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The Geomorphology of The Anthropocene: Emergence, Status and Implications

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Abstract

The Anthropocene is proposed as a new interval of geological time in which human influence on Earth and its geological record dominates over natural processes. A major challenge in demarcating the Anthropocene is that the balance between human-influenced and natural processes varies over spatial and temporal scales owing to the inherent variability of both human activities (as associated with culture and modes of development) and natural drivers (e.g. tectonic activity and sea level variation). Against this backdrop, we consider how geomorphology might contribute towards the Anthropocene debate focussing on human impact on aeolian, fluvial, cryospheric and coastal process domains, and how evidence of this impact is preserved in landforms and sedimentary records. We also consider the evidence for an explicitly anthropogenic geomorphology that includes artificial slopes and other human-created landforms. This provides the basis for discussing the theoretical and practical contributions that geomorphology can make to defining an Anthropocene stratigraphy. It is clear that the relevance of the Anthropocene concept varies considerably amongst different branches of geomorphology, depending on the history of human actions in different process domains. For example, evidence of human dominance is more widespread in fluvial and coastal records than in aeolian and cryospheric records, so geomorphologically the Anthropocene would inevitably comprise a highly diachronous lower boundary. Even to identify this lower boundary, research would need to focus on the disambiguation of human effects on geomorphological and sedimentological signatures. This would require robust data, derived from a combination of modelling and new empirical work rather than an arbitrary 'war of possible boundaries' associated with convenient, but disputed, `golden spikes'. Rather than being drawn into stratigraphical debates, the primary concern of geomorphology should be with the investigation of processes and landform development, so providing the underpinning science for the study of this time of critical geological transition.

Keywords: aeolian, anthropogenic, coastal, cryosphere, fluvial, stratigraphy

Introduction

The Anthropocene has been proposed as a new interval of geological time to account for the 'dominant' or 'overwhelming' influence of human activities on the Earth's surface and its geological record (Crutzen, 2002; Waters et al., 2016). As geomorphology is concerned with understanding Earth surface processes and landforms it cannot logically avoid engagement with the Anthropocene debate (Brown et al., 2013a). Indeed, from the 19th Century onwards, both physical geography and geology have addressed human impacts on the Earth's surface (e.g. Marsh, 1874; Gilbert, 1877; Happ et al., 1940; Hooke, 1994; Church, 2010). This position paper builds on initial considerations by the British Society for Geomorphology's Anthropocene Fixed Term Working Group, which outlined the role of geomorphology in the Anthropocene debate (Brown et al., 2013a), whilst also drawing on similar discussions in allied fields such as Quaternary Science (Gale and Hoare, 2012) and in biology (Caro et al., 2011).

Although it can be argued that "wilderness has effectively gone" (Wohl, 2013, p.4), human impact on the terrestrial environment has varied, and continues to vary, in nature (e.g. directly, indirectly), intensity and duration. This variable impact is highly relevant for key elements of the Anthropocene debate such as the lower boundary problem (Brown et al., 2013a). If we recognise that human activities now dominate over natural processes over the vast majority of the Earth's surface, just when did this dominance start and so usher in a new geological interval (Lewis and Maslin, 2015; Waters et al., 2016)? In answering this question, even a selective consideration of geomorphic environments would pose related theoretical and methodological challenges, namely defining what we mean by human dominance in geomorphology (*sensu* Crutzen, 2002) and then measuring the relative geomorphic role of humans in recent Earth history. Addressing such challenges, however, is central to defining a role for geomorphology in debates over the credibility and practicality of recognising the Anthropocene as a new interval of geological time.

The Anthropocene debate contains strong elements of a human-nature dichotomy. The idea of demarcating an interval of geological time - of whatever rank (e.g. Era, Period, Epoch, Stage) - during which human actions have been dominant, implies that in earlier intervals Earth surface processes can be seen as 'natural' with little or no human impact. This human-nature dichotomy has been questioned, both in the social and physical sciences (Rhoads and Thorn, 1996), but what is not disputed is that first-order processes that underlie geomorphology are external to human actions (Church, 2010). In short, humans operate within the laws of physics, from which fundamental geological principles are derived (e.g. superposition, isostasy). Nonetheless, human activities (e.g. mountain top removal, reservoir construction) can significantly affect the operation of some fundamental autogenic geological processes (e.g. neotectonic movements and seismic activity). More commonly, human activities alter the boundary conditions of second-order (or mixed) processes (e.g. sediment erosion, transport and deposition). This impacts on the trajectories and rates of process-response systems through effects on connectivity, inequality and thresholds (tipping points, nonlinearity) of matter and energy fluxes (Haff, 2010; Wainwright et al., 2011; Wohl, 2013).

Against this background, this paper has five main aims. First, we describe approaches to defining 'dominant' or 'overwhelming' human impact. Second, we sample geomorphological studies across four key second-order process domains (aeolian, fluvial, cryospheric, coastal) to address the nature, magnitude, diachrony, longevity and preservability of human impacts on landforms, sediments and stratigraphy. Third, we consider a selection of anthropogenic landforms, namely those created as a direct and commonly deliberate result of human activities. Fourth, we address the contribution of geomorphology to stratigraphic debates about an Anthropocene. Finally, we draw attention to other geomorphologically-relevant topics that have emerged during the Anthropocene debate, including the reciprocal effect of anthropogenic landforms on second-order processes, and the implications for differentiating between human and natural forcing. Many of these topics have not yet been regarded as high priority by the geomorphological or wider geoscience community but arguably are going to be of increasing importance in future.

Defining Dominant or Overwhelming Impact

The formal recognition of the Anthropocene is contingent on being able to identify an undisputed dominant, or overwhelming, impact of human actions on second order processes. This requires a workable distinction between human and non-human process or mass transport dominance. For geomorphology, ‘dominant’ must imply humans are the most influential driving factors (over 50% outcome determination), whereas ‘overwhelming’ might be considered as higher (at least 95% outcome determination). In practice, this distinction has always been difficult to establish, and in many instances may be impossible. One approach is to concentrate on humans as stressors, which in essence is what the global atmospheric modification argument is predicated upon (Hulme, 2009). This is more difficult in geomorphology, although attempts have been made using global estimates of surface mass action (Haff, 2010). Although this approach has limitations, such as having no boundaries with socio-economic systems (e.g. oil transportation) and not necessarily being related to geomorphological features, it can indicate process dominance in key sub-systems, the most obvious of which is soil (*cf.* the critical zone). If we make the reasonable assumption that in all soils under cultivation, bioturbation is dominated by direct human actions (e.g. through tillage), and that in pasture lands bioturbation is indirectly influenced by human actions (e.g. through grazing practices, use of fertilizers, and associated changes in soil fauna), then we can estimate the minimum area of the Earth’s land surface where human activity dominates soil processes. Using world agricultural land estimates, this would give human dominance over at least 38% of the Earth’s ice-free terrestrial surface. In urban areas, bioturbation is suppressed by human activity, so the total figure rises to 45% of the ice-free terrestrial surface (Hooke, 2012). Based on similar estimates, several geomorphologists have tried to compute anthropogenic soil transport rates by taking the difference between natural (i.e. geological) and agricultural estimates of soil erosion rates (Hooke, 2000; B. Wilkinson, 2005; Montgomery, 2007). Whilst this latter approach is the most obvious for quantitative partitioning of natural and human contributions to erosion and sediment transport, it requires comparative data and involves several assumptions. Several methods have been used to estimate natural rates (Table 1) and all have their limitations, so that even for climatically-comparable areas, calculated rates vary by at least one order of magnitude. This variability is because the range of methods used to calculate rates typically do not measure the same ‘events’; for instance, denudation rate estimates from a long-lived cosmogenic isotope are significantly different in both temporal and spatial scale from erosion rate estimates made from naturally vegetated plots on a slope. Furthermore, ‘within method’ estimates also vary considerably due to differences in soils and vegetation (Kosmas et al., 1996; Wainwright and Thornes, 2004). For example, even the estimates derived just from cosmogenic isotopes used by Montgomery (2007) vary by over one order of magnitude (0.001-0.034 mm yr^{-1}), and as more basin-outlet studies have been undertaken, this variance has increased (Brown, 2016).

There is also an embedded assumption of equilibrium with climate, an assumption that is increasingly being questioned and that in many ways is at odds with the nature of geomorphology in the putative Anthropocene (Bracken and Wainwright, 2006; Hoffmann et al., 2010). Below, we consider the case for an Anthropocene in more detail for various process domains.

Second-Order Process Domains

We have divided the terrestrial Earth system into aeolian, fluvial, cryospheric and coastal domains in order to examine human impacts at the second-order level. This division does not imply that these are the only, or even the most, anthropogenically-sensitive process domains (others might include weathering, hillslope or karstic systems), only that they are major subdisciplines of geomorphological research.

Aeolian process domain

Human activity primarily affects aeolian processes by directly or indirectly changing the erodibility of sediments that are suitable for wind transport or by altering aeolian sediment budgets. One of the most commonly cited causes of increased aeolian surface erodibility is vegetation cover reduction resulting from agricultural or pastoral activities. In China, these activities are widely cited as increasing dust flux (Li et al., 2009; Wang et al., 2013), with agricultural practices estimated to have increased wind erosion rates by two to five times background levels (Shia et al., 2004). Nevertheless, the drylands that are most prone to anthropogenically-enhanced aeolian activity are also prone to marked climatic variability, which itself contributes to natural vegetation cover changes and to consequent temporal and spatial variations in aeolian activity. Remote sensing has been employed, however, to distinguish natural (climatically-induced) variability in bare surfaces in aeolian landscapes from those enhanced by agriculture, as the latter tend to persist through wetter years (Thomas and Leason, 2005). Remote sensing techniques can also be used to distinguish anthropogenic sources of dust (Hahnenberger and Nicoll, 2014).

