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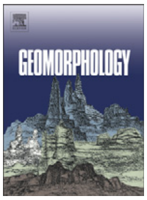

Geomorphology, complexity, and the emerging science of the Earth's surface

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ABSTRACT

The following is a white paper (adapted here for print) for the U.S. National Research Council's committee on Challenges and Opportunities in Earth Surface Processes, drafted at a National Science Foundation sponsored workshop associated with the 38th Binghamton Geomorphology Symposium, "Complexity in Geomorphology," held at Duke University in October 2007.

1. State of the art

1.1. Motivation

Landscapes, and how they change over time, provide the template on which life must function and dictate the ecosystems and human activities that can exist in a given place. Rugged and steep landscapes, for example, tend to limit human development and agriculture; coastal landscapes support wetland nursery habitats crucial to the world's marine life and also sustain myriad human industrial, agricultural, and economic activities around major population centers.

Biological influences – especially human actions – in turn directly affect landscape-forming processes, helping steer landscape change. Wetland vegetation, for example, plays an essential role in determining how coastal morphology and ecosystems respond to sea-level rise, and land-use changes alter the feedbacks between biological and physical processes in such environments. In hilly regions, vegetation dictates the shape of the whole landscape; as humans alter vegetation cover (a typical effect of land use), the steepness and stability of the ground changes, which then affects humans.

Geomorphology, the study of landscape change, thus stands in the center of a newly emerging science of the Earth's surface, where strong couplings link human dynamics, biology, biochemistry, geochemistry, geology, hydrology, geomorphology, and atmospheric dynamics, including climate change (Fig. 1). We are now beginning to address the feedbacks between geomorphology and these linked disciplines. Adaptive environmental management on a changing globe requires rapid advancements in our understanding of Earth-surface dynamics; understanding these dynamics will allow us to influence our habitats in a purposeful manner. In this paper we emphasize novel investigative

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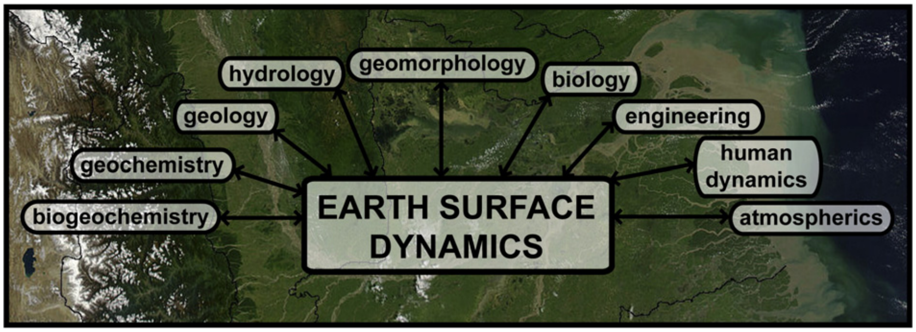

Fig. 1. The study of Earth-surface dynamics is inherently interdisciplinary. The cultivation of a new, unified Earth-surface science will catalyze otherwise disparate disciplines to interact and collaborate, increasing our understanding of landscape, ecosystem, and human behaviors and the complex couplings that connect them (in the background: a source-to-sink image of the Ganges River and related terranes, courtesy of the NASA Visible Earth image database, http://visibleearth.nasa.gov).

approaches being applied at the fast-expanding frontiers of Earth-surface science, address the principal challenges presently facing the geomorphologic research community, and look to what the future of Earth-surface science might hold.

1.2. Recent rapid advances

Geomorphologists today are employing a rapidly expanding, interdisciplinary set of tools that are revolutionizing how we understand Earth-surface processes. Historically, qualitative, descriptive modes dominated geomorphology. More recently, however, the discipline has turned the corner and is now accelerating along the leading edge of quantitative science. The wealth of data collected in the past, along with the development of an array of new quantitative techniques for characterizing landscapes and landscape change, has enabled a renaissance in theory and modeling; modern geomorphology is feeding off of its observation-rich history.

Many of the recent advances hinge on the ideas and quantitative tools of complex systems research. The umbrella of "complexity" encompasses several related theoretical approaches that originated in nonlinear dynamics. The Earth's surface exhibits some of the most striking examples of self-organized phenomena, with spontaneous spatial and temporal localizations, emergent patterns and structures, and fractal patterns and power-law scaling. Recognizing the possibility of each of these types of phenomenon recasts how we interpret much of what we observe and often what we forecast for the future. Many geomorphological studies today benefit from these complex systems perspectives and analyses, even when these influences are not explicitly mentioned; complexity-related concepts, listed below, permeate and are propelling the field:

(i) Chaos theory showed that rich, complicated, and perpetually dynamic behavior can arise from simple, nonlinear interactions. Recent geomorphological work is revealing many cases where local, deterministic interactions in a spatially distributed system can explain complicated behaviors that would previously have been ascribed to complicated (usually unknown) causes that defy holistic understanding.

(ii) An array of local nonlinear interactions can give rise to the self-organization of patterns with strong spatial gradients and localizations that had been attributed to hypothesized "forcing templates" (Fig. 2A). Knowledge and models of the interactions that create these localized structures facilitate explorations of how the landscape will change as climate or land-use forcing shifts (Fig. 2B).

