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Forecasting the response of Earth's surface to future climatic and land-use changes: A review of methods and research needs

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: eft2.2014EF000290

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Abstract

In the future, Earth will be warmer, precipitation events will be more extreme, global mean sea level will rise, and many arid and semi-arid regions will be drier. Human modifications of landscapes will also occur at an accelerated rate as developed areas increase in size and population density. We now have gridded global forecasts, being continually improved, of the

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climatic and land-use changes (C&LUC) that are likely to occur in the coming decades. Aside from a few exceptions, however, consensus forecasts do not exist for how these C&LUC will likely impact Earth-surface processes and hazards. In some cases we have the tools to forecast the geomorphic responses to likely future C&LUC. Fully exploiting these models and utilizing these tools will require close collaboration among Earth-surface scientists and Earth-system modelers.

This paper assesses the state-of-the-art tools and data that are being used or could be used to forecast changes in the state of Earth's surface as a result of likely future C&LUC. We also propose strategies for filling key knowledge gaps, emphasizing where additional basic research and/or collaboration across disciplines is necessary. The main body of the paper addresses cross-cutting issues, including the importance of nonlinear/threshold-dominated interactions among topography, vegetation, and sediment transport, as well as the importance of alternate stable states and extreme, rare events for understanding and forecasting Earth-surface response to C&LUC. Five supplements delve into different scales or process zones (global-scale assessments, and fluvial, aeolian, glacial/periglacial, and coastal process zones) in detail.
Keywords: global change, forecasting, Earth-surface processes

1. Introduction

1.1. Problem statement

Many of the most significant effects of future climatic and land-use changes (C&LUC) will occur on Earth's surface, which we consider to be synonymous with the critical zone [e.g., *Anderson et al.*, 2008] and includes the near-surface environment where humans obtain, produce, and consume the air, water and food necessary for life. The delicate balance of human and

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ecosystem prosperity on Earth's surface is challenged by climatic variability, climate change, and unsustainable human activities.

The community of Earth-surface scientists (including, but not limited to, geomorphologists, hydrologists, physicists, and applied mathematicians who work on landform evolution) has developed powerful conceptual and mathematical models for how Earth's surface and near-surface environments are likely to respond to and feed back on potential future C&LUC. For example, models have been developed that reproduce observed recent changes in arctic permafrost landscapes [e.g. *Plug and West*, 2009], aeolian dune systems [e.g. *Pelletier et al.*, 2009], and the response of coastal and river systems to sea-level rise [e.g. *Marani et al.*, 2007; *Fagherazzi et al. 2012*] and land-use change [e.g. *Kirwan et al.*, 2011]. In many cases, however, these models have not yet been systematically applied to forecasting landscape changes over large regions, which limits their potential impact.

Earth-system modelers, in contrast, excel at working at the global scale. They have successfully represented the key physical and chemical processes occurring in the atmosphere and oceans within their Earth System Models (ESMs). ESMs have been less successful, however, at representing some Earth-surface processes, including the lateral redistribution of water, sediment, and nutrients near Earth's surface. For example, land models (for hydrometeorology, climate, and carbon cycle studies) often assume a globally uniform soil depth (e.g., 2 m in *Gochis et al.* [2010]) above bedrock. Even the use of an unconfined aquifer in land models implicitly assumes a global constant bedrock depth [e.g., *Lawrence et al.*, 2011]. The land-model components of ESMs solve the governing equations for subsurface water flow in the vertical direction only, even though water moves in all three directions in the subsurface [e.g., *Miguez-Macho and Fan*, 2012]. Riverine sediment flux, an important control on biogeochemical

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processes in wetlands, is another important component of land-surface processes not adequately accounted for in current ESMs. Given these limitations of current ESMs, there is much to be gained if Earth-surface scientists and Earth-system modelers collaborate more closely to assess the impacts of likely future C&LUC on human health, safety, and resource sustainability.

More basic research is also needed to further develop and refine Earth-surface response models so that they can be applied to forecasting changes in the state of Earth's surface in response to likely future C&LUC. Quantitative modeling of Earth-surface processes and testing and calibration of models against data is still in a relatively early stage of development compared with the advanced state of General Circulation Models (GCMs) that comprise the atmospheric and oceanic components of ESMs. As such, the Earth-surface scientific (ESS) community needs additional time and resources to develop models that accurately forecast how some Earth-surface processes will respond to likely future C&LUC. Alluvial rivers, for example, tend to aggrade when the ratio of sediment supply to transport capacity increases, and they tend to incise when that ratio decreases [e.g. *Bull*, 1991]. Forecasting whether an alluvial river will aggrade or incise in response to future C&LUC scenarios is complicated, however, by the fact that the relationships among sediment supply, transport capacity, rainfall, and vegetation cover are incompletely known. Similarly, we cannot yet forecast whether future climate change will lead to an overall increase or decrease in dust emitted to the atmosphere. Partly this inability reflects uncertainty in whether greater water-use efficiency in a world of higher atmospheric CO_2 concentrations will outweigh the negative effect of limited water availability in areas undergoing desertification. Our inability to forecast whether the future will be more or less dusty also reflects uncertainty associated with the relationship between vegetation cover and wind erosion. More vegetation cover leads to higher turbulent stresses near the ground and hence may be expected to

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increase rates of wind erosion. However, vegetation cover also acts to protect the underlying surface from erosion and the tradeoffs between providing protection and causing higher turbulent shear stresses need to be further resolved. To better forecast how dust emissions will change under future C&LUC scenarios, the portion of the ESS community working on wind erosion must also collaborate more closely with scientific communities working to predict future groundwater levels [e.g. *Scanlon et al.*, 2006] and the vegetation response to climate change in arid and semiarid regions [*Munson et al.*, 2011].

Natural experiments in the response of Earth-surface processes to C&LUC are constantly playing out across a wide range of time scales from human to geological, and across a wide variety of process zones. Such natural experiments provide essential data for developing and testing conceptual and mathematical models of how geomorphic systems will respond to likely future C&LUC. In all cases, landform responses are known to be complex, depending on recent history (antecedence), the existence of internal system dynamics that can amplify C&LUC forcings preferentially at particular spatial and temporal scales, and on decisions made by humans at both individual and societal levels. The net effect is that landscapes are highly non-linear systems, and the probability of particular impacts cannot be simply mapped to the state of forcing or rate of forcing change. For example, in the North American Cordillera tree mortality is increasing nonlinearly with temperature increases [e.g. *Preisler and Westerling*, 2007]. The geomorphic response to wildfires (e.g. debris-flow generation) is also highly nonlinear [e.g. *Cannon et al.*, 2010]. As such, there are compounding types of nonlinearity that must be accounted for in relating hillslope and/or fluvial-system responses to likely future C&LUC in mountainous regions.

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From the perspective of modern climatic changes, high-level governmental discussions now acknowledge that some amount of human-induced change is occurring and more change is inevitable. As a consequence, significant effort is being steered toward the development of adaptation strategies. At the same time, climate scientists are acknowledging that a critical aspect of climate is its variability (particularly the increased frequency of extreme events) rather than its mean value [e.g. *Katz and Brown*, 1992]. Therefore, the need to develop adaptation strategies requires a rigorous understanding of how landscapes respond to both the mean and variability of C&LUC. In turn, the state of Earth's climate depends in part on the response of landscapes to C&LUC. That is, the behavior of Earth's surface feeds back on the climate system in ways that are currently underrepresented in ESMs. Thus, a rigorous understanding of landscape response to external forcings is important in the contexts of both adaptation and mitigation to climate change.

