Geomorphology 214 (2014) 1–9

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Review

Cause and effect in geomorphic systems: Complex systems perspectives

A. Brad Murray [a,*], Giovanni Coco [b], Evan B. Goldstein [a]

[a] Division of Earth and Ocean Sciences, Nicholas School of the Environment, Center for Nonlinear and Complex Systems, Duke University, Box 90227, Durham, NC 27708, USA
[b] Environmental Hydraulics Institute, "IH Cantabria", c/Isabel Torres nº 15., Universidad de Cantabria Santander, 39011, Spain

ARTICLE INFO

Article history:
Received 18 April 2013
Received in revised form 26 February 2014
Accepted 2 March 2014
Available online 10 March 2014

Keywords:
Self organization
Emergence
Feedbacks
Nonlinear dynamics
Complex systems
Autogenic phenomena

ABSTRACT

Applying complex systems perspectives to geomorphic systems leads to the conclusion that cause and effect in landscape systems does not always apply in the ways that common sense and traditional assumptions would suggest. Geomorphologists have long thought that events must have causes and that landscape structures exist where they do for particular reasons. In addition, since the rise of process geomorphology, geomorphologists have often assumed that small-scale processes directly cause large-scale, long-term landscape evolution; that for understanding or predicting the large-scale behaviors, the details of the small-scale processes matter; and that large-scale processes do not directly cause behaviors at much smaller scales. However, in self-organized systems, autogenic events can arise from feedbacks internal to the system, without any variation in the forcing to cause the event. Similarly, structures within self-organized patterns in the landscape can emerge spontaneously, even though there may not be any pre-existing heterogeneity to cause the localization of the structure. In addition, cause and effect can operate from large scales to small ones as well as the reverse, and interactions that emerge at larger scales can determine the characteristics of the landscape, independent of the details of the small-scale processes.

To exemplify these points, we will use research on 'sorted bedforms', striking shallow seabed grain-sized sorted patterns on scales ranging from tens of meters to kilometers. The stripes of coarse sand or gravel that are segregated from intervening fine-sand domains were originally ascribed to hypothesized, spatially focused currents. However, more recent modeling and field observations point to a self-organization mechanism in which the locations of the features do not correspond with any heterogeneity in the forcing or antecedent conditions. Very recent modeling work shows that regionally the pattern can spontaneously break down and reform, without any corresponding change in the forcing. Experiments with different approaches to modeling these features, and very different ways of representing the small scale processes, tend to cause essentially identical behavior and characteristics at the scale of the pattern—suggesting that emergent interactions at the large scale more directly explain, or cause, the phenomena than do the small scale processes. Finally, as for many systems, behaviors at small scales are strongly influenced by larger scale behaviors. We also use select examples from a range of landscape-evolution studies to contrast predictions made using traditional assumptions about cause and effect from those made using a complex-systems approach.

1. Introduction

In recent decades, the application of complex-systems approaches in geomorphology has produced numerous insights into how landscapes are shaped and how they change over time (Anderson, 1990; Werner and Fink, 1993; Werner and Hallet, 1993; Murray and Paola, 1994; Phillips, 1995; Werner, 1995; Falqués et al., 2000; Ashton et al., 2001; Kessler and Werner, 2003; Murray and Thieler, 2004; Baas, 2005; Calvete et al., 2007; Defina et al., 2007; Marani et al., 2007; Fagherazzi, 2008; Limber and Murray, 2011). The complex systems umbrella encompasses a range of perspectives and techniques sprouting initially from studies of nonlinear dynamics, including deterministic chaos, self-organization, and emergent phenomena (Nicolis, 1995; Prigogine, 1997; Solé and Goodwin, 2000; Strogatz, 2001; Dronkers, 2005). As we discuss in this discussion paper, a common theme arises from many applications of these approaches: cause and effect in landscape systems does not always apply in the ways that common sense and traditional assumptions would suggest (Murray et al., 2009).

