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# GEOMORPHOLOGY AND EARTH SYSTEM SCIENCE

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**Abstract**

Earth system science is an approach to obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time-scales. The aim of this review is to introduce some key examples showing the role of earth surface processes, the traditional subject of geomorphology, within the interacting Earth system. The paper considers three examples of environmental systems in which geomorphology plays a key role: (i) links between topography, tectonics, and atmospheric circulation; (ii) links between geomorphic processes and biogeochemical cycles; and (iii) links between biological processes and the earth's surface. Key research needs are discussed, including the requirement for better opportunities for interdisciplinary collaboration, clearer mathematical frameworks for earth system models, and more sophisticated interaction between natural and social scientists.

## 1. Introduction

On May 12th 2009, the United States National Aeronautical and Space Adminstration (NASA) issued a press release which began as follows: "Twenty years ago NASA embarked on a revolutionary new mission for its Earth science program: to study our home planet from space as an inter-related whole, rather than as individual parts." (NASA, 2009). Few would doubt the revolutionary impact of this "mission", and of the concomitant allocation of the US national science budget to Earth Sciences. As NASA themselves went on to claim that their: "…vision laid the groundwork for advances in global climate change and understanding natural and human-induced changes in the land surface, atmosphere, oceans, biosphere and Earth's interior that affect all aspects of life."

The emergence of Earth Systems Science is therefore closely linked with the development of space-borne sensors for monitoring the Earth System at global and regional scales. Since it is information from the earth's surface which the satellite sensors receive, the role of geomorphology in Earth Systems Science had the potential to be huge, both as the object of direct investigation, and as a surrogate for processes that operate in the zone where the biosphere, hydrosphere, atmosphere and lithosphere interact. Another key technical advance, which was to provide a crucial dataset showing the link between the biosphere and the atmosphere, was provided by Keeling's (1960) installation of infra-red gas analysers at locations in Antarctica, Hawaii, and California. Prior to Keeling's observations, it was believed that fluctuations in atmospheric carbon dioxide contained no systematic trend. By carefully isolating the influence of volcanic emissions and locally-emitted $CO_2$, Keeling (1960) revealed two key aspects of the coupled atmosphere-biosphere. The most celebrated finding was a secular increase in carbon dioxide concentrations which is attributed to a combination of fossil fuel combustion and changes in land-use (Keeling, 1960), and which has been monitored continually at many locations over the 50 years since. The second of Keeling's findings concerned the natural seasonal cycle of atmospheric $CO_2$ concentration, in which higher rates of plant photosynthesis during the boreal summer lead to a relative decrease in globally-averaged concentration of atmospheric $CO_2$ during this period. Taken together, these findings were among the first to combine precise measurements of earth system properties, with the concept of meaningful interactions between the biosphere and the atmosphere. These links occur through variations in earth surface properties, placing geomorphology in a key position to contribute to the wider debate. The aims of the present review are therefore to describe some of the contributions that Earth System Science has made to geomorphology, to evaluate some of the contributions that geomorphology has made to Earth System Science, and to suggest some key areas of Earth System Science to which geomorphology can contribute in the future.

## 2. What is Earth System Science?

The first widely-cited use of the term Earth System Science is in a report written for NASA in 1988 by Francis Bretherton, entitled *Earth System Science: A Closer View*. This report set out a goal for Earth System Science: "to obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all timescales." (Bretherton, 1988, p. 11). Moreover, the report recognizes a new challenge to: "develop the capability to predict those changes that will occur in the next decade to century, both naturally and in response to human activity" (p. 11).

Whilst acknowledging that "Global connections among the Earth's components began to be recognizes in the last [i.e., 19th] century" (p.25), and pointing specifically to the contributions of Hutton, Lyell and Darwin, Bretherton's (1988) report passes only briefly over the intellectual history of Earth Systems Science insofar as it is connected to (physical) geography. As Richards and Clifford (2008) point out, it is: "in NASA's interests to promulgate a totalizing view of ESS, since its mission is Earth Observation" (p. 1325). Bretherton's proposed methodology is that: "By examining our present knowledge of [these] processes and phenomena we can identify what are probably the most significant interactions among them, quantify that understanding in terms of explicit models, and devise observations and experiments that test many of the important conclusions." (p. 26).

Since the publication of NASA's manifesto, several other groups have discussed the relevance of Earth System Science and the integration of geomorphology within its remit (Church, 1998; NERC, 2007). Paola *et al.* (2006) positioned their vision of a “predictive science of Earth surface dynamics” in the context of a series of integrating challenges (p.1), noting that pursuit of these aims required collaboration between hydrologists, geomorphologists, ocean and atmospheric scientists, sedimentary and structural geologists, geochemists, and ecologists. They call for: “…the scientific community to work together towards this grand goal [to develop] a unified surface process science that would integrate insight from all of the above fields to provide a comprehensive and predictive understanding of the dynamics of our planet’s surface” (p.1). Whilst this viewpoint is grand, integrative, and inspirational, it finds a counterpoint in the notion that the *general* answers that science can provide are inextricably linked to the *particular* questions that different human societies and communities wish to pose (see Richards and Clifford, 2008, for a closer look at the problem through this lens).  The role of humans has always been central to Earth System Science: for Bretherton (1988), the activities of humans were supposed to be incorporated into predictions using “scenarios” based on plausible trajectories of social behaviour. A clear example of the use of scenarios to represent possible human behaviour is in the set of $CO_2$ emission scenarios published in the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (IPCC, 2001). Nevertheless, as Liverman and Roman-Cuesta (2008, p. 1458) explain: “for interactions between the social and earth to succeed, a certain level of tolerance and mutual understanding will be needed so that the social scientists understand the earth science aspiration for quantitative socioeconomic scenarios and predictions, and earth scientists understand the variation in how social scientists explain human behaviour and institutions and accept the clear limits to predicting human activities and decisions”.

