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Recasting geomorphology as a landscape science

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ABSTRACT

There is a common acceptance that the Anthropocene epoch is characterized by the increasing dominance of human activity as a driver of global terrestrial change. Geomorphology, with its historical roots in geology and geography, would seem to be ideally positioned as a geoscience to tackle the well documented, rapidly degrading health of that environment. However, the word 'geomorphology' is problematic outside the academy in a way that 'landscape' is not. A more explicit identification of geomorphology as a landscape science would encourage engagement by geomorphologists in one of the most urgent environmental questions of our time. If humanity is indeed the most important driver of environmental change, we propose that geomorphologists need to engage more seriously with the cognate landscape sciences, such as landscape architecture, anthropology and political ecology. In particular, there are landscapes that are more threatened than others and critical zones in landscapes that must be protected and enhanced with greater care than others. We argue that recasting geomorphology as not only a geoscience but also a landscape science would highlight issues of human well-being at different spatio-temporal scales and we illustrate this in three case studies from our respective countries: UK, Canada and Austria. As traditional geoscientists, we are not used to thinking of coastal flooding, permafrost degradation and snow depletion as centrally important to our science. But as landscape scientists the inclusion of these and all other components of the cryosphere's interaction with human wellbeing is entirely logical and the distinction between systemic and cumulative environmental responses provides a key to unravelling the variable contributions of local actors, managers and decision makers to environmental degradation. Decision making at zonal, regional and local scales are integral to the way in which geomorphic systems function. This argument clearly has wider application. It is up to geomorphology, acting as a landscape science, to provide the underpinning principles that identify landscape-changing actions as being unsustainable and in providing better-informed future pathways away from such actions.

1. Introduction and objectives

In light of the environmental and social crisis driven by humanity's stress on the terrestrial surface of Earth, we believe that there is a need to recast geomorphology as a landscape science (Goudie and Viles, 2010). Landscape science takes its definition from Alexander von Humboldt's definition of "landschaft" (landscape) as the "totalcharakter einer Erdgegend" (literally meaning the total character of a region of the Earth, which includes landforms, vegetation and landuse) (Humboldt, 1849–1864). Consistent with Humboldt's discussion, we propose a definition of landscape as 'an intermediate scale region, comprising landforms and landform assemblages, ecosystems and anthropogenically modified land' (Slaymaker et al., 2009). The declaration that an Anthropocene epoch has arrived (Crutzen and Störmer, 2000) has provoked a re-evaluation of the nature and purpose of many landscape sciences, including, for example, ecology (Gunderson and Holling, 2002); geography (Turner et al., 2007; Castree, 2016); and anthropology (Monastersky, 2015). Although the debate is many-sided and contested (cf. Lewis and Maslin, 2018; Ruddiman, 2018) there is a common acceptance that the Anthropocene epoch is characterized by the increasing dominance of human activity as a driver of global environmental change. No part of Earth's terrestrial surface is without human impact (where interventions are at regional and national scales). Furthermore, human agency (the capabilities of human beings, primarily limited to local scale activity) is everywhere seen to transform that surface, whether for good or ill (Fraser et al., 2003). The deteriorating state of the global environment as identified by a number of global research groups, such as the IPCC (Vaughan et al., 2013; Masson-Delmotte et al., 2018; IPCC, 2019), the Resilience Alliance (Holling, 2001), and the Global Footprint Network (Wackernagel and Rees, 1996) have challenged nation states to adopt environmental sustainability policies. Yet within these framings, geomorphology has achieved relatively little influence (Slaymaker, 2001; Lane, 2013; Spencer and Lane, 2017). A second, intellectual pathway has been from UNEP's Global Biodiversity Assessment (1995), through the Millennium Ecosystem Assessment (2000–2005) to the

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Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (2019). The absence of any reference to geomorphology in the recent report on declining biodiversity and associated threats to ecosystem services (IPBES, 2019) is a further indication of the limited engagement by geomorphologists in one of the most urgent questions of our time. We identify a few of the possible reasons for this situation in Section 2.

Making a judgment on the sensitivity of a landscape to change requires deep understanding of landscape changing processes, and such understanding is the professional geomorphologist's primary responsibility. Understandings of connectivity and disconnectivity, proximity to thresholds and non-linear change have become focal issues in landscape change (Brunsden, 1993; Harvey, 2002; Slaymaker, 2019-2020). Where the drivers of change are understood, landscapes can be respected as sources of human well-being, providers of water, food, timber and fibre; regulators of land use and land cover, water supply and water quality; and supporters of soil formation, photosynthesis and nutrient cycling. If humanity is indeed the most important driver of environmental change then geomorphologists must also engage more seriously with cognate landscape sciences, such as landscape architecture and political ecology (Dauvergne, 2008; Lave et al., 2014; Tadaki et al., 2017). In addition, a longer geoscience perspective remains essential to understand the events of the Anthropocene epoch in perspective. Thus, for example, fossil and paraglacial landscapes are still adjusting to the legacy of the Pleistocene Epoch (Church and Slaymaker, 1989). In light of the rapidly degrading environment, geomorphologists cannot avoid participating in the environmental change debate. In particular, there are landscapes that are more threatened than others and critical zones in landscapes that must be protected and enhanced with greater care than others (NRC, 2001; Harden, 2014).

We have three objectives:

(a) To recast geomorphology as not only a geoscience but also a landscape science (Section 2).
(b) To demonstrate the usefulness of the distinction between systemic and cumulative environmental change in interpreting landscapes at different spatio-temporal scales in three case studies (Section 3) and
(c) To underline some of the different human wellbeing issues at stake in our respective case studies (Section 4).

2. Recasting geomorphology

Geomorphology is most simply defined as the study of Earth's surface and the processes that shape it (Goudie and Viles, 2010). Yet, surprisingly, the word ‘geomorphology’ is known neither to the general public nor to many members of the academy. By contrast, the word ‘landscape’ is universally recognized even if not universally understood (Williams, 1989; Wylie, 2011; Stilgoe, 2015). Geomorphologists have made many contributions to understanding humanity's role in landscape change. Examples include, inter alia, man's (sic) role as a geological agent (Jennings, 1966), accelerated sedimentation (Trimble, 1974), the human impact (Goudie, 1981), coral reef degradation (Stoddart, 1982) and the erosion of civilizations (Montgomery, 2007). But geomorphology as a discipline has been arguably the least resilient of the landscape sciences in responding to the new reality of the Anthropocene (Goudie and Viles, 2016). Reasons for this lack of resilience include, inter alia, emphasis on microscale studies to the near exclusion of landscape scale studies, and resistance to incorporation of questions of human agency as being beyond the remit of geomorphology as a geoscience (Braun and Castree, 1998). Geomorphology finds its disciplinary origins in a positivist tradition that views “the sense of causality running from the physical environment to its social impacts” (Hewitt, 1983, p.5). But the sense of causality does not run exclusively from nature to culture (Bhaskar, 2008, 2010). Phenomena that can neither be seen nor measured are as much part of the real world as measurable and visible phenomena (Polanyi, 1958; Goudie, 2002). One of the serious consequences of this reticence to commit to questions of human agency in landscape scale studies has been the comparatively muted voice of geomorphology in global environmental crises of the past few decades.

We propose to address the problem of geomorphology's comparative absence from the core of the environmental debate by (a) recasting our discipline as a landscape science so that geomorphology can engage the broader debate, both in academic and societal context; and (b) arguing that awareness of the discipline would likely increase if it were to be recast as both landscape science and geoscience (Slaymaker, 2001, 2009). The central thesis of this paper is that geomorphology's identification as a geoscience needs to be complemented by a stronger identification as landscape science, in which human agency plays an increasingly central role (Turner et al., 1990; Slaymaker and Spencer, 1998; Slaymaker et al., 2009; Church, 2010, 2013; Gregory and Lewin, 2000; Spencer and Lane, 2017). Three case studies from the UK, Canada and Austria are used to illustrate the advantages of viewing the central role of geomorphology as a landscape science, specifically in relation to its enhancement of human well-being.