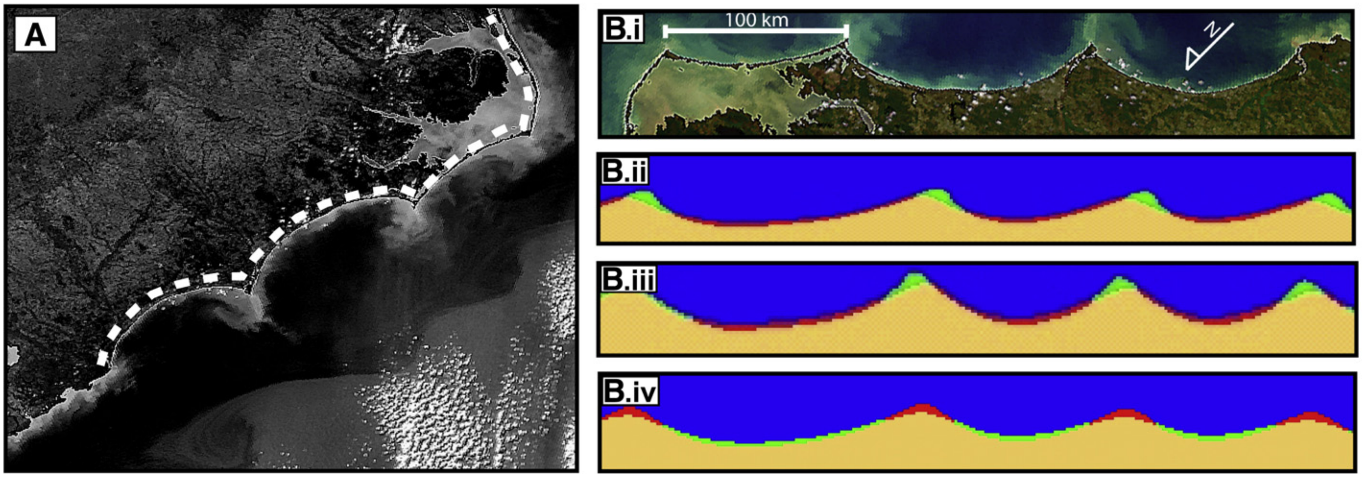

Fig. 2. (A) Satellite image of the sandy, cuspate Carolina Cape system (highlighted by the white dotted line); cape tips are ~100 km apart. The spatial regularity of the cuspate pattern was for decades assumed to be the result of peculiarities in the underlying geology, the classic argument of "template forcing." Recent numerical modeling work, however, grounded in complexity theory, has shown that the capes could be self-organized, emergent features formed from fluxes of alongshore sediment transport, obviating the need to invoke a specific forcing template to explain their formation. (B) An extension of the same shoreline modeling examines how the coast might change under various hypothetical climate-change scenarios; the numerical model is not a direct representation of the Carolina cape system (B.i) nor intended to be, but is nevertheless analogous to it as an exploratory tool and illustrative of the large-scale, long-term processes driving changes in the landscape. The model output, in planview, shows that (B.ii) if stronger storms send larger waves from the left (NE), the cape tips will grow (shown in green) and shift to the right (SW) and the embayments will erode landward (shown in red); (B.iii) if more or larger storm waves arrive from the right (SW), the cape tips will grow and shift to the left (NE); and (B.iv) if stronger winds tend to direct waves straight onshore (to the NW), the cape tips will erode landward and the embayments will accrete seaward (adapted from Ashton et al., 2001; Slott et al., 2006).

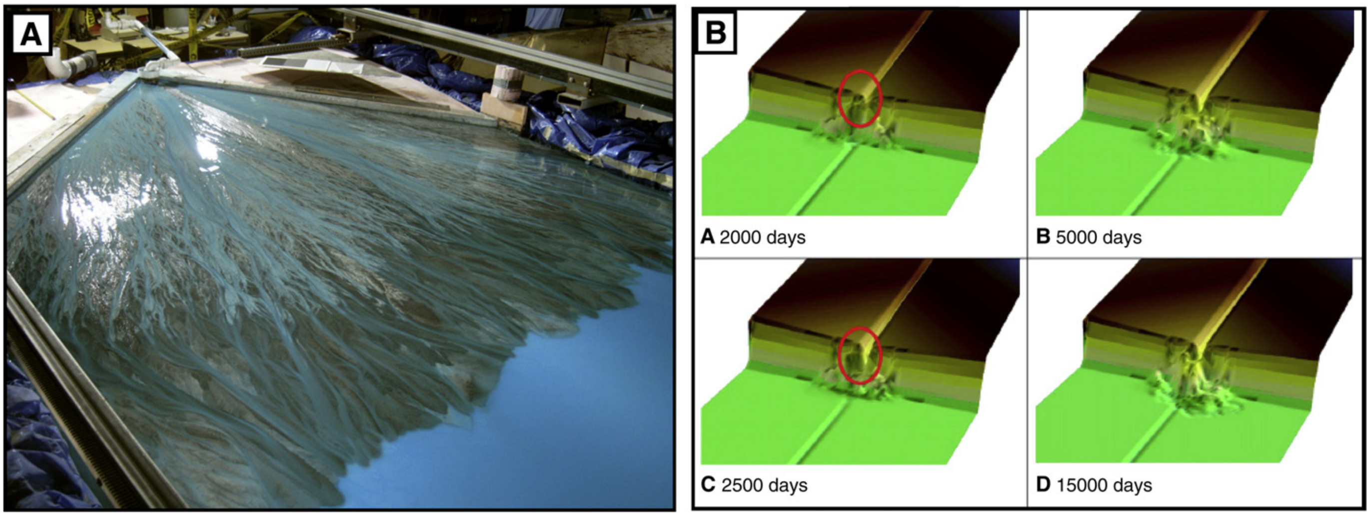

Fig. 3. (A) A physical model of delta formation set in a sediment basin. At laboratories such as the St. Anthony Falls facility at the University of Minnesota, physical models of sedimentary systems combine state of the art technology (imaging, dyes, real and artificial sediment mixes with specific cohesive properties) with transparent, simple theoretical designs that help researchers isolate and distinguish among different landscape-evolution processes. Cross sections through such delta deposits can lend insight into new ways to read and interpret the geologic sedimentary record for signs of self-organized autogenic behavior. (Image courtesy of the National Center for Earth-surface Dynamics.) (B) Output from a numerical landscape-evolution model showing the topography of an alluvial fan as it develops over time, highlighting abrupt changes in the fan's morphology that appeared autogenically without changing any forcing to the system, in this case rainfall and sediment availability. Analyzing patterns in the sediment flux recorded in the model reveal sharp fluctuations that could easily be mistaken for shifts in climate forcing (image from Coulthard and Van De Wiel, 2007).

(iii) Patterns, regular or irregular, can self-organize in time as well as in space. In what is increasingly termed “autogenic” behavior, interactions internal to a system generate changes – even abrupt switches – in the system's state. Recent models (physical and numerical) of landscape evolution show that: (a) contrary to long-standing, prevailing assumptions, major