In this paper, we argue that, first, ESMs have simplified representations of many Earth-surface processes and characteristics that could be improved with greater involvement of the ESS community in developing the next generation of ESMs. Second, many of the consequences of future C&LUC are felt locally and will depend sensitively on local topography, soil characteristics, vegetation cover, the degree of human disturbance, etc. Improving our ability to forecast Earth-surface hazards will thus require that the ESS community improve its ability to 1) work at larger (i.e. regional and global) scales, and 2) develop forecasts (and hindcasts, to test models against measurements) that use the forcing variables output by ESMs. Third, understanding and forecasting future landscape responses will require that the nonlinearities and threshold-dominated nature of Earth-surface systems be honored and better quantified. Fourth, a better understanding of the feedbacks among vegetation, sediment transport, and topographic

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change is central to improved forecasting in all Earth-surface process zones, hence collaboration among geomorphologists, geographers, hydrologists, ecologists, and Earth system modelers is needed.

1.2. Structure of this review

In Section 2 we describe the nature of Earth-surface processes and hazards and their relationship to C&LUC forcing variables, rank Earth-surface hazards in terms of their relative risk to society, explain how Earth surface processes and hazards relate to C&LUC forcing variables, and present a global map of where particular types of surface processes are likely to be dominant. Section 3 discusses opportunities for spatially explicit global-scale assessments of future changes in Earth's surface. Section 4 highlights the importance of nonlinearity, tipping points, and alternate stable states in Earth-surface systems. Section 5 emphasizes the importance of the couplings among vegetation, sediment transport, and topography in forecasting future landscape states. Section 6 argues for the importance of long time scales and natural experiments in the geologic record in validating landscape response models before they can be used for forecasts. Section 7 discusses how landscape response models can be useful for evaluating alternative mitigation strategies. Section 8 summarizes our recommendations how the ESS and broader geoscientific research communities could work to improve forecasts of Earth-surface response to likely future C&LUC. We also include five supplements that address specific scales and process zones. Text S1 expands on section 3 and reviews the global gridded forecasts currently available from the ESM community that the ESS community could use now to forecast Earth surface responses to likely C&LUC. Text S1 also provides exemplar models and data that have been used or could be used to perform global-scale assessments of landscape response to C&LUC. Texts S2-S5 provide exemplar models and data that are being used or could be used to

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forecast landscape responses within the hillslope/fluvial, glacial/periglacial, aeolian, and coastal process zones, respectively. These supplements serve several purposes. They identify 1) the Earth-surface processes within each process domain that are most sensitive to C&LUC, 2) models and data that have been or could be used to forecast Earth-surface responses to C&LUC, and 3) key knowledge gaps and suggested pathways for filling them, including the development of coupled process-based models, leveraging off of community-based code repositories/portals such as the Community Surface Dynamics Modeling System (CSDMS) and greater collaboration across disciplines.

2. The nature of Earth-surface processes and hazards

The hazards associated with Earth-surface processes include acute events (e.g. floods) in addition to more chronic events such as soil loss and the associated loss of food-production potential. Examples of societally relevant landscape properties in need of better forecasting include:

- the elevation of the land surface, including its changes in space and time (i.e. subsidence, river aggradation/incision, coastal erosion, etc.),
- the fluxes of sediment and nutrients (as well as contaminants such as metals that impact water quality) laterally across Earth's surface,
- the frequency and magnitudes of landslides, floods, dune encroachment, and other hazards related to mobile water and sediment at or near Earth's surface,
- particulate matter (PM) concentrations in the atmosphere, including those associated with fugitive dust.

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Not all Earth-surface hazards and/or changes in societally relevant properties pose an equal risk to society. Therefore, it is useful to identify the most significant hazards to provide guidance on which hazards should be prioritized for the development of improved forecasting tools. The risk associated with these hazards can also be divided into a direct and an indirect risk. A direct risk is associated with loss of life and property. An indirect risk is one that does not directly threaten a large number of lives or properties but may have catastrophic effects in concert with another process (e.g. the greenhouse effect). An example of an indirect risk is the potential release of CO_2 and methane into the atmosphere associated with thawing permafrost and loss of ground ice, thus accelerating the greenhouse effect. In our ranking we focused primarily on direct risks. The ranking is subjective, but it is broadly consistent with order-of-magnitude estimates of the financial risk posed by these different types of hazards [e.g. *Tol*, 2002; 2009]. We believe that future Earth surface hazards can be approximately ranked in terms of their potential impact as follows: 1) coastal erosion and inundation, 2) river flooding and channel change, 3) water-resource impacts (drought, desertification, and water quality), 4) erosion and soil loss (including mass wasting and wildfire hazards), and 5) cryosphere impacts (progressive thaw or melt in the cryopshere).

One challenge of forecasting Earth-surface responses to C&LUC is the fact that land surface processes depend sensitively on secondary drivers related to but distinct from the basic variables of C&LUC. Figure 1 illustrates how different Earth-surface process types relate to the primary C&LUC variables of temperature, precipitation, wind, and land use (including their mean values and their variability over a range of time scales). Secondary variables include runoff and infiltration (i.e. hydrology), land cover (including changes in the natural vegetation cover of landscapes and human disturbance, e.g. ecology and human geography), and the coastal-zone

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forcings of sea level, storm surge, and wave heights. While the effects of climate hazards such as heat waves or droughts involve fairly direct linkages with primary climate variables, forecasting Earth-surface processes and hazards requires the translation of primary forcing variables into secondary forcing variables before any forecasting can be done. The relationships among primary and secondary variables are, in some cases, clear. For example, warming of the polar regions and continued extraction of fluids from deltaic regions will drive relative sea-level rise in many regions. In other cases, the relationships are less clear. For example, how precipitation changes are likely to alter land cover in the future is complex and incompletely understood. As such, Figure 1 underscores the need for collaboration among specific geoscientific research communities, including among geomorphologists and hydrologist, ecologists, and the human geographers who forecast land-cover changes.

The types of Earth-surface processes and associated hazards that dominate landscape response to C&LUC vary regionally and globally (Fig. 2). Glacial/periglacial zones are defined in Figure 2 as those with mean annual temperatures less than 0°C as determined using the WorldClim database [*Hijmans et al.*, 2005]. Increasing temperatures in such regions are likely to drive land subsidence due to thawing permafrost, leading to a release of soil carbon that feeds back on the global climate system. Aeolian/arid areas are defined to be those with less than 200 mm a^{-1} of rainfall. Dust emission from such areas may increase in the future due to increased aridity and reduced vegetation cover. Fluvial areas are delineated by routing hypothetical extreme flows through the global 30-arc-second-resolution SRTM-derived DEM [*Farr et al.*, 2007] augmented with ASTER GDEMV2 data where SRTM data were unavailable. Such areas are likely to experience more frequent flooding in response to future increases in precipitation intensity. However, changes in sediment supply from hillslopes could cause valley floors to

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incise, thus decreasing flood risk in areas adjacent to valley floors. Coastal areas are considered to be areas within 10 m of sea level. Many of these areas will experience an increase in the frequency and magnitude of flooding and erosion, particularly in areas where land subsidence is occurring simultaneously with the rise in global mean sea level. Urban areas are mapped based on the Global Land Cover database [*Hansen et al.*, 1998]. As the population densities of these areas increase it is likely that peak flood discharges will be greater due to the lower infiltration rates of impervious surfaces relative to natural surfaces. Hillslope areas are those not included in any of the other process zones. On hillslopes in arid and semiarid regions, increased potential evapotranspiration and fuel loads will likely trigger larger and more severe wildfires resulting in increased rates of soil erosion.

The thresholds of mean annual temperature, rainfall, and elevation that define the boundaries between the process zones in Figure 2 are not unique. In presenting Figure 2, we are not suggesting that there is a unique global map of process dominance. Rather, we are proposing that there is value in mapping regional "hotspots" where landscapes are likely to be most sensitive to certain types of C&LUC. Such a map will be useful in focusing research in those hotspots. In some cases the hotspots of landscape response may occur at the boundaries between process domains. For example, it is reasonable to expect that land degradation (e.g. hillslope gullying, valley-floor incision) is most likely to occur in semiarid regions that transition to arid regions, rather than in areas that are already arid.