3. Systemic and cumulative global environmental change

At the start of the IPCC process (Houghton et al., 1990), a landmark paper by Turner et al. (1990) argued that global environmental change consists of two components: systemic change and cumulative change. Systemic change is global-scale, physically, ecologically, and socially interconnected change; cumulative change deals with local- to intermediate-scale processes which, when summed, have a significant net effect on the global system (Slaymaker et al., 2009; Spencer et al., 2009; Hulme, 2010; Kondolf and Podolak, 2013; Spencer and Lane, 2017). We interpret this distinction by plotting system size (in log. km^2) against system response time to perturbation (in log.yrs) (Fig. 1).

The systemic response is represented by the global environment-human interaction system, driven by solar energy flux, terrestrial relief, geodynamic processes and land use. In the ensuing discussion, we focus on sea level rise, permafrost thaw and snow depletion, firstly at global scale and secondly at regional and local scales. The system is defined by Earth's terrestrial surface, A (of order 10^8 km^2) and a wide range of response times, T (of order $10^{-3}$to 10^9 yrs). The cumulative sub-systems that are discussed *seriatim* include regional and local ways in which human interactions with sea level change, permafrost thaw and snow depletion enhance human well-being. These sub-systems can be

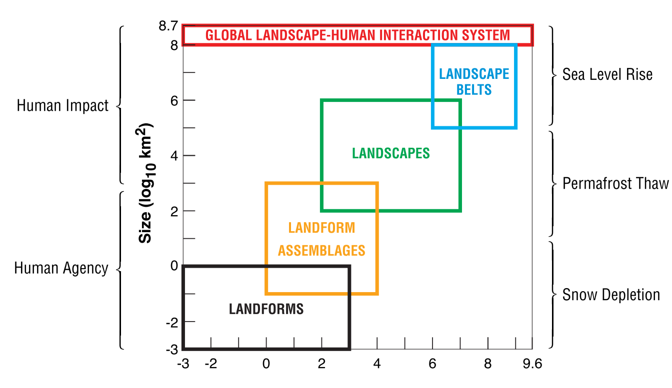


Fig. 1. The spatio-temporal hierarchy of global landscape-human interaction systems: systemic and cumulative response. Systemic change is global scale and is depicted as the global landscape-human interaction system (in red); cumulative response is represented by the subsystems nested within the global system. The right-hand column lists the three case studies discussed in the text and the left-hand column makes a broad distinction between the spatial scales at which the environment is commonly studied in a “human impact” or a “human agency” framework. Note: the figure deals with order of magnitude phenomena; no claims are made about the precision or accuracy of the spatial or temporal “limits” of subsystems.

characterized in decreasing order of magnitude as subsystems of landscape belts (A = 5–8 (100,000–100 million km^2); T = 6–9 (millions-billions of years)), landscapes (A = 2–6 (hundreds to millions of km^2); T = 2–7 (hundreds to tens of millions of km^2), landform assemblages (A = 0–3 (1–1000 km^2); T = 0–4 (1–10,000 years)) and landforms (A = -3–0 (1000 m^2 to 1 km^2); T = -3 − +3 (hours to 1000 years).

A fuller understanding of the human dimensions of environmental change requires attention to both systemic and cumulative responses through research that integrates findings from spatial scales ranging from the global to the local.

4. Sea level rise and change on low-lying coasts

4.1. Historical and projected global to regional sea level rise

The rate of global mean sea level (GMSL) rise is estimated to have increased from a rate of -0.1 ± 0.3 mm yr^{-1} during the 18th century to ca. 1.3 mm yr^{-1} between 1901 and 1990 (Church and White, 2011). Over the period of satellite altimetry (1993–2018), rates of sea -level rise have accelerated to ca. 3.1 mm yr^{-1} and have probably exceeded 4 mm yr^{-1} since 2007 (Cazenave et al., 2018). Relative contributions from thermal expansion, glacier and ice sheet loss and freshwater storage on land are relatively well understood (Watson et al., 2015) and their attribution is dominated by anthropogenic forcing since 1970 (Slangen et al., 2016; Dangendorf et al., 2019). This global rise, however, is a synthesis of many different regional rates of relative sea-level (RSL) rise resulting from a range of factors, including atmosphere-ocean dynamics, the effects of ice and water mass redistribution on Earth, changes in the geoid, tectonic-epeirogenetic activity and local subsidence – dominant in many deltaic regions (Tessler et al., 2018) – driven by a combination of natural sediment consolidation and anthropogenic activities, such as groundwater and hydrocarbon extraction (Fig. 2).

Some regions exhibited rates of sea level change some five times the global mean during the decade 1993–2003 (Solomon et al., 2007). GMSL is projected to rise between 0.43 m (0.29–0.59 m, likely range; emissions scenario RCP2.6) and 0.84 m (0.61–1.10 m, likely range; RCP8.5) by 2100 relative to 1986–2005 (Oppenheimer et al., 2019). RSL change will differ from GMSL over this time period; thus higher RSL will characterise the eastern and western seaboards of both North America and southern Africa under RCP4.5 in the period 2081–2100 (Oppenheimer et al., 2019). Interannual RSL variability is also likely to be significant, perhaps locally as much as several centimetres, so it may take until ca. 2040 for the signal of anthropogenically forced RSL change to be clearly detectable throughout the world ocean (Lyu et al., 2014). Furthermore, landscapes on micro-tidal coasts are likely to be more vulnerable to global change because the sea level rise signal becomes a larger component of the overall sea level variability signal, showing an earlier 'time to emergence' than in meso- to macro-tidal systems (Ponte et al., 2019). Finally, due to projected GMSL rise, extreme sea level events that are historically rare (for example, the current 1 in 100 year event) will become more common by 2100 under all emissions scenarios (Oppenheimer et al., 2019).

4.1.1. Low-lying coasts

Low-lying coasts are, and over the course of the 21st century will be, particularly vulnerable to the effects of sea level rise, coming as this does on top of centuries of modification, degradation and loss from the anthropogenic activities of land conversion (for agriculture, aquaculture, industry, housing and infrastructure) and mis-use (dredging and canalisation, waste disposal and pollution). In particular, it is clear that a typical element of such coasts, coastal wetlands, are subject to concurrent multiple drivers, with the interaction of i) acute shocks (from