The approach of the present review will be first to quantify the growth of Earth System Science as a motivator of research grant funding and in publication trends. Second, I shall consider three sets of key geomorphological studies, which contribute to the aims of Earth System Science, and which themselves are informed by a deeper understanding of the importance of interactions in the Earth System.

## 3. Research trends

Funding and publication trends can be assessed using publicly-available metrics, such as those released by funding bodies and records of citations such as the Science Citation Index (SCI). Clearly, these sources are not infallible: much good research is done outside the auspices of mainstream funding; and the Science Citation Index captures work published in a finite range of journals, potentially missing many pieces of work published in other forms such as research reports and books. Nevertheless, these sources of information provide a suitable indicator of research trends. For example, over the past eight years, funding from the UK Natural Environment Research Council (NERC) for Earth System Science has increased from under £1m to over £6m (Figure 1). Indeed, Earth System Science now features as a distinct ‘theme’ within NERC’s funding strategy. This funding has been directed to a number of high-profile collaborative and interdisciplinary projects, including QUEST (Quantifying the Earth System), SOLAS (Surface Ocean Lower Atmosphere Study), and IODP (Integrated Ocean Drilling Programme). Of course, it is possible that increase results from a recognition by applicants that Earth System Science is a promising field of enquiry rather than through an organic evolution of interest in the topic. As Figure 2 illustrates, over half of the money allocated to Earth System Science was spent in Geography and Earth Science departments. A 20 percent share of the overall spend occurred in departments where these two disciplines had been amalgamated. A further 26 percent of the total was spent in ‘traditional’ science departments (physics and maths, chemistry, biology), and the balance of 18 percent was allocated to directly-funded Research Council facilities such as the British Antarctic Survey, British Geological Survey, National Oceanography Centre, and Centre for Ecology and Hydrology.

The number of publications containing the term “Earth System Science” in the topic field has increased from under 50 in 1988 to over 400 in 2004 (Figure 3), although there is considerable inter-annual variability (and a problematic hiatus in 2002–3). The top five disciplines contributing to the growth in popularity of the term “Earth System Science” in the literature are: engineering, geology, physics, environmental sciences and ecology, and geochemistry and geophysics. Geography (as a search term) ranks 21st in the list of Earth System Science disciplines, producing less than two percent of the total publication output. Given the strong emphasis placed by geographers on interactions between human and physical components of the Earth System, there is a clear opportunity here. Of course, there is no separate record of publications from *physical* geography and much of the work produced by the latter sub-discipline will undoubtedly have been recorded in one of the other five preceding categories.

## 4. Geomorphology in the Earth System

The increase in research funding and publications relating to Earth System Science has led to a partial re-orientation of research questions. Instead of pursuing finer and finer detail in simulations of environmental systems, there is a recognition that coarser-scale models with reduced complexity can contribute to collective understanding of interactions between components of environmental systems. Richards and Clifford (2008) provide a stimulating philosophical and sociological discussion of this trend; my aim here is to pick out several key strands of the debate using three examples of environmental systems in which geomorphology plays a key role: (i) the links between topography, global tectonics and atmospheric circulation; (ii) the link between geomorphic processes and biogeochemical cycles; and (iii) links between biological processes and the earth’s surface.

### *4.1 Tectonic uplift and Cenozoic climate change*

The role of earth-surface processes in interactions between the lithosphere, atmosphere and hydrosphere has received renewed interest on a global scale over the past twenty years. Erosion controls the topographic evolution of active mountain belts (Koons, 1989; Beaumont *et al.*, 1992; Willett, 1999) and is the main source of sediment delivered to the sea (Milliman and Syvitski, 1992). Climate-driven erosion removes surface material, which modifies the topographic expression of tectonic processes and alters the state of stress in the lithosphere (Molnar and England, 1990; Willett, 1999). In turn, construction of mountain belts modifies global and regional atmospheric circulation patterns and composition (Kutzbach *et al*., 1989) because atmospheric carbon dioxide is consumed by rapid weathering of fresh silicate crust exposed in active orogens (Raymo *et al*., 1992), and particulate organic carbon is buried in nearby sedimentary basins (Lyons *et al*., 2002; Hilton *et al*., 2008).

In the context of Earth System Science, which is concerned with interactions between processes across different time- and space-scales, erosion provides a two-way link between tectonics and climate. This link is especially effective in active, compressional orogens which deliver most clastic sediment and a significant component of the chemical and organic discharges to the ocean, and it is to these settings that much attention has been directed (Milliman and Syvitski, 1992; Gaillardet *et al*., 1999). The links between erosion, climate, and tectonics vary across time-scales, from enhanced erosion associated with individual earthquakes, to feedbacks between orographic precipitation and the growth of mountain topography. Thus observations of erosion rates across multiple time-scales provide essential information on the links between climate, tectonics, and topography. Mountain erosion rates have been successfully quantified in localized areas (e.g., Burbank *et al*., 1996; Burbank *et al.*, 2003; Dadson *et al*., 2003; Reiners *et al.*, 2003; Wobus et al., 2003), and attempts have been made to predict long-term erosion rates from present-day relief and precipitation (e.g., Finlayson *et al*., 2002).