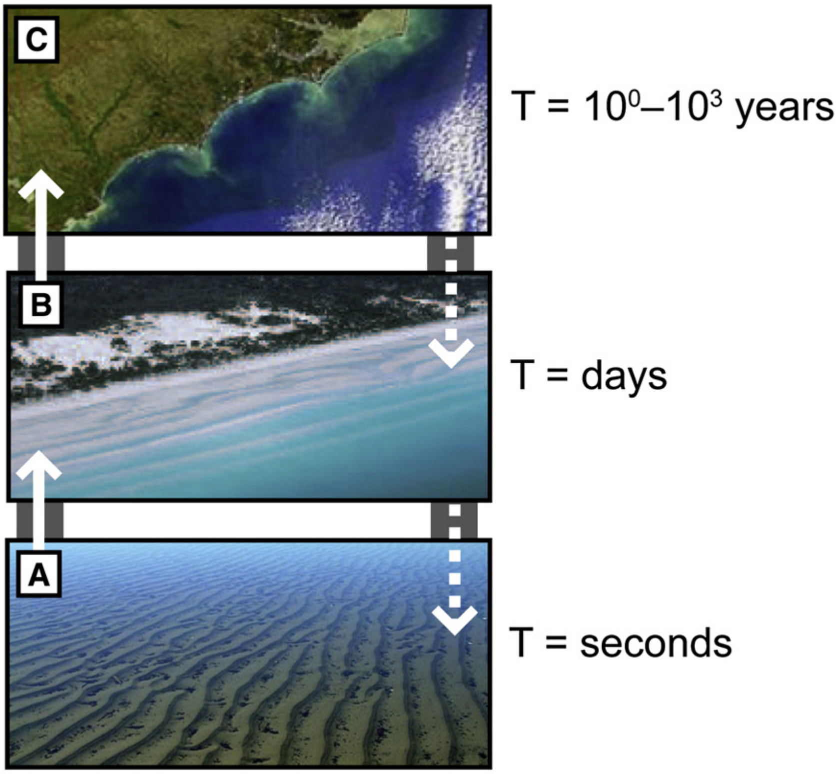

Fig. 4. In Earth-surface science, with so many diverse processes occurring simultaneously and interacting across a vast range of spatial and temporal scales, how do researchers choose to begin their investigations? The answer depends on the scale of the feature they wish to resolve. Consider landscape change in a sandy coastal environment: (A) bedforms such as ripples develop from interactions at the scale of sand grains at time scales on the order of seconds. Those bedforms influence the currents and sediment transport that over days build (B) sandbars and channels in the surf zone. The aggregate effects of those bars and the associated patterns of wave breaking and currents add up to alongshore sediment fluxes that drive large-scale, long-term landscape change at regional scales (C). The larger scales set the physical context in which the smaller-scale dynamics must operate, thus completing the feedback (dashed arrows). For example, the pattern of bars and channels in (B) dictates where ripples can form. To model (C), should researchers begin with the dynamics of (A)? or (B)? Such an approach would be consistent with “explicit numerical reductionism,” in which a model is based on the smallest, fastest practical scales (from the bottom up, in the above figure). The alternative is “top–down” or “synthesist” modeling, which treats only the pertinent effects of the smaller-, faster-scale processes by abstracting and parameterizing their collective behavior.

"events" can occur without a triggering change in the forcing to the system; and (b) signals from climatic and tectonic changes can disappear amid the feedbacks and self-organization within the landscape system that tend to "hash" them (Fig. 3). These realizations can alter our interpretation of paleoclimates and sea level, as well as our expectations for how the Earth surface will respond in the future.

(iv) The analytical lens of emergent phenomena highlights the idea that studying the building blocks of a system – the small-scale processes within a landscape, for example – may not be sufficient to understand the way the system works on much larger scales. The collective behaviors of small-scale components synthesize into effectively new interactions that produce large-scale structures and behaviors — the way molecular dynamics in a fluid give rise to what we characterize as macroscopic variables, which can then interact to form water waves. These emergent structures can then strongly influence the smaller-scale processes: waves in turn affect molecular motions; or in a desert context, a sand dune, the emergent result of grain interactions and wind-blown sand fluxes, determines new patterns of wind-blown fluxes and grain avalanching. Thus, when nonlinear feedbacks lead to the self-organization of large-scale patterns and behaviors, causality extends in both directions through the scales; and the most "fundamental" scale on which to base an analysis may not be the smallest (Fig. 4). This perspective holds great promise for the continued flourishing of numerical modeling in Earth-surface science, especially if combined with new data-collection strategies and techniques (as discussed below).

(v) Landscapes provide some of the classic examples of fractal patterns (Fig. 5), including the rocky coastline geometry that helped Mandelbrot introduce the concept. The self-similarity or self-affinity of a landscape (including the extension of multifractality), detected and quantified by power-law scalings, suggests that the same dynamics produce similar effects across a wide range of scales. Power-law scaling can also arise from self-organized critical behavior, in which events of any scale can occur at any time under constant forcing, with probabilities that vary in a self-similar way across the scales. Power-law scalings in space or time can quantitatively characterize a natural system, providing model tests. Such a "heavy-tailed" distribution, in which the largest events have much higher probability than other statistical characterizations would suggest, also has implications for forecasting natural disasters.

Geomorphology is incorporating ever more interdisciplinary research, recognizing the integral couplings in landscape-forming processes between geology, hydrology, biology (from microbiology to ecology), human dynamics (from engineering to economics to sociology), geochemistry, and biochemistry (Fig. 1). In most environments, and over a wide range of scales, morphology and physical sediment-transport processes exhibit two-way couplings with biological processes; and the resulting feedbacks can play essential roles in steering landscape evolution and the response to changing conditions (Fig. 6). Human land use and engineering manipulations have substantial effects on landscape change over a range of temporal and spatial scales. Researchers are beginning to focus on two-way human-landscape couplings and feedbacks, bringing to bear the quantitative tools of complex systems analysis and modeling (Fig. 7). Though such studies are in their infancy, they hold considerable promise for the future. Geomorphology is poised to play a key role in a new Earth-surface science that will speak not just to the past and present, but to the future — and not just to scientists, but to all of society.

1.3. Grand challenges

The rapid advances outlined above allow the Earth-surface science community to address several overarching, linked questions, including:

1.3.1. How predictable are changes in the Earth-surface system, and how does the answer depend on temporal and spatial scales? Can we develop "Earthcasts" analogous to weather forecasts, of both gradual changes and extreme landscape-changing events?

To answer these questions, we must understand and quantify the uncertainty stemming from at least three sources (in addition to inevitable model imperfections). First, our ability to predict changes in forcing from outside the Earth-surface system – meteorologic, climatic, tectonic, and volcanic events – is limited. Second, as is the case for the weather, data availability limits forecasting ability. Third, and perhaps most interestingly, we need to untangle to what degree, and under what circumstances, landscape and ecosystem changes result from nonlinear feedbacks and self-organization within the Earth-

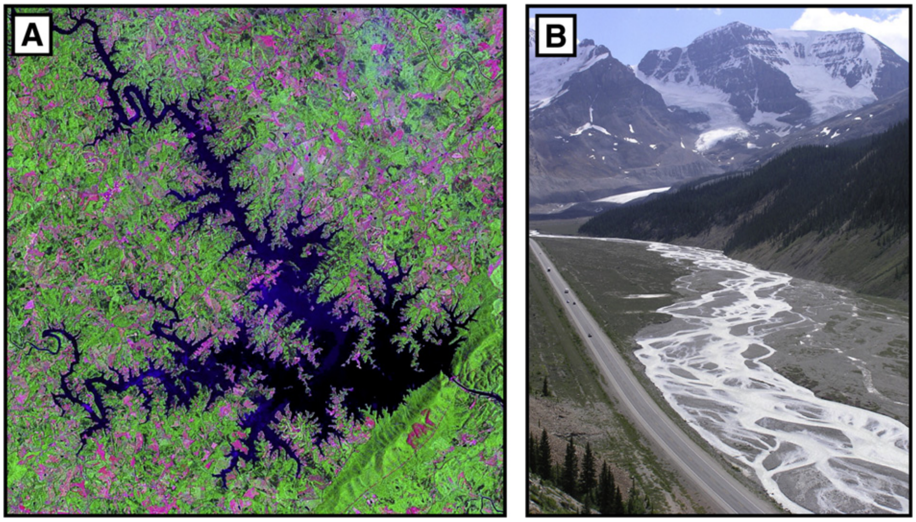

Fig. 5. (A) Smith Mountain Lake, in western Virginia, offers a classic example of a fractal pattern in the landscape where the lake (formed by damming the Roanoke River at Smith Mountain, the diagonal ridge visible at bottom right) rose to fill the fluvially dissected valley terrain of the Appalachian foothills; the dendritic splay of the lake that is evident as shown here is replicated at progressively smaller scales — at the scale of any splay arm, and again at each of the smaller tributary valleys within that arm. (Image courtesy of NASA Applied Research and Technology Project Office.) (B) Braided streams are a poster case for self-similarity because of the scale invariance of their channel networks — with shapes and behaviors that are similar from the floodplain scale (shown above) to the scale of trickles and sand grains. (Image courtesy of the National Center for Earth-surface Dynamics).