3. Opportunities for spatially explicit global-scale assessments of future changes in Earth's surface

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The ESS community has a long and successful tradition of investigation at scales from individual hillslope segments to the scale of whole watersheds. The ESM community, however, necessarily works at the global scale. One of the challenges of integrating process models and data from the ESS community into ESMs is the disparate scales at which most (though certainly not all) Earth-surface scientists and Earth-system modelers work. Earth-system modelers require data and process models that have global coverage and are globally applicable. Many Earth-surface scientists do not develop data or models with such global applicability in mind. In this section we argue for enhanced collaboration between the ESS and ESM communities.

Readily available data for future climates include near-surface temperature (and its daily and seasonal variability), precipitation (and its event-scale and seasonal variability), potential evapotranspiration, and near-surface wind speeds. Readily available data for future land-use changes include changes in the percent area (within 1°x1° pixels) that will likely transition among crop, pasture, urban, primary (actively disturbed), and secondary (previously disturbed but recovering) land-use types. In order to make forecasts of the Earth-surface response to C&LUC, the ESS community must further develop predictive Earth-surface response models so that they work with available input data for future C&LUC scenarios. At the same time, the ESS community needs to collaborate with Earth-system modelers and the climate and geography communities to provide the most appropriate and useful inputs for Earth-surface response models. For example, future vegetation states have been predicted, but these data usually predict vegetation type only. Few Earth-surface response models are designed to work with vegetation type. Instead, many existing models work with leaf-area index [e.g. *Pelletier*, 2012] or other quantitative measures of vegetation cover such as percent bare area. As such, the ESS community should collaborate more closely with Earth-system modelers and the climate and

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geography communities to ensure that data products are being produced that meet the needs of their models.

In this section we use riverine sediment flux (or yield, defined as flux in mass per unit time divided by drainage basin area) as an example of an Earth-surface process for which global-scale models exist that could be used in the near future to forecast changes in response to likely future C&LUC. Quantifying sediment yield in rivers has been a central topic in geomorphology for at least a century. Sediment yields influence biogeochemical processes in wetlands [*Reddy et al.*, 2000]. Most predictive models for global sediment yield focus on the suspended-load component of the total load, which is the dominant component of the total load for most large rivers. *Pelletier* [2012] developed a model that includes mean monthly precipitation, soil texture, and vegetation cover (quantified as leaf-area index (LAI)) explicitly (Fig. 3). Sediment yield in this model increases in direct proportion to average rainfall and decreases exponentially with increasing LAI.

It is straightforward to include the effects of agriculture in the *Pelletier* [2012] model, at least in a simplified way, as an example of how the land-use changes could be be explicitly included in current land-surface response models. Figure 3B illustrates the impact of modern agriculture on long-tem-average sediment yields, assuming that croplands are areas of bare undisturbed ground in the model framework of *Pelletier* [2012]. This is a simplified approach because croplands are bare only part of the time. Neglecting plant cover during the growing season likely leads to an overprediction of sediment yield, but this effect is somewhat counteracted by the fact that cropland soils are disturbed by tillage, thus reducing their shear strength relative to bare undisturbed surfaces. When agriculture is included in the model, the region of largest sediment yields in the U.S. shifts from the western U.S. to the eastern U.S. and

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the average sediment yield increases by a factor of approximately 30, consistent with the findings of *Wilkinson and McElroy* [2007].

The challenge of quantifying the geomorphic responses to land-use changes reflects uncertainty both in how sediment yield relates to land use and how land use should be quantified for input into models. Existing global gridded datasets for land use predict the locations and density of transitions between primary land and agricultural land, but it remains unclear how best to quantify the relationships between erodibility and land-use type. The effects of land-use changes have been incorporated into empirical models for hillslopes sediment yield such as the Universal Soil Loss Equation (USLE) [*Wischmeier and Smith*, 1978]. The effects of dams in storing sediments released from uplands have not been well quantified on a regional or global basis, but the effect is substantial. Despite the recent order-of-magnitude increase in soil erosion in the eastern U.S., the flux of sediment reaching the oceans is lower today that it has been in the past, indicating that large volumes of sediment are being stored within the fluvial system [e.g. *Walter and Merritts*, 2008; *Wisser* et al., 2013]. *Syvitski and Milliman* [2007] included anthropogenic effects on sediment yield with drainage-basin-specific coefficients that depended on population density and GNP per capita. Additional research is needed to identify how best land-use/land-cover data types can be used to quantify sediment yield.

4. Cross-cutting importance of nonlinearity, tipping points, alternate states and uncertainty propagation

Earth-surface systems are typically controlled by nonlinear and/or threshold-dominated responses to changes in external forcings [e.g. *Schumm*, 1979]. These nonlinearities imply that landscape responses to ongoing and likely future C&LUC will be both amplified and difficult to

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predict. Here we provide a discussion of the basic concepts of nonlinear dynamical system theory [*Strogatz*, 2001], which provides an essential framework for understanding Earth-surface response to likely future C&LUC.

Nonlinear systems respond at a variable rate to changes in external forcings. These responses can gradually amplify the forcing, and/or they can include thresholds or "tipping points" that mark abrupt changes in the forcing–response relationship. Nonlinear relationships between forcing and response lead to disproportional responses to possibly subtle changes in forcing (Fig. 4A), while feedbacks among processes governing system dynamics are often responsible for threshold responses to C&LUC (Fig. 4A), and for driving some systems into one of multiple alternative equilibrium states, with the associated potential for sudden landscape/ecosystem transitions from one state to another (Fig. 4B). Positive feedbacks have important implications for Earth surface science [e.g. *Murray et al.*, 2008] (producing, for example, drainage-network development [*Rinaldo et al.*, 1998], conversion of alpine glaciers into debris-covered rock glaciers [*Scherler et al.*, 2011], and river avulsions [*Slingerland and Smith*, 1998]), including these forms of rapid change and instability in the face of gradual shifts in C&LUC.

An example of gradual amplification of a forcing change is dust entrainment, which is a major player in Earth's energy balance (because dust is a radiatively important aerosol) and exerts a significance influence on human health. Dust entrainment scales approximately with the shear velocity exerted on the surface to the third power, and also depends nonlinearly on moisture/water-table depth [e.g. *Pelletier*, 2006]. Landsliding provides an example of a threshold-dominated behavior, in which slow soil creep can give way to catastrophic failure [*Ritter et al.*, 1999]. Bed-load sediment transport rates relate to turbulent bed shear stresses in a

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way that is both nonlinear and threshold-dominated [*Gomez and Church*, 1989]. These nonlinear responses make landscapes highly sensitive to C&LUC. In the southwestern U.S., for example, a transition from woodland to desert scrub species within elevation zones from approximately 800-1800 m a.s.l. caused an order-of-magnitude increase in sediment supply from watersheds during the Pleistocene-to-Holocene transition that triggered two downstream cycles of river and alluial-fan aggradation, incision, and renewed aggradation [*Pelletier*, 2014]. In recent decades, small increases in springtime temperatures have exponentially increased wildfire size and severity [*Westerling* et al., 2006], consistent with the measured correlation between modest warming and dramatically increased burn extent and severity in the western U.S. through the Holocene [*Pierce et al.*, 2004]. In many semi-arid areas of the western U.S., drought-stressed forests will not recover from vapor-pressure deficits that manifest in non-replacement following disturbances such as fire and insect infestations [*Williams et al.*, 2013]. This suggests that a vegetation-type conversion similar in scope to vegetation changes recorded at the Pleistocene/Holocene transition [*Whitlock and Bartlein*, 1997] may be ongoing now, with important consequences for flood probabilities and soil sustainability.

