Research in Landscape Sustainability:
Earth-surface processes in the SEES context

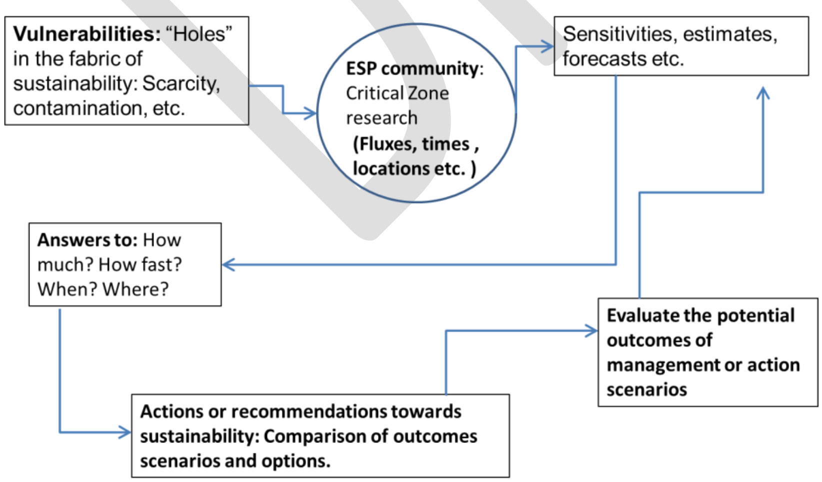
GLD SEES workshop group*, October 6-7, 2011

CONTEXT

The National Science Foundation (NSF) recently developed a series of new and updated initiatives grouped under the umbrella of Science, Engineering, and Education for Sustainability (SEES). SEES comprises sustainability 'tracks' for several existing NSF initiatives as well as a group of new initiatives. These are discussed in the Tutorial section below; together they comprise a major new initiative in NSF research. The purpose of this document is to explore ways in which the Earth-surface process (ESP) community can participate in the SEES program.

The SEES program lies at the intersection of two themes that are central to ESP research: the environment and the long-term view inherent in the concept of sustainability. The "environment" means different things to different people, but we stress that *the Earth's surface* <u>*is*</u> *the environment* – the arena in which most life and human activity unfolds. Sustainability also can be defined in different ways, but a common central theme is meeting current needs without compromising the ability of future generations to meet their needs: use without using up. Central themes in sustainability include learning to live and work with natural processes; developing renewable resources; and adapting our resource use to a shifting mosaic of natural landscape dynamics.

Putting these ideas together, we see Earth-surface dynamics at the center of SEES: understanding how to accommodate a still-rising human population within the web of physical, geochemical, and biologic systems that make up the surface environment in a way that works with the natural processes that have brought the landscape to its present state. The concept of sustainability incorporates notions of recycling in a broad sense: recycling of energy, water, rock materials, organic and inorganic chemicals. Characterizing these cycles and the wide-ranging time and space scales over which they play out is at the very heart of the earth sciences, and conversely places our discipline at the heart of the sustainability discussion.



Landscape sustainability requires that Earth surface processes be quantified to predict trajectories of landscape response to perturbations. This means quantifying fluxes of particulates and solutes that control landscape evolution. For sustainability purposes we consider the prediction time scale to be in the range of a few hundred years. Interestingly, this time scale falls between what might be considered a typical engineering time scale (~50 yr) and classical geologic ("deep time") scales of the order of 10^4 yr and up. Landscape prediction can be seen within a larger logical framework

**SEES-GLD workshop group: Anne Chin, Gordon Grant, Liz Hajek, Arjun Heimsath, John Holbrook Doug Jerolmack, Stephen Lancaster, Dorothy Merritts, Cailin Orr, Chris Paola, Paola Passalacqua, Jim Pizzuto, Cliff Riebe, Ray Torres, Andrew Wilcox, Ellen Wohl, Elowyn Yager, and Kyungsoo Yoo. For NSF: Jun Abrajano, Paul Cutler* motivated by vulnerabilities – which might be thought of informally as the "holes" in a sustainability fabric – which are then connected to prediction and eventual action via the linkages diagrammed above.

Research on landscape dynamics has identified a number of sources of nonlinearity in landscape response to change. Among the forms of nonlinearity, thresholds figure prominently: for example, threshold conditions to energize sediment transport; for abrupt change (avulsion) in rivers; and for mass failure of soil, sediment, and rock on hillslopes.

