable a network is, the smaller or finer the time step must be to observe stability. In a geomorphic context, the relative stability indicates the likelihood that localized changes or disturbances will persist and grow over time. Synchronization may be literal—i.e., are state transitions in response to environmental change contemporaneous throughout the landscape? Phillips (2013) also discussed inferential synchronization in geomorphic systems: the extent to which observations or inferences at a given time can be applied to historical reconstructions or future predictions.

2. State transitions

2.1. Standard models of state transitions

Patterns of state transitions, whether temporal sequences or spatial gradients, may be analyzed as networks, using graph theory. Thus the standard, canonical, or benchmark models are discussed here in terms of the structure of a graph depiction.

Single-path, linear sequential succession-type models describe a pattern whereby after a change or disturbance the environmental system follows a regular progression of stages or states, before reaching some final stable condition. This is the case, for example, in many channel evolution models for incised or channelized alluvial streams (c.f. Schumm et al., 1984; Simon, 1989; Bledsoe and Watson, 2002; Doyle et al., 2002; Watson et al., 2002). The classic model of the stages of karst landscape evolution originating with Cvijic (1918) is another example; classical Clementsian-type ecological succession models are also of this type. The chrono-, topo, bio-, hydro-, and lithosequence models in soil geomorphology are also linear sequential forms, though they are based on the notion of holding all but a single soil-forming factor constant (Birkeland, 1999; Schaetzl and Anderson, 2005).

Cyclical state transition models are characterized by a repeated single-path cycle through a sequence of states. W.M. Davis's (1922) cycle of erosion is one example, whereby uplifted peneplains evolve through stages of youthful, mature, old age, and peneplain topography, with uplift renewing the cycle. Sequence stratigraphy models of sedimentary system tracts in response to sea-level change are linear sequential in the context of a single episode sea-level rise or fall, but cyclical in the context of both transgressive and regressive episodes (e.g., Christie-Blick and Driscoll, 1995; Miall and Miall, 2001; Catuneanu, 2006).

Radiation-type models involve landscape divergence from a single state or condition into multiple discrete states. One example is the degradation of semiarid grasslands, where the uneroded grasslands may be transformed into a mosaic of uneroded, vegetated, nutrient-rich patches; minimally-vegetated nutrient-poor patches; and unvegetated, highly eroded sectors (e.g., Parsons and Abrahams, 1996; Bergkamp, 1998; Puigdefabregas et al., 1999). Another is the fragmentation of salt marsh surfaces into a mixture of marsh, mudflats, salt pannes, and open water in response to relative sea level rise (e.g. Reed, 1990; Reed and Cahoon, 1992; Day et al., 2011).

Convergence models are the conceptual opposite of radiation—in this case different states all transition to the same end or attractor state. For instance, if various straight, convex, and concave slope profiles all eventually evolve toward a convexo-concave (convex upper, concave lower) profile, as sometimes occurs in humid climates, this is a convergent pattern of state transitions. This type of pattern is implied in several conceptual models of landform and landscape evolution, including the traditional dynamic equilibrium model and hypotheses of convergence toward a critical state (c.f. Phillips, 1999a). Likewise, some narratives of desertification postulate expansion of ergs or other desert environments at the expense of other landforms and ecosystems (for a summary and critique, see Thomas and Middleton, 1994). The network structure of convergence and divergence/radiation models are mathematically identical, so they will be treated together in that respect.

A cross type pattern has been identified in spatial patterns of connections among habitat types in landscape ecology (Cantwell and Forman, 1993). The cross graph has a single key component connected to all other nodes, but the other nodes are connected only to the central key node, and to two other adjacent nodes. No obvious geomorphic STM examples are known, but the cross represents one standard type of graph structure that is much more strongly connected than the linear sequential, cyclical, radiation, or convergence types. The cross model is potentially applicable to patterns of geomorphic spatial interactions or mass fluxes with a critical central transfer point or corridor.

The most strongly connected type is the maximum connectivity graph, where any state can potentially transition into any other. Some vegetation community STMs identified for U.S. rangelands have this structure (NRCS, 2013). A geomorphic example is the bedform state of sandbed streams, where rapid changes in flow conditions can result in changes among plane bed, ripple, dune, and antidune states without necessarily passing through intervening bedform states. Notwithstanding these examples, the maximum connectivity graph is independently useful as a benchmark or reference structures.

Other models of geomorphic state changes are variations on the types above, or have a mesh structure (Cantwell and Forman, 1993; Phillips, 2011b). The mesh is a relatively well-connected network (for graphs with >5 nodes, lying between the cross and maximum connectivity types above in this regard), with a relatively uniform number of edges associated with each node. More complex channel evolution models incorporating multiple pathways may have this structure (e.g., Leyland and Darby, 2008; Phillips, 2012a), along with some ecological STMs.

These standard graph types are summarized in Table 1. In this paper key properties of graphs representing patterns of geomorphic state changes will be derived for the standard structures described above, and for three case studies. Though the case studies below all involve decadal-scale state transitions, the examples of standard graph structures given above illustrate the fact that state transitions occur at, and can be analyzed as such at, a broad range of spatial and temporal scales.

Table 1
Standard graph structures for models of geomorphic and other environmental state changes.

Graph structure	*Geomorphic examples*	*Comments*
Linear sequential	•Simple channel evolution models •Karst landscape evolution model •Soil state factor sequences	Traditional vegetation succession models also linear sequential
Cyclical	•Davisian cycle of erosion •Sequence stratigraphy	Incomplete cycles are linear sequential; linear paths reset by disturbance are cyclical
Radiation	•Fragmentation of degraded grasslands •Marsh fragmentation	Represents divergent evolution
Convergence	•Steady-state attractors ("dynamic equilibrium") •Desertification by dune encroachment	Represents convergent evolution
Cross	•Spatial interaction or flux models with a critical central intersection or bottleneck point	Involves a single key state connected to all others
Mesh	•Complex channel evolution models •Some ecological state-and-transition models	For $N > 5$, intermediate in connectivity between cross and fully-connected structures
Fully connected	•Some ecological state-and-transition models •Sand-bed fluvial bedforms	Commonly a reference condition representing a random system where any state can transition to any other