Recent studies of tidal-marsh dynamics highlight the importance of multiple stable states, and the associated potential for instability. For example, vegetation stabilizes tidal marshes by dissipating wave energy and producing and trapping sediment. However, once sea-level rise is sufficiently rapid enough to outpace this sediment production, marshes may be rapidly submerged and converted into sub-tidal platforms [*Marani et al.*, 2010]. In addition, recent modeling suggests that increasing storm frequency or sea-level-rise rate can shift barrier islands from a regime with a single stable state featuring high dunes and complex ecosystems, into a

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regime in which a wave-swept, low-topography state is an alternate possibility--or even into a regime in which the high-dune state is no longer possible.

ESMs predict an increase in hydrologic variability as a result of human-induced global warming [*IPCC*, 2007; 2013], which should lead to enhanced geomorphic change [*Lane*, 2013]. However, uncertainties in future landscape forcings obtained from climate models may translate into large uncertainties in forecasts of future Earth surface states due to nonlinear and possibly threshold-dominated geomorphic responses. Figure 5 illustrates the propagation of uncertainty from forcing forecasts to Earth-surface-system responses and finally to impacts on humans and infrastructure for two contrasting cases of linear and threshold responses, assuming Gaussian distributions of uncertainty (Fig. 5B). If the geomorphic response is threshold-dominated (Fig. 5A), the distribution of responses is partitioned into two very distinct sets of likely responses: both minor and major geomorphic responses may become plausible, thus increasing the degree of uncertainty of the forecast (Fig. 5D). The projected impact of the Earth-surface response (e.g., on ecosystems or infrastructure; Fig. 5C) must be combined with the probability distribution of plausible geomorphic responses to statistically characterize the risk (Fig. 5D). These schematic examples underscore how essential it is to understand the linear/non-linear nature of the processes at play in the Earth-surface system in order to determine, and correctly interpret, potential landscape responses to C&LUC.

5. Cross-cutting importance of vegetation dynamics in future landscape-change forecasts

Stable landscapes reflect complex feedbacks among surface processes, climate, and vegetation. Slope stability is enhanced through lateral reinforcement by roots [*Schwarz et al.*, 2010], which allows steepening of hillslope profiles and reduction of drainage density that, in

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turn, may increase the intensity of erosive events when the vegetation cover is disturbed [*Collins et al*., 2004]. Vegetation cover fundamentally influences geomorphic processes and landforms, e.g. through sediment-trapping potential, influences on surface hydrology, interaction of roots and soil cohesion/erodibility, and via rock weathering and soil production. For example, the stability of barrier islands depends on the ability of foredunes to develop in both height and extent [*Houser et al.*, 2008], which, in turn, depends on the distribution and density of dune-building vegetation [*Durán and Moore*, 2013]. Resiliency of an island, therefore, is dependent on the regrowth of vegetation through the re-emergence of buried plants, seed banks, and colonization from adjacent areas. Dune-building grasses can alter dune geomorphology within months, and different plant species build dunes of different shapes resulting in variable levels of exposure to coastal hazards posed by intense storms and sea level rise [*Seabloom et al.*, 2013]. The case of dune grasses also exemplifies the widely applicable point that we need to understand not just how vegetation affects physical processes, but also how vegetation responds to physical processes [e.g. *Murray et al.*, 2008].

Indirect influences of climatic changes and direct human modification of the landscape can alter vegetation cover, which can lead to a new landscape. The stability and morphology of coastal marshes as sea level rises depends on the ability of salt-marsh vegetation to promote sediment deposition and limit erosion [*Morris et al.*, 2002]. If growth of the marsh surface through organic and inorganic sediments is unable to keep pace with sea-level rise, there is the potential for the entire marsh surface to become unstable and irreversibly change to a tidal flat or sub-tidal platform [*Marani et al.*, 2007], with spatially-complex biogeomorphic responses [*D'Alpaos et al.*, 2007; *Kirwan and Murray*, 2007; *Marani et al.*, 2013].

More extreme modifications such as deforestation, alteration in vegetation type (e.g., in

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response to fire or drought-induced tree die-off), and introduction of exotic species can cause further geomorphic changes. For example, climate-driven increases in wildfire extent and severity since the mid 1980's have also increased burn areas exponentially [e.g. *Westerling et al.* 2006]. In areas of steep topography, this has resulted in large and often damaging debris flows [C*annon et al.,* 2010]. In central Idaho, fire-related erosional events increase sediment yield from channels and hillslopes by almost four orders of magnitude over background rates [*Meyer et al.,* 2001], and two orders of magnitude over average Holocene rates [*Kirchner et al.,* 2001; *Meyer and Pierce, 2*003].

Changes in vegetation can result from changes in sediment supply and water discharge at a distant location. For example, there has been a large loss of cottonwood trees downstream of dams because of a disconnection from the floodplain, caused by both channel incision (due to a lack of sediment supply from upstream) and lack of inundating flows (due to flow regulation) [e.g. *Polzin and Rood*, 2000; *Amlin and Rood*, 2002]. In addition to these changes, invasive species such as salt cedar have taken over in areas downstream of dams in part because of these changes in hydrology [*Friedman et al.*, 2005].

Changes in vegetation often trigger dramatic landscape responses by altering the forces both driving and resisting erosion. Changes in resisting forces effectively alter the thresholds between the stable states of landscapes, whereas changes in driving forces alter the ability of the system to overcome those thresholds. Reducing vegetation cover on hillslopes generally increases erosion by changing both the driving and resisting forces; runoff increases because interception, surface roughness, and water consumption are all reduced, while root cohesion which inhibits erosion is also reduced [e.g *Cerda and Doerr*, 2005]. Changes in vegetation type may directly alter root cohesion, surface roughness, and geomorphic process dominance (e.g.

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tree throw), while indirectly altering erosive processes such as bioturbation from local fauna dependent on the vegetation (e.g. ground squirrels). Reducing vegetation cover and associated transpiration and increased albedo and near-ground solar radiation can cause the local climate to become more arid [*Royer et al.*, 2010]. A reduction in transpiration could increase the vapor pressure deficit of the air, thereby exacerbating vegetative water stress and possibly further reducing vegetation cover through wildfire.

The importance of vegetation is quite evident in arid and semi-arid environments where it limits erosion by wind and water and feeds back to the local climate through evapotranspiration. The ability of vegetation to withstand periodic drought introduces resiliency to the landscape, while the expansion and contraction of vegetation in response to prolonged changes in climate enhance low-frequency variations in rainfall [*Wang and Eltahir*, 2000] and an alternation between different vegetation states (i.e. type and/or percent cover). Specifically, the loss of vegetation through prolonged drought further limits moisture availability through a loss in soil and an increase in the vapor pressure deficit, which increases the potential for degradation through both water and wind [*Middleton and Thomas*, 1997; *Breshears et al.*, 2003]. In low-gradient arid and semi-arid fluvial environments, plant mounds can lead to episodic water detention and striking patterns of vegetation banding [*Pelletier et al.*, 2012], demonstrating the bistability of ecohydrogeomorphic processes in arid and semi-arid regions. Whether by water or wind, erosion tends to lead to a loss of biodiversity and soil resources, and a decrease in water holding capacity, which, in turn, can limit primary productivity and carbon sequestration [*Chapin et al.*, 1997]. The continued loss of biodiversity may decrease system resiliency to periodic droughts, which may increase the potential for these systems to jump to an irreversible state of desertification.