The feedbacks between focused climate-driven erosion and the tectonic evolution of entire mountain belts are most clearly shown in geodynamic models of orogenic evolution. These models range in complexity from simple analytical models of critical wedge topography (Davis *et al*., 1983) to more complicated numerical simulations of the links between tectonic and erosional processes (Willett, 1999). Critical wedge models treat the crust as a plastic frictional material in front of a moving backstop. The material deforms so that it attains the minimum taper angle at which it can slide on its base. The slope of the wedge reflects a balance between gravitational stresses arising from the surface topography and basal shear stresses resulting from stronger material underthrust beneath. The wedge grows by continued accretion, whilst its shape remains the same. The balance between the tectonic mass flux and erosional mass flux determines the rate of orogen growth. If tectonic input and erosional output are equal, the orogen is in a flux steady state and its size and deformation fronts will not change (Willett and Brandon, 2002). If the tectonic input exceeds erosional output, the orogen will grow through outward propagation of its deformation fronts. If the erosional output exceeds the tectonic input, the zone of active deformation will reduce in size, and previous deformation fronts will become inactive. It is important to note that spatial variations in erosion rate will lead to locally varying deformation and rock uplift. If erosion is focused in areas of high precipitation, the crustal deformation field will adjust to maintain the critical taper. This mechanism can produce local zones in mountain belts through which rock mass is advected and eroded (Willett, 1999; Beaumont *et al*., 2001).

Willett (1999) investigated the coupled system of uplift and erosion using a finite element, plane strain model of deformation with a stream power erosion model of bedrock incision. The numerical model showed that if erosion rates are low, crustal thickening continues until the lower crust is sufficiently warm that it flows laterally. This flow prevents further thickening, promotes outward propagation of the deformation fronts, and leads to the formation of a high elevation plateau. An example of such a plateau is the Altiplano in the central Andes, the location of which coincides with low precipitation rates (and therefore presumably low erosion rates; Willett, 1999; Montgomery *et al.*, 2001). Willett (1999) showed that adding erosion to his model led the topography to attain a steady-state in which elevation was constant over time. Fundamental results of this model included asymmetric topography with shallower slopes facing the subducting plate, and an asymmetric pattern of exhumation with the deepest levels opposite to subduction (Figure 5). In subsequent numerical simulations, Willett (1999) added asymmetrically-varying precipitation across the mountain belt, to represent orographically-enhanced precipitation in response to a dominant regional wind direction. This addition modified the first-order orogenic features. With the dominant wind and moisture flux in the direction of subduction, a broad zone of exhumation was predicted, with maximum exhumation in the orogen interior. This case is similar to the situation in the Olympic Mountains of Washington State, USA, where metamorphic index minerals and fission-track thermochronometry have shown a broad, bull's-eye pattern of exhumation, which is deepest in the area well behind the leading edge. In the contrasting case, with a dominant wind in the opposite direction to subduction, the model predicted a focused zone of exhumation at the margin of the orogen.

The results from coupled geomorphic and geodynamic models suggest that climate-driven erosion is of first-order geophysical significance in the evolution of mountain belts across a range of time-scales. However, the recent advances in modelling have outpaced the analysis of relevant field observations, with the result that most models are underconstrained. The links between erosion, tectonics, and climate are complex and understanding them requires detailed quantitative observations of erosion, and better constraints on the rates of climatic and tectonic process that drive erosion across a range of time-scales. Important questions that must be addressed are: what processes drive, and limit, the rate at which crustal material is removed from mountain belts? Do erosion rates inferred from topography match measured erosion rates? Are the dominant processes that drive erosion consistent across time-scales ranging from decades to millions of years? How do climate-driven erosional and tectonic processes interact to create topography on the scales of individual faults and entire landscapes? Many of these questions have been investigated using surface process models, but real world patterns are not well known and further progress requires quantitative observations of mountain erosion across a range of time-scales.

A controversial feedback was proposed by Molnar and England (1990), who claimed that in the late Tertiary and Quaternary the global shift to a cooler and more erosive climate has enhanced topographic relief in mountain ranges. They argued that the isostatic response to increased erosion of valley floors would raise mountain peaks higher. Moreover, higher peaks would accumulate more snow, which would promote rapid glacial weathering and erosion. In turn, rapid silicate weathering and erosion would withdraw atmospheric carbon dioxide and lead to further reductions in global temperature.

The feedback proposed by Molnar and England (1990) has provoked much debate; it rests on the assumption that the transition to a more erosive climate enhances mountain relief (Small, 1999; Whipple *et al.*, 1999). In fact the opposite may be true, although in 1990 when Molnar and England were writing only statistical studies had demonstrated that higher erosion rates were correlated with reduced relief (Melton, 1957). Topographic relief at the scale of a mountain range consists of hillslope and fluvial components. River incision can increase relief only if hillslopes can simultaneously become steeper. This is possible only if hillslopes are shallower than their angle of repose (van Burkelow, 1945). To investigate typical hillslope angles in rapidly-uplifting mountain belts, Schmidt and Montgomery (1995) analysed slope profiles in the Washington Cascade Range, and the Santa Cruz Mountains of central California, USA. These areas have both exhibited widespread bedrock landsliding. Schmidt and Montgomery (1995) compared observed slope angles with predictions from a model of hillslope stability based on a Coulomb-type failure criterion and concluded that natural slopes do not become steeper than the angle of internal friction of the material from which they are made. Accordingly, they proposed that mountain-scale material strength places a limit on the topographic relief that can develop as a result of river incision.