It is also possible to monitor the impact of human activities on the morphology and dynamics of continental dune systems that are a legacy of periods of drier and windier conditions earlier in the Quaternary. Today, these dunes tend to be stabilised by vegetation cover but remain vulnerable to anthropogenic disturbances (Barchyn and Hugenholtz, 2013). Intermittent late Holocene dune mobilisation in the northwestern Negev Desert has been linked to various human activities that have reduced vegetation cover and disturbed biogenic soil crusts. The resulting increases in surface erodibility have triggered changes to dune morphology, including planform realignment and increased height (Tsoar and Møller, 1986). These changes have in turn facilitated short-term increases in wind power to trigger major dune mobilisation events (Roskin et al., 2013). There are also model-based analyses that hypothesise reactivation of presently stable dunefields under anthropogenically-influenced warmer future climates (Thomas et al., 2005; Ashkenazy et al., 2012). Even away from desert and semi-desert regions, there is evidence of past human activity affecting stabilised dunefields by changing vegetation cover; for example, Mauz et al. (2005) ascribed multiple late Holocene reactivations of dunefields in Schleswig-Holstein, Germany, to anthropogenic activity.

There are instances where aeolian activity can decrease when human activity reduces sediment supply. For instance, the connectivity between fluvial (supply) and aeolian (accumulation) sedimentary systems may be disrupted, as demonstrated by Draut (2012) in dunefields adjacent to the Colorado River, southwest USA. Here, dam construction has decoupled dunes from fluvial sand supply, resulting in dune surfaces developing biogenic soil crusts and greater biomass, and leading to less aeolian sand transport. The proportion of active aeolian sands is substantially lower in heavily regulated river reaches than in less regulated reaches with otherwise similar environmental conditions (Draut, 2012).

Widespread human modification of the aeolian process domain does not necessarily mean that anthropogenic signatures can be identifed in aeolian landforms and sedimentary records, as resultant sedimentary units are rarely distinguishable from their natural counterparts, and may be very dispersed in the landscape. Nevertheless, anthropogenically-enhanced aeolian activity has been proposed as an explanation for step-changes in dust deposition rates recorded in marine, ice, lake and peat cores, including in Greenland (Sandgren and Fredskild, 1991), USA (Neff et al., 2008), off the coast of north Africa (Mulitza et al., 2010), Australia (Marx et al., 2014) and Antarctica (McConnell et al., 2007). The timing of increased deposition rates varies in association with the spatially-specific human causation. For example, Atlantic marine core records suggest wind erosion in the Sahel increased fivefold since the onset of agricultural irrigation in the 1700s (Mulitza et al., 2010) but in southwestern Colorado, USA, lacustrine dust deposition increases from <150 g m^{-2} yr^{-1} to >400 g m^{-2} yr^{-1} are attributed as a response to the expansion of livestock grazing in the mid 1800s (Neff et al., 2008). In some instances, local, 'on site' aeolian deposition is attributed to human disturbance. In the Free State, South Africa, unconformable sand cappings on stable dunes, field-boundary dunes and buried boundary fences have been associated with the establishment of permanent farm units by European farmers in the 1880s (Holmes et al., 2012).

In some regions, anthropogenic impacts on aeolian processes are now being reduced. In Australia, soil conservation measures have reduced dust deposition rates to pre-anthropogenic levels (Marx et al., 2014; Figure 1). However, the failure of the (probably over-) ambitious Green Dam project in Algeria (Ballais, 1994), which involved large scale afforestation of landscapes vulnerable to aeolian erosion, highlights our lack of skill in attempting to control aeolian processes (Benazzouz and Boureboune, 2009). More promisingly, systematic monitoring of aeolian dynamics in agricultural fields in South Africa has led to simple changes in agricultural practices being proposed that could significantly reduce wind erosion (Wiggs and Holmes, 2011) although modelled predictions of future changes in wind power and moisture availability may more than negate the benefits of such action. Given the unconstrained nature of aeolian sediment movement when compared to fluvial systems, and the complex, sometimes nonlinear, interactions between atmospheric and surface parameters that generate or limit aeolian processes, identifying anthropogenic impacts on aeolian landforms and sediments remains challenging.

Fluvial process domain

Human activity can influence fluvial processes indirectly through land-use changes that modify flow discharge, sediment loads and river system connectivity (Notebaert et al., 2011; Fryirs, 2013) or directly through mining activities and various forms of river management (Hudson et al., 2008). The latter include within-channel constructions (e.g. dams, weirs) that modify river long profiles and create anthropogenic sediment sinks (Syvitski et al., 2005; Walter and Merritts, 2008) as well as floodplain structures (e.g. levées) that impede channel-floodplain connectivity (Hudson et al., 2008). Since Leopold and Miller (1954) outlined palaeohydrological research as a means of elucidating human agency in soil erosion problems, various approaches have been employed to quantify the magnitude, patterns, rates and timing of anthropogenic changes to the fluvial process domain (Thorndycraft, 2013). Approaches include: i) documenting changes to spatial patterns and rates of key fluvial processes such as avulsion (Tooth et al., 2009); ii) identifying and dating stratigraphic markers of human impact, such as sedimentological changes in floodplains (Walter and Merritts, 2008) or lakes (Dearing and Jones, 2003), the presence of inter-stratified cultural material (Brown, 1997), mineral or element changes (Hudson-Edwards et al., 1999), and palaeoecological biostratigraphic markers (e.g. Brown, 1988); iii) quantifying long-term sediment fluxes through sediment budget approaches (Brown et al., 2009), cosmogenic nuclide studies (Wittmann et al., 2011), or global scale models (Syvitski et al., 2005); and iv) modelling catchment scale river response using landscape evolution (e.g. Coulthard and Van De Wiel, 2012) or hydrological models (e.g. Notebaert et al., 2011).

These approaches show that human impacts may either increase or decrease fluvial activity. Globally, however, some floodplains possess stratigraphic units attributable to anthropogenically-enhanced soil erosion, principally overbank loams that host archaeological remains (Brown, 1997) (Figure 2). A similar anthropogenic stratigraphy may also be recorded in lake sediment archives (Dearing and Jones, 2003), possibly in association with anthropogenic geochemical (Boyle et al., 2015a) or even DNA signatures (Taberlet et al., 2007). In extensively studied regions such as northwest Europe, the Mediterranean and North America, such floodplain and lake stratigraphic markers are diachronous, the timing of anthropogenic increases in soil erosion being dependent on the regional history of deforestation and agriculture. In addition, human impact on floodplain ecosystems can be reconstructed using palaeoecological evidence from alluvial peats (Brayshay and Dinnin, 1999). For example, many pollen stratigraphies reveal anthropogenic deforestation signals, again showing diachronous timing of human impact, even within the same river catchment (Brown, 1988).

Considering human impact on fluvial activity at the global scale, Syvitski et al. (2003) outlined a relief-area-temperature model to predict sediment flux to oceans. For 75% of 320 river catchments, modelled fluxes were within a factor of two of the observed data. Modelled fluxes, however, were overestimated where major reservoir storage reduced sediment loads (e.g. Tagus River, Portugal) and underestimated in some areas of anthropogenic soil erosion (e.g. Huang River, China), most commonly in smaller catchments where the anthropogenic impact was magnified. Applying the model to 4464 river catchments across the globe with drainage areas >100 km^2, it was found that the net balance was a 1.4 Bt yr^{-1} reduction in sediment flux to the oceans due to reservoir sediment retention, despite increased anthropogenic soil erosion (Syvitski et al., 2005). By simplifying processes to enable global scale modelling, however, such approaches may not accurately represent the role of sediment storage. Using digital topographic data and an empirical volume-area scaling of valley fills, Blöthe and Korup (2013) quantified the sediment stored in over 38 000 Himalayan valley fills, and found millennial-scale time lags in the sediment routing systems of the Brahmaputra and Ganges, rivers that deliver ~10^3 Mt yr^{-1} to the ocean. Such storage can complicate the attribution of climate or seismic controls to sedimentary records (Blöthe and Korup, 2013) and, by extension, the attribution of human activity. Based on cosmogenic nuclide-derived sediment fluxes, a sediment storage buffering capacity has also been noted in the Amazon basin (Wittmann et al., 2011). Sediment production in the Andes was the same as the sediment delivery to the ocean, suggesting little change in sediment flux over recent millennia and implying that potential human impact on this flux was limited due to the large scale of the Amazon system (Wittmann et al., 2011).

Some studies have focused more explicitly on the profound, often highly visible, changes to fluvial process and form resulting from mining. Mining may involve many catchment hydrological and sediment supply changes as a consequence of deforestation, road construction, and river diversion (Mossa and James, 2013). Ever since Gilbert's (1917) pioneering studies, geomorphologists have used mining-impacted rivers as an outdoor laboratory for studying the major, commonly abrupt, changes to channel form resulting from sediment supply increases, including in California (James, 2004, 2005, 2013; Singer et al., 2013) and Australia (Knighton, 1989, Pickup et al., 1987; Erskine and Saynor, 2000). Lakes within fluvial catchments affected by mining also may preserve evidence of increases in sediment flux and contaminant delivery (Boyle et al., 2015b). A range of other human activities such as irrigation and navigation also can result in profound changes to fluvial processes and forms, particularly through radically altering channel-floodplain connectivity. For example, in a multi-faceted review, Lewin (2013) showed how many British floodplains have been genetically transformed through four phases of human activity over the last 400 years.

From these case studies, it is clear that, with the exception of heavily-modified catchments, the relative magnitude of human impact on the fluvial process domain is dependent on catchment scale, tectonic activity and relief, and susceptibility to erosion. The anthropogenic signal may be more clearly defined in small- to medium-sized catchments draining, for example, highly erodible loessic landscapes (e.g. Notebaert et al., 2011). The signal may be less clear in large catchments such as the Ganges and Brahmaputra that are subject to active tectonic activity and high sediment supply, and characterised by accommodation space for medium term sediment storage, subsequent erosion of which can nourish sediment flux for millennia (Blöthe and Korup, 2013). The complexities of the processing of human impacts through the fluvial system to alluvial sedimentary records are illustrated in Figure 3 and it is this complexity that renders simplistic approaches to human attribution (e.g. sediment delivery ratio) as unreliable (Parsons et al., 2006a). While human activity can be seen to influence all four areas of the fluvial system (Figure 3), the magnitude, patterns, timing and rates of these impacts and the recognition of anthropogenic markers in landforms and sediments are dependent on catchment characteristics and exhibit large spatial and temporal variability.