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Despite the importance of vegetation, direct incorporation of vegetation into geomorphic models is relatively limited. This is partly a result of the complex feedback processes among vegetation (both individual plants and communities), soil strength, fluid hydraulics, hydrology, and sediment transport. For example, in fluvial systems, vegetation is often indirectly modeled using high drag coefficients but such simplifications do not account for the impact of vegetation on flow turbulence [*Nepf*, 1999] and associated spatial changes in suspended sediment [*Zong and Nepf*, 2011] and bed-load transport [*Yager and Schmeeckle*, 2013]. The divergence in sediment transport caused by vegetation could then lead to local scour and deposition [*Temmerman et al.*, 2007] that influence subsequent stem-scale survival [*Yager and Schmeeckle*, 2013] or vegetation-patch growth [*Meire et al.*, 2014]. A better predictive understanding of these couplings – in the contexts of both air and water flows – and the importance of vegetation characteristics (e.g. species, density by area, root strength) is needed to determine how future changes in vegetation will influence geomorphic processes. Predicting vegetation dynamics is also challenging because important information on basic ecological processes such as plant mortality and its response to climate change are complex and remain highly uncertain [*McDowell et al.* 2011]. Vegetation effects on geomorphic responses can require not only predicting vegetation succession but also responses to disturbances such as drought and wildfire [*Breshears et al.,* 2012].

6. Cross-cutting importance of long time scales and natural experiments in the geologic record

The ESS community utilizes the geologic record as well as natural experiments of landscape dynamics that span a range of time scales from individual events (e.g. floods or wind storms) to the time scales involved in mountain building. Pertinent to understanding the effects

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of ongoing and future climatic changes are datasets ranging from the glacial-interglacial changes of the Quaternary epoch, to the millennial- and centennial-scale changes affecting Earth systems during the Holocene, to historic and ongoing natural experiments that we can monitor and study as they happen. All of these types of natural experiments have a primary role/purpose in testing conceptual and numerical models, providing essential grounding for any future forecasts.

The geologic record provides our essential understanding of past climate variability (paleoclimatology), placing the pace and magnitude of modern climatic change in context. It also provides case studies of landscape response to change and has the potential to test surface-process models projecting future changes. This potential for model testing seems underdeveloped at this time, perhaps because it is only recently that multiple high-resolution geochronologic and isotopic tools have revolutionized our capabilities to study these natural archives. Now we are better able to reconstruct past change, and more fundamentally, to better address the issue of what incomplete stratigraphic archives actually record in terms of process.

Often the largest changes evident in landscapes occurred in response to the glacial-interglacial oscillations of the Quaternary. For example, by reconstructing the timing and extent of former glacial advances on the ground, we have been able to model both precipitation and temperature changes through time through the glacial-interglacial transitions. Stream-terrace records are, in places, approaching a level of understanding that makes them useful for testing of landscape-evolution models [e.g. *Hancock and Anderson*, 2002; *Wegmann and Pazzaglia*, 2002; *Pelletier et al.*, 2011]. Yet, there is a critical need for well-constrained geologic records that link hillslopes to drainages through these large-scale changes to complete our picture of landscape response [e.g. *Harvey*, 2002; *Anders et al.*, 2005; *Enzel et al.*, 2012; *Pelletier*, 2014].

Some landscapes have been sensitive to the more moderate and recent climatic changes

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over the Holocene, at millennial to decadal timescales--thus recording responses to changes of the same magnitude as forecast over the upcoming century. These records caution us about the less-predictable influence of catastrophic events such as high-magnitude storms and floods, which may define or reset much of the geologic record itself. Examples are alluvial records of flood magnitude/frequency and changes in sediment supply [e.g. *Macklin and Lewin*, 2008; *Harvey and Pederson*, 2011] and landsliding [*Korup et al.*, 2012].

Natural and artificial experiments remain the mainstay of understanding the response of landscape processes to climatic changes. Because large-scale experiments on geological time scales are not possible, much of our understanding of process response to climatic forcing is based on natural experiments. Natural experiments usually rely on a particularly well-expressed geomorphic process, or a particularly well-documented part of the geologic record. They allow us to isolate the effects of physical climate variables such as temperature or precipitation rate [e.g., *Abbühl et al.*, 2011; *Menking et al.*, 2013; *Ferrier et al.*, 2013] on specific geomorphic processes.

Finally, landscape-evolution models can bridge the gap between process understanding and the geologic record. These models integrate physical understanding from natural and controlled laboratory and field experiments. A common modeling goal is to simulate how various processes interact to produce a realistic synthetic landscape (i.e., one that compares well, at least statistically, to the modern landscape and the evidence from the geologic record) [*Dietrich et al.*, 2003]. Calibrating models based on landscapes produced by an integrated history of climate change over geologic timescales runs the risk of generating false confidence in the predictive power of such models, because incomplete geological records of landscape change do not allow strong assessment of equifinality in model results [e.g., *Brazier et al.*, 2000; *Beven*,

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1996]. Continual refinement of these models based on independent understanding of individual processes is required to rigorously evaluate the model outcomes and any predictions they make [*Dietrich et al.*, 2003]. The natural experiment that is anthropogenic C&LUC, and the associated rapid, measureable response of sensitive landscapes, provides an important opportunity for landscape modelers: models of landscape processes can be used to make predictions of change that will manifest on ~5-10 year timescales, and the models can be continually refined based on real-time monitoring of these processes (i.e., data assimilation) in order to improve their predictive power [*Paola et al.*, 2006].

Data are needed by numerical models to both 1) develop or improve empirically based parameterization and parameter values, and 2) test diagnostic model predictions. Although the types of data needed are specific to each model context, existing data are often not complete or otherwise optimal for these two sorts of needs. More communication and collaboration between researchers developing models and those with observational expertize is needed, so that resources that go into collecting data can be better directed toward collecting the types of data that will allow modeling capabilities to advance more rapidly.

7. Adaptation strategies

Recognizing that changes in the state of Earth's surface are an inevitable and ongoing part of Earth's dynamics, society is developing strategies for adapting to these changes. Investigations of the geomorphic processes governing landscape response to C&LUC at a variety of spatial and temporal scales are essential precursors for developing appropriate adaptation and mitigation strategies for hazards associated with Earth-surface processes. Geomorphic studies can provide guidance for direct site-specific human modification of Earth-surface systems (e.g.

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environmental restoration, hazard mitigation) and the development of realistic policy alternatives for future landscape and climate states. Such efforts require close collaboration between the scientific community and stakeholders (government agencies at all levels; communities, land owners etc.) to ensure that the best available scientific knowledge is used appropriately. In some cases, knowledge gaps may need to be filled by targeted investigations (e.g. determining dust emission potentials from disturbed and undisturbed surfaces [e.g. *Macpherson et al*., 2008]). Some examples of successful adaptation strategies include:

- An improved understanding of how fluvial systems have evolved in the northeast U.S. in response to widespread human manipulation has informed stream restoration projects in Pennsylvania. The result is that such restoration efforts now provide increased ecosystem services compared to previous practices (see text S2 for details).
- Models of the response of coastal sediment transport to human manipulations have shown that shoreline stabilization in one location affects distant coastal communities as well as neighboring ones, especially as climate forcing changes; this insight provides a framework for more coordinated holistic management of coastlines (as opposed to the ad hoc approach prevalent currently)—with the goal of increasing the net benefits to the stakeholders involved (see text S5 for details).
- Coastal areas in the U.S. are beginning to incorporate adaptation to climate change impacts into their community planning. One significant example of this is the 2012 Louisiana Coastal Master Plan, available at http://coastal.la.gov/a-common-vision/2012-coastal-master-plan/. This effort involves an assessment of future system states if no new action is taken along with portfolios of policy scenarios or management solutions to guide systems toward alternate states. Such an effort incorporates a mix of coupled

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geomorphic/ecological/hydrodynamic models along with socio-economic data and models to guide policy choices that will reduce coastal change and flood risk for coastal communities.

8. Next steps

To improve our ability to forecast changes in the state of Earth's surface in response to future C&LUC, we recommend several steps. These can be divided into steps that the ESS community can take working largely within its community, and work that requires collaboration with other research communities.