SEES Tutorial

"A sustainable world is one in which human needs are met equitably without harm to the environment, and without sacrificing the ability of future generations to meet their needs." NSF has developed a new foundation-wide paradigm, Science, Education and Engineering for Sustainability (SEES) with the mission "***To advance science, engineering, and education to inform the societal actions needed for environmental and economic sustainability and sustainable human well-being.***"

The Earth-Surface Processes community has much to contribute to SEES. Current solicitations fall into two groups (SEES overview):

- General programs: SEES Fellows, Sustainability Research Networks, SEES Research Coordination Networks, and Partnerships for International Research and Education, and
- Targeted programs: Sustainable Energy Pathways, Dynamics of Coupled Natural and Human Systems, and five Climate Research Initiative programs.

Deadlines are imminent for FY12; universities may have earlier deadlines. NSF hopes to offer new elements of the SEES portfolio in future years (e.g., natural hazards, coastal vulnerability). Competitive proposals to NSF may require collaborations with social scientists, engineers, biologists, and others.

SEES FY12 activities and deadlines

Water, Sustainability and Climate [WSC]: 10/19/11

Partnerships for International Research and Education [PIRE]: 10/19/11 (preproposal), full proposal (5/15/12)

Dynamics of Coupled Natural and Human Systems [CNH]: 11/15/11

Sustainability Research Networks [SRN] : 12/1/11 (preproposal), 4/1/12 (full proposal)

SEES Fellows: 12/5/11

Sustainable Energy Pathways [SEP]: 2/1/12

Research Coordination Networks-SEES: 2/3/12

Two broad avenues exist for using studies of natural landscapes to provide insight for landscape sustainability. One is based on the idea that the current state of a given landscape is no accident: it has reached its present configuration through the interaction over time of the web of interconnected physical, geochemical, biotic, and (increasingly) human processes that shape the surface environment. In traditional "hard" (and generally short-term focused) engineering, the evolution of the landscape to its present state could be ignored, but if the goal is to create a system in which humans live sustainably with a dynamic landscape, the way the landscape has reached its present state becomes central to understanding its natural tendencies and its vulnerable locations.

The second avenue arises from the self-recording nature of Earth's landscape. This is obviously true of depositional landscapes, which create a record through their own deposits, but also of erosional landscapes that represent a mosaic of forms created over long spans of time and reflective of the processes that have shaped them. These records are in effect archives of past behavior that can be mined to provide insight on alternate states of the landscape, the important processes that shape it, probabilities of rare but consequential events and hazards, and landscape response to imposed changes.

LANDSCAPES ON THE EDGE (OF SUSTAINABILITY)

We can make the connection between ESP and SEES more concrete using the research framework presented in the recent NRC report *Landscapes on the Edge.*[1] The centerpiece of the report is a set of nine grand challenges, which then lead to four proposed research initiatives. Though the report was prepared before the SEES initiative was developed, the nine grand challenges dovetail nicely, with minor rewording, with the main SEES themes. The following is a re-ordered list of the nine grand challenges articulated by the *Landscapes on the Edge* report. The last two challenges are slightly modified to better articulate how they bridge basic Earth surface process research challenges with issues directly related to sustainability. (The original order of the Grand Challenges is given in parentheses.)

1. (9.) How can Earth surface science contribute to a sustainable Earth surface?

Earth surface science is fundamentally concerned with the functioning and evolution of both natural and impacted landscapes. Hence it provides an understanding of the cumulative effects of human activities and is well poised to inform strategies for restoration and sustainable land use.

2. (7.) What controls landscape resilience to change?

A key concept for assessing resilience is landscape "stiffness" – the nature of response to an applied stress. We can visualize these responses as elastic and brittle: Some landscapes may respond quickly and sensitively to applied change, but recover quickly if the change is removed; others may show no response up to some threshold limit, beyond which abrupt and potentially irreversible change occurs.

3. (8.) How will Earth's surface evolve in the Anthropocene?

Understanding, predicting, and responding to rapidly changing landscapes that are increasingly altered by humans is among the most pressing challenges of our time. Meeting these challenges is critical for developing the tools needed to guide decision-making, and for producing innovative management solutions toward a sustainable Earth surface.

4. (6.) How do ecosystems and landscapes coevolve?

Maintenance of sustainable landscapes requires identification of tipping points, stable states, and the natural range of variability in eco-geo interactions. Earth surface science provides insight on rates of processes and how they change over time in response to factors such as climate variability and ecosystem dynamics.

5. (4.) How does the biogeochemical reactor of the Earth's surface respond to and shape landscapes from local to global scales?

Soil, saprolite, and alluvial deposits embody the life-sustaining matrix of Earth's biogeochemical reactor. From the standpoint of sustainability, it may be helpful to view them as reservoirs for which thickness, composition, and texture are vulnerable to loss and/or degradation due to human activities. Tracking these changes – a subject that is central to Earth surface science – is essential to sustainable land-use management.