Cryospheric process domain

At a global scale, net loss of ice is already happening (Vaughan et al., 2013) and is highly likely to continue in a warming world (Kirtman et al., 2013). Ice sheets, glaciers and permafrost respond principally to climate, but given the now well-established anthropogenic influence on global warming, this cryospheric response potentially might be regarded as a global-scale manifestation of an Anthropocene.

The majority of the world's monitored glaciers have retreated and lost mass during the 20th Century, with deglaciation increasing since the 1960s (WGMS, 2008; Vaughan et al., 2013). The geomorphological imprint of such rapid deglaciation includes both near-field and far-field effects. In ice-proximal settings, ice-marginal retreat and declining ice volume lead to exposure of new terrain and extension of proglacial systems (Evans, 2003), thereby encompassing a variety of landforms and sediments. There are also associated changes in paraglacial processes (Ballantyne, 2002). Farther afield, there are changes to river hydrology, and implications for the coastal zone in terms of changing sediment supply and sea level rise (WGMS, 2008).

Deperiglaciation is also significantly affecting many areas rich in ground ice (permafrost). In high latitudes, thawing of permafrost (thermokarst) can be initiated, retarded or counteracted by numerous factors operating on local to regional scales: from local damage to the vegetation or organic layer, to regional increases in snow cover or mean annual temperature (Table 2). Human activities can affect these factors, both directly and indirectly, but can be hard to separate from natural drivers. For instance, disturbances that initiate thermokarst activity are often compound and interactive, such as where a boreal forest fire – either natural wildfire or anthropogenic fire – initiates active layer deepening and thermokarst subsidence by destroying the shading effect of the vegetation canopy, reducing heat loss from evapotranspiration, and lowering surface albedo (Kokelj and Jorgensen, 2013). There is clear evidence that thermokarst activity during the last 100-150 years has spread and intensified as result of multiple causes (Murton, 2009) but if global warming continues, thermokarst activity is likely to intensify and spread farther during this century (e.g. see projections of future permafrost extent in Vaughan et al., 2011; Lawrence et al., 2012; Koven et al., 2013). In lower latitude but mountainous regions, there is also evidence of recent increased periglacial activity. As ground ice warms, it softens, accelerating creep in rock glaciers and talus, and weakening ice-filled joints in rockwalls (Davies et al., 2001; Haeberli et al., 2010). Potentially, this can destabilise rock slopes and enhance mass movement (Krautblatter et al., 2013).

Viewed in the context of Quaternary ice extent, however, recent rapid deglaciation and deperiglaciation are not unprecedented. For instance, rapid and widespread deglaciation occurred at the end of every previous glacial, and although ice extents are difficult to gauge during previous warm intervals in the Holocene, in parts of the world (e.g. Alps, Scandinavia, Altai) there is evidence for more restricted ice extent than at present (Masson-Delmotte et al., 2013). Similarly, while the strongest manifestation of thermokarst activity in the geological record is from the last glacial-interglacial transition and from the penultimate interglacial (Murton, 2009; Reyes et al., 2012), comparison of natural activity rates with recent anthropogenically-influenced rates is extremely difficult. Furthermore, it remains difficult to discern a landform or sediment signature uniquely attributable to anthropogenically-influenced cryospheric change. Hence, despite the clear evidence for the contribution of human activities to recent deglaciation and deperiglaciation, it seems premature to identify an Anthropocene from landforms or sediments in the cryospheric process domain.

Coastal process domain

Human impact on the coast is arguably more pronounced than for any other part of the Earth system. A significant proportion of the world's population lives in coastal lowlands (e.g. Small and Nicholls, 2003) and this population is growing, especially in the world's megacities (Sekovski et al., 2012). Consequently, the coastal process domain is increasingly impacted, both directly and indirectly. River catchment developments (e.g. reservoir construction) may reduce coastal sediment supply (Syvitski et al., 2005), and coastal engineering and management interventions (e.g. groynes, harbour walls, navigation structures, storm surge barriers, dredging, recharge and reclamation) exert considerable control over coastal hydrodynamics and, hence, sediment transport. For instance, maintenance dredging for safe navigation is often required to remove sediment from channels that would not otherwise be flushed naturally, and locally increases the net sediment budget and accretion rates (e.g. Blott et al., 2006). Indeed, manipulation of hydrodynamics and sediment flux is an underpinning principle of both 'hard' and 'soft' engineering approaches but commonly has led to 'down coast' or 'downdrift' problems as humans have been, in essence, interfering with the natural redistribution of a limited sediment budget (Bruun, 1995). This human influence has controlled the existence of thresholds, creating geomorphic coastal regime shifts since the mid to late Holocene (e.g. Beets and van der Spek, 2000; Cooper et al., 2007; Blum and Roberts, 2009) such as where sediment starvation has led to reduced progradation and coastal erosion (e.g. Nile delta: Fornos, 1995). Recently, human intervention has tended to move from hard to soft engineering, which may involve augmenting and maintaining coastal sediment supply (dredging and beach recharge). In recent years, monitoring of coastal erosion has undergone a revolution owing to the availability of high speed high-resolution terrestrial laser scanning (TLS) that is capable of recording cliff faces at mm spacing at over 1 million points per second. TLS has recently been used in a study of cliff erosion rates in Druridge Bay, northeast England (Figure 4), where archaeological heritage is being lost due to a combination of natural change and sediment starvation caused by erosion protection elsewhere along this coast (Lobb and Brown in press).

Anthropogenic modification of shorelines, either deliberate or otherwise, has a long history. Some large delta systems have been able to keep pace (or even exceed) regional sea-level rise and coastal subsidence through changes to fluvial sediment supply (Syvitski et al., 1988; Saito et al., 2001). Probably the best example is the Ebro delta, Spain, which did not exist prior to the Roman period, and so is the creation of a late Holocene, anthropogenically accelerated sediment supply (Xing et al., 2014). Past manipulation of tidal inundation and sedimentation has included intertidal wetland 'reclamation' and 'warping' as well as the Terpen mounds in Zeeland and Friesland, where mounds were artificially created to provide flood protection in inhabited coastal lowlands (Charlier et al., 2005). These human interventions differ from the more widespread activity of reclamation (land claim *cf.* Allen, 1987), which involves preventing marine inundation of tidal wetlands by construction of embankments, then enabling dewatering and desalinisation of the soil for the creation of highly productive lowland agriculture (e.g. the English Fenland or Dutch Zuiderzee). In recent decades, large scale shoreline modifications have led to the emergence of entirely new anthropogenic coastal landforms (e.g. Palm Islands, Dubai; Kansai Airport, Japan).

The sedimentary consequences of these anthropogenic modifications are manifold. Coastal reclamation includes artificial fill of low-lying land, leading to anthropogenic deposits ('made ground') that overlie natural Holocene sediments (Jordan et al., 2016). In the Dee estuary, UK, navigation works at the head of the estuary caused rapid salt-marsh accretion along the English shore, replacing the low-water tidal channel and beach (Marker, 1967). Also, there is the 'unseen' legacy of human activities in the form of pre-historical and historical pollution, which can be used to reconstruct the diachronous impact of human activities on the world's coastlines. Much pollution is linked to ore mining and metal production in river catchments (e.g. Allen and Rae, 1986), but coasts also have been the main locations for metal and chemical industries (e.g. Plater and Appleby, 2004). In Europe, many salt-marsh sediments preserve a record of pollution from the Bronze Age, through the Roman and Medieval periods, to the more recent industrial era (e.g. Haslett et al., 1998; Plater et al., 1998; Davis et al., 2000; Alfonso et al., 2001; Carretero et al., 2011). Heavy metals, for instance, have been used to define a late Holocene stratigraphy in estuaries such as the River Severn, UK (Allen, 1987; Allen and Haslett, 2014). In other locations, pollen can record catchment land-use changes. In the US, for example, 'exotic' taxa in estuarine and lagoonal sediments can be linked to ranching, agriculture and logging arising from Mexican and European immigration (Mudie and Byrne, 1980; Brush, 1989).

Against the backdrop of dramatic eustatic sea level variations during the Quaternary but relative stability over the last 8 ka, human activity in the coastal process domain can be characterised as changing from process manipulation and consequential (often unintended) changes in coastal geomorphology to more direct shaping of coastal sediments and landforms. Many human activities have had a detrimental impact on coastal geomorphology, in some cases leading to significant shoreline degradation. This has worked against actions to artificially supplement coastal sediment supply through dredging and beach recharge, without which coastlines would experience wider sediment starvation. This does not bode well for future coastal developments, unless there is a managed transition to coastal ecosystems that are better suited to low sediment input and high rates of relative sea-level rise (e.g. perimarine wetlands; Plater and Kirby, 2006). For example, in the UK, there are currently several major managed re-alignment schemes that involve the deliberate breaching of sea defences to flood areas of coastal lowlands (e.g. Steart Peninsula, southwest England, and Medmery, southern England). In other cases, if present barriers were to be breached, they would probably not be re-built, such as was the case at Porlock, southwest England, in 1996 (Jennings et al., 1998).

In the coastal process domain, the interactions between natural controls, as exemplified by El Niño/La Niño dynamics, and human influences remain poorly understood but are critical to the understanding and management of landform dynamics. Nonetheless, the foregoing case studies demonstrate that an anthropogenic signature can be found in landforms and sediments along many coastlines worldwide.

Anthropogenic Landforms

Geomorphologists have long recognised the profound human influences on Earth surface processes and landforms caused by activities such as mining (e.g. Gilbert, 1917) and urbanisation (e.g. Wolman, 1967). Until relatively recently, however, the quantification and characterisation of human agency in geomorphology tended to focus on the identification of impacts of land use change, the global differentiation of sediment transfer masses and rates, and engineered environments. Following the `Great Acceleration´ (post-World War II), the rapid spread of mechanised agriculture, extractive industries and urbanisation has resulted in an increase in the abundance and prominence of anthropogenic landforms, namely those created as a direct and commonly deliberate result of human activities (e.g. Szabó et al., 2010). In some extensively farmed, mined or urbanised areas, the scale of human modification is now so great that anthropogenic landforms provide the main Earth surface boundary conditions for geomorphic processes (Foley et al., 2005; Ellis, 2011; Tarolli et al., 2014, 2015; Tarolli and Sofia, 2016). To illustrate our case, below we provide selective coverage of a range of anthropogenic landforms, including slopes, road networks, heavily modified drainage networks and mining-related features.