Burbank *et al*. (1996) observed a similar situation to Schmidt and Montgomery (1995) in the north-western Himalayas, near Nanga Parbat. Burbank *et al*. (1996) showed that, despite very rapid erosion (2–12 mm $yr^{-1}$), average and modal hillslope angles are independent of erosion rate. They suggested that slope angles are controlled by a common threshold process, which is dictated by the material properties. Mean relief is set not by erosion rate but by the spacing of large rivers. Burbank *et al*. (1996) proposed that a balance is maintained between bedrock uplift and river incision: landslides allow hillslopes to adjust efficiently to rapid river downcutting. Moreover, the findings of Burbank and coworkers (1996) imply that the greatest relief develops either where rocks are less fractured (Schmidt and Montgomery, 1995), or where drainage density is lowest (Melton, 1957).

The studies by Schmidt and Montgomery (1995) and Burbank *et al*. (1996) demonstrate that in many tectonically active mountain ranges, hillslopes fail by bedrock landsliding to keep pace with bedrock river incision. This finding is important in understanding the relation between climate, valley incision and the uplift of mountain peaks, because it challenges the assumption of Molnar and England (1990) that relief can be increased by the incision of deep valleys. If hillslopes are typically at their angle of repose, then changes in mountain relief can occur only through incision of mountain rivers into bedrock, and rates of river profile evolution will dictate the link between erosion and mountain scale relief.

Taken together, results from geomorphological modelling studies show that the links between erosion, tectonics, and climate are complex. Much of the argument has been driven by modelling, yet models are heavily parametrized and poorly constrained. Understanding natural patterns of erosion requires more detailed, quantitative observations of erosion. Important questions that must be addressed are: what are the relative roles of extreme and moderate floods in driving erosion rates in tectonically active landscapes? Over what time-scales does climatic variability matter? Can erosion rates be inferred from topography, and what is the role of substrate strength in determining the expression of climatic and tectonic processes in topography? To answer these questions requires observations of average erosion rates and their variability over a range of time-scales.

The work described so far clearly shows the importance of interactions in the Earth System. Recent advances in our collective understanding of these interactions have involved simplifications of several sets of dynamical processes that would be treated in a very different ways if they were the sole focus of study (e.g., processes in fluvial geomorphology are increasingly treated using approaches based on computational fluid dynamics (see Bates *et al.*, 2005, for some examples); detailed modelling of strain rates in the continental lithosphere would adopt a similarly involved procedure (see Jackson and McKenzie, 1988; Hu *et al.*, 2001 for two contrasting approaches). The challenge presented by the papers described above (e.g., Willett, 1999) is to integrate these processes at the appropriate time and space scales, with appropriate levels of conceptual simplification. This is the central goal of Earth System Science. It is, of course, a goal familiar to physical geographers, and this aim will no doubt strike a resonant note among geomorphologists familiar with the analysis of Schumm and Lichty (1965), which demonstrates how processes can be conceptualised at different scales.

*4.2 Geomorphology and biogeochemical cycles*

Rapid changes over the past decade have seen the role of earth-surface processes as drivers of changes to biogeochemical cycles such as the carbon cycle. For example, rates of soil erosion are sensitive to changes in surface runoff. Soils store a significant amount of carbon: globally, the equivalent of approximately 200–300 times the amount of carbon released annually through the burning of fossil fuels (Cox *et al*., 2000). Any enhancement of soil erosion caused by changing runoff can be expected to make a major contribution to carbon cycle feedbacks in a changing climate. Indeed, preliminary estimates of large-scale soil carbon fluxes suggest that an important component of this feedback may be attributable to the effects of soil movement by geomorphic processes (Stallard, 1998). Nevertheless, the role of soil erosion and redistribution in the carbon cycle remains an area of some controversy with estimates of the global carbon flux associated with erosion ranging from a 1 Gt $year^{-1}$ source to a 1 Gt $year^{-1}$ sink (Stallard, 1998; Lal, 2003). The magnitude of carbon redistribution by sediment erosion and deposition demonstrates the potential for geomorphic processes to make a major contribution to the global carbon budget. For example, Jacinthe and Lal (2001) estimate that 5.7 Pg C $yr^{-1}$ are mobilised by water erosion. Soil erosion exposes fresh material at the surface which results in a disequilibrium between soil carbon content and crop carbon input that maintains a continuous supply of carbon for transfer to sedimentary environments. Stallard (1998) has hypothesized that this conveyor of sediment-associated carbon from hillslope to sedimentary environments has the potential to sequester atmospheric CO2 at the rate of 1–2 Gt C $yr^{-1}$ globally.