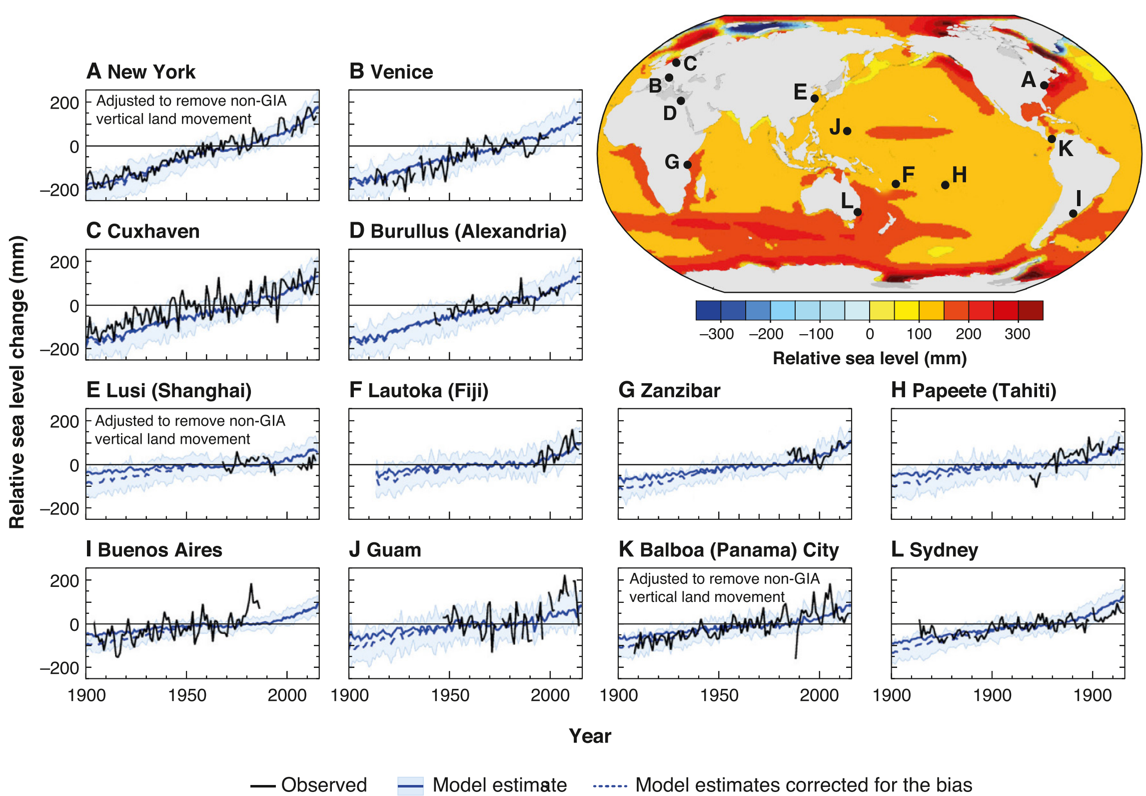


Fig. 2. 20th century simulated regional sea level changes by coupled climate models and comparison with a selection of local tide gauge time series. Upper right: global changes in simulated relative sea level (RSL) for the period 1901–1920 to 1996–2015 estimated from climate model outputs. Insets A-L: Observed RSL changes (black lines) from selected tide gauge stations for the period 1900–2015.
(Source (and further details): Oppenheimer et al., 2019).

tropical and extratropical storms, associated storm surges, marine heat waves, freshwater flood inputs) and ii) slow onset, chronic changes, not only from sea level rise but also including ocean warming and ocean acidification (e.g. Magnan et al., 2019). In the case of i), storm impacts on wetlands can be both negative and positive (Hanley et al., 2019). In the case of ii), as we have seen above, systemic drivers are subject to spatial variability at the global scale and issues of locational downscaling from global to regional to local levels. All these drivers show high levels of temporal variability which themselves interact with 'normal' process levels. However, some consensus is emerging on broadscale controls, highlighting the importance of not only the rate of sea level rise but also sediment supply to survivability. Thus, for example, mangrove forests at sites with low tidal range and low sediment supply could be submerged as early as 2070 (Lovelock et al., 2015).

Sea-level rise can lead to the frequency of flood events exceeding the recovery time in vegetated subtidal and intertidal ecosystems, a phenomenon termed 'critical slowing down' (van Belzen et al., 2017). This is important because on many low-lying coasts and islands, coastal wetlands perform important ecosystem service and food security functions, at a time when coastal populations are growing at faster rates than the global mean. As a result, the question of global coastal wetland loss sits high on the environmental agenda. On the basis of a medium sea level rise scenario of 50 cm between 1995 and 2100 a significant number of coastlines will require >79% diking (Fig. 3).

At the landscape scale (Fig. 1), it is clear that vulnerability of coastal communities in developing countries is greater than in developed countries due to inequalities in adaptive capacity. Low lying densely populated areas, including, for example, in India, China and Bangladesh, Vietnam, and Thailand, and the economies of small islands will suffer most. The freshwater resource, agriculture, human settlement, health, biodiversity, recreation and tourism (especially travellers from northern Europe to the Mediterranean and North America to the Caribbean) are all implicated. In order, therefore to maintain, and improve, human wellbeing, geomorphologically-informed ocean and coastal management will be critical under the rising sea levels of the twenty first century.

Unfortunately, considerations of climate change impacts on coasts have often been reduced to the single factor of sea level rise. The fixation with sea level rise has led to an evaluation of coastal responses to systemic changes only in the vertical whereas in fact lateral changes may be as, or even more, significant. But here, change rates remain highly contested, ranging from areal losses of 20–90% versus low losses, and even some gains, in global wetland area by 2100 (Wiberg et al., 2020). This is partly because global-scale modelling has often struggled to address the role of intrinsic feedbacks in modulating external forcing. For Kirwan et al. (2016, p.253) "marsh vulnerability tends to be overstated because assessment methods often fail to consider biophysical feedback processes". But ambiguity is also because of cumulative regional and local factors that we consider below.

4.1.2. Aspects of coastal flooding as a cumulative response: Managed realignment

At the present time, wetland dynamics often most strongly reflect not large-scale climate change-related impacts but rather regional and local human-induced habitat degradation, fragmentation and restricted landward migration. All these factors result in reduced adaptive potential to climate-induced change (Schuerch et al., 2018). It is particularly important, where possible, to allow wetlands to migrate landwards under sea level rise and thus maintain their position in the coastal 'accommodation space' (French, 2006). But in many cases, wetlands are trapped in front of, over time, progressively higher and more massive hard defences; this 'coastal squeeze' leads to the accelerated loss of fronting wetlands. One solution – often termed 'Managed Realignment' – is to set back the defence line and allow for the development of 'natural coastal protection' between the old and the new defence (e.g. Esteves and Williams, 2017). However, the scale of wetland loss means that a great deal of new habitat needs to be created, and at a much greater rate, than has been achieved thus far. With respect to England and Wales, the UK Government's Adaptation Sub-Committee reported that the rate of managed realignment would have to increase five-fold, from the current levels of around 6 km of coastline realigned

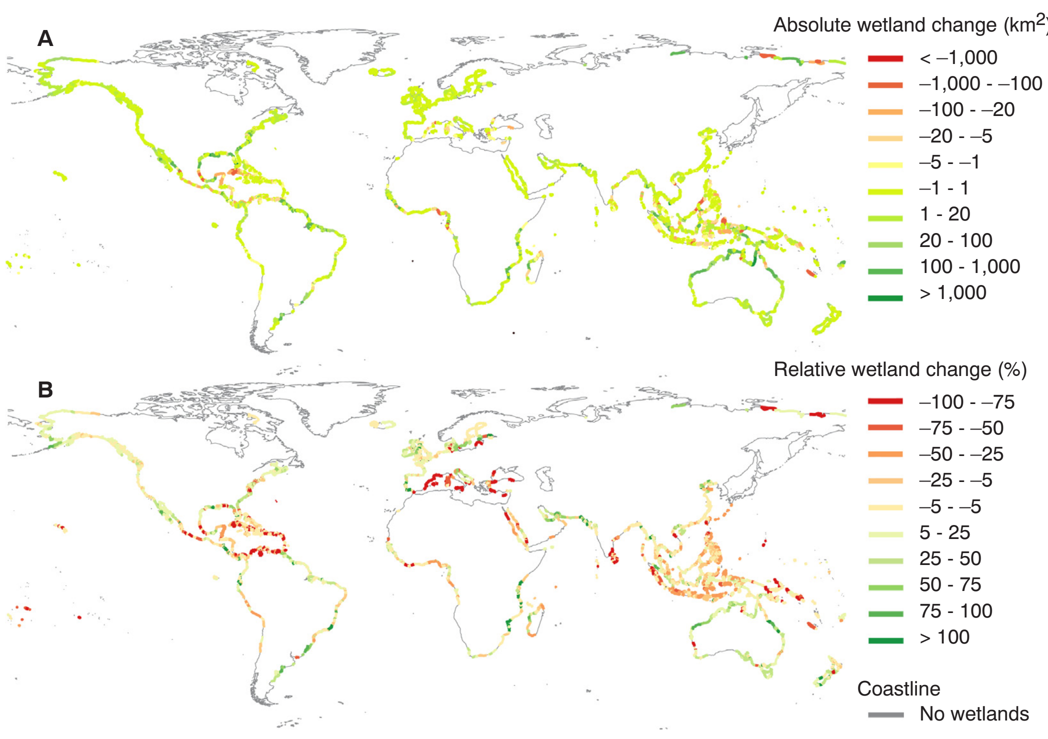


Fig. 3. Spatial distribution of absolute (A) and relative (B) changes in coastal wetland areas for a medium SLR scenario (RCP4.5). Assuming inhibition of wetland inland migration everywhere, but in (nearly) uninhabited regions with a population density of less than 5 people km^{-2}, is subject to the population growth throughout the simulation period, following SSP2. The displayed coastline was generated during the DINAS-COAST FP5-EESD EU project (EVK2-CT-2000-00084) (from Schuerch et al., 2018).