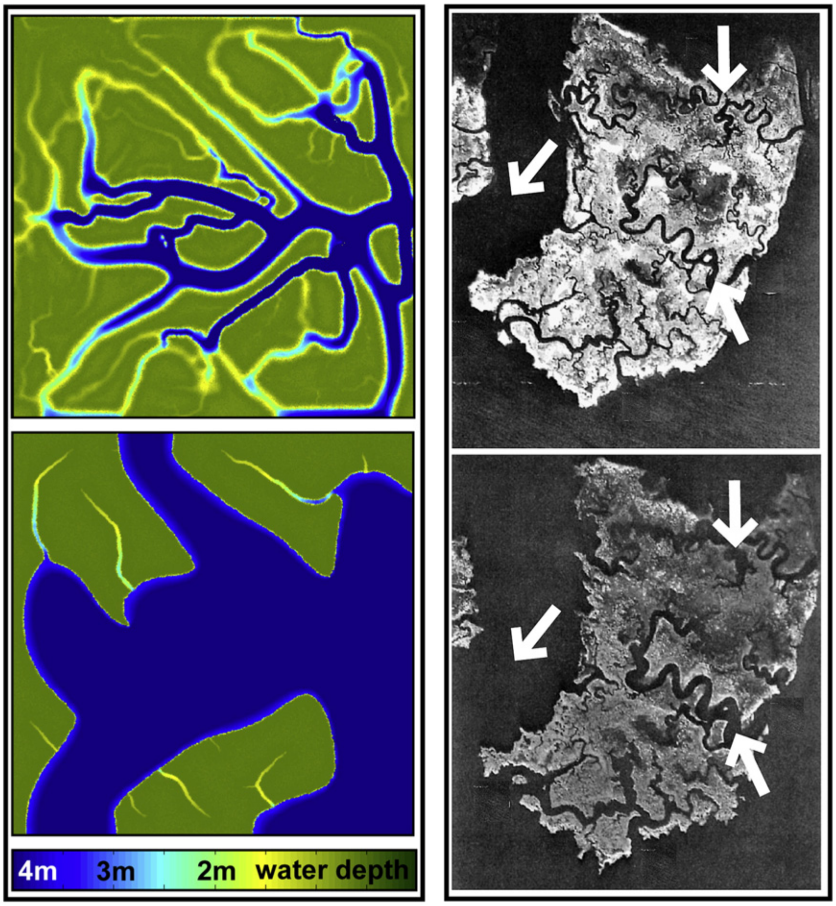

Fig. 6. At left, marsh topography generated from numerical modeling suggests that vegetation feedbacks tend to make marshes keep up with sea-level rise, even when subjected to extremely high sea-level-rise rates (upper left). However, changes in land use that alter the sediment supply to the system can have dramatic effects — a reduction in sediment supply when sea-level-rise rates are high results in marsh drowning (lower left). At right, photos from Jamaica Bay, New York, show a loss of marsh platform between 1959 (top) and 1998 (bottom). Arrows note channel widening and increased network dissection. Understanding marsh response to changes in sea-level-rise rates and sedimentation rates – and translating those findings from the insular language of research science to make them available to broad audiences – will inform societal notions of and expectations for such landscapes, and enable planners, managers, and lawmakers to reach better development and conservation decisions (images adapted from Kirwan and Murray, 2007).

surface system. We separate this vital scientific question into our second challenge.

1.3.2. What are the magnitudes and spatial and temporal patterns of self-organized, autogenic processes in the Earth-surface system? And how do these processes interact with changes in external forcing?

For spatially extended systems with nonlinear interaction between the constituent parts, numerical modeling represents a key means of theoretical investigation that will be essential for addressing these questions.

That said, the record of past landscape behaviors also provides invaluable information. New geochronologic and remote-sensing observational techniques are providing unprecedented information about rates and patterns of recent, ongoing landscape change, but sedimentary deposits allow us to look farther into the past. Shallow deposits represent the results of relatively short-term landscape changes, while deeper stratigraphic records implicitly tell the tales of longer-term processes. These records have typically been read and interpreted as stories about changes in the forcing conditions (meteorologic, climatic, tectonic, and volcanic), with some superimposed noise. With their new theoretical perspectives, however, researchers are coming to view the sedimentary record as also representing "fossilized complexity" — preserved patterns resulting from autogenic behaviors, sometimes interacting with forcing events.

Distinguishing the roles of forcing changes and autogenic dynamics over a range of scales requires a deliberate synthesis of numerical modeling efforts and observations of past and current Earth-surface evolution. Understanding paleoclimate events as well as how the Earth surface will respond to future changes requires just such a disambiguation of self-organized and forced behaviors.

1.3.3. How will the Earth's surface respond to climate change, including accelerating sea-level rise? From a complex systems perspective of climate change, what are the roles of nonlinear thresholds, and how do landscape/ecosystem transformations occur? What are the sources of resilience and vulnerability in Earth-surface systems?

Climate change alters the contexts in which Earth surface systems operate, tending to transform landscape and ecosystem regimes. In the parlance of nonlinear dynamics, when a system has settled into an attractor, manifested by a specific type of spatial and/or temporal pattern, understanding and predicting its behavior is easier than (i) when the system is shifting from one attractor to another (analogous to a phase change), or (ii) when the structure of the attractor itself changes over time. If the forcing on a system is itself changing gradually, then crossing a process threshold can catalyze new nonlinear feedbacks and regime shifts. Loss of tidal marsh area in many locations within the last century may provide an apt example, as changing land use (affecting sediment and nutrient supply) and sea-level-rise rate may be pushing tidal embayments away from previously stable configurations of extensive vegetated marsh surfaces, fed and drained by networks of tidal channels, and into a regime of marsh drowning.

Understanding and predicting transitions in overall system behavior is undoubtedly one of the most difficult challenges facing Earth-system science — a challenge that the interdisciplinary nature of