[1] *Report available at NRC website: http://www.nap.edu/catalog.php?record_id=12700*.

6. (5.) What are the transport laws that govern the evolution of the Earth's surface?

A fundamental goal of Earth surface process research continues to be the quantification of transport laws, which enables enhanced prediction of responses to perturbations. For example, predicting the sustainability of soils, floodplains, coastal systems, water quantity and quality, as well as predicting susceptibility to hazards such as flooding and landsliding, are greatly furthered by the use of transport laws.

7. (2.) How do geopatterns on Earth's surface arise and what do they tell us about processes?

Landscapes are a product and a filter of Earth surface processes; although these processes are exceedingly varied and complex, only a small subset contributes to pattern formation. Determining these linkages will allow us to anticipate what kinds of change – anthropogenic and climatic – will drive landscape response, and how to mitigate adverse impacts.

8. (3.) How do landscapes influence and record climate and tectonics?

This challenge can be reworded to map directly to sustainability: *How does our understanding of how landscapes influence and record climate and tectonics enhance predictive capabilities*? Feedbacks between landscapes and these two external drivers of change on the Earth's surface can significantly alter the sustainability of any given system. Major advances driven by this challenge feed naturally into projects focused on predicting the sustainability of any subset of the Earth's surface.

9. (1.) What does our planet's past tell us about its future?

This challenge maps readily to sustainability if we reword it to: *What does our planet's landscape record tell us about future landscape sustainability*? How and how fast do landscapes respond to changes in climate and other forcings? The need here is to connect records of change preserved in landscapes and sediments with past forcings (e.g. climate, water cycle, sea level) and an understanding of Earth-surface response to changes in forcings such as climate as a basis for prediction and thus sustainability.

We note that innumerable sustainability experiments already have been run, e.g., feedbacks in past natural systems of the earth became unsustainable but reached new conditions. The archive of natural

Tipping Points, Soil Erosion, and Landscape Sustainability

A number of the above grand challenge questions are addressed in the following example of identification of stable states and tipping points in landscape history. Identifying such states and tipping points is central to evaluating the sustainability of Earth surface processes and reservoirs. Recent advances in understanding the balance between production and erosion of soil in mountainous landscapes provide an illustrative case in point. Cosmogenic nuclides in soil, saprolite, and rock consistently show that soil production rates are faster in soil-mantled landscapes than they are where bare rock has been exposed. Hence, the presence/absence of soil in itself represents a crucial tipping point in the sustainability of soils. As first proposed by Carson and Kirkby (1972), when soils are present, soil production rates can more readily maintain a stable, and thus sustainable soil thickness. Conversely, when soils have been stripped from landscapes, soil production rates generally slow down, such that reestablishment of a sustainable soil becomes problematic.

Carson, M. A., and Kirby, M. J., 1972, Hillslope form and process: University Press (Cambridge), 475

experiments preserved in landscapes and sediments also provides information on resilience, in that we can learn how the landscape system adjusts to gradual and sudden changes of a range of magnitudes.

SEES EDUCATION

The ESP community has an important role in educating a range of learners and the general public about sustainable landscapes and their central place in the environment, and in training students in conducting the interdisciplinary research that is central to sustainability initiatives. These aspects are clearly reflected in the high profile of education objectives in the overall NSF SEES "Dear Colleagues" letter http://www.nsf.gov/pubs/2011/nsf11022/nsf11022.jsp:

- support for interdisciplinary education/learning science research, development, and professional capacity-building related to sustainability science and engineering;
- creation of research and education partnerships around forefront developments in sustainability science and engineering, both nationally and internationally;
- development of the workforce required to understand the complexities of environmental, energy, and societal sustainability;
- engaging the public to understand issues in sustainability and energy.

We would like to call our colleagues' attention to the possibilities in SEES-ESP research projects for informal education programs that address some of the points above.

The National Center for Earth-surface Dynamics (NCED) has worked successfully with the Science Museum of Minnesota on high-profile landscape-themed exhibits, some of which have toured internationally. The intrinsic visual appeal and familiarity of landscapes make them especially attractive ways of drawing the public into the broader discussion of environmental sustainability. We encourage our colleagues to seek out museums and other educational institutions (e.g. schools, community and tribal colleges, and programs such as SERC/Carleton College) to partner with in their SEES proposals.