every year, to around 30 km if the 2030 goal of nature-based protection stated in Shoreline Management Plans is to be met (Committee on Climate Change, 2013).

4.1.3. Realigning the coast in NW England: potentialities and challenges

For North West England, the proposed length of coast currently planned for managed realignment in the first epoch of Shoreline Management Plans (i.e. to 2030) is 124 km, out of a total 795 km of coastline. Here we describe an example of managed realignment from this coast. On the south side of the Ribble estuary, at Hesketh Outmarsh West, a 180 ha site claimed for agricultural production in the 1970s was returned to tidal exchange in 2008–2009 through the creation of four breaches in the outer seawall around the reclaimed land. The old (1883) inner sea wall was raised by 1 m; this new seawall protects a flood risk zone comprising 1260 ha of farmland, 74 residential properties and over 100 farm buildings and greenhouses (Fig. 4).

Using the TESSA ecological toolkit (Peh et al., 2013), MacDonald et al. (2017) showed that the sequestered carbon in accreting sediments in the created new wetland outweighs the income foregone from crops and grazing. Furthermore, the value of ecosystem services is increased by the reduction to flood risk from the strengthened inner defence and the presence of developing intertidal saltmarsh. Additionally, the presence of a fronting saltmarsh dissipates wave energy, and thus reduces wave heights at a defence, often to zero / almost zero (Fig. 5).

At Hesketh, the old inner defence would have been over-topped by any expected storm event but the new seawall provides protection up

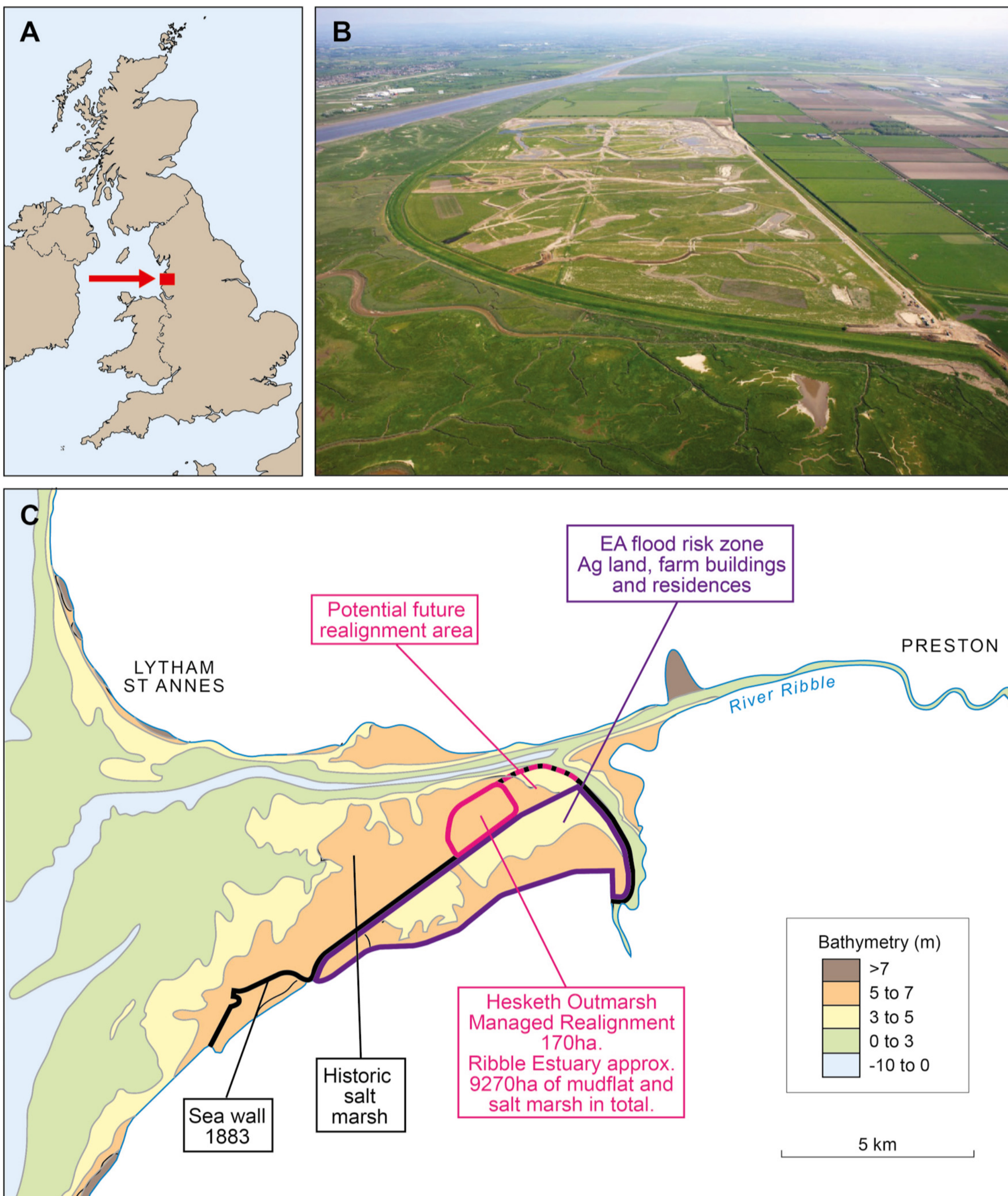


Fig. 4. Hesketh Outmarsh West Managed Realignment. A. Location map. B. Aerial view on 15 May 2008, looking NE. Ribble estuary upper left, breaches in curved seawall with managed realignment to landward, straight seawall to right is the raised 1883 defence line (reproduced with kind permission of The Royal Society for the Protection of Birds (RSPB) © RSPB; C. Topography and site details (EA = Environment Agency of England & Wales).

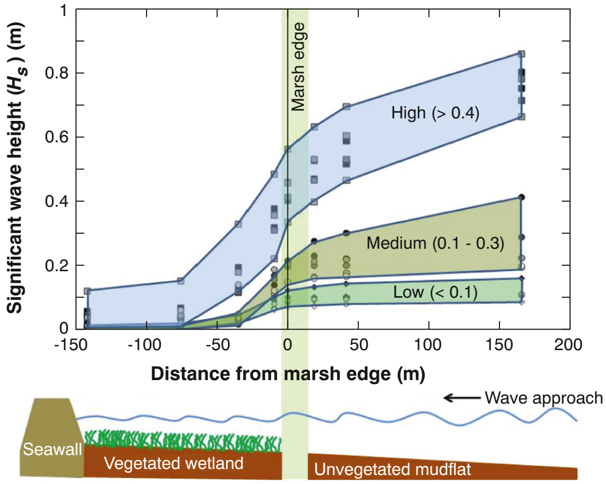


Fig. 5. Wave energy dissipation as measured by a reduction in significant wave height (Hs) across a mudflat to saltmarsh transect, Dengie Peninsula, Essex, E. England. 'High', 'Medium' and 'Low' groupings refer to relative wave heights on the inner tidal flat (H/h where H = wave height (m) and h = water depth (m)).
Based on data from Möller et al. (2003) and UKRI NERC CBESS project (unpublished Cambridge Coastal Research Unit, University of Cambridge files).

to 2100, even under the highest rate of projected sea level rise (Fig. 6a). With the addition of wave energy dissipation by the saltmarsh, the 'time to overtopping' can be extended by 5 to 15 years, under low to moderate attenuation respectively (Fig. 6b).