Steps that the ESS community can take largely independently include:

- Develop additional process models that couple process zones that have traditionally been considered separately,
- Develop additional datasets that can be used to test numerical models (particularly over decadal to century time scales),
- Develop forecast models that can use existing data, and
- Extend models developed based on one location to other locations by testing those models against data for areas having different characteristics and then updating the models so that they apply more broadly.

Tasks that require collaboration with other research communities include:

- Develop improved input datasets and component models for Earth surface processes in ESMs,
- Focus on the development of datasets for testing models (particularly over decadal to century time scales).

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Landscape responses to C&LUC often involve critical linkages between disparate processes in different process zones. For example, the maintenance of tidal wetland and delta landscapes depends in part on hillslope and fluvial processes that may be thousands of kilometers away. Events that occur in watersheds, such as land-use change, or widespread vegetation change related to climate shifts, can drastically alter the rate sediment is delivered to the fluvial system, and transported to coastal environments. Because of these linkages, we need to couple together models of processes in different environments to be able to address many key questions regarding our planet's future. The Community Surface Dynamics Modeling System (CSDMS) exists to facilitate such model coupling. More broadly, the ESS community should more fully engage with Earth system modelers to develop ESMs that incorporate the state-of-the-art models identified in the supplement.

Acknowledgements

We wish to thank the NSF Geomorphology and Land-Use Dynamics program and its manager Paul Cutler for supporting this effort intellectually and financially through award #1250358. We also thank the many members of the broader Working Group on Predicting Landscape Response to Climatic and Land-Use Changes that commented on drafts of the manuscript at http://geomorphicprediction.geo.arizona.edu/. Data used to make any of the figures can be obtained upon request from J.D.P.

Figure 1. Conceptual diagram illustrating the linkages among the primary C&LUC forcing variables, secondary forcing variables (i.e. those that depend on the primary forcing variables but involve additional ecohydrologic and/or anthropogenic processes), and the main types of Earth

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surface processes and their associated hazards. The numbers indicate dependencies. For example, the secondary forcings of sea level, storm surge, and wave height (#7) depend on global temperature changes (#1, e.g. melting polar ice), wind speeds (#3, e.g. stronger winds lead to greater storm surges and wave heights), land use (#4, e.g. fluid extraction from deltaic sediments can drive sunsidence that contributes to relative sea level rise), and land cover (#6, e.g. changes in vegetation cover that can modify storm surges, dune mobility, etc.).

Figure 2. Map of dominant surface process zones, along with examples of the hazards and potential changes in hazards under future C&LUC scenarios. See text for a description of the criteria used to define each zone.

Figure 3. (A) Color map of the natural/pre-dam sediment yield as quantified by the model of *Pelletier* [2012]. (B) Sediment yield with agricultural effects included.

Figure 4. Schematic diagram illustrating the linear and nonlinear responses of an Earth-surface system to changes in forcing. (A) Land-surface systems in the presence of a positive feedback can present several competing states. (B) Illustrates the case of a system with two possible stable states. Shifts can occur because of short-term variability in the forcing (weather) overcoming the energy barrier separating the two co-existing states or because long-term changes in the forcing (climate) change the shape of the potential defining the available stable states, making one of the states disappear and leading the system to occupy the surviving lower-energy stable state.

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Figure 5. Schematic diagram illustrating the propagation of uncertainty from models of C&LUC to Earth-surface-system responses and societal impacts for nonlinear and/or threshold-dominated systems. Gaussians distribution of uncertainty in ESM-generated forcing of Earth-surface processes (shown in B) propagate to give very different probability distributions of responses and impacts depending on the degree of nonlinearity of Earth surface processes. If the response is thresholded (shown in A), the probability distribution of the response is partitioned into two very distinct and widely different ranges of possible states (shown in D). The possible impacts, computed through a conventional impact function (C), are similarly distributed around two distinct possible impact ranges (shown in D).

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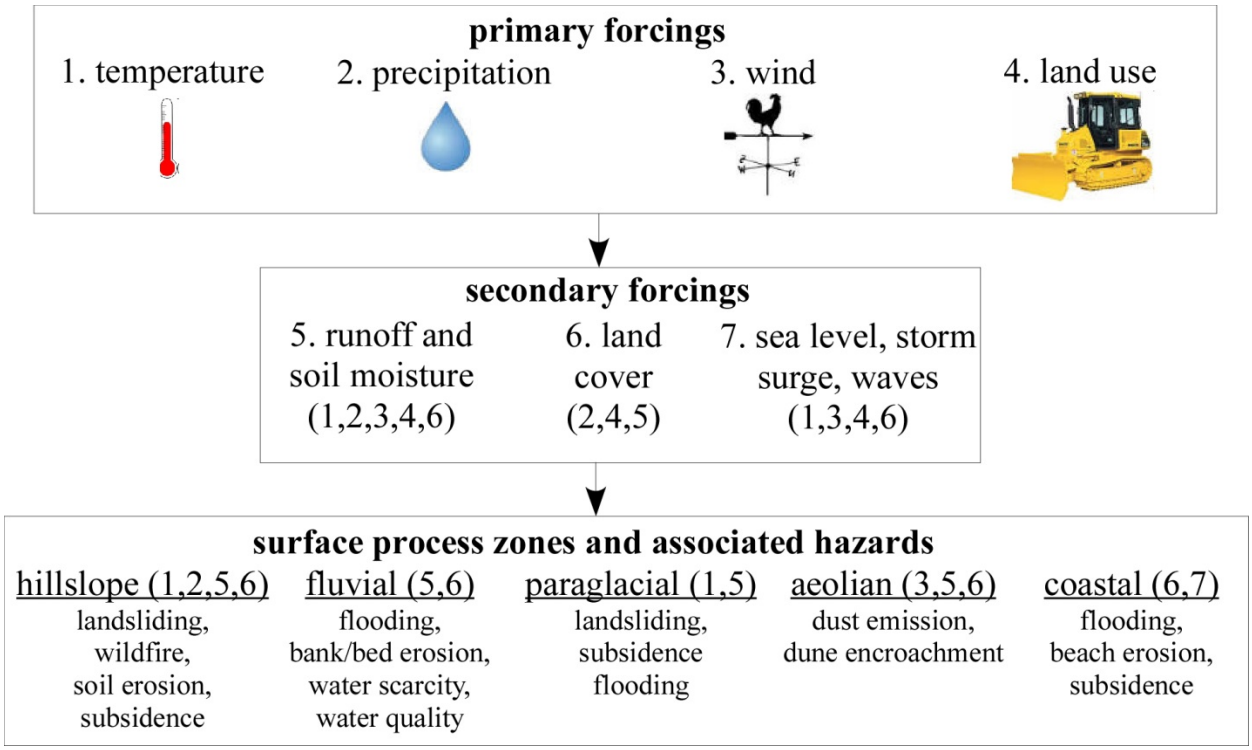

Figure 1. A conceptual diagram illustrating the linkages among the primary C&LUC forcing variables, secondary forcing variables (i.e. those that depend on the primary forcing variables but involve additional ecohydrologic and/or anthropogenic processes), and the main types of Earth surface processes and their associated hazards. The numbers indicate dependencies. For example, the secondary forcings of sea level, storm surge, and wave height (#7) depend on global temperature changes (#1, e.g. melting polar ice), wind speeds (#3, e.g. stronger winds lead to greater storm surges and wave heights), land use (#4, e.g. fluid extraction from deltaic sediments can drive sunsidence that contributes to relative sea level rise), and land cover (#6, e.g. changes in vegetation cover that can modify storm surges, dune mobility, etc.).