EXISTING INFRASTRUCTURE

The SEES initiative offers an unparalleled opportunity to leverage the enormous and ongoing investment that NSF has made over the past few decades in environmental observatories, new remote sensing technologies, targeted Science and Technology Centers (STCs), and community-based models and cyberinfrastructure. Moreover, SEES-oriented proposals could serve as much-needed "glue" and motivation for cross-site investigations and synthesis. Especially relevant examples include: 1) place-based research centers, i.e., Critical Zone Observatories (CZOs), Long-Term Ecological Research (LTER) Network sites, NEON

Building interdisciplinary collaborations

Competitive SEES proposals typically will involve interdisciplinary research questions and collaborations that extend beyond the Earth-surface processes community. Mechanisms for developing such collaborations include:

- Seeking institutional support in the form of cross-disciplinary centers or institutes that bring together researchers within a university to foster proposal preparation.
- Proposing and/or attending NSF workshops designed to bring together investigators from different disciplines.
- Taking advantage of resources describing previous efforts to build collaborative networks, such as those associated with GEON

<http://interoperability.ucsd.edu/docs/08RibesBowker_OrganizingforMultidisciplinaryCollaboration.pdf>

or products of previous workshops e.g., the Human-Landscape Project

<http://clas.ucdenver.edu/ges/landscapes/index.html>.

transects, and ULTRA urban environments; 2) data acquisition and distribution programs, i.e., NCALM, Open Topography; PRIME laboratory 3) research centers for experimentation and innovation, i.e., NCED, SAHRA; and 4) community based modeling enterprises, i.e., CSDMS.

This broad, diverse portfolio of sites and programs can contribute to SEES in significant ways. Given the prominent role that landscape monitoring plays at CZO, LTER, NEON, and ULTRA sites, these sites could logically be seen as places where environmental trends can be assessed; this is an explicit objective of NEON but could be extended to other sites as well. More importantly, these sites could be used as venues for developing and testing new metrics for assessing landscape sustainability, resilience, and vulnerability. Exploring this concept could serve as the basis for a cross-site RCN proposal.

Moreover, this rich panoply of observatories could serve as a test bed for examining how diverse landscapes respond to environmental stressors. Building on the range of environmental "states" represented by different locales, we envision efforts to rigorously characterize system resilience and vulnerability. For example, common stressors (water, climate) could be arrayed across a spectrum of levels of anthropogenic disturbance, from "wild" to agricultural to suburban to urban, and common methods used to measure response over time, along with common models to predict responses (i.e., CSDMS). A further opportunity exists to use major facilities at STCs (e.g. NCED) to design experiments that explore the limits of adaptation of natural systems to disturbance and provide ideas and data to apply in field settings. Finally, the wide range of observatories means that we are poised to exploit opportunistic field experiments offered by events such as natural disasters, dam removals, and contaminant spills.

SPECIFIC EXAMPLES

Many surface processes questions fit naturally into a sustainability context, and we identify some examples of overarching science questions as well as topics of varying specificity. These examples, while not comprehensive, are surface processes questions and topics that contribute to a “systems-based approach to understanding, predicting, and reacting to change in the linked natural, social, and built environment,” and require interdisciplinary collaborations (SEES Dear Colleague Letter, NSF 11-022). We stress that these are simply example ideas. They reflect the interests and expertise of this particular workshop group, but provide some examples of the broad spectrum of ways that ESP research fits with the SEES initiatives. Where appropriate, these are targeted to specific SEES sub-programs (“SEES Tutorial” above).

Can we identify and quantify a threshold beyond which a landscape becomes unsustainable (and predict irreversible damage)?

Can we quantify and predict relevant fluxes through the landscape?

What is the relative importance of anthropogenic vs. historical/inherited natural changes? Can we detect the differences (i.e., are perceived changes real or related to increased detection capabilities)?

What management recommendations can we make based on historical data and mechanistic understanding of landscape processes?

Examples of human-landscape interactions across time that result in loss of sustainability:

- **loss of soil fertility [CNH]**

- **historical example:** The Hohokam people of central Arizona had an extensive system of irrigation canals circa 12th-15th centuries. Excessive soil salinization resulting from these canals creates persistent soil infertility today.
- **contemporary example:** Widespread salinization associated with irrigated agriculture is severely reducing crop yields across large portions of the crop lands associated with the lower Nile River.

- **persistent highly toxic contaminants in river sediments [CNH]**
    - **historical example**: 19th century placer mining in the Rocky Mountains and the Sierra Nevada introduced mercury and heavy metals. Nuclear power and weapons activities resulted in contamination of Columbia River sediments near Hanford, Washington by various radioactive isotopes.
    - **contemporary example:** Concentration of industrial pollutants in river sediments along the Yangtze River, China is exacerbated by sediment retention upstream of major dams such as the recently completed Three Gorges Dam.