Artificial slopes and other landforms

Some of the most prominent anthropogenic landforms are agricultural terraces (Tarolli et al., 2014). Modification of slopes to form terraces had its origins in early agriculture in southwest Asia, northern China and Korea, and the practice later spread farther afield. In parts of southwest Asia, such as the Yemen, agricultural terracing is thought to date to the Neolithic (c. 3500 BC) while in much of the Mediterranean and northwest Europe, terraces date to the Bronze and Iron Ages (c. 3000-0 BC) (T. Wilkinson, 2005; Walsh, 2014). By reducing slope gradient, terraces facilitate cultivation on steep slopes, increase infiltration, and control overland flow volumes and velocity. Archaeological or historical terraces are generally of the bench (or fast) type with stone walls that require maintenance, so poorly designed or maintained terraces can enhance soil erosion rates, while well designed and maintained systems can reduce erosion rates (Tarolli et al., 2015). Consequently, once constructed, terraces document social history, in particular rural population densities, and influence soil erosion and land degradation. Geomorphologists are now making considerable advances in the automated detection of agricultural terraces from LiDAR and other forms of remote sensing (Sofia et al., 2014a; Tarolli et al., 2014) and this will feed into distributed basin models for water, sediment and pollutants. Sofia et al. (2014b) showed that natural slopes are more variable and less correlated, while artificially modified slopes with terraces have a high level of self-similarity. These differences can be statistically and automatically distinguished using a new topographic indicator termed Slope Local Length of Auto-Correlation (SLLAC) (Figure 5).

Other major anthropogenic slope forms include cuttings and embankments for railways, roads, canals and irrigation networks (Tarolli et al., 2013; Sofia et al., 2014a, 2014c). Since these forms are almost universally rectilinear and fall within a narrow range of gradients, particularly for embankments (26-32^o), this introduces a systematic element into regional slope-area relationships. Although fundamentally engineering structures, studies of their stability and sustainability have owed much to geomorphologists (Fookes et al., 2009). Geomorphological processes on engineered slopes will continue to be important in future, as unpaved roads ('dirt tracks') in the developing world are upgraded and metalled, invariably being associated with large areas of artificial slope that need to remain stable under changing climatic conditions. These new and expanded road networks, artificial slopes, and their related drainage systems will affect surface morphology, change local flow directions, and possibly increase soil erosion or landslide risk.

Urban development is also commonly associated with significant anthropogenic landforms (Thornbush, 2015). At least 741 630 km^2 (0.5%) of the Earth's terrestrial area is now urbanised (Schneider et al., 2009), in most cases leading to widespread removal of natural vegetation, creation of entirely artificial surfaces, and heavily modified drainage systems, as epitomised by Manhattan Island, USA (Figure 6). Urban drainage systems in particular exemplify many anthropogenic landforms (e.g. heavily channelised rivers, artificial flood basins, and sewerage systems) and have been the focus of much research (e.g. Chin, 2006; Chin et al., 2013; Gurnell et al., 2007).

Many other large-scale examples of anthropogenic landforms can be found, especially in China. The largest ever human refashioning of the landscape is currently taking place in central China (Lanzhou) where 700 mountains are being levelled to create more than 250 km^2 of flatter land. This is causing a host of geomorphic problems including subsidence, landslides, flooding and air pollution (Li et al., 2014). China is also undertaking large-scale land reclamation (island building) around atolls, reefs and sand bars in the South China Sea, with unknown implications for sediment dynamics and island stability.

There are also many medium- to small-scale landforms that appear to be entirely the result of human activity. Examples include 'roddons' - low raised palaeochannel infills that cross temperate wetlands - that are the result of artificial drainage and shrinkage of these lowlands (Brown, 1997). More diminutive human-influenced landforms include grazing steps, vehicle ruts and footpaths (Garland, 1990) but in most cases, these landforms do not have uniquely anthropogenic morphometric signatures and commonly are identified indirectly by vegetation change. Even human conflict has left a significant geomorphological signature through the construction of trenches and earthen banks, and the formation of bomb craters and vehicle tracks (Hupy and Koehler, 2012).

Holes in and under the ground

Holes in the ground (e.g. from quarrying and opencast mining activities) are morphologically different from natural landforms (Figure 7A) and will have longevity into the future, either in surface expression and/or stratigraphy (Zalasiewicz et al., 2011). In some cases, the spoil from these activities can also lead to the creation of distinctive landforms, such as the conical piles of china clay mining waste that have given rise to the 'Cornish Alps' near St Austell, southwest England, or the flat-topped and terraced gold mining dumps around Johannesburg, South Africa (Figure 7B). In developed economies, especially densely populated countries, the extent of anthropogenic landform creation through quarrying and mining is substantial, although as yet not fully quantified. Nonetheless, besides the impact on fluvial and coastal processes (see above), mining has become a focus of research because of its implications for geomorphic hazards (Mossa and James, 2013; Tarolli and Sofia, 2016). Open-cast mining, for instance, causes severe land disturbance that affects vegetation, soil, bedrock and landforms (Martín-Duque et al., 2010) as well as surface hydrology, groundwater levels and flow paths (Osterkamp and Joseph, 2000; Nicolau and Asensio, 2000). Together with climate (Erginal et al., 2008) and geology (Laimer and Mulleger, 2012), mining morphology can contribute significantly to landsliding susceptibility.

These and other examples of mining-related activities demonstrate that along with the creation of agricultural terraces, embankments and cuttings (see above), the volumes of rock/earth moving by human action can be considerable. For instance, in the UK, Price et al. (2011) have estimated that over the last 200 years people have excavated, moved and constructed a volume of soil and rock at least six times the volume of Ben Nevis, Scotland's tallest mountain. Artificial or 'worked' ground has long been a category on geological maps but it is now categorised into a series of 'domains' at 1:50 000 by the British Geological Survey (Figure 8). The practical reason for undertaking this exercise is to allow estimation of potential threats of instability or pollution under changing climatic conditions.

Geomorphology and Stratigraphy

Stratigraphic status, whether formal or informal, garners much attention in geological science. As pointed out by Gibbard and Walker (2014, p.30), stratigraphy "is the foundation upon which the discipline of historical geology, and therefore the accurate reconstruction of Earth history, depends." Stratigraphic status gives a level of authority to an assemblage of rocks, landforms, biota or chemistry and to the period of time involved, yet tends to provoke emotional judgements and generate contentious debate, as seen with the recent re-definition of the base of the Quaternary and Pleistocene (Gibbard et al., 2009 and references therein). A number of recent papers and volumes have been concerned specifically with the stratigraphic basis of an Anthropocene (e.g. Finney, 2014; Gibbard and Walker, 2014; Waters et al., 2014a, b; Zalasiewicz et al., 2011, 2014). Here, we seek to identify the geomorphological contribution to the debate. Four issues are considered: i) geomorphological evidence as a stratigraphic method and the source of stratigraphic units (morphostratigraphy) in a putative Anthropocene; ii) geomorphological processes as key drivers for the formation of sediments, biota and chemical compounds that constitute the materials of an Anthropocene chronostratigraphy; iii) a geomorphological perspective on the timing of the onset of an Anthropocene; and iv) alternative stratigraphic schemes.

Geomorphology, morphostratigraphy and an Anthropocene

By definition, stratigraphical criteria based on geomorphological features are morphostratigraphical, which means that landform shape provides the critical evidence. This is the case, for instance, with features such as displaced shorelines, moraine ridges, or river terraces that represent land-forming events over a given time interval (Frye and Willman, 1962; Allen, 2003; Lukas, 2006). With respect to an Anthropocene morphostratigraphy, this should mean that human processes are involved in the formation of a given landform, and that the human influence should be recognisable from the shape of that landform. Again, by definition, this should mean that landforms composed of made-ground or spoil, or that are specifically created (e.g. embankments, artificial levées, agricultural terraces and even ski-slopes) are anthropogenic morphostratigraphic units (Price et al., 2011; Ford et al., 2014). Likewise, depositional landforms built to imitate natural features for restoration, aesthetic planning or recreation purposes (e.g. hills, man-made pleasure beaches) are anthropogenic morphostratigraphic units, although they may be more difficult to differentiate from natural features (see below). Nonetheless, it may be possible to use anthropogenic morphostratigraphy to determine particular periods of time. For instance, English ridge and furrow are typically medieval (5th to 17th Century), although some were formed during 20th Century wars (Mead, 1954). In other parts of the world, as noted above, agricultural terraces define particular periods of landscape change (Hooke, 2006; Chepstow-Lusty et al., 2009). Documentation associated with industrial spoil heaps, quarries, open cast mines and strip mining also can provide an age for the morphostratigraphical features (Ford et al., 2014). The application of this principle is almost infinite, with a temporal resolution determined by the quality of the historical, archaeological or geochronometric dating.

Morphostratigraphy is clearly critical in making the case for an Anthropocene, as these landforms are unique to a human-influenced geological time interval. However, evidence of human activity is not restricted to landforms but also affects the constituents of sediments and rock that make up landforms, as these also may contain traces of anthropogenic input (e.g. 'plastiglomerate' now forming on certain Hawaiian beaches: Corcoran et al., 2014). In these cases, which are perhaps best approached through the perspectives of sedimentology, biology, meteorology or chemistry, the geomorphological contribution will be to clarify how geomorphic processes help to determine the end product: the polluted sediments, exotic plant or animal characteristics, and the anomalous atmospheric chemical compounds. An array of these highly diachronic anthropogenic signatures from megafaunal extinctions to radionuclides is listed in Waters et al. (2014b).

Geomorphological processes, chronostratigraphic evidence and an Anthropocene

From the foregoing, it is evident that understanding of an Anthropocene relies on the processes that act at the Earth's surface. Geomorphological processes are critical because they are responsible for landscape erosion and material transport to sediment sinks. Whereas the link between morphostratigraphy and an Anthropocene through identification of diagnostic landforms is straightforward, at least in principle, the proposition that geomorphology is key for investigating human-induced Earth surface changes may not be so clear, as many landforms are not diagnostic of human activity, and other evidence is needed to recognise the human impact. For instance, a river floodplain or delta, formed in response to human activity, may be morphologically similar to a floodplain formed without human influences, but may be clearly differentiated by sedimentology, or by lithological and biological evidence contained within the sediments comprising the landform (Evans, 2012; Brown et al., 2013b). Similarly, aeolian dunes, formed in response to vegetation clearance for agriculture may be morphologically indistinguishable from dunes formed without human influence, so differentiation requires evidence from geochronology and/or historical records (Bateman and Godby, 2004). To identify human impact in these cases, a multi-proxy approach to stratigraphy is necessary, for where a number of proxies coincide, the more credible is the stratigraphic outcome.