There is a clear research need to quantify the effects on the carbon cycle of soil erosion and deposition, however, approaches capable of doing this at appropriate scales have yet to be developed. A number of recent quantitative studies stand out in this respect. Lyons *et al*. (2002) showed that over one third of the total particulate organic carbon flux from the land surface to the ocean derived from sediment-laden rivers draining the mountainous western Pacific region. Moreover, in a detailed study of the role of storm flows in triggering carbon delivery, Hilton *et al*. (2008) have shown that, in the mountainous Li Wu River in Taiwan, between 77 and 92 percent of modern particulate organic flux was transported during large, cyclone-induced floods. The impact of land-management practices is also of potential importance. Indeed, recent hillslope-scale modelling has shown that within-field soil redistribution, principally driven by tillage, has been responsible for a net sink in the order of 5–10 g C $m^{-2}$ $year^{-1}$ over the last half century at two sites in

NW Europe (Van Oost *et al*., 2005). Quantification of feedbacks between the geomorphic system and the carbon cycle offer a clear example of a critically-important scientific activity that is likely to benefit from a funding framework influenced by Earth System Science

Another biogeochemically-active constituent of the geomorphic system is found in mineral dust aerosols. As one of the most abundant atmospheric aerosols, mineral dust plays a key role in determining the planetary radiation budget. Whilst this effect may be to increase the amount of short-wave radiation reflected back into space (leading to a cooling effect), the presence of mineral aerosols may also lead to increased absorption of outgoing long-wave radiation (having a warming effect similar to that of greenhouse gases). The balance between the two is governed by the vertical profile of dust concentration (Washington *et al*., 2008).

Dust aerosols also provide iron and other nutrients to marine phytoplankton populations and terrestrial vegetation during deposition.  Dust emissions occur in response to aeolian deflation, and are controlled mainly by variability in vegetation, soil moisture, and surface erodibility. Dry low-lying regions such as dry lake beds  are the main source of African dust events (Ginoux *et al*, 2001; Prospero *et al*, 2002; Washington *et al*., 2009). Consequently there are clearly potential feedbacks involving dust associated with a changing climate. It is hypothesised that during glacial-interglacial cycles, increases in the dust supply of iron to the ocean resulted in a significant Earth system feedback, driving about one third of the observed glacial-interglacial variations in atmospheric $CO_2$ (Kohfeld *et al*., 2005). Some early studies (e.g., Tegen & Fung, 1995) have found that, in the modern setting, human influences have increased dust emissions directly via changes in land use by as much as 20–50 percent (Tegen *et al*, 1996; Sokolik & Toon, 1996). However, more recent estimates have revised the anthropogenic increase to be less than 10 percent (e.g., Tegen *et al*., 2004; Prospero *et al*., 2002). Further work is clearly required to quantify the potential effect of a future climate change scenario on dust emission, transport, and deposition, through to their effect on the ocean carbon cycle.

*Geomorphology and the biosphere*

The role of vegetation in geomorphic processes has been the subject of research ever since Darwin's study of the effect of earthworms on reworking of soil organic matter (see Kennedy, 2006, for a review). Nevertheless, one of the stated aims of Earth System Science is to examine linkages between the lithosphere, hydrosphere, atmosphere *and* biosphere. Before the explicit emergence of the Earth System Science paradigm, the work of Langbein and Schumm (1958) was influential in demonstrating the links between climate, vegetation, and erosion. These authors showed that rather than scaling simply with precipitation rate, erosion rates were highest in semi-arid climates (rather than arid or humid climates), because in these regions, there was sufficient precipitation for erosion to occur, but insufficient to ensure perennial vegetation cover. More recent reviews by Viles (1988), Naylor *et al*. (2002) and Stallins *et al*. (2006) have summarised the many developments in the field of biogeomorphology to date.

Whilst the role of biota in governing geomorphic process rates has been recognized, Dietrich and Perron (2006), recently turned the question around, asking: "is there a topographic signature of life?" That is, would a unique set of topographic properties be evident in a map from which all vegetation and artefacts of human activity had been removed. The motivation for this question illustrates the role that Earth System Science can play in setting the range of appropriate questions. Although not stated explicitly, Dietrich and Perron's (2006) paper clearly addresses a key aim of Earth System Science. The basis of Bretherton's original manifesto was that NASA should embark on a mission to Planet Earth. Clearly, if it is possible to detect life topographically (i.e., by measuring nothing more than the elevations of points on a planet), then exploration for extra-terrestrial life is immediately made much easier.

Dietrich and Perron (2006) structure their analysis to consider three distinct, but connected, questions: (i) what is the influence of biotic processes on weathering, erosion, and sediment transport mechanisms; (ii) how do biotic processes affect climatic and tectonic processes globally; and (iii) what are the implications of biogeomorphic processes for the development of topography in abiotic environments. In addressing the first question, it is clear that biological processes can exert a strong control on the rates and styles of geomorphic processes such as soil production and creep (through animal burrowing, tree throw and root growth), landsliding (through enhanced root cohesion and provision of surface cover), debris flows and river incision (via presence of large woody debris in channels). As Dietrich and Perron (2006) note, a key challenge is to develop geomorphic transport laws which represent these processes in ways that can be justified with reference to high-quality field data. Nevertheless, even with a preliminary understanding of such processes, model experiments are already providing qualitative explorations of the effects of biotic processes on landforms (see Kirkby, 1995 and Collins *et al.*, 2004). Indeed, Istanbulluoglu and Bras (2005) have demonstrated numerically that changes in vegetation cover can lead to a transition from runoff-dominated erosion to landslide-dominated erosion (Figure 6)

In a thought experiment, Dietrich and Perron (2006) also consider what climate and tectonics would look like without the presence of life. They note that an obvious consequence of the removal of biotic influence would be a "rapid erosion of the soil mantle that covers semi-arid to wet landscapes" (p. 413), but they go further to state that it is not correct to suppose that the presence of "smooth, rounded, soil-mantled hillslopes are a topographic signature of a biotic world" (p.413). They key point here is that whilst biotic processes interact strongly with the lithosphere through geomorphic processes, the link does not result in a unique topographic form. There is an element of equifinality in the system under study, in the sense that the same set of physical features can be created by a range of different processes and that it is not possible to attribute a particular cause to their creation (see Schumm, 1991 for further discussion). The answer that Dietrich and Perron arrive at is illuminating, not only because it reveals how the earth's surface is a critical site for interactions in the earth system, but also because their analysis demonstrates how Earth System Science can itself benefit from an understanding of some of the older concepts that have emerged in earlier studies of complex systems in physical geography (such as equifinality, emergence, interactions of processes across a range of time- and space-scales; see Schumm, 1991, for a detailed review).