- **localized sedimentation and subsequent release that causes loss of riverine and nearshore habitat and degraded water quality [CNH]**
    - **historical example**: Widespread construction of mill dams on small rivers in the eastern US during the 18th and 19th centuries resulted in subsequent sedimentation and abandonment of the dams. As these dams fail or are removed, the resulting release of sediment downstream degrades riverine and nearshore environments such as Chesapeake Bay.
    - **contemporary example**: Contemporary dam removals in the Pacific Northwest, the upper Midwest, and the eastern US result in flushes of sediment, some of which contains contaminants, to downstream river and nearshore ecosystems.

- **groundwater depletion and contamination [CNH]**
    - **historical example:** New Orleans pumps water from canals to limit flooding, which causes groundwater to flow into the canals, lowering the level of the city through time.
    - **contemporary example:** Depletion is particularly severe in the Ogallala Aquifer, as well as smaller scale riparian aquifers and intermontane aquifers in the desert Southwest around the cities of Phoenix, Tucson, and Las Vegas. Contamination is severe in many shallow aquifers that supply drinking water, as revealed by the US Geological Survey's National Water Quality Assessment program during 1991-1995.

- **Gullying [CNH]**
    - **historical example**: Widespread channel incision in the arid and semiarid regions of the western US during the late 19th and early 20th centuries. Lively debate continues concerning the relative importance of internal thresholds versus human activities as triggers that initiate channel incision in these river networks.

- **contemporary example**: Widespread channel incision is common in stream networks subject to channelization, such as many networks in the southeastern US and Midwestern US.

- **Dust Bowls [CNH]**
  - **historical example**: Much of the western and central prairies of North America experienced severe 'dust bowls' – widespread soil erosion, eolian transport, and desertification – during the 1930s and the 1950s. The relative influences of naturally occurring drought and human land use as triggers of these dust bowls remains in debate.
  - **contemporary example**: The arid portions of Australia, in particular, continue to experience periodic severe dust storms and loss of fertile topsoil.

- **Human development encroaching on steep terrain susceptible to mass instability of hillslopes [CNH]**
  - **contemporary example**: The La Conchita, California, landslide that killed several people in 1995 provides an unfortunate example of encroaching development that may have contributed to hillslope instability, and certainly put people in harm's way when the adjacent hillslopes became unstable.

- **Sustainable deltas [CNH, SRN]**
  - Decades of narrowly focused management of river and sediment flows in the Mississippi Delta have caused the loss to drowning of some 1/3 of the wetlands area of the Mississippi Delta, with concomitant loss of recreation lands, productivity of commercial fish, nutrient uptake, storm buffer, and a host of other environmental services. Living sustainably on and with these critical ecogeomorphic systems involves the full range of SEES elements: the suite of processes that shape deltas landscape involve strong two-way coupling among physical processes of sediment transport, deposition, and channel-network development; biotic processes including habitat for a broad range of marine organisms, and vegetation that stabilizes land and is controlled by elevation; and the delivery, uptake, and flux of nutrients and salinity.

- **Water use and desert landscapes [CNH, SRN]**
  - Recent research at White Sands shows how a delicate dynamic equilibrium depends on complex linkages among wind, sediment transport, vegetation growth, and groundwater that have 'tuned' the landscape to its present state. Groundwater withdrawal would abruptly decouple the groundwater from this system, where the current vegetation that currently limits the rate of dune migration is dependent on that groundwater.

- **Hydrokinetic power [SEP]**
  - This can involve emplacement of turbines in rivers and tidal (or coastal in general) zones to harvest the kinetic energy of the flowing water, or retrofitting dams constructed for other purposes (e.g. flood control) for energy generation. All types of hydrokinetic

energy generation have important surface-process dimensions: for example, the possibility of enhanced bank collapse or damage to in-stream biota from turbine installations, or damage to installations because of poor siting decisions in active river channels, as well as the larger question of the limits to energy availability imposed by stream geometry and siting restrictions.

- **Road networks and landscape energy [SEP]**
    - An easily overlooked element of several forms of distributed energy generation (wind, solar) is the effect on the landscape and its biota of the network of roads needed to service the facilities. Roads disrupt ecosystems and increase erosion rates; a potential sustainability theme could involve using an understanding of landscape dynamics and ecology with green engineering methods to create less disruptive access networks for energy and other projects.
- **Landscape impact of biofuel development [SEP]:**
    - soil degradation, surface and groundwater contamination, nearshore water quality degradation, limited fertilizer supplies