Human-driven or human-influenced geomorphological processes bring about the series that constitute the chronostratigraphy (Salvador, 1994; Zalasiewicz et al., 2014). Along with the morphostratigraphic units, they would make the Anthropogenic Series of an Anthropogenic Epoch. As such, they are similar to stratigraphic units from other parts of the geological column, and are very similar to the stratigraphic elements that underpin Quaternary stratigraphy. Attention has been given, however, to their limited potential for survival and thus for becoming a significant part of a long-term geological record (see Waters et al., 2014b). This concern can be addressed by noting that similar evidence, formed by geomorphological processes at the Earth's surface, has survived throughout the geological column, albeit less frequently than ocean or basin sediments. Attention is also drawn to the fact that these series are the basis for the classification of the Holocene as a separate epoch, despite that fact that this time interval is simply the last of many interglacials in the Quaternary Period (Gibbard and Walker, 2014). This is a semantic issue and not the concern of geomorphology; the critical fact is that human-driven or human-influenced geomorphological processes determine an Anthropocene. These processes form a definitive part of the Holocene, although they are independent of the currently proposed subdivisions thereof (Walker et al., 2012). Geomorphology therefore plays a major role in establishing the stratigraphic elements upon which an Anthropocene could be defined, both now and in a long-term stratigraphic record.

Anthropogenic geomorphological processes and the lower boundary of an Anthropocene

The location of a lower boundary for an Anthropocene has concerned many (e.g. Zalasiewicz et al., 2011, 2014; Gibbard and Walker, 2014, and references therein). Lewis and Maslin (2015) discuss two possibilities in defining the lower stratigraphic boundary of the Anthropocene: i) earliest evidence for human-induced stratigraphy which would be of local or regional significance only; or ii) a more distinctive event that can be recognised globally. The magnitude of this problem can be seen by the fact that the time span over which humans began to influence the Earth's surface may be greater than the span of an Anthropocene interval, depending upon which definition of an Anthropocene is adopted. In a consideration of possible alternative boundaries, Lewis and Maslin (2015) have proposed AD 1610 based on the Orbis spike dip in CO_2 observed in two core records from the Antarctic Ice Sheet, or AD 1964 based upon the bomb peak in ^{14}C. However, as they admit, these are only two possible candidates out of a large number of possible dates varying from early in the Holocene to the radionuclide events in the 1960s. Some have argued we have yet to reach the boundary (Monastersky, 2015).

An attempt to resolve this issue has been proposed by Foley et al. (2013), with the proposition that the time identified by the presence of hominins and by local and regional evidence should be known as the Palaeoanthropocene, and the interval after the Industrial Revolution (c. post-AD 1780), when human-induced changes started to significantly influence global climate, should be the Anthropocene proper. Alternative views can also be found (e.g. Ruddiman, 2003). In some ways the proposition for a Palaeoanthropocene recognises the importance of human activities in forcing geomorphological processes (e.g. Neolithic farming) but it does not solve the problem of the diachroneity of the lower boundary and it subsumes archaeological chronology. All stratigraphic boundaries are arbitrary, and arrived at by consensus through an 'accepted' procedure (Finney, 2014; Gibbard et al., 2009) but as far as geomorphology is concerned this issue should not be important. The geomorphological concern should be with process *per se*, rather than the formalisation of stratigraphy. It should provide the science behind the stratigraphic decisions, which even with the clarity or lack of resolution associated with geological time are often highly contested and generally represent compromises between universality, visibility and signal clarity.

Geomorphology and alternative stratigraphic schemes

The formal division of geological time is the responsibility of the International Commission on Stratigraphy, which is a constituent group of the International Union of Geological Sciences (Salvador, 1994). Any stratigraphic considerations should refer to the procedures of this organisation, especially with reference to the delimitation of timescales, and it is through these procedures that stratigraphic schemes are given authority. However, time is not the only information provided by stratigraphy, and for many professions, such as engineering, utility operations, the aggregate industry or the planning, finance and legal sectors, other geological properties are more important, such as lithology and texture, shrinkage potential (Harrison et al., 2012), flood potential, groundwater recharge potential, and erodibility. In these cases, the stratigraphic scheme approved by the International Commission on Stratigraphy may not be the most appropriate. Consequently, other schemes have been proposed, concentrating on surface materials where the industrial and commercial interest is focused (Walton and Lee, 2001). Rose (2010) has proposed a scheme for temperate latitude regions, exemplified by the British Isles, in which the stratigraphy is determined by processes operating on the landscape, and has identified four major systems, of which one is Holocene and Human Activity (HHA). By definition, HHA incorporates anthropogenic processes and identifies their importance within the areas concerned. McMillan and Merritt (2012) provided a scheme, again appropriate for the Quaternary (and hence an Anthropocene), in which the lithological properties of surface rocks are given priority, with time taking a secondary role. As geomorphology determines the distribution of different lithologies, say through ice-flow direction or sediment transport in drainage networks, it is a prime factor in the differentiation of the various stratigraphic units, but human impact is not traditionally considered. Thus, when geological materials are defined in terms of functionality rather than age, geomorphology can be a prime factor in deriving a stratigraphic scheme and the consideration of anthropogenic processes may be obligatory.

The Reciprocal Impact of Anthropogenic Landforms on Second-Order Geomorphic Processes

As outlined in the foregoing sections, mass fluxes associated with anthropogenic landforms such as agricultural terraces and engineered slopes are a prime feature of the putative Anthropocene. Geomorphology and civil engineering have a long history of studying such landforms and fluxes, partly because they can be viewed as open-air laboratories where boundary conditions are more easily controlled or measured. Classic examples include studies of rill and gully erosion on mining spoil heaps (e.g. Nyssen and Vermeersch, 2010), water chemistry changes resulting from acid mine drainage (Pirrie et al., 1999) and the failure of engineered slopes (Hutchinson, 2001; Fookes et al., 2009).

As areal coverage of anthropogenic landforms increases (*cf*. ‘made ground’ – Figure 8), then these fluxes will become proportionately or even disproportionately important. A related, more geological, argument is one of persistence, namely that these landforms, mass fluxes and sedimentary products are not transient but will persist into the future, with potential to enter the geological record. This potential depends upon the tectonic and physiographic content and the nature of the associated processes. For example, in fluvial systems, preservation is determined by tectonic setting (uplift, subsidence) and the relative importance of aggradation, incision, lateral migration and avulsion (e.g. Lewin and Macklin, 2003) so preservation patterns vary geographically in response to local and regional factors. For the Frome catchment, southwest England, it has been estimated that anthropogenically-accelerated floodplain alluviation has been so great over the last 4 ka that it would take in the order of 20-30 ka to remove the alluvium at the current rate of fluvial erosion (Brown et al., 2013b), which might render it geologically persistent. A complication here is the length of the current interglacial: if Berger and Loutre (2002) are correct, the ultimate geological signature of the Anthropocene will be a delay in the timing (or even suppression) of the next glacial. This scenario would facilitate the preservation of most lowland anthropogenic fluvial sediments and would be by far the largest geomorphological and stratigraphic impact of humans. Such fluvial mass balance changes can also impact on other geomorphological process domains, especially at the coast (see above). A subtle and yet to be fully elaborated effect is that of changing the tidal reach of rivers through increasing channel confinement and reclaiming marginal saltmarshes; in effect, creating a pseudo-regressive boundary that is not related to relative sea level fall (Havelock, 2009) and that is the opposite of the sediment starvation effects mentioned above.

Globally and on a geological timescale, this question of reciprocity may have profound dimensions. The view that humans are now the dominant force in global environmental change has led some to argue that we are outside the geological timescale and that maybe the geological scale stops now (Finney, 2014). However, it is hard to reconcile this viewpoint with the continuation of fundamental geomorphic processes and landform development. Humans can drive geomorphic systems, the products of which will persist and affect the future. Geological processes driven by the Earth’s internal dynamics will also continue (e.g. global tectonics), although even they may be sensitive to feedback processes of vegetation and soil that may be influenced by human activity (Herman et al., 2013). Nevertheless, although we will remain within the geological timescale, how we segment and classify that timescale may have to change, since we may now lie outside the past geological norms that formed the basis of international stratigraphic procedures as formalised by Hedberg (1976).

Human Versus Nature in the Anthropocene

Both the underlying rationale for the Anthropocene and its manifestation through Earth surface processes may have profound conceptual implications for geomorphology and the wider geosciences. For such disciplines, the climate system has tended to be viewed as driven naturally by energy from the sun and distributed naturally by the global atmospheric and oceanic systems, and for many researchers this is still the case. This assumption fed into the difficult, but possible, differentiation of human versus natural forcing factors on Earth surface systems. However, if the climate system is significantly influenced by human activities, even if this is to an unquantifiable extent, then it cannot be equated with natural forcing in geomorphology. Therefore, it follows that attempts to differentiate between human and natural forcing become intractable, so representing a spurious or a meaningless vestige of Cartesian dualism (Rhoads and Thorn, 1996). The most pertinent aspect of this discussion is what effect the formalisation of the Anthropocene could have on geomorphology as a discipline, as there is the distinct risk that it could require reconsideration of its uniformitarian underpinnings (cf. Knight and Harrison, 2014; Paul, 2014). It follows that geomorphology, by definition, should provide the authority and substance for morphostratigraphy, even if this is not divisible into human versus natural forcing.

This pragmatic approach is also required because the changes to aeolian, fluvial, cryospheric and coastal process domains resulting from human-modified sediment fluxes and energy distributions have also altered ecosystems and critical zone processes responsible for ecological integrity (*sensu* Graf, 2001), ecosystem service provision (Millennium Ecosystem Assessment, 2005) and sustainability (*sensu* Parrish et al., 2003). Perhaps the most obvious example is the vast literature on the effects of soil erosion on the spawning of salmonid fish (e.g. Lisle, 1989; Sear, 1993; Jensen et al., 2006). Less obvious examples are the effects of exotic riparian plants on bank stability (e.g. McCarthy et al., 2010), or the little-researched effect of solar panel arrays on soil erosion due to runoff redistribution.