**6. Geomorphology in ESS: revolution, evolution or recapitulation**

The conclusions to the previous section raise several key questions for the future of geomorphology in Earth System Science. According to Paola et al.'s (2006) analysis, the greatest need is for better collaboration between the many disciplines that pertain to geomorphology. This integration can happen only when opportunities are sought for geoscientists to exchange ideas with colleagues from other disciplines. In practice, this can actually be quite challenging: one is forced out of one's comfort zone. Yet numerous biographical accounts of major interdisciplinary scientific achievements reveal the range of strategies that may be employed (see, for example, the accounts by Peter Molnar and Dan McKenzie, in Oreskes, 2003). There may well be some technical solutions: better training in advanced mathematics is an obvious way to equip geoscientists with a *lingua franca* with which to communicate with a wider range of other scientists. Better mathematics should also mean smarter mathematics: not just fiddling about with a complicated computer simulation until it produces results that look a bit like the real world (see Molnar, in Oreskes, 2003, for a more florid description of the drawbacks of such an approach), but understanding how to make appropriate simplifications to a model of, say, river channel dynamics so that it may communicate with a model of, say, ecological succession or climate change. Beyond the technical challenge of enabling communication between geoscientists of different backgrounds is the need to include social science in Earth System Science. Here, Liverman and Roman-Cuesta (2008, p.1459) note the considerable barriers: “At worse, earth scientists sometimes assume that the role of the social sciences is little more than that of a public relations effort to translate science to stakeholders. In other cases earth scientists believe that the qualitative nature of some social science research sets insurmountable barriers to integrated analysis or modelling”. Insofar as geographers possess skills and interests that can bridge the potential barriers between natural and social science, they are well placed to advance the debate. The challenge in the coming years will be for University departments, research institutes, funding bodies, and learned societies to provide suitable training and research, funding, and networking opportunities in order for this potential to be realised.

Aside from these practical needs, some more conceptual issues are raised by the rise of Earth System Science. Whilst it should of course be clear that it is possible to pursue rigorous and meaningful research in geomorphology without involving or appealing to the imperatives of Earth System Science; and, conversely, it is possible to understand major parts of the Earth System without developing anything more than a cursory concept of geomorphology. However, where there *is* a meaningful interface between geomorphology and other components of the Earth System (and I hope to have introduced a wide-ranging set of examples of such circumstances), three key questions arise: (i) explanation and scientific method for earth systems science; (ii) questions of time and space scales and links between process operating at different scales; and (iii) the status of humans as actors/agents in a framework defined by Earth Systems Science. These are not trivial questions, and they cannot be approached as afterthoughts. They will require changes to the curriculum; they will require changes to funding frameworks. But the rewards that come with an integrated understanding of the earth system can be great: from more robust models of the effects of climate and land-use change on geomorphic processes, to a greater understanding of interactions of physics, chemistry and biology. Physical geographers have a significant contribution to make, not just to the integration of knowledge of the biosphere, lithosphere, hydrosphere and atmosphere; but to the detailed and nuanced ways in which the actions of and impacts upon human societies can be enumerated, quantified, and communicated.

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**FIGURES**

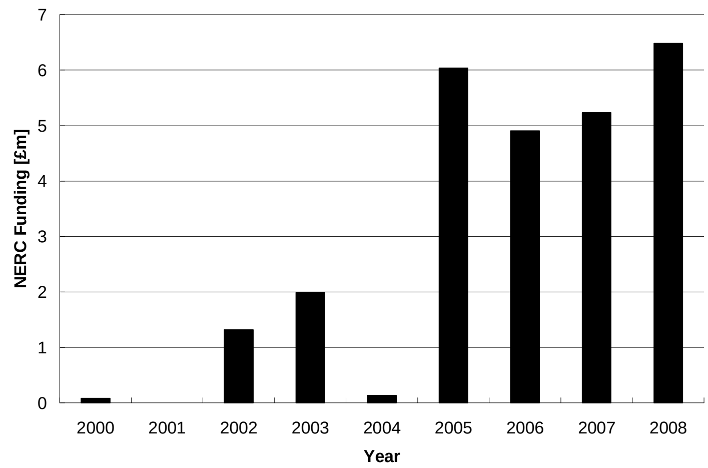


Figure 1: Funding by year from the UK Natural Environment Research Council for grant, fellowship and training awards containing the phrase “Earth System” in the title or abstract. Publicly-accessible data source http://gotw.nerc.ac.uk/, accessed 14th June 2009.

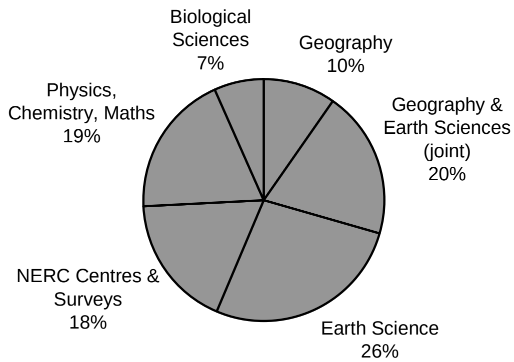


Figure 2: Breakdown of NERC research funding by discipline. from the UK Natural Environment Research Council for grant, fellowship and training awards containing the phrase "earth system" in the title or abstract. Publicly-accessible data source http://gotw.nerc.ac.uk/, accessed 14th June 2009.