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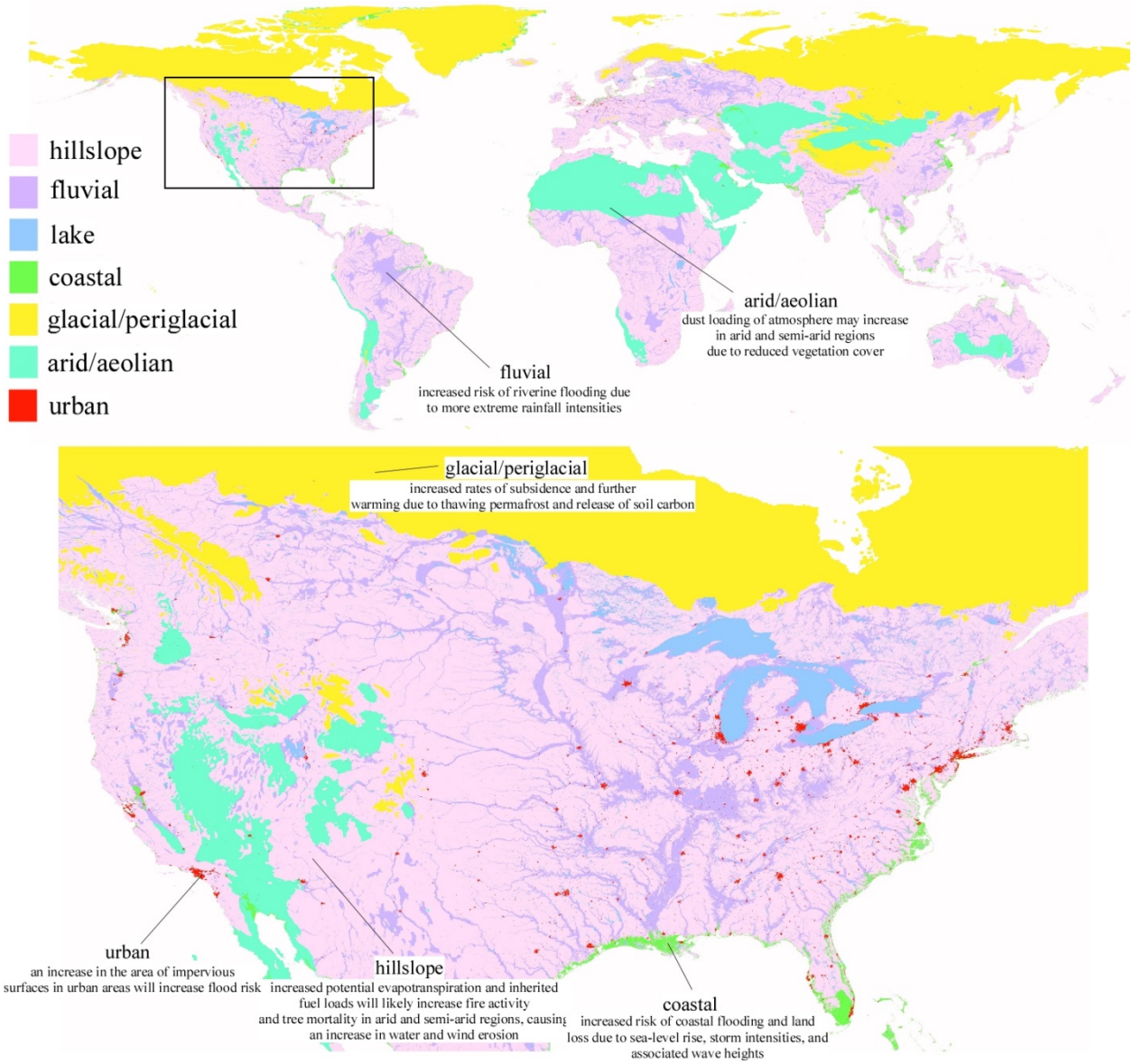

Figure 2. Map of dominant surface process zones, along with examples of the hazards and potential changes in hazards under future C&LUC scenarios. See text for a description of the criteria used to define each zone.

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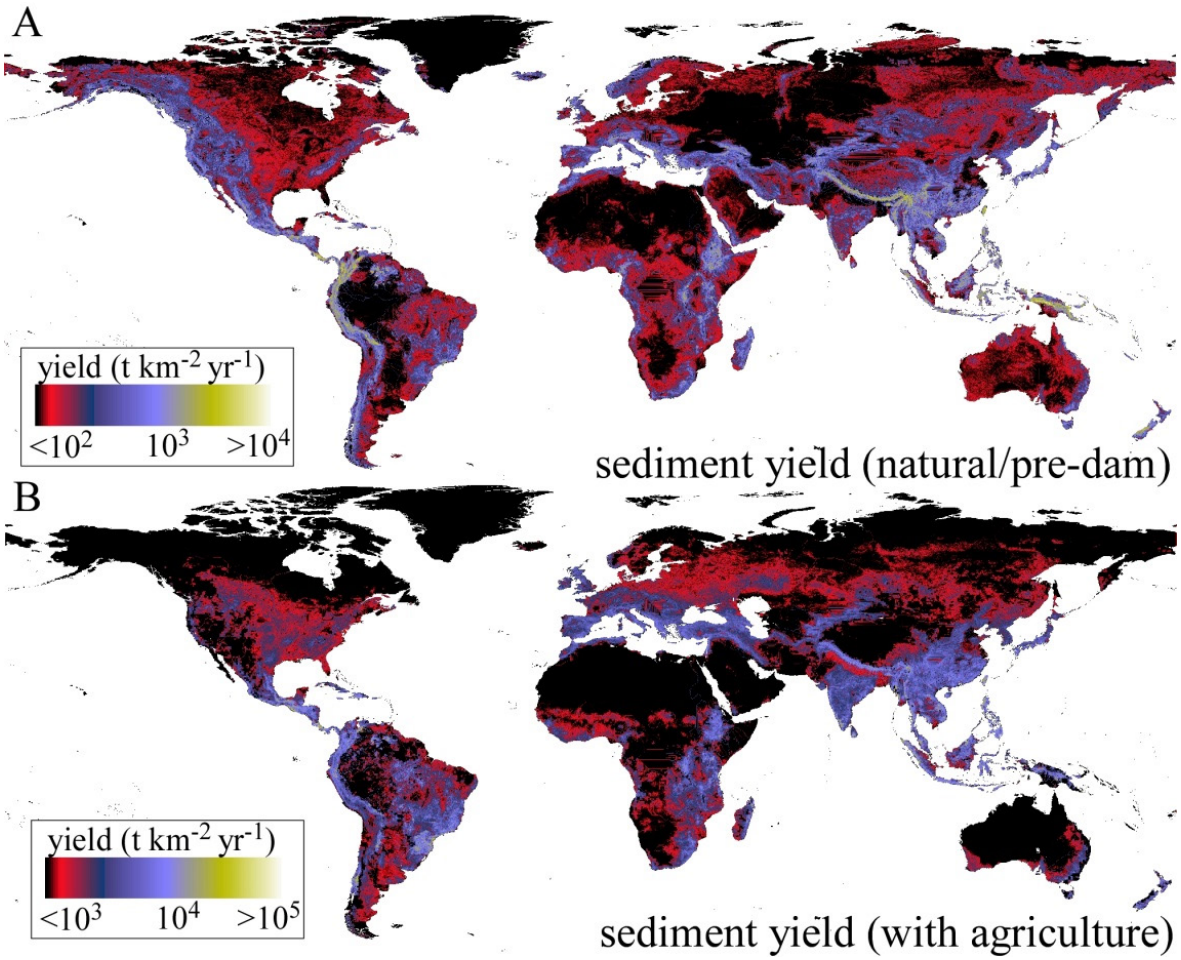

Figure 3. (A) Color map of the natural/pre-dam sediment yield as quantified by the model of *Pelletier* [2012]. (B) Sediment yield with agricultural effects included.