Conclusions

From our review of four key process domains, it is clear that the relevance of the Anthropocene concept varies substantially between different branches of geomorphology. Fluvial and coastal geomorphologists, especially those working in densely populated regions, tend to see human impact throughout the landscape (e.g. Wohl, 2013). Periglacial and glacial geomorphologists, mostly working in sparsely populated regions, tend to see vast expanses of tundra, boreal forest or ice sheets as fundamentally natural with little direct human impact. Aeolian geomorphologists, commonly working in drylands, recognise that aeolian landscapes increasingly are impinged upon by human activities, but any resultant landforms rarely, if ever, display features that allow their unequivocal distinction from the natural. Increasingly, however, all these process domains are being impacted by anthropogenically-driven climate change, albeit as mediated by the respective geomorphological reaction times. It is theoretically possible that even tectonic forces could be affected by human activities as there appears to be a correlation between zones of rapid uplift and intense precipitation, and this accords with model predictions where the trigger is a climate-driven increase in the erosion rate (Whipple, 2008). So by altering synoptic weather patterns, humans could influence some components of tectonic evolution, although it is likely that such influences would be small relative to other geodynamic forces.

The implication from the perspective provided by geomorphological considerations is that the putative Anthropocene should have an *informal* stratigraphic status accommodating a highly diachronous lower boundary. Formal identification essentially would be arbitrary and impractical under existing stratigraphic procedures (Lewin and Macklin, 2013) and would also be very unlikely to garner universal or even majority support amongst geomorphologists or the wider geoscience community. Where different outcomes are required, such as utilitarian information for society, Earth history can be told using other stratigraphic schemes, in which geomorphology has a prominent role in providing explanations for the form, composition and distribution of surface materials. Societal implications may include the maintenance of ecological functionality, ecosystem service provision and sustainability.

Two practical implications follow. First, the less obvious effects of humans on geomorphic systems warrant increased research. This is the 'knowledge for mitigation' that needs to be in place to advise policy makers. Second, we need to improve the criteria for *diagnosing* human impacts on the connectivity, integrity and resilience of critical zone processes, and this can be seen as an opportunity (Wohl, 2013). This recognition not only includes the development of existing techniques such as the remote sensing of land cover and landforms and the biogeochemical analysis of sediments, but also a new way of conceptualising the role of humans both through processes and materials within ecosystems as well as at the global scale. The geomorphological impact of new materials from geotextiles to smart concrete is clearly a part of an Anthropocene that we can recognise at a variety of spatial and temporal scales. While this scale dependency of the Anthropocene complicates its formal recognition in geological terms, it is a key element in the application of geomorphology for environmental management in a future world that may host nine billion people by mid-century.

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Figure captions

Figure 1. Dust deposition rates (AD 1700 to 2006) in the Snowy mire core (Marx et al., 2014). The grey outline shows 2 sigma errors. The letters on the plot refer to key events: A = dust pulses during the Little Ice Age; B = the onset of agriculturally-induced wind erosion; C = the Federation Drought; D = the 1914 drought; E = the Dust Bowl era; F = the early 1970s and G = 1980s droughts; and H = implementation of concerted soil conservation measures.

Figure 2. Radiocarbon-constrained Holocene floodplain sedimentation rates for the UK, with summed probability distribution of cereal/crop dates (derived from Macklin et al., 2010 and Stevens and Fuller, 2012).

Figure 3. Summary of the fluvial system over 10-1000 year timescales. The diagram is divided into four areas: i) allogenic drivers; ii) catchment characteristics; and iii) the fluvial process domain, which includes iv) the autogenic process domain (image produced by V. Thorndycraft). The outer box includes the main allogenic drivers (at centennial-millennial timescales), including human impact. The grey box includes some general catchment characteristics that could produce spatially variable fluvial responses; within this box is the fluvial processes domain, with an inner box (dashed outline) showing key parts of the system affected by autogenic processes. Arrows show some key pathways operating within the fluvial system: black arrows show the natural allogenic drivers, grey arrows show the main processes, and dashed lines show the key human impacts. In italics are the key human impacts: note how they can influence all four areas of the diagram. The regional geography and geological setting of a particular river will influence the relative magnitude of the impacts of the natural and human drivers, and the signal of those drivers in alluvial sedimentary records will depend on catchment characteristics and autogenic processes that can influence geomorphic thresholds.

Figure 4. Oblique model of the results of a Terrestrial Laser Scanning survey of rapidly eroding Quaternary cliffs at Low Hauxley, Druridge Bay, northeast England. The image shows the difference (in metres) between scans in May 2013 and March 2014 and the cliff section is c. 100m long. The image was produced by M. Lobb using a Leica C10 Scanstation with CloudCompare©.

Figure 5. Images illustrating the detection of the anthropogenic topographic signature of terraced landforms in the Alpine context (Trento Province, central Italian Alps, Italy). Images of natural (a-d) and terraced landscapes (e-h) are derived from: aerial photographs (a and e); shaded relief maps derived by 2 m Lidar DTMs (b and f); slope maps (c and g); and maps of Slope Local Length of Auto-Correlation (SLLAC) (d and h). The Lidar dataset is offered for free download by the Autonomous Province of Trento (Alps). Natural landscapes show maps of SLLAC with randomly distributed elements and a highly noisy background, whereas the construction of terraces leaves a clear topographic signature that results in more regular SLLAC maps with ordered elongated elements that follow the terrace benches.

Figure 6. Images illustrating land transformation on Manhattan Island, east coast, USA. Top: artistic impression of the landscape before urban development (reproduced from National Geographic Magazine, September 2009, with permission of the National Geographic Society). Bottom: the present-day city of New York City (© Robert Clark/INSTITUTE for Artist Management).

Figure 7. Oblique aerial views of mining-related landforms: A) the Udachnaya pipe, an opencast diamond mine in the Daldyn-Alakit kimberlite field in Sakha Republic, Russia. At more than 600 m deep, it is the third deepest opencast mine in the world. For scale, note the large vehicles around the sides and at the bottom of the mine. Photo licensed under the Creative Commons

Attribution-Share Alike 3.0 Unported license; B) gold mining dumps (pale, partially vegetated areas) south of Johannesburg, South Africa. For scale, note the roads and the low rise dwellings adjacent to the dumps. Many other hundreds of dumps up to ~50 m high dot the area around the central city (the skyline is just visible on the horizon), and stand testament to the major transformation of the landscape that has taken place since the late 19th Century.

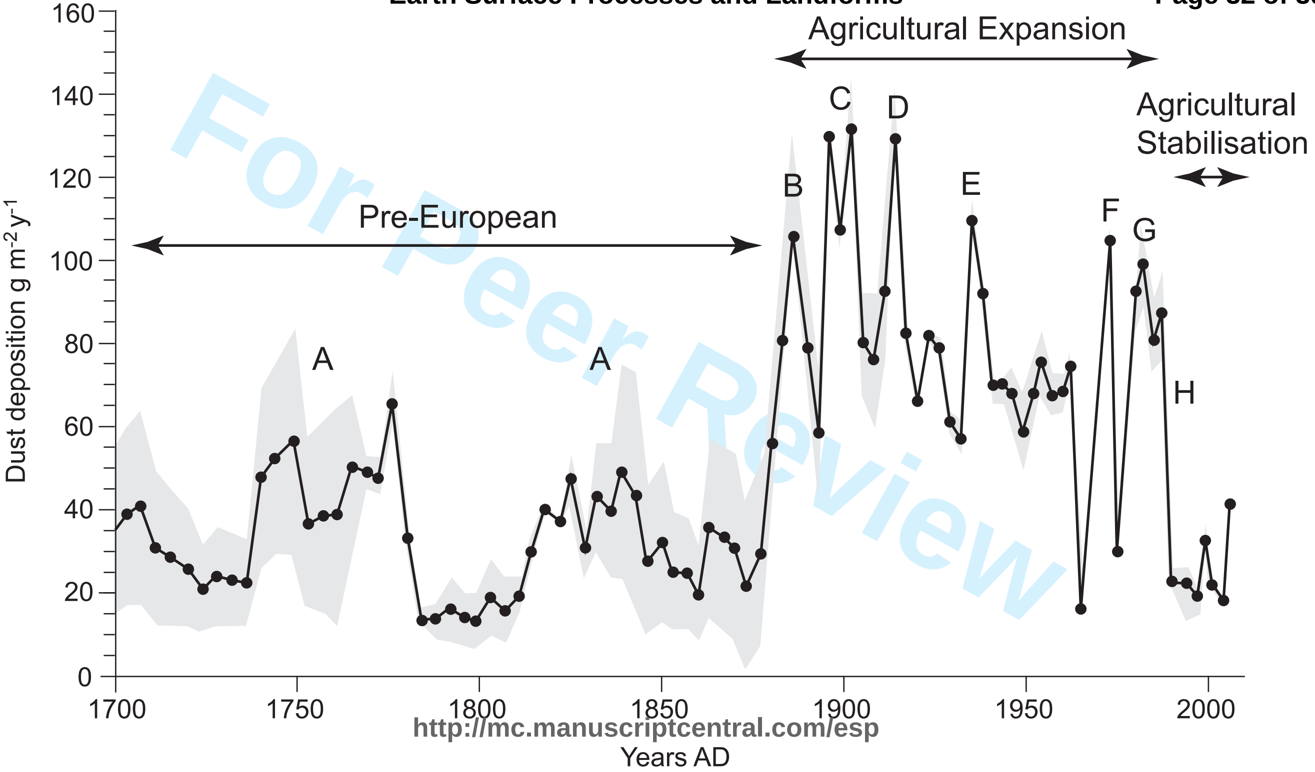
Figure 8. The mapped distribution of artificial ground in Great Britain (from Price et al., 2011 and OS Topography © Crown Copyright. All rights reserved. 100017897/2010. DiGMapGB BGS © NERC).