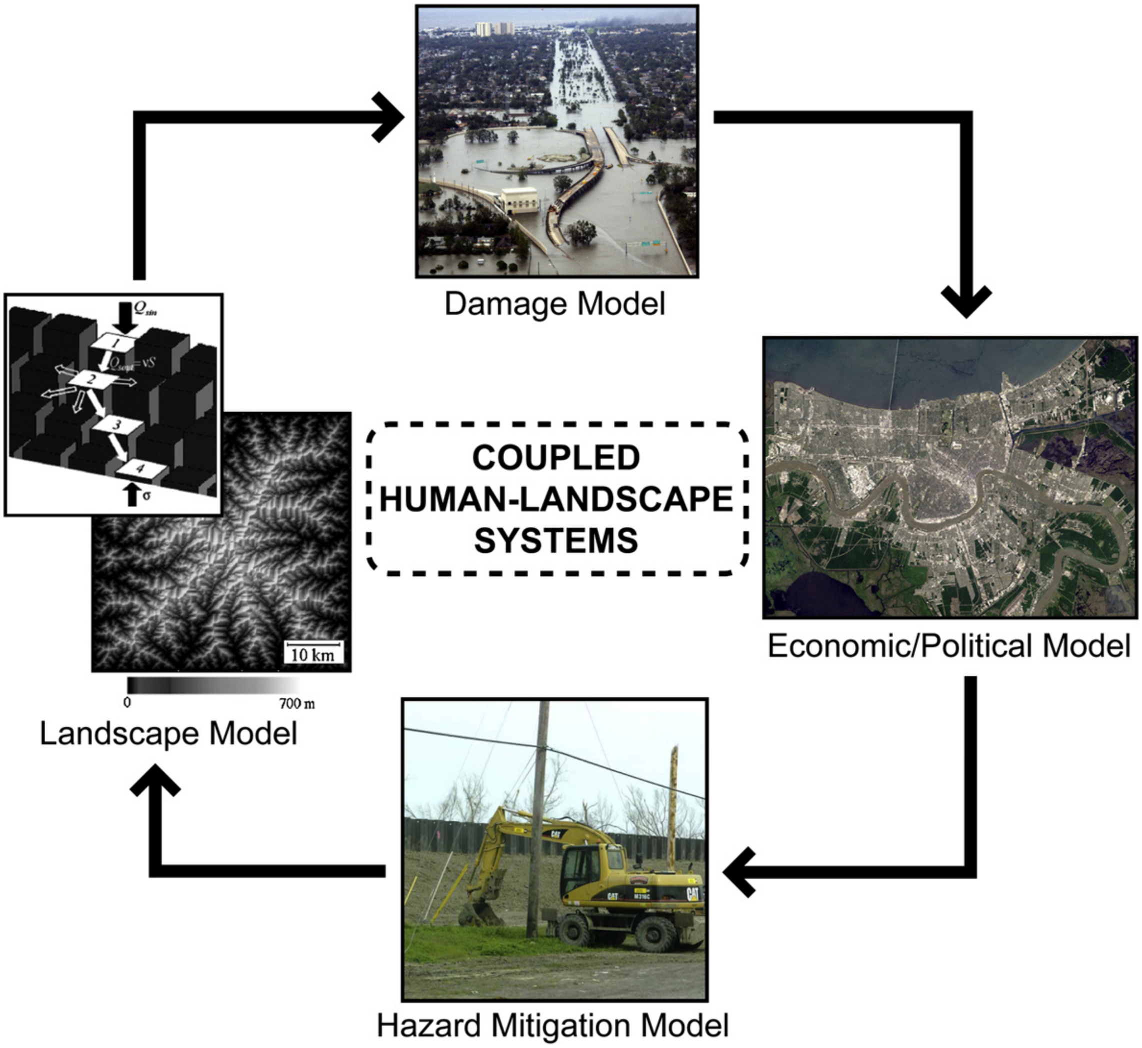

Fig. 7. A schematic of coupled human-landscape systems, using New Orleans, Louisiana, as an example. A numerical (cellular) landscape model might include processes dominated by water, sediment, or biological transformation; landscapes impact humans through natural-disaster events, captured in a damage model that simulates floods by wiping out discrete zones of human infrastructure; human dynamics are represented by an economic- or political-processes model (perhaps agent-based), that results in decisions to develop or change human infrastructure, which in turn links back to the landscape through an economically driven hazard-mitigation model that represents human choices to modify the landscape in ways that will moderate future damage (adapted from Werner and McNamara, 2007).

Earth-surface phenomena further amplifies. Climate change affects physical components (size and frequency of floods, sediment fluxes) and biological components (sediment-stabilizing vegetation, destabilizing macroscopic animals) alike — and therefore also the feedbacks between them. Direct, large-scale human manipulations of landscapes and ecosystems can be considered as (i) changes to the forcing, or (ii) part of an evolving, coupled human-natural system. Either way, analyzing Earth-surface transitions will demand unions of interdisciplinary research, as we address in the final challenge in our list.

1.3.4. How can we blend human and technological dynamics, biological processes, geochemistry, and physical processes into a unified science of the Earth's surface?

Two-way couplings between biological, geochemical, and physical processes range from the scales of microbes to those of mountains. Two-way couplings also link human actions and landscape/ecosystem processes from the scales of engineering projects and flood/landslide events to the scales of long-term landscape evolution. With the exponential increase in technology and associated accelerated changes to human societies, the dynamic aspects of the human component of the newly emerging Earth-surface system are of undeniable importance. From this point of view, we have entered a new geological epoch — the Anthopocene. Because neither human nor other biological dynamics can be considered peripheral influences in geomorphology and to make progress on all the grand-challenge questions above, the research community must foster a fully multidisciplinary science.

1.4. Societal applications

Formulating policies that will lead to the long-term stability of human-occupied and human-influenced environments requires understanding how Earth-surface systems operate. Such understanding, and the predictive/forecasting ability that stems from it, will also inspire and inform adaptive management strategies for mitigating the societal impacts of climate change. The trend toward “soft” or “green” engineering highlights the need to understand how Earth-surface systems self-organize. We list below a few (interrelated) examples of how the development of an integrated Earth-surface science, rooted in complexity theory, will benefit society:

(i) *Desertification*. Researchers are beginning to address feedbacks between wind-blown sediment, biology, and human land use that can lead to hysteresis between a stable, vegetated state and fully mobile sand dunes (Fig. 8). Increased understanding will allow marginal landscapes (such as fringe agricultural lands) to be nudged into a more desirable state.

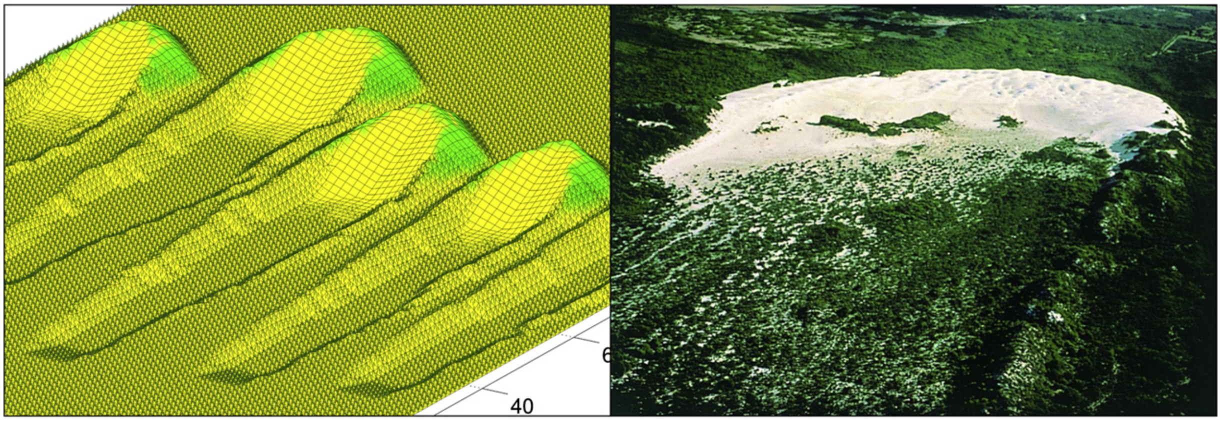

Fig. 8. A numerical simulation of a parabolic sand dune (left) and a parabolic dune in nature (right). Parabolic dunes are another example of a self-organized system with strong feedbacks between geomorphic processes (aeolian sand transport) and biological response and control (vegetation growth and stabilizing effects). The dark-green sticks in the simulation represent woody-shrub climax vegetation (visible in the dune track in the photo at right) and the light-green shading marram grass, the successional pioneer species. Marram grass can only thrive under fresh sediment input and has a positive growth response to sand burial as the dune advances (but declines under a neutral or negative sediment balance); parabolic dunes are specifically ecogeomorphic landforms that only develop as a result of biological influence (figure after Baas and Nield, 2007; photo at right courtesy of Patrick Hesp).