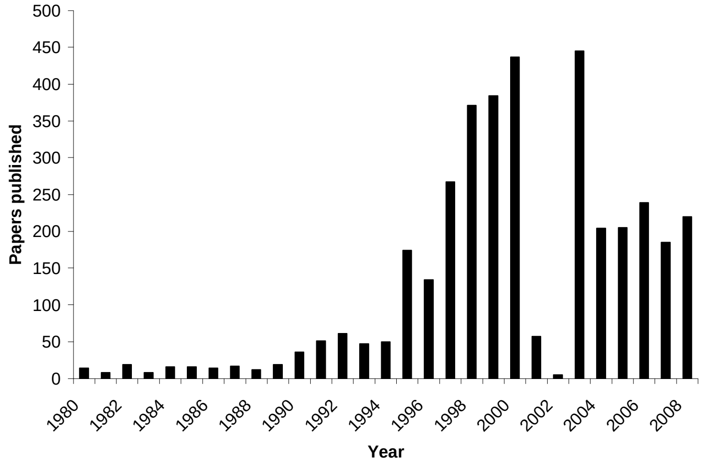


Figure 3: Annual number of publications in the ISI Web of Science database where the topic field contains the phrase “Earth System Science”. (Source: http://wos.mimas.ac.uk/, accessed 14th June 2009).

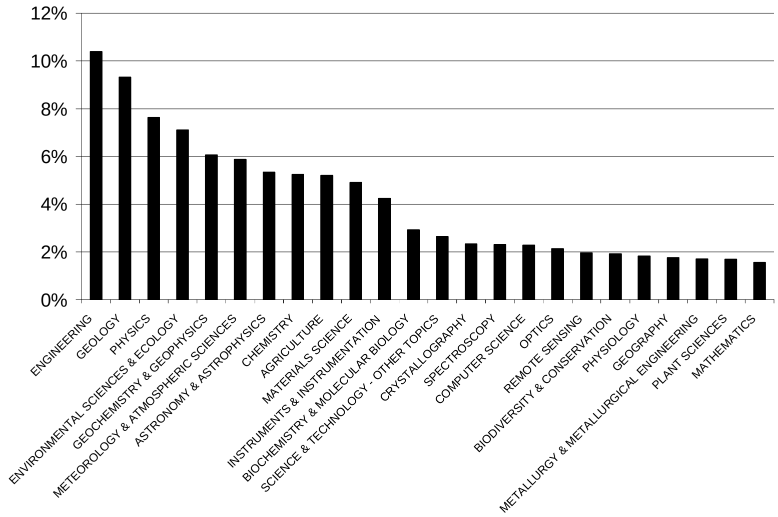


Figure 4: Publications in the ISI Web of Science database, broken down by discipline, where the topic field contains the phrase Earth System Science. (Source: http://wos.mimas.ac.uk/, accessed 14th June 2009).