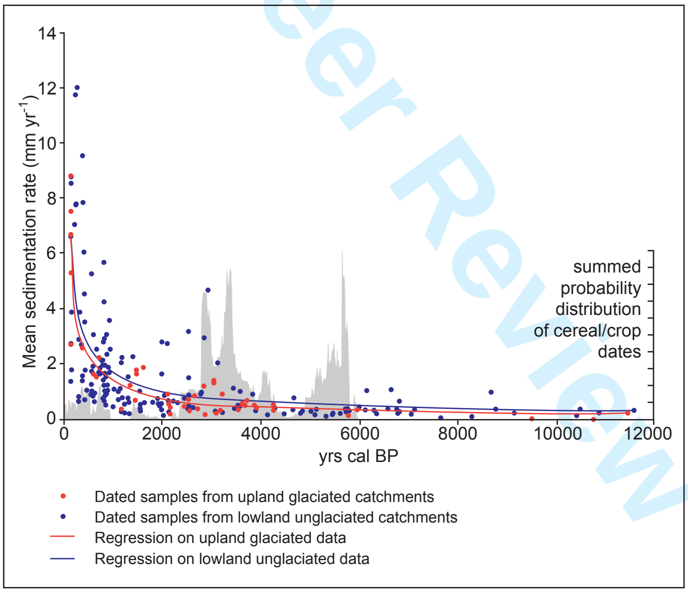
Table 1. Approaches to the measurement of natural erosion and denudation rates.

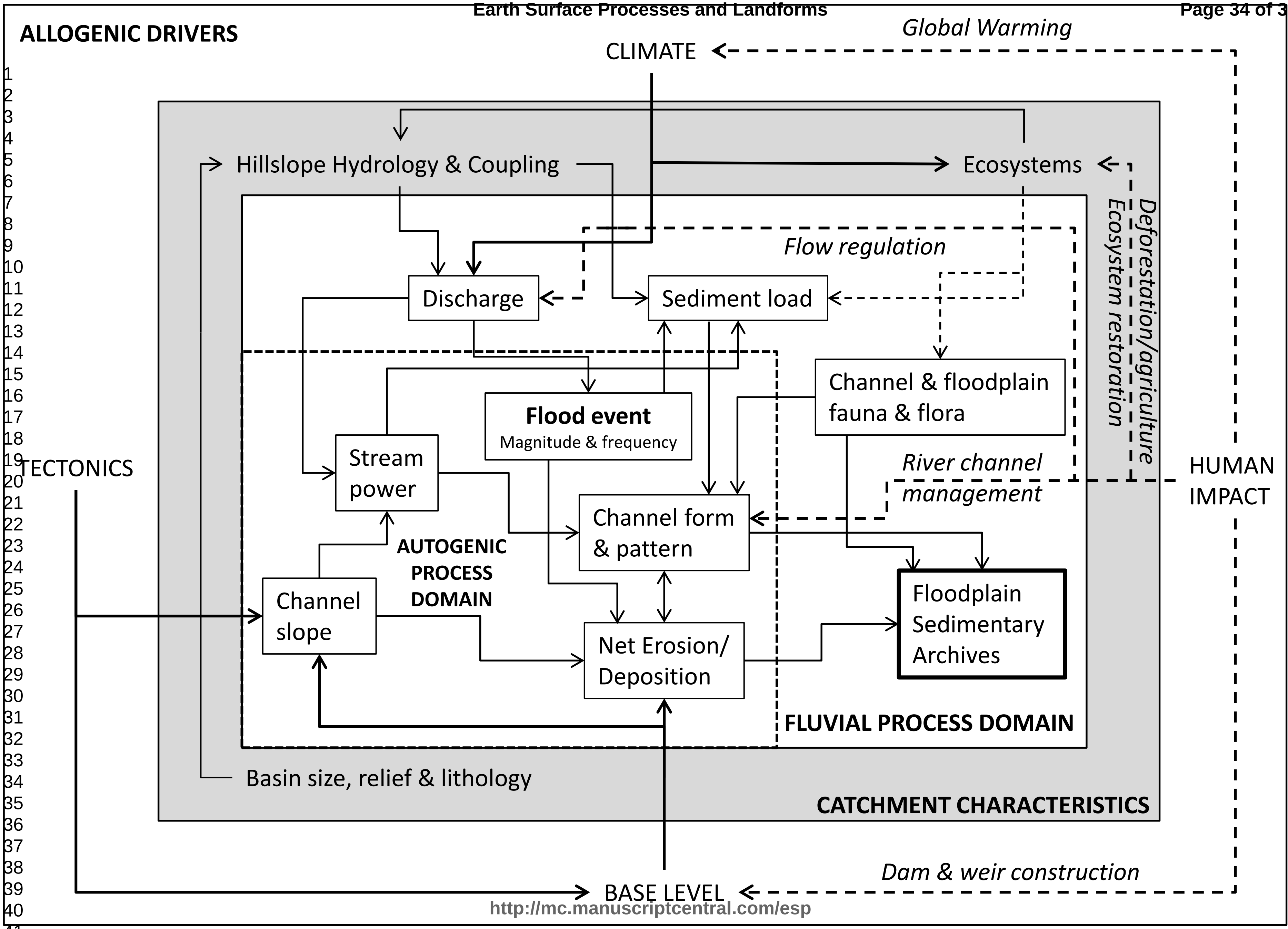
Method	**Spatial Scale (m^2)**	**Temporal Scale (years)**	**Limitations**	**Example references**
Erosion plots under natural vegetation (incl. Cs method)	10^2-10^3	10^1-10^2	a) Assumption of naturalness of vegetation including past soil history b) Limited sample size c) Restricted soil/bedrock types d) Lack of representation of conditions over multi-annual timescales because of closure of the upper boundary of the plot e) Poor recognition of controls on the scales of operation of different parts of the erosion process	Ritchie and McHenry, 1990; Risse et al., 1993; Kinnell, 2005; Parsons et al., 2004, 2006b
Natural river basin sediment loads	10^4-10^{10}	10^1-10^2	a) Assumption of naturalness of vegetation including past soil history c) Storage assumptions (steady state)	Walling and Webb, 1996; Syvitski et al., 2005
Cosmogenic isotope-based basin denudation studies	10^4-10^{10}	10^3-10^6	a) Storage constancy – assumption of equilibrium b) Non-anthropogenic climate change c) Bias to hard lithologies (granites etc.)	Small et al., 1999; Heimsath et al., 1997, 2000; Wilkinson et al., 2005
Denudation rates from compositions of sedimentary rocks	Continental/global	$>10^6$?	a) Very approximate mass estimates b) Variable and unknown temporal scales	Ronov, 1983: Pinet and Souriau, 1998

Table 2. Factors that initiate, retard or counteract thermokarst activity (Murton, 2009). Human activities can affect many of these factors, either directly or indirectly.

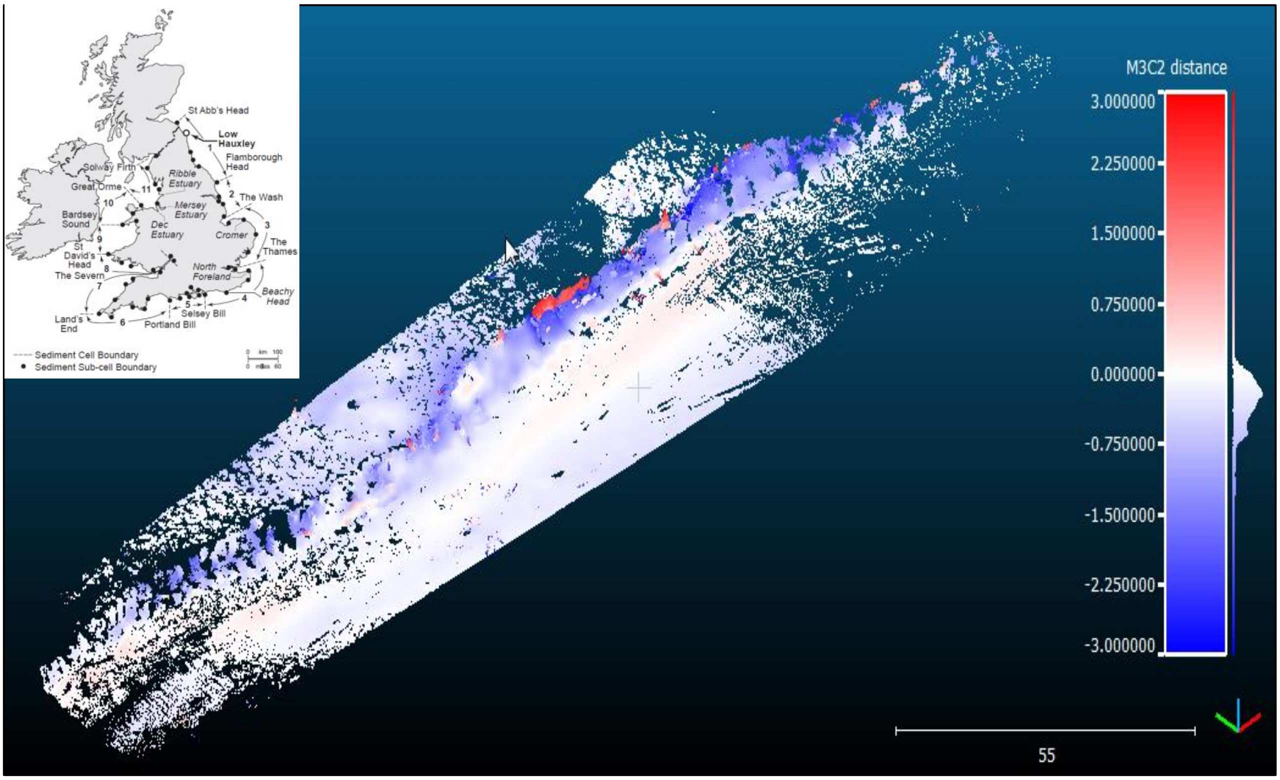
Scale	**Factors**	**Initiating disturbances**	**Retarding or counteracting factors**
Local	Vegetation and surface organic mat	Damage or removal	Regrowth of vegetation
		Compaction of peat or organic soil	Accumulation of peat or organic soil
	Water	Ponding on ground surface or underground	Drainage of ponds, lakes or cavities
		Flowing surface or groundwater	Refreezing of underground pools
			Reduction or diversion of drainage
		Wetting of dry peat in summer	Drying of peat in summer
	Snow cover	Thicker snow cover	Thinner snow cover
		Reduced snow density	Increased snow density
		Early snowmelt in summer	Late snowmelt in summer
	Overburden thickness	Soil erosion exposes ice-rich ground	Deposition of sediment
		Artificial removal of soil	Burial of ice-rich ground by spoil
	Artificial substrate	Laying of gravel pad too thin to contain seasonal freezing and thawing depth	Thicker gravel pad Insulation placed beneath gravel
	Artificial heat source	e.g. Heated buildings, pipelines, utilidors	Dissipate heat (e.g. allow cold air circulation or use thermosyphons)
Regional	Mean annual air temperature	Climate warming	Climate cooling
	Regional snowfall	Thickening snow cover	Thinning snow cover
		Early accumulation of snow in winter	Later accumulation of snow in winter
	Summer weather	Unusually warm weather	Typical weather
	Continentality	Increased continentality	Decreased continentality
	Large forest fires	Damage vegetation or surface organic mat	Regrowth of forest