(ii) *River restoration and management*. Development and conservation designs based on knowledge of how rivers and riparian ecosystems mutually self-organize will be more effective, less vulnerable, and more resilient.

(iii) *Delta restoration*. Understanding the interactions between river dynamics, coastal-wetland evolution, wave and storm processes, and human changes to sediment routing and subsidence rate is fundamental to hazard identification and mitigation, development, management, and future planning.

(iv) *Coastal management*. Awareness of large-scale spatial localizations and associated autogenic changes and how these self-organized aspects of sandy coastlines interact with changing storm and sea-level forcing and human stabilization attempts will allow more effective management strategies.

(v) *Mitigating impacts of climate change*. In many environments, including alpine and arctic settings where glaciers and permafrost are melting, landscape-shaping processes are shifting, as are geochemical cycles (carbon and nutrients) and biodiversity within ecosystems. Understanding feedbacks in Earth-surface systems will help minimize the related impacts to society and maintain ecological resilience.

(vi) *Land use*. Urban development, shifting agricultural practices, river control, and a host of other human actions affect sediment and geochemical fluxes, altering the landscapes and ecosystems on which society depends.

(vii) *Geohazards*. Changing climate and land use alter the frequency and severity of floods, landslides, and severe storms. Understanding the nonlinear feedbacks that complicate the relationship between forcing changes and system responses will help inform land-use planning — revealing what areas and land uses are most prone to disasters that can wipe out communities or cripple entire regions.

(viii) *Geoengineering*. Large-scale, purposeful manipulations of landscapes and landscape functions, analogous to iron fertilization of ocean basins, will likely become even more prevalent and ambitious than current projects to shift large quantities of water across drainage divides. Understanding of landscape/ecosystem dynamics will help avoid unwanted surprises.

2. Rate-limiting factors and community needs

Several sociological and scientific realities currently prevent geomorphology and the broader science of the Earth's surface from moving forward as rapidly as they might. Each rate-limiting factor corresponds to a community need, a positive step that would facilitate transformations in Earth-surface research. We group these factors into three sets, enumerated below:

2.1. The interdisciplinary nature of the science and the fragmented nature of the scientific communities

2.1.1. Barriers between disciplines

Obstacles are common when conducting interdisciplinary research within a discipline-based academic structure; and with so many discrete disciplines addressing different aspects of the coupled dynamics of Earth-surface systems, disciplinary fragmentation tends to inhibit communication and collaboration. Researchers addressing Earth-surface systems come from an array of scientific branches (Fig. 1) and serve as faculty members in distinct academic units. For example, even within geomorphology, researchers are split into two communities (especially in North America): one based primarily in geography departments, and the other composed of geologists and engineers. The two communities typically attend different meetings and favor different journals, with limited intellectual cross-fertilization. Such divides are even deeper between other disciplines that need linking in Earth-system science, such as biology and physics.

Uniting diverse collections of Earth-surface scientists in the same physical space will spur crossdisciplinary collaborations, necessary innovations, and ultimately the creation of a truly multidisciplinary Earth-surface science. Such a blending of communities and disciplines should proceed on multiple levels, starting with an increased frequency of ad-hoc interdisciplinary conferences and extending to ongoing synthesis centers — physical homes for interactions between disciplines. These centers should not be based in any discipline but instead provide neutral, common ground to promote the interweaving of different branches of science.

2.1.2. Funding hurdles for interdisciplinary research and increasing interdisciplinary funding initiatives

In addition to discipline-derived hindrances to interdisciplinary work, structural separations within funding agencies tend to make financial support for interdisciplinary research difficult to obtain. One important example is within the U.S. National Science Foundation, where interdisciplinary proposals are typically evaluated separately in multiple discipline-specific programs. The need to include in a single proposal levels of detail sufficient to satisfy reviewers and panel members from a broad range of backgrounds lowers the chance of the proposal's success, as does the need to excite the diverse audience of panel members enough to make that proposal a priority for multiple panels. Funding agencies issuing calls for proposals that explicitly involve multiple disciplines, each featuring a single panel, would considerably reduce the extra barriers that interdisciplinary collaborations tend to face.

2.1.3. Geographical fragmentation and encouraging international and interregional interactions

Analogous to disciplinary fragmentation, geographical separations also hinder progress. Researchers within the same field but in different countries are typically isolated from each other, especially in the case of less-developed nations. Researchers from different parts of the world do not attend the same meetings often enough, decreasing the opportunities for collaborations to nucleate. Furthermore, attaining funding for collaborations between researchers of different nationalities tends to be especially difficult.

Researchers studying geographically distinct Earth-surface systems also tend to be fragmented — a characterization that applies to those studying different types of environments (alpine versus coastal settings, for example) as well as those studying different parts of the world. We are missing the opportunities for advancements in Earth-surface science that could result from greater exchange of tools and findings between communities with different geographic foci.

An increased emphasis on explicitly international and interdisciplinary conferences, held in overseas locations (especially in less-developed regions) will help integrate knowledge bases currently isolated from each other. Joint U.S.-overseas funding initiatives aimed at Earth-surface science would allow currently impractical collaborations to flourish; some of these initiatives should specifically involve less-developed nations.

2.1.4. Synergy between observation and modeling is not sufficient

Some division also exists between researchers observing and documenting natural systems and those conducting theoretical investigations with analytical and numerical models. For the health of Earth-surface science, field, remote-sensing, and laboratory observations should feed the development of theory/modeling, which should in turn help motivate the kinds of data that get collected. While such interactions do occur to some extent, the surge in modeling tools and theoretical perspectives from complex systems research has created the need for increased fusion of observations and theory (as we describe in the next subsection). Given the rapid advance of theoretical perspectives, modeling techniques, and observational technologies that is currently underway, Earth-surface science will require increased consultation and coordination between modelers and observational specialists to guide both data collection and model content.

2.2. Challenges in characterizing the states of Earth-surface systems and changes in those states, and the need for new modeling methods, new kinds of data, and coupling between them

2.2.1. System characteristics, Earth-surface complexity, and modeling

Several aspects of Earth-surface systems make gathering data appropriate for use in developing and testing models a particular challenge: many biological and physical processes interacting across a wide range of scales (Fig. 4); links between the scales, leading to emergent structures and interactions; nonlinear thresholds and feedbacks and self-organization, leading to steep gradients and spatial localization as well as temporally abrupt changes (Fig. 9); and historical contingency, which produces spatial and temporal variations in lithological, sedimentological, and ecological variables (local variations in the boundary conditions within which processes operate). These properties mean that a strategy of gathering data in limited places, even with high temporal and spatial resolution locally, is not sufficient, and beg the need for collection strategies in which resolutions are variable.