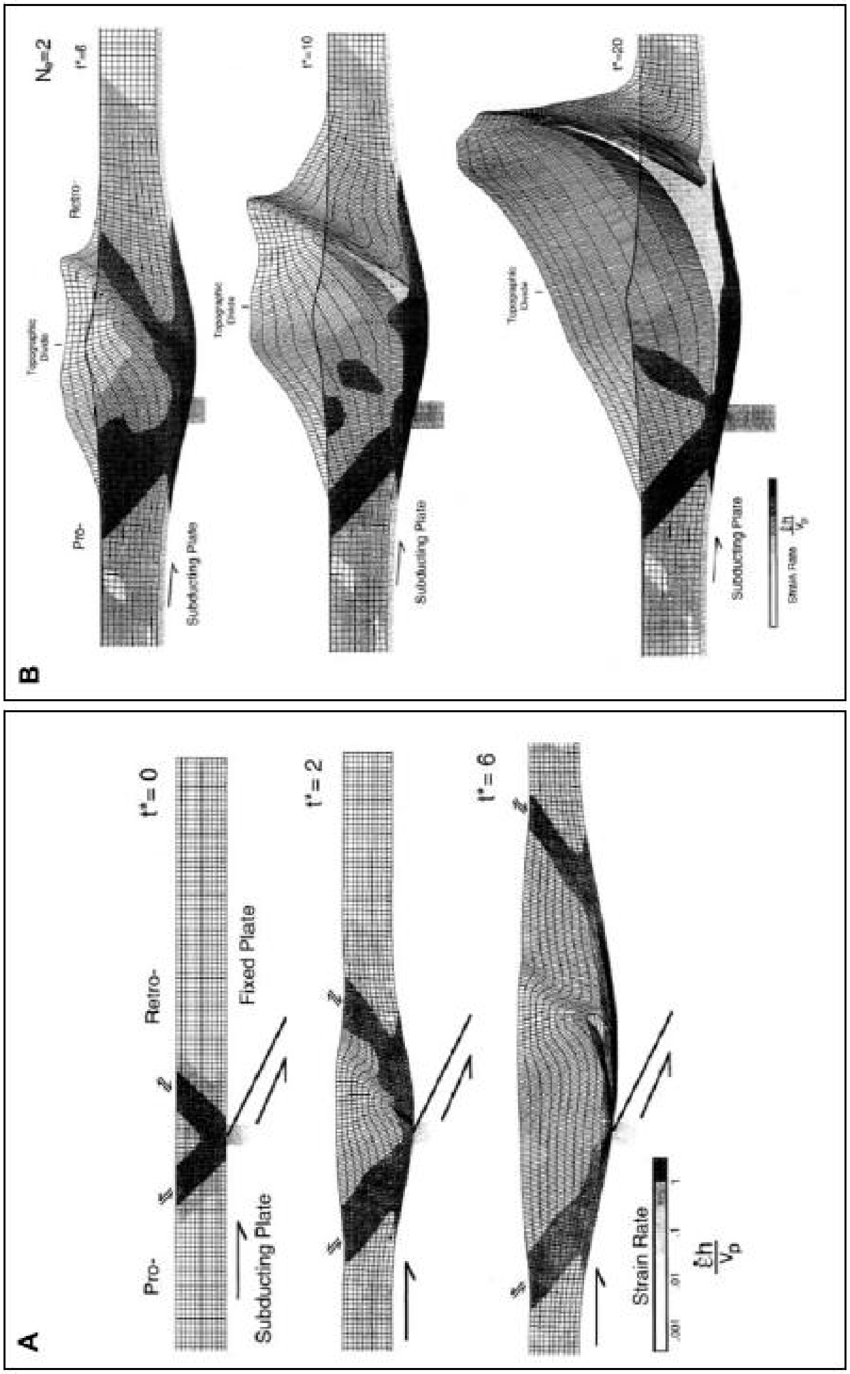


Figure 5: Finite element model for viscous-plastic deformation during convergence (Willett, 1999). Subduction is to the right, with a constant velocity applied at the base of the crustal layer. The applied velocity is zero to the right of the grey block. Coulomb friction angle is 15 degrees. Below the Coulomb yield stress, crust deforms according to a temperature-dependent viscous constitutive relation. Time is nondimensionalized by (subduction velocity / crustal thickness) to give $t^*$. The Argand number is initially 0.5 at the base of the crustal layer. Shading indicates the instantaneous

nondimensional strain rate. The pro-wedge moves in the direction of subduction, against the retro-wedge. The mesh follows particle motion and indicates total deformation. In cases with erosion the topographic surface is shown in bold. A, no erosion; B, uniform erosion with $N_e = 2$. The erosion number characterizes the erosion rate relative to the rate of rock uplift.

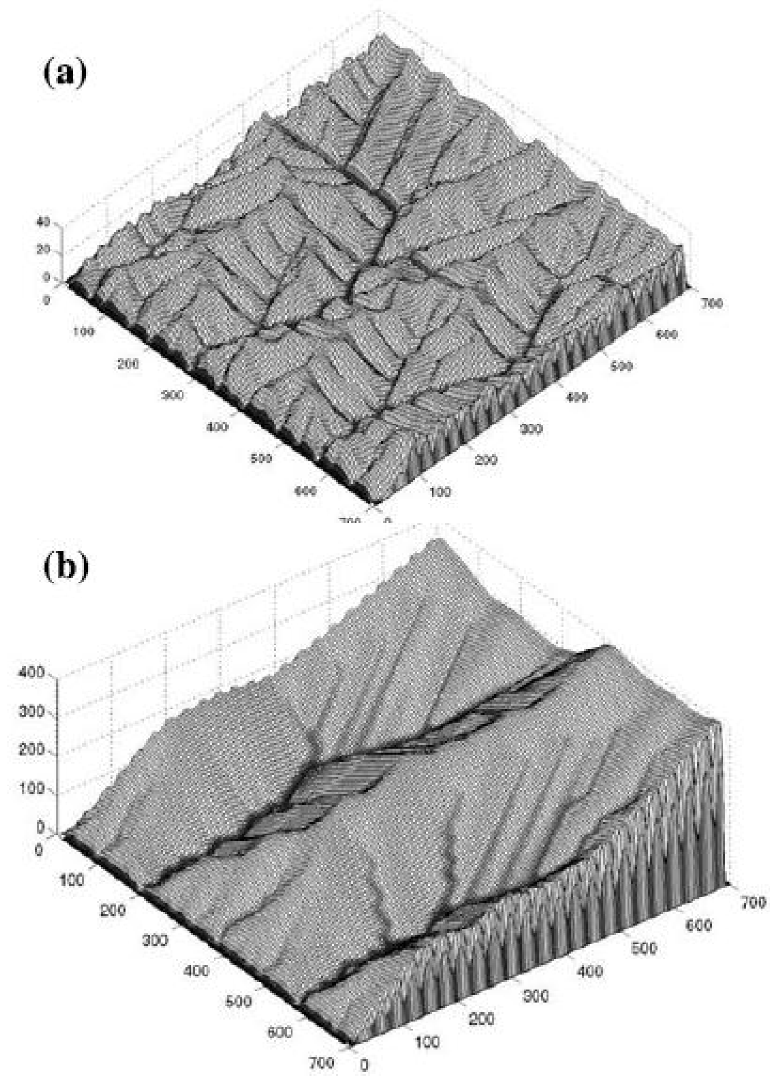


Figure 6. Results of numerical simulations showing the difference between landscapes simulated with (a) no vegetation cover and (b) static vegetation cover. Both landscapes are in topographic steady-state, where there is no trend in mean elevation over time (although inevitable fluctuations about a long term mean occur due to stochastic climate forcing and static erosion thresholds). From Istanbulluoglu and Bras (2005).