Agricultural Expansion
Agricultural Stabilisation
Pre-European
A
A
B
C
D
E
F
G
H
Dust deposition g m-2 y-1
160
140
120
100
80
60
40
20
0
1700
1750
1800
1850
1900
1950
2000
Years AD


14
12
10
8
6
4
2
0
Mean sedimentation rate (mm yr^{-1})
0
2000
4000
6000
8000
10000
12000
yrs cal BP
summed
probability
distribution
of cereal/crop
dates
Dated samples from upland glaciated catchments
Dated samples from lowland unglaciated catchments
Regression on upland glaciated data
Regression on lowland unglaciated data



Fluvial System: centennial /millennial timescales


St Abb's Head
Low Hauxley
Flamborough Head
Solway Firth
Ribble Estuary
Great Orme
Mersey Estuary
The Wash
Bardsey Sound
Dee Estuary
Cromer
The Thames
St David's Head
The Severn
North Foreland
Beachy Head
Land's End
Portland Bill
Selsey Bill
1
2
3
4
5
6
7
8
9
10
11
Sediment Cell Boundary
Sediment Sub-cell Boundary
0 km 100
0 miles 60
M3C2 distance
3.000000
2.250000
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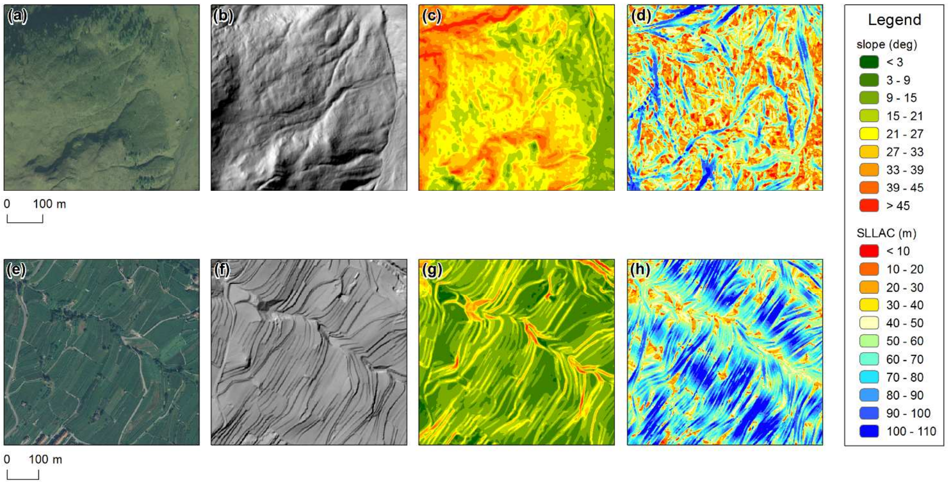
-2.250000
-3.000000
55



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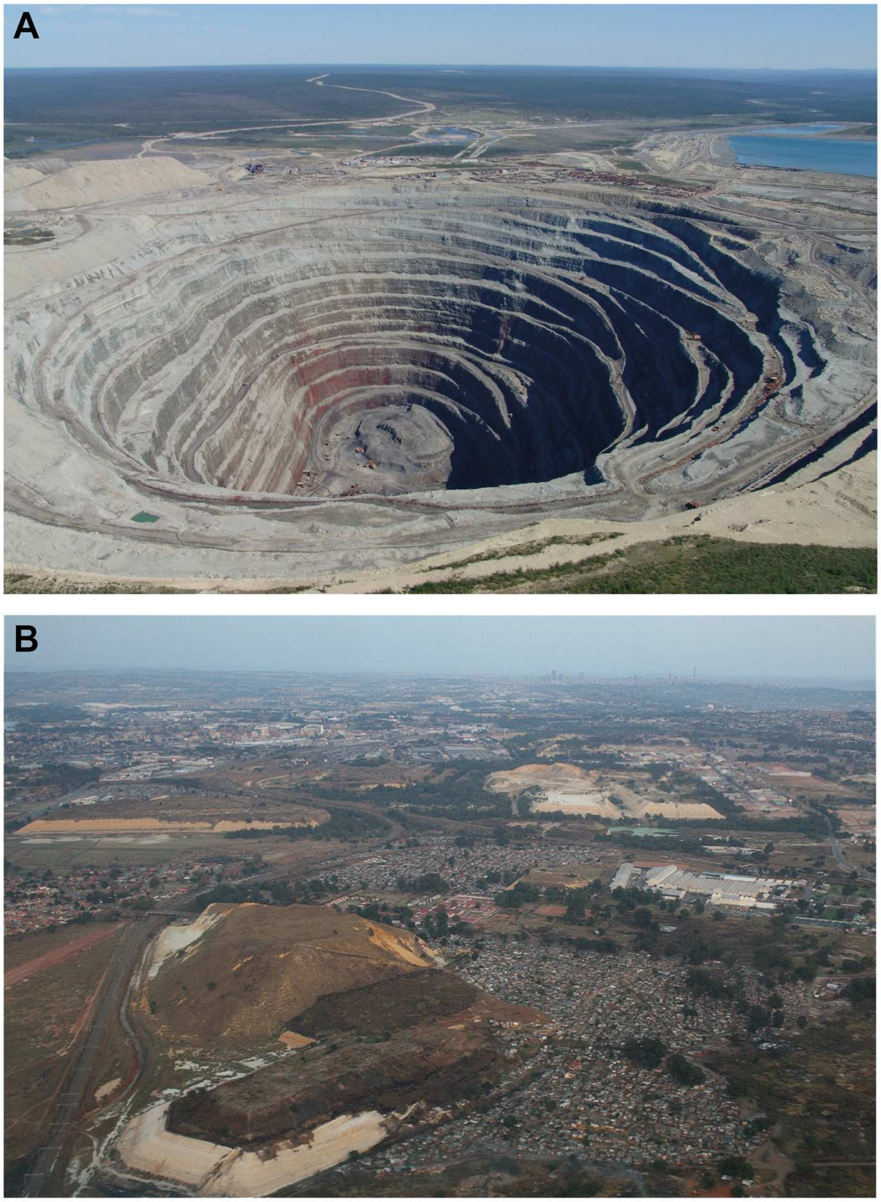
479x250mm (150 x 150 DPI)



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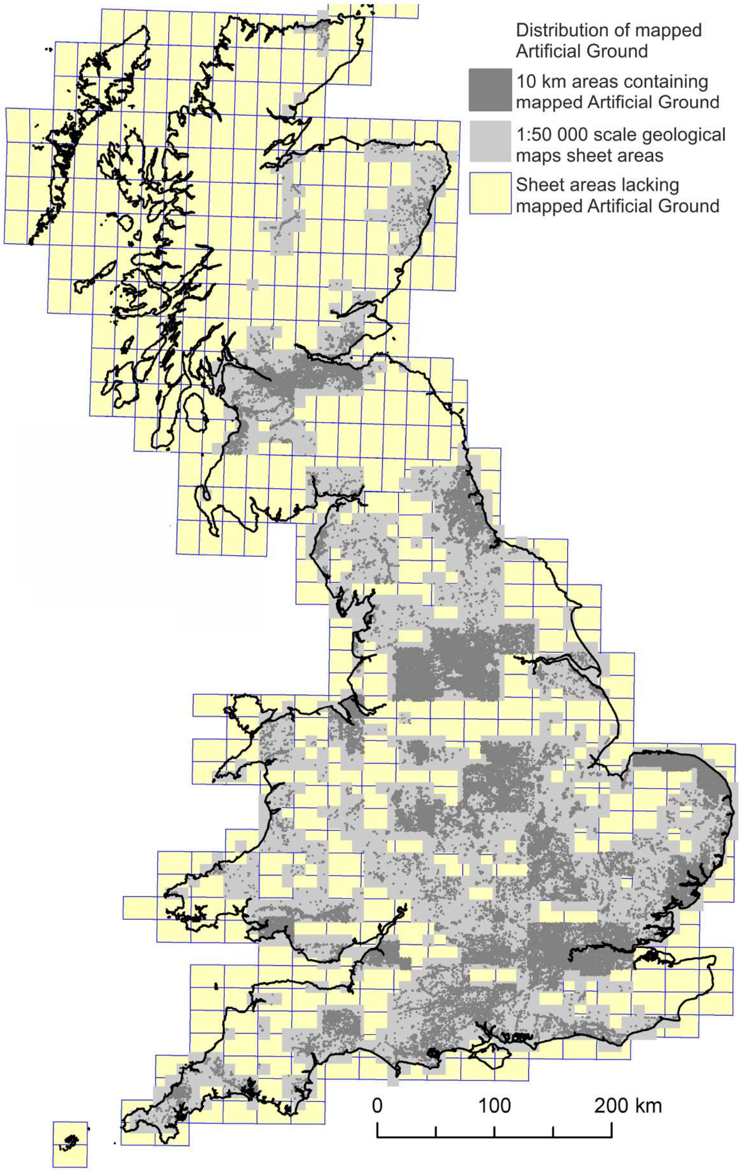
152x207mm (300 x 300 DPI)



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