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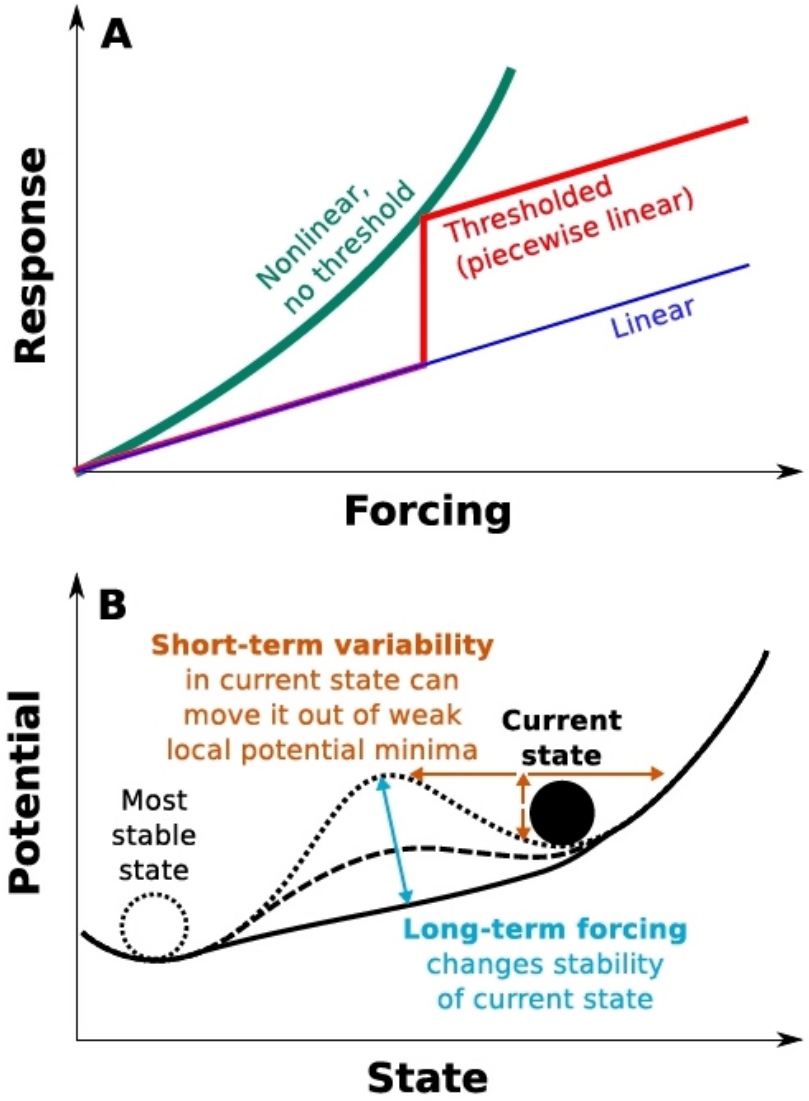

Figure 4. Schematic diagram illustrating the linear and nonlinear responses of an Earth-surface system to changes in forcing. (A) Land-surface systems in the presence of a positive feedback can present several competing states. (B) Illustrates the case of a system with two possible stable states. Shifts can occur because of short-term variability in the forcing (weather) overcoming the energy barrier separating the two co-existing states or because long-term changes in the forcing (climate) change the shape of the potential defining the available stable states, making one of the states disappear and leading the system to occupy the surviving lower-energy stable state.

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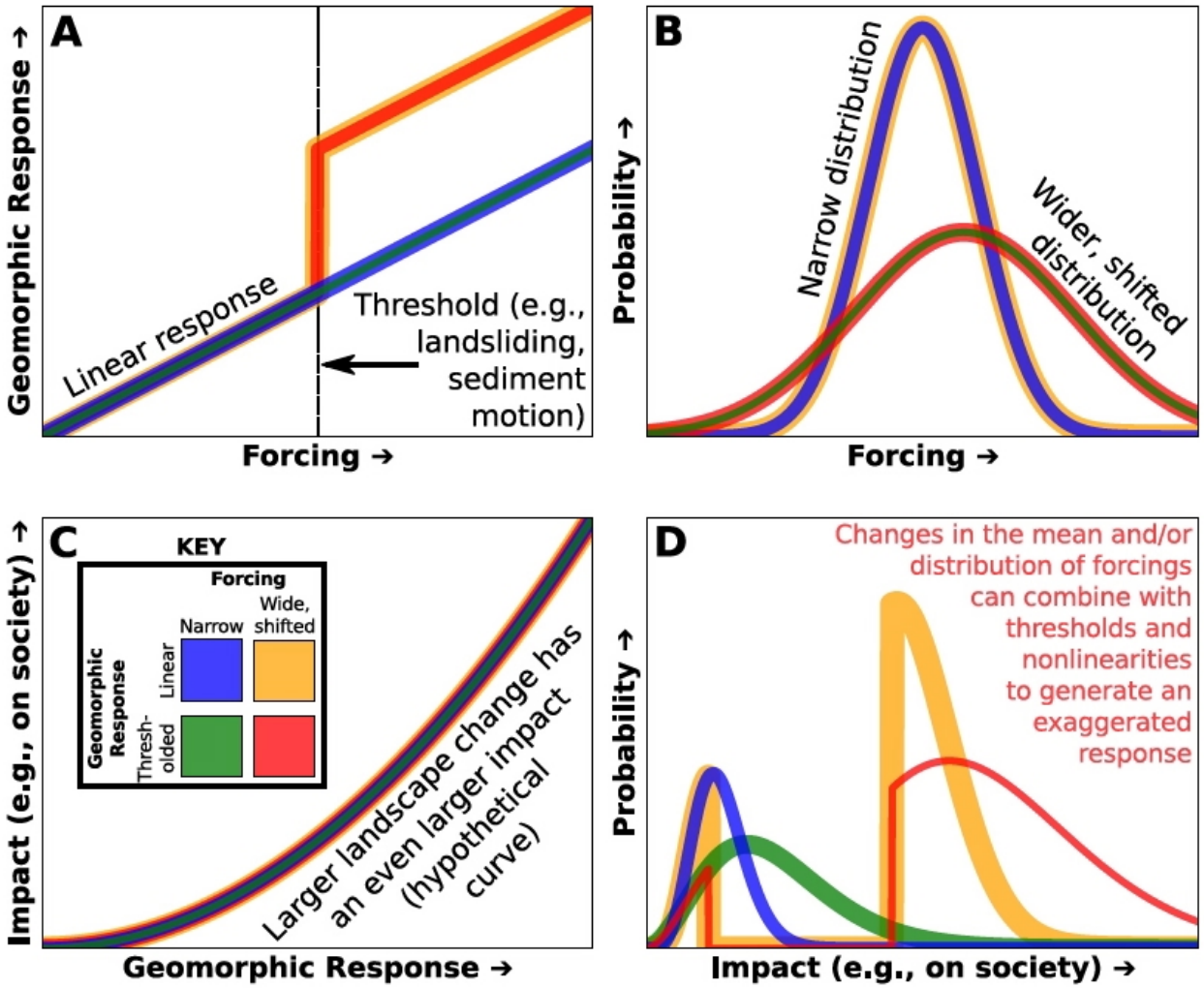

Figure 5. Schematic diagram illustrating the propagation of uncertainty from models of C&LUC to Earth-surface-system responses and societal impacts for nonlinear and/or threshold-dominated systems. Gaussians distribution of uncertainty in ESM-generated forcing of Earth-surface processes (shown in B) propagate to give very different probability distributions of responses and impacts depending on the degree of nonlinearity of Earth surface processes. If the response is thresholded (shown in A), the probability distribution of the response is partitioned into two very distinct and widely different ranges of possible states (shown in D). The possible impacts, computed through a conventional impact function (C), are similarly distributed around two distinct possible impact ranges (shown in D).

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