How do we maximise the wave energy reduction (i.e. 25 cm/km rather than 5 cm/km; Fig. 6b) across created wetlands and thus increase design life, and reduce maintenance costs, of the landward defences around managed realignments? The existing literature (e.g. Vafeidis et al., 2019; Kiesel et al., 2019) suggests a great range of attenuation potentials but few clear design rules on how to proceed. (Kiesel et al., 2020). Furthermore, unlike defences of fixed height, saltmarshes have the ability to track sea level rise by continued vertical accretion, offering the possibility of a long-term, sustainable form of coastal defence (Spalding et al., 2014). The rate at which this geomorphic process can be achieved depends in part upon sediment supply. Thus, in the sediment-rich (typical suspended sediment concentrations = 200 mg l^{-1}) Wash embayment, eastern England infilling of the tidal frame to create 'mature' marsh surfaces is estimated to take 150 years whereas on the neighboring sediment-poor (45 mg l^{-1}) North Norfolk coast the same processes take 300 years (French, 1993). Engagement with, and development of, geomorphologically-informed landscape science offers the possibility of truly functional natural coastal protection, in contrast to schemes which simply aim to create a range of habitats for nature conservation purposes (Fig. 7).

4.2. Permafrost degradation: global, regional and local

4.2.1. Global permafrost response to climate change

Seasonally frozen ground is arbitrarily defined as ground that is frozen for two weeks per year or more. It occupies approximately 50% of the terrestrial surface in the Northern Hemisphere (NH) (Zhang et al., 2003) (Fig. 8). Perennially frozen ground (permafrost) covers c. 24% of the NH. Permafrost is defined as a thermal condition in the ground that remains at or below 0 °C for more than two years (Muller, 1943, p.3) and is a zonal phenomenon (Smith et al., 2001; Barry and Gan, 2011; Woo, 2012) (Fig. 8). Along a line from the pole to the equator, these zones are underlain successively by continuous (>90%), discontinuous (50–90%), sporadic (10–50%), and isolated <10%) permafrost. This conformal pattern is broken when local factors such as topography, thickness of overburden and ground ice content in the upper 10–20 m of the ground are included (Fig. 8).

The presence of ground ice is particularly important in assessing the stability of the permafrost in the context of climate warming. Because mean annual temperature in Alaska, Nunavut, Svalbard, northern European Russia and Siberia is increasing more rapidly than elsewhere, permafrost thawing is a global concern (Lemke et al., 2007; Vaughan et al., 2013). During the decade between 2007 and 2016, the annual rate of increase in permafrost temperatures was c. 0.4 °C for colder continuous zone permafrost monitoring sites, c. 0.2 °C for warmer discontinuous zone permafrost (IPCC, 2019). The rate of permafrost thawing is reported to have accelerated in the past three decades (Jorgenson et al., 2006; Romanovsky et al., 2010).

4.2.2. Factors that influence regional and local permafrost stability

Permafrost covers about half the land area of Canada (c.5.7 million km^2) (Fig. 9A). The atmospheric climate, ground ice, the thermal properties of the substrate, vegetation type and density, and snow cover properties, presence or absence of an organic layer, soil moisture and drainage are the most important local controls of permafrost. Superimposed on these variables are the impacts of coastal erosion (Pollard, 2000; Rachold et al., 2007; French, 2017)) and land use activities (Pelletier et al., 2015). The upper part of the ground that thaws each summer and refreezes each winter is the so-called active layer and the thickness of this active layer also varies as a function of environmental and surface material properties.

Permafrost degradation is the term used to describe decrease in the thickness and/or areal extent of permafrost. The amount of thaw is a function of the thickness of the permafrost, pre-existing permafrost temperature, and the nature of the ice that is present: either bedrock

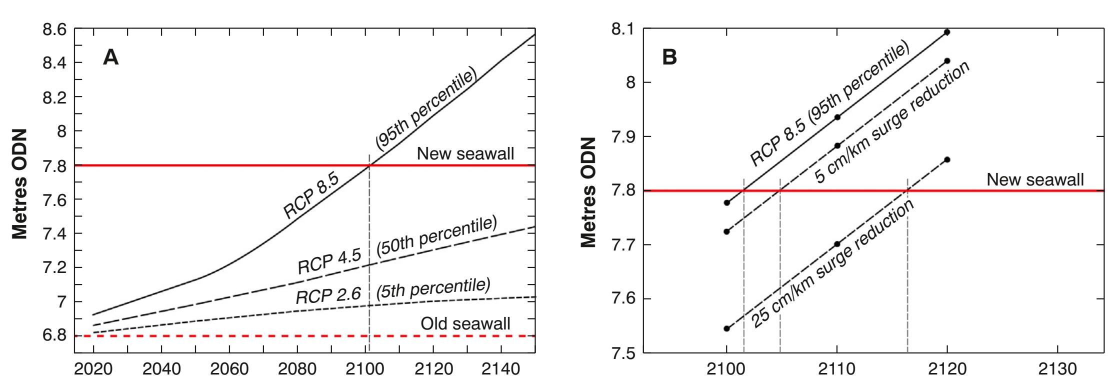


Fig. 6. Changes to flood risk with managed realignment, Hesketh Outmarsh West, NW England. A. UK Climate Projections 2018 (UKCP, 2018) of projected change in still water level, 1 in 200-year event for range of sea level rise scenarios (following Hinkel et al., 2014) for Heysham tidegauge. B. New seawall is overtopped with extreme sea level rise (RCP 8.5 95th percentile) by 2102. Water level reduction from wave energy dissipation by fronting saltmarsh extends time to overtopping by an additional 3 years (if the wave height reduction is 5 cm per km) to 15 years (if the wave height reduction is 25 cm per km).

Fig. 7. Managed realignment under a nature conservation imperative: Wallasea Island, Crouch-Roach estuary, Essex, E. England, April 2015 (reproduced with kind permission of The Royal Society for the Protection of Birds (RSPB) © RSPB).

with no ice involved, particulate ice within fine grained sediments, or massive ice (Brown et al., 1997). The degradation can be evidenced by a deepening of summer thaw, top-down or bottom-up permafrost thawing, and development of taliks (unfrozen pockets of water surrounded by ice). Thawing of ice-rich permafrost, a phenomenon known as thaw settlement, can result in subsidence of the ground surface and development of uneven and frequently unstable topography known as thermokarst terrain (French, 2017).

A variety of models has been developed to estimate the “thaw settlement index”, an index that is crucial in the context of predicting permafrost related hazards following climate change (Fig. 9B). Geomorphological evidences of this degradation include expansion of thaw lakes (Sannel and Kuhry, 2011), so-called active layer detachment slides along slopes (Kokelj et al., 2017), rock falls and destabilized rock glaciers (Haeberli and Gruber, 2009).