Not only do Earth-surface scientists need to develop new methods, but new modeling methods being developed across science and mathematics need to be adopted in Earth-surface science. Such adoptions and developments are underway, but this trend should grow. For example, the new paradigm of emergent phenomena, which highlights the ubiquitous tendency for new variables and interactions to form as length and time scales increase, arose initially in physics, but an increasing number of Earth-surface scientists are embracing this perspective and constructing more models based on emergent interactions rather than directly on the smallest- and fastest-scale processes feasible.

Until recently, most modeling and observation efforts have tended to focus on relatively small scales; flux laws have been based on experiments in the lab or on small areas of land in the field. The existence of emergent phenomena suggests that, to most effectively achieve explanatory and predictive power for Earth-surface phenomena over the vast range of scales involved, we need to develop a hierarchical suite of Earth-surface models, with the variables at each level and the laws governing their interactions treated separately — and for this we need to develop flux laws that capture the effects of emergent phenomena at various scales. Hierarchical observation will provide solid footing for a hierarchical suite of models, and parameterizations at one scale can be derived from models of much smaller- and faster-scale processes — or, perhaps more reliably, they can be empirically based.

2.2.2. Flux laws, Earth-surface complexity, and data

Modeling changes in landscapes and ecosystems through time requires the intersection of laws governing fluxes of water, sediment, chemicals, and nutrients at appropriate length and time scales — laws that in most cases we have not yet developed or discerned. This point relates to those described immediately above in Section 2.2.1: data collected on small scales (grain motions on a patch of stream bed, or groundwater fluxes in a restricted domain, for example) generally cannot be “scaled up” in any straightforward way; larger-scale emergent structures constrain the larger-scale fluxes (the way the migration of a sand dune determines large-scale sand fluxes in a desert).

A lack of interdisciplinary data sets designed to aid and guide models with a range of native scales inhibits progress in understanding and predicting Earth-surface phenomena, so to devise or discover quantitatively accurate flux laws across a range of scales will require targeted field, laboratory, and remote-sensing observation strategies and technologies. Multiscale, multiresolution sensing from near-ground and near-Earth space (including interferometric radar, optical and thermal hyperspectral imaging, and water-penetrating lidar) and the eventual implementation of self-configuring sensor networks (“smart dust”) will need to play a significant role in providing new multiscale data sets and flexible data-collection strategies.

Geochemical and geophysical methods for measuring rates of landscape change and the fluxes involved on various scales (involving relatively short-lived isotopes and optically stimulated luminescence, for example) have burgeoned in recent years. These developments and access to the methods need to continue to expand. Other forms of historical data, ranging from historical maps and photos to the stratigraphic archive (sediment-core and high-resolution, three-dimensional seismic data), also need to become more widely available to provide other types of information about rates and styles of landscape change over a range of scales.

To provide the multidisciplinary data sets necessary for modeling interactions between physical, geochemical, biological, and human processes, researchers from different disciplines need to conduct coordinated experiments in common field and laboratory sites; supporting the Critical Zone Observatories represents an endeavor fundamental to the advance of Earth-surface science. In addition, researchers should take advantage of the “experiments” that human interventions in landscape/ecosystems represent (including engineering and restoration projects), collecting multidisciplinary

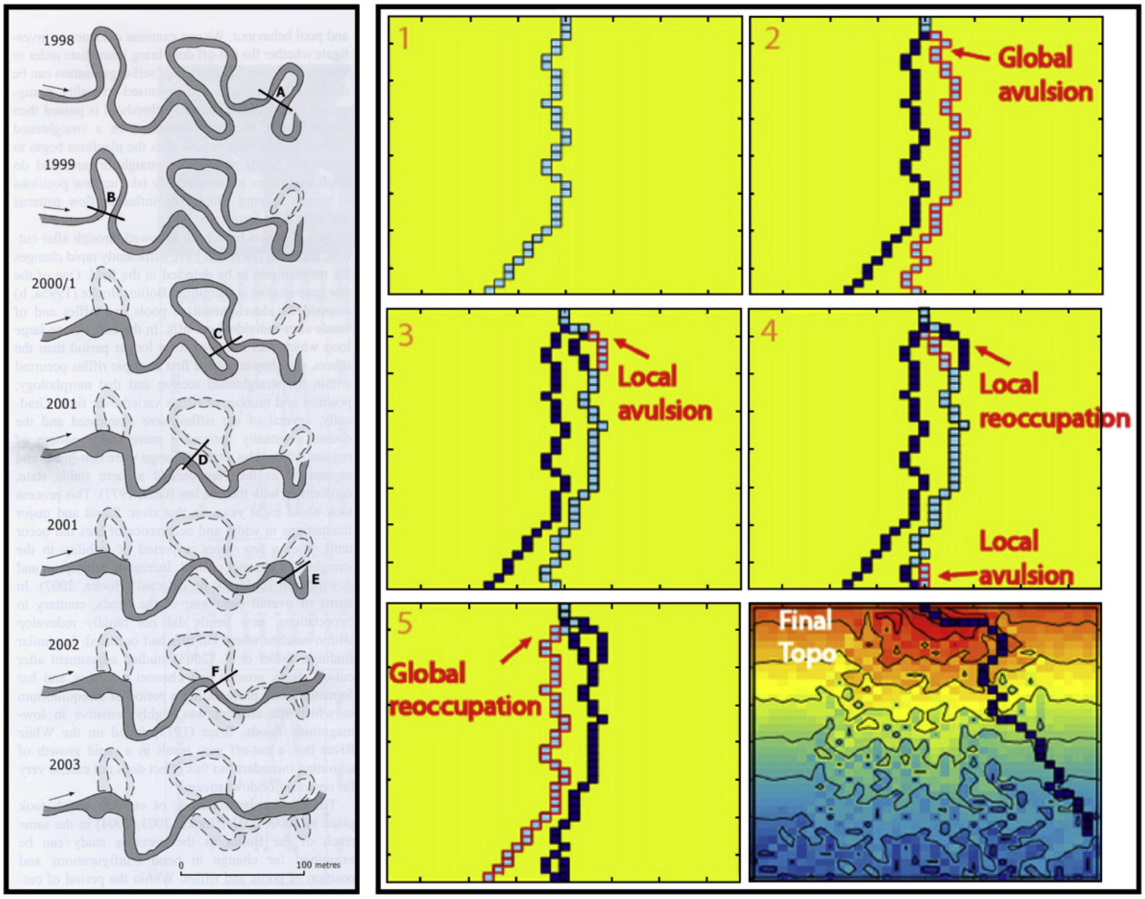

Fig. 9. Channel avulsions – sudden shifts from one channel path to another – are a characteristic feature of fluvial systems. The time-series map at left shows a sequence of abrupt and localized changes along the River Bollin in NW England between 1998 and 2003; in the field, such stranded oxbows raise the complication of historical contingency — local variations in substrate that influence where and when changes occur. The six-panel box at right shows styles of avulsion captured in a numerical model of a floodplain. The final panel at bottom left illustrates the complex floodplain topography that evolves simply from channel avulsion and reoccupation over time (figures from Hooke, 2007, and Jerolmack and Paola, 2007, respectively).

data about the responses to such significant human-induced perturbations.