1.1. Perspectives on cause and effect

To start with, geomorphologists have long thought, understandably, that events must have causes. Often, we can indeed identify clear triggers or direct causes for events. For example, large landscape-rearranging floods occur for clear reasons—because of a large storm, a pulse of melting, or some sort of release of stored water. An even more clear example of a direct cause for landscape change is given by

* Corresponding author. Tel.: +1 919 681 5069; fax: +1 919 684 5833.
E-mail address: abmurray@duke.edu (A.B. Murray).

http://dx.doi.org/10.1016/j.geomorph.2014.03.001
0169-555X/

humans and the instantaneous effect their construction (e.g., the construction of a dam or a breakwater, or a sand nourishment) has on the system's evolution. On longer timescales, changes in sea level cause adjustments in the locations of erosion and deposition near river mouths, producing signatures in the stratigraphic record (e.g., Blum and Törnqvist, 2000). Furthermore, climate changes cause shifts in patterns of erosion and deposition, reshaping terrestrial landscapes (e.g., Hancock and Anderson, 2002). However, as we will discuss and illustrate with examples, in complex systems autogenic events can arise from feedbacks internal to the system, without any variation in the forcing or boundary conditions (e.g., Paola, 2000; Paola et al., 2009; Hajek and Wolinsky, 2012). Of course, landscape change requires material to be transported, and transport results from the application of force; so in a sense nothing happens without some cause—without forcing, nothing would change. However, the relevant point in the context of our discussion is that events can occur without any corresponding instigation, or 'cause,' in terms of 'changing external forcing'; events can occur spontaneously, from internal system dynamics, even though nothing external to the system would lead us to expect it.

In addition, geomorphologists have often assumed that landscape structures exist where they do for particular reasons. Heterogeneities in forcing conditions or landscape substrate certainly can cause the localization of structures. In an erosional landscape, for example, harder rocks can determine the location of ridges or mountain peaks (Fig. 1) and fault zones can lead to gullies or valleys. However, in self-organized landscape patterns, as we will discuss, structures or sharp gradients can potentially emerge spontaneously from dynamics within an Earth-surface system, without any preexisting heterogeneity to cause the localization of the feature.

Finally, since the rise of 'process geomorphology' (e.g., Rhoads, 2006; Rhoads and Thorn, 2011), geomorphologists have commonly assumed that small-scale processes directly cause large-scale, long-term landscape evolution; that for understanding or predicting the large-scale behaviors, the details of the small-scale processes matter—and that large-scale processes do not directly cause behaviors at much smaller scales. Of course, the large-scale, long-term landscape behaviors would not occur in the absence of the small scale processes within a landscape. Eolian sand dune fields, for example, would not exist if sand grains were not being moved by the wind (Fig. 2), and mountain valleys would not develop if streams and rivers were not somehow eroding their

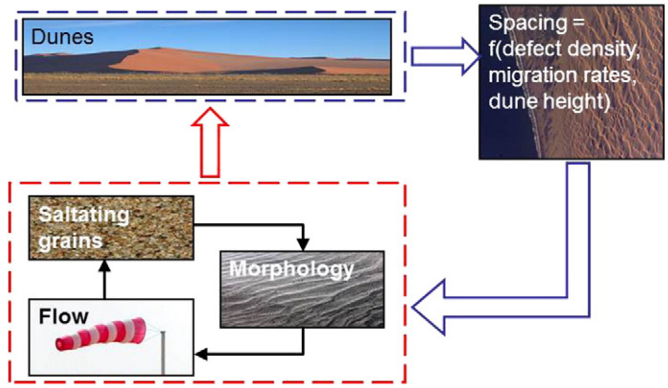

Fig. 2. An example of feedback. In sandy deserts, the shape of a sand-covered bed affects the pattern of wind velocities, which affects the patterns of sediment fluxes, which then affect how the bed changes shape. If this loop reinforces a bed-shape perturbation, the feedback is positive. In addition, once a large-scale structure emerges (e.g., a dune), associated large-scale variables affect smaller scale processes.

beds. However, we will describe examples suggesting that cause and effect sometimes operates from large scales to small ones as well as the reverse and that interactions that emerge at the larger scales can determine the characteristics of the landscape, independent of the details of the small-scale processes and potentially limiting the range of effective behavior of small-scale processes.

1.2. Feedbacks and emergent phenomena

The spontaneous behaviors that challenge our intuitive notions of cause and effect arise ultimately from positive feedbacks and the nonlinearities that link interacting variables and processes (e.g., Fig. 2). Feedbacks, which we define as mechanisms capable of reiterating themselves, can be the fundamental drivers of the system: they connect, modify, and control the system's evolution up to the point where it becomes impossible to isolate cause and effect (in terms of external influences or changes in the forcing). Feedbacks can be termed as 'positive' if they loop back into the system so that an initial perturbation from a steady state can grow, creating an accelerating run-away reaction (at least for a while). 'Negative' feedbacks tend to dampen the growth

Fig. 1. Mount Tongariro and Emerald lakes (New Zealand). Ridges correspond to flanks of former volcanos. Photo courtesy of T. Rodríguez Castillo.