The quantity of ice in the ground varies widely. Locally, it can exceed 90% of the volume of the ground. Hence, the proportion of ground ice is an important indicator of potential hazardousness following climate warming. Wedge, pingo and massive ice are the categories of ice that contribute most instability to thawing permafrost. The presence of wedge ice in the ground is evidenced by ice wedge polygons at the surface ice; pingos and palsas at the surface imply pingo ice in the ground; and massive ice may be buried deposits of glacier ice (Fig. 10), river icings, snow banks or lake ice. Permafrost thawing and thermokarst threaten the integrity of residential, municipal and transportation infrastructures. (Williams, 1986; Lenngren, 2000). Infrastructures are affected in three main ways: (a) thaw settlement, (b) terrain destabilization by landslides, and (c) thermal erosion. Infrastructure foundations settle and lose their compaction when the permafrost starts thawing. This affects buildings which then settle unevenly with resulting damage such as cracks in walls and warped floors. Snow accumulation, water ponding and advected heat from seepage water contribute to warming permafrost and generating thaw settlement, which damages infrastructures.

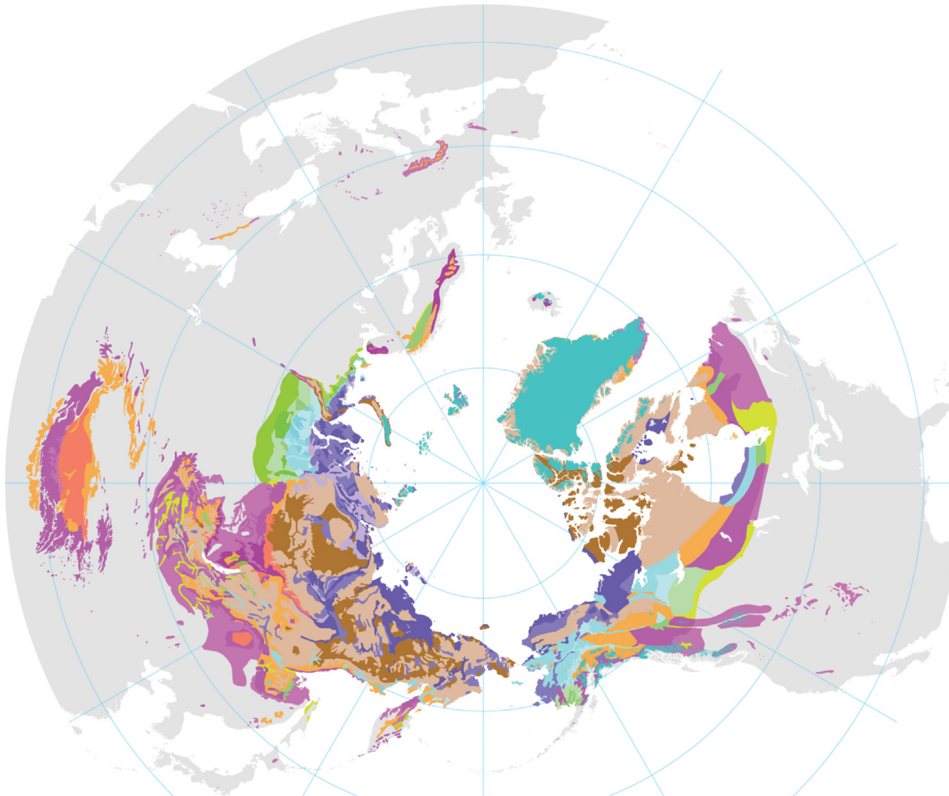
Large amounts of late Pleistocene ground ice favour the development of contemporary retrogressive thaw slumps and mass movement (Kokelj et al., 2015, 2017) (Fig. 10). The pock-marked landscape of the Peel Plateau in the Northwest Territories results from mass movement induced by thawing of this Quaternary legacy. Active layer detachment slides disrupt transportation corridors and damage buildings and also have impacts on urban areas (Lewkowicz and Harris, 2005). The most sensitive regions of permafrost degradation are coasts with ice-bearing permafrost that are exposed to the Arctic and North Atlantic oceans (Fig. 11). In the context of a rapidly warming climate, early effects of permafrost degradation are felt in the sporadic discontinuous zone and in isolated patches of permafrost (sporadic zone) where the permafrost itself is relatively warm and thin. Landslides have been shown to happen particularly at the end of warm summers when the thaw depth is deeper than in previous years, therefore melting ground ice at the active layer/permafrost transition, which frees water in an otherwise impervious soil, thus creating excess pore pressures just over the icy permafrost. As for thermal erosion, it occurs when water happens to flow directly along the icy permafrost. Often this occurs at the outlets of culverts and in tracks made by vehicles in the tundra.

4.2.3. The societal context

Permafrost lands are home to many northern communities, including indigenous peoples, such as the Inuit, who have lived in the Arctic for millennia, and increasingly are the adopted home of many people who have moved from the south. The infrastructure and resources for all of these settlements, from drinking water and exploited wildlife to industry, runways, roads, and housing, critically depend on the state of the permafrost (Bowden, 2010). Small climate- or human- induced changes in temperature can weaken the ability of permafrost to serve its various functions, such as being a stable foundation for transportation infrastructure, sequestering carbon, or retaining freshwater in permafrost-bound lakes. Northern residents are affected by vegetation change, expansion of water bodies, and modification of soil drainage, which has an impact on resources traditionally available.

Pulse disturbances of the permafrost, such as wild fire and abrupt thaw, are not included in most model projections. Because the observed trend of increasing fire is projected (with medium confidence) to continue for the rest of the century across most of the tundra and boreal region, this is a mechanism for accelerated change that should not be ignored (Kokelj et al., 2017).

Coastal indigenous communities are vulnerable to cryosphere changes because of their close relationship with the land, geographical location, and reliance on the local environment for aspects of everyday life such as diet and economy. Today, most arctic residents live in permanent communities, many of which exist in low-lying coastal areas. Despite the socio-economic changes taking place, many arctic communities retain a strong relationship with the land and sea, with community economies that are a combination of subsistence and cash economies strongly associated with mineral, hydrocarbon and resource development.



Legend for EASE-Grid Permafrost and Ground Ice Map

Permafrost Extent (percent of area)	Ground Ice Content (visible ice in the upper 10–20m of the ground; percent by volume)				
	Lowlands, highlands, and intra- and intermontane depressions characterized by thick overburdencover (>5–10 m)			Mountains, highlands, ridges, and plateaus characterized by thin overburden cover (<5–10 m) and exposed bedrock	
	High (> 20%)	Medium (10–20%)	Low (0–10%)	High to medium (>10%)	Low (0–10%)
Continuous (90–100%)	Ch	Cm	CL	Ch	CL
Discontinuous (50–90%)	Dh	Dm	DL	Dh	DL
Sporadic (10–50%)	Sh	Sm	SL	Sh	SL
Isolated Patches (0–10%)	Ih	Im	IL	Ih	IL

Variations in the extent of permafrost are shown by the different colors; variations in the amount of ground ice are shown by the different intensities of color. Letter codes assist in determining to which basic permafrost and ground ice class any particular unit belongs. Letter codes are defined in the documentation that accompanies the data files.

Ice caps and glaciers

Fig. 8. Distribution of frozen ground in the Northern Hemisphere based on Brown et al. (1997, updated 2001) [Courtesy of NSIDC, Boulder, Colorado] http://nsidc.org/data/docs/fgdc/ggd318_map.

Some arctic communities are adapting to local environmental changes through wildlife management regimes and behavioural change. But some arctic peoples are finding that movement into permanent communities, along with shifts in life style and culture limits their adaptive capacity (Allard and Lemay, 2012). A more sedentary life style minimizes mobility and increased participation in wage economy jobs decreases the number of individuals able to provide food from the local environment. In some cases, indigenous peoples may consider adaptation strategies unacceptable, as they impact critical aspects of traditions and cultures. For example, the Inuit Circumpolar Conference has framed the issue of climate change in a submission to the US Senate as an infringement on human rights because it restricts access to basic human needs as seen by the Inuit and will lead to the loss of culture and identity (Watt-Cloutier, 2004).