2.2.3. Access to and availability and coordination of interdisciplinary Earth-surface data and models

Without coordination, data collection and model development will not move Earth-surface science forward with maximum efficiency. Simply accessing data sets and models can be difficult for researchers, and the lack of common data sets – in common formats – accessible through a common repository, inhibits model development. Without access to shared models and model components, researchers end up reinventing models individually.

Improved data sets could allow widespread advances in understanding and predicting Earth-surface dynamics by spurring improved models — but such advances will be limited unless the data sets can be easily accessed and used by the broad Earth-surface community. Data sets need to be collected in a central clearinghouse; and such a facility should, to the extent possible, translate the data sets into a common format. In addition, workshops and institutes are needed to educate researchers about the observational technologies available, how to employ given methods, and ways in which they might make use of extant data.

Similarly, models of Earth-surface systems should be collected and made available to all researchers — and to society at large. A centralized modeling facility should also make it possible to link together a select set of models from each Earth-surface environment so that scientists and environmental managers can address questions involving interactions between multiple environments (between watersheds, rivers, and coastal environments, for example). The recently funded Community Surface Dynamics Modeling System (CSDMS) is initiating such an effort, and support should be continued so that it can become an effective clearinghouse for and coordinator of numerical models.

Interactions between researchers developing and testing models and those conducting experiments and collecting data need systematic facilitation. Ad-hoc workshops and institutes for this purpose should be encouraged, allowing theoretical and observational specialists to physically mix and share ideas. In addition, an ongoing synthesis center focusing on enhancing coordination between modelers and observational experts would efficiently spur progress in Earth-surface science.

2.3. Future generations of Earth-surface scientists

2.3.1. Student skills and researcher training

If graduate students, collectively, possessed a more extensive quantitative background, including skills in programming, math, and physics, as well as interdisciplinary experience in interpreting Earth-surface systems and their complex properties, Earth-surface science would advance more rapidly. Training students in how to use new observation technologies and field techniques will lead to better empirical bases for theory and modeling. Short courses and summer schools or institutes teaching graduate students and early-career scientists about complex systems perspectives and quantitative tools, as well as the inherently interdisciplinary aspects of Earth-surface science, are needed to boost the level of Earth-surface researcher competence. Web-based opportunities to learn about these topics would also promote an appropriate Earth-surface knowledge base.

Increased emphasis on geomorphology-led, crossdisciplinary conferences and meeting sessions would raise awareness among scientific communities of the importance of landscape-change processes in environmental science, as would distinguishing geomorphology as a separate section or focus group within the structure of the American Geophysical Union (geomorphology currently exists as a semiautonomous subunit within the hydrology section).

2.3.2. Public perceptions and K16 and informal education

If the excitement and relevance of geomorphology and broader Earth-surface science were projected more prominently to the general public, students at all levels would be more motivated toward graduate studies and careers in these fields. Presently, geomorphology and the interdisciplinary nature of the Earth's surface are invisible to many people. Common perceptions equate “the environment” to “ecology,” with little or no awareness that landscapes are the requisite platforms that support and evolve in tandem with ecosystems. If students equated “the environment” with “Earth-surface science” and realized that understanding Earth-surface dynamics is key to improving future human well-being through steering the evolution of our habitats, more of them would be attracted to math and science. Moreover, if they were aware that the Earth's surface provides a prime laboratory for the new physics of complexity, more quantitatively inclined students would be attracted to study Earth-surface processes.

Individual researchers and organizations need to use a variety of approaches to educate, excite, and inspire younger students and the public about Earth-surface science and the inseparability of landscape and ecosystem processes and change. Curricular materials such as plans and kits for lessons, laboratory experiments, and demonstration projects should be prepared and distributed to teachers at various levels. For example, instructors can construct small “stream tables,” so that students can participate in informative and entertaining experiments involving water and sediment. As a more veiled way to teach about the physics, biology, and chemistry of Earth-surface processes, computer games should be developed. These might resemble “Sim Earth” or “Second Life,” but would incorporate realistic interactions between landscape, ecosystem, and human processes.

Other media can also be of use. Earth-surface researchers should seek out and make themselves available to television and radio producers to discuss exciting and relevant science. We should also produce videos for YouTube and similar websites. GoogleEarth initiatives could tag locations of interesting or important research, as well as landscape and ecosystem features and events — and links to relevant papers could be added. Earth-surface scientists should also more frequently write popular articles about their work or their field.

3. Recommendations: an Earth Surface Institute

Many of the needs listed in the previous section could be rephrased as recommendations for action by individual researchers, informal or structured groups of scientists, and funding agencies; the actions that would require coordination of the scientific community range across all the listed needs, from facilitating the blending of disciplines and communities, to enhancing synergies between modeling and observation of complex Earth-surface phenomena, and developing educational initiatives. Each of these numerous endeavors could be initiated, planned, and conducted separately.

However, to focus these efforts and more effectively catalyze the emergence of an integrated, multidisciplinary science of the Earth's surface, we recommend the creation of a new institute.

Similar to major institutions like the Santa Fe Institute and the National Center for Atmospheric Research (NCAR) in the U.S., this Earth Surface Institute should feature a physical facility where visiting researchers from around the world can interact face-to-face with each other and with resident scientists. The Institute should be truly interdisciplinary — not associated primarily with geomorphology, hydrology, biology, engineering, or physics. The Institute should house, administer, and disseminate the field, laboratory, and remote-sensing data sets needed for the advance of Earth-surface science, and it could provide laboratory facilities for interdisciplinary experiments. This Institute should provide sufficient staff to assist with the planning and logistics of the various workshops, summer schools, and ongoing centers described above.

Earth-surface processes affect human civilization as directly as atmospheric processes. Geomorphology is blossoming into a quantitative and compelling field, and a melding of disciplines into a new Earth-surface science seems inevitable. As an ambitious and progressive nexus, an Earth Surface Institute would foster a more timely and vital scientific transformation from which not only the research community but all of society would benefit.

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References

Ashton, A., Murray, A.B., Arnoult, O., 2001. Formation of shoreline features by large-scale instabilities induced by high-angle waves. Nature 414, 296–300.

Baas, A.C.W., Nield, J.M., 2007. Modeling vegetated dune landscapes. Geophys. Res. Lett. 34, L06405.

Coulthard, T.J., Van De Wiel, M.J., 2007. Quantifying fluvial non linearity and finding self organized criticality? Insights from simulations of river basin evolution. Geomorphology 91, 216–235.

Hooke, J.M., 2007. Complexity, self-organisation and variation in behavior in meandering rivers. Geomorphology 91, 236–258.

Jerolmack, D.J., Paola, C., 2007. Complexity in a cellular model of river avulsion. Geomorphology 91, 259–270.

Kirwan, M., Murray, A.B., 2007. Temporary vegetation disturbance as an explanation for permanent loss of tidal wetlands. Geophys. Res. Lett. 35, L05403. doi:10.1029/2007GL032681.

Slott, J., Murray, A.B., Ashton, A., Crowley, T., 2006. Coastline responses to changing storm patterns. Geophys. Res. Lett. 33, L18404. doi:10.1029/2006GL027445.

Werner, B.T., McNamara, D.E., 2007. Dynamics of coupled human-landscape systems. Geomorphology 91, 393–407.