In 1998, a massive landslide took place in Salluit, an arctic coastal village in Nunavik, Quebec, prompting the abandonment of a new housing development project and the removal of 20 newly constructed houses in the face of the landslide hazard at that location. Permafrost and climate specialists, indigenous co-managers, land use planners, economists, engineers, architects, local authorities and community members were brought together to address the crisis. The population of the village is expected to increase from c.1300 in 2006 to c.2000 inhabitants by 2025 (Institut national de la statistique du Québec, 2006). By 2008, housing numbers were already showing a shortage of 131 units (Carbonneau et al., 2015). Accommodating this increase in population is a complex issue as Salluit lies in the base of a valley underlain by ice-rich permafrost in saline marine clays or tills which are sensitive to thaw and under potential risk of landslides. It was decided to develop detailed maps of permafrost conditions and risk indices for Salluit (Allard et al., 2012) (Figs. 12A and b).

These maps are based on risk indices integrating three layers of information: (a) slopes; (b) permafrost conditions: and (c) identified zones of severe constraints for construction, such as wetlands, ice wedge polygon networks, frost boils, active layer detachment scars, thaw settlement and surface thermo-erosion, stream bank erosion scars and thermokarst features which are all indicative of ground ice content.

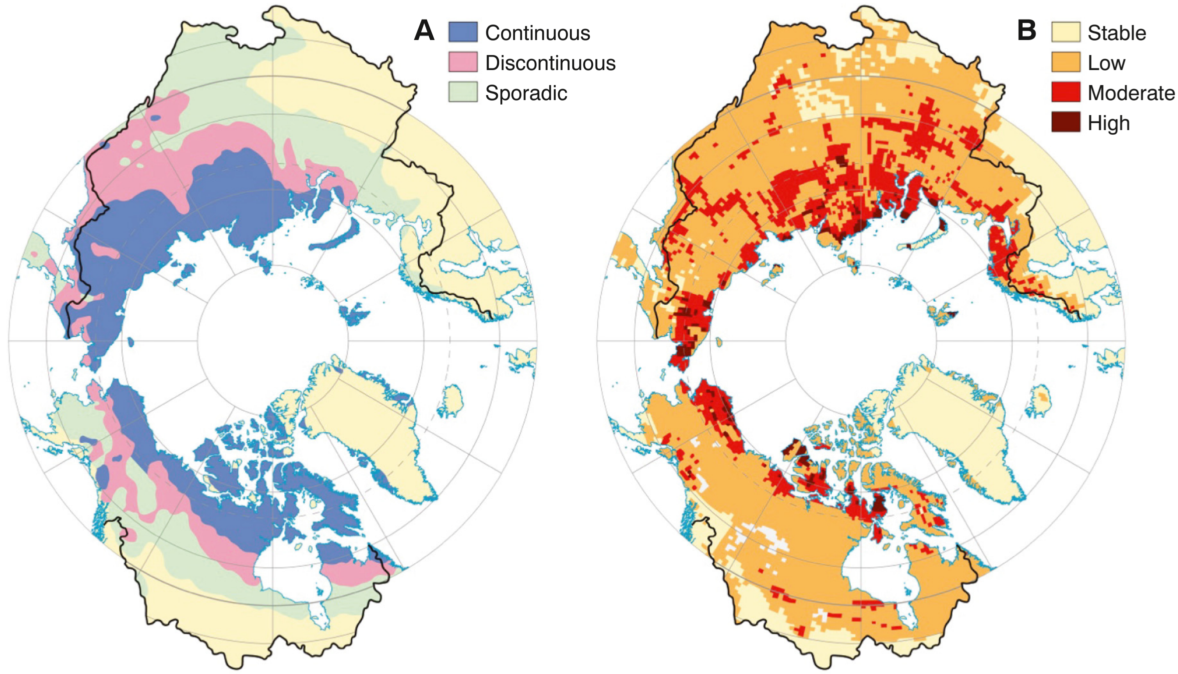


Fig. 9. A. Zonation of permafrost in the Northern Hemisphere under climate scenario predicted by ECHAM1-AGCM (Cubasch et al., 1992). B. Hazard potential associated with degradation of permafrost under ECHAM1-A climate change scenario. Map shows areas of stable permafrost and low, moderate and high susceptibility to subsidence. Classification is based on a "thaw settlement index" calculated as the product of existing ground ice content (Brown et al., 1997) and predicted increases in depth of thaw (Anisimov et al., 1997). Hazard zone intervals were derived through division of resulting frequency distribution using a nested-means procedure (Scripter, 1970).

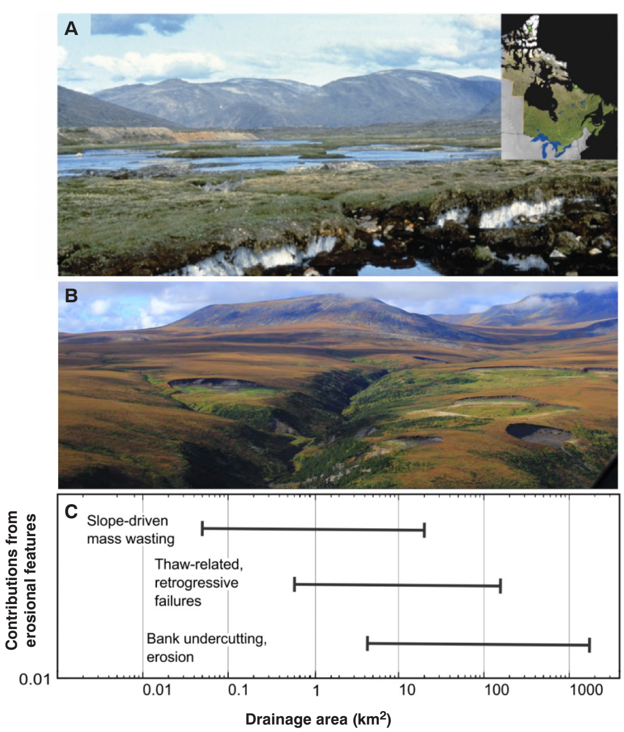


Fig. 10. A. Exposed permafrost in Katherine River Valley, Torngat Mountains, Labrador (Slaymaker and Catto, 2020). Source NRCan A92S044 by M.J. Van Kranendonk, Natural Resources Canada http://open.canada.ca/en/open-government-licence-canada; B. Incised valleys, flow tracks and thaw slump disturbances, northwestern Canada. Photograph by Scott Zolkos, University of Alberta; C. Disturbance inventories of the characteristic scales of erosional features throughout the northern Keele Plateau in Canada's Northwest Territories (Kokelj et al., 2017).

Arctic settlements require understanding of the spatial variability not only of permafrost thawing but of people's perceptions of desirable construction areas: this observation supports the close link between geomorphology as both geoscience and landscape science. We know, with high confidence, since Vaughan et al. (2013), that the climate in the Arctic is warming more rapidly than temperate environments and this causes thickening of the active layer as well as thinning and destruction of permafrost. Permafrost degradation is confidently predicted to continue to increase beyond 2100 (Masson-Delmotte et al., 2018; IPCC, 2019). Throughout the North, much permafrost is on the brink of massive change (Rowland et al., 2010; Derksen et al., 2019). In Low Arctic Canada, the southern limit of discontinuous permafrost has moved northward by 130 km over the past few decades, and thermokarst lakes have become larger and more abundant (Thibault and Payette, 2009). Throughout the Canadian Arctic, a deepening of the active layer has accompanied increasing air temperatures since the end of the 20th century (Smith et al., 2010; Vincent et al., 2013; Masson-Delmotte et al., 2018). Some of the related changes anticipated with continuing warming of the climate were projected in the early1990s (Fig. 13; Slaymaker and French, 1993). Wisely, in retrospect, no specific time frame for these changes was suggested at that time. In all cases, the predicted trends have been confirmed and the rate of change is significantly more rapid than anticipated. The Inuit Circumpolar Conference concerns over loss of cultural identity and reduced access to basic human needs have also been amply confirmed (Watt-Cloutier, 2004).

4.3. Mountain snow depletion

Geomorphology as geoscience rarely considers the case of snow depletion but all aspects of the cryosphere are important in a geomorphology defined as landscape science. Here we focus on just one aspect of the cryosphere's response to environmental change, that aspect that most directly affects the wellbeing of those engaged in the winter sports and tourism industries.

Fig. 11. Active layer retrogressive thaw slumps and scars of coastal permafrost disturbances on the Fosheim Peninsula, Ellesmere Island, Nunavut. (Slaymaker and Catto, 2020). A. Cassidy/flickr CC BY 2.0.

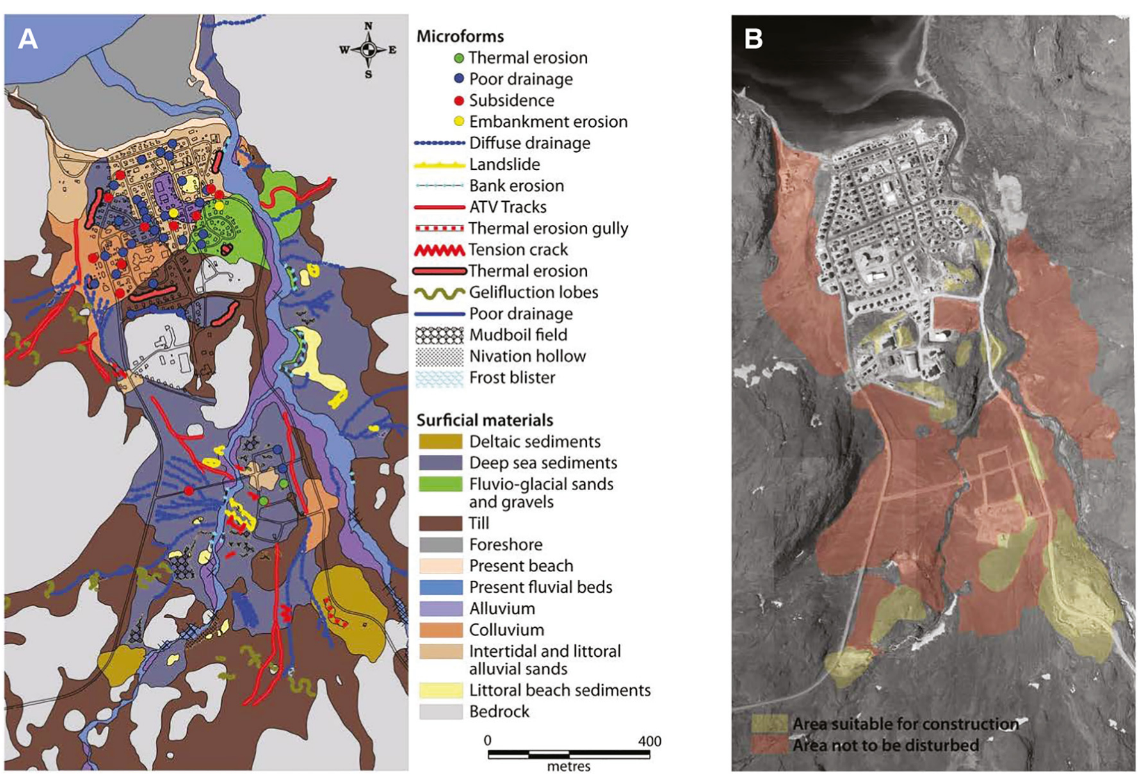


Fig. 12. A. Detailed geomorphological map of surficial deposits and microforms associated with permafrost instability: the case of the Salluit community, Nunavik, northern Quebec (André and Anisimov, 2009; Allard et al., 2012). B. Map of recommended and not recommended zones for building purposes in Salluit (André and Anisimov, 2009; Allard et al., 2012).

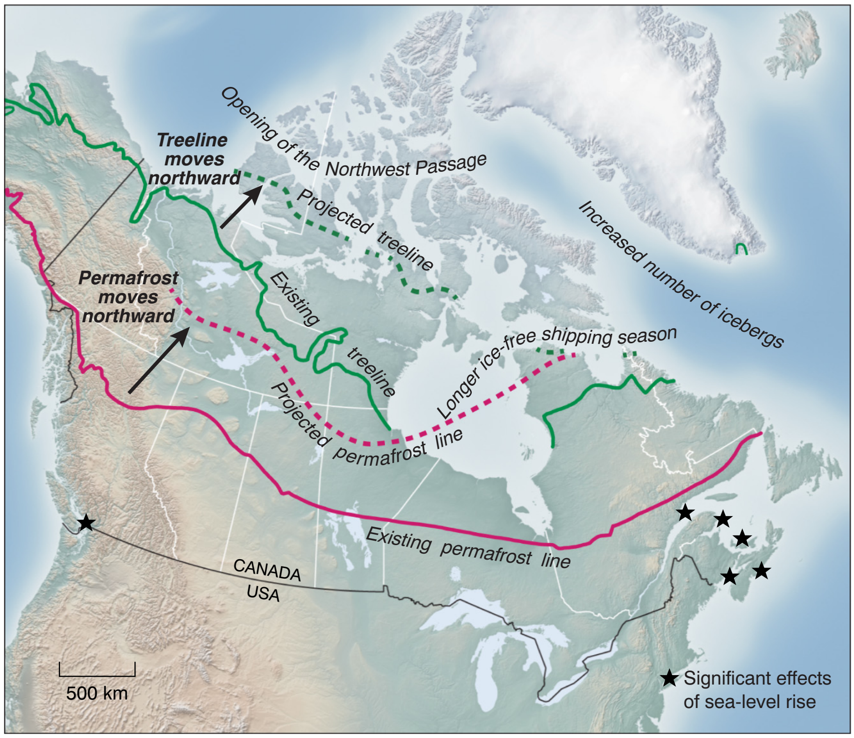


Fig. 13. Projected changes in northern Canada following climate warming (after Slaymaker and French, 1993).

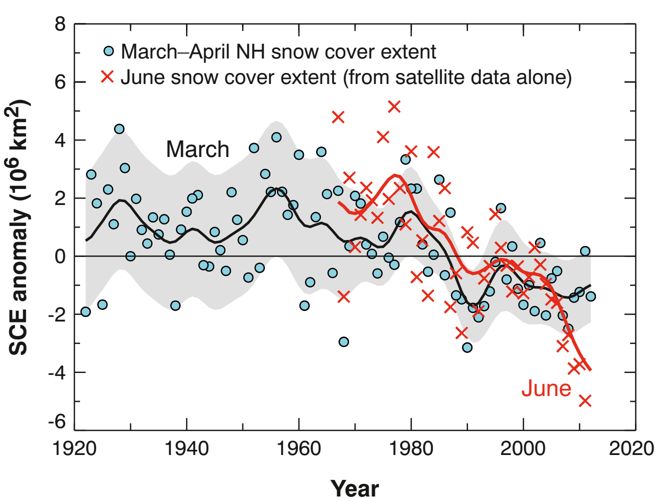


Fig. 14. March–April Northern Hemisphere snow cover extent (in circles) and June snow cover extent (red crosses from satellite data alone). For both time series the anomalies are calculated relative to the 1971–2000 mean (after Vaughan et al., 2013).

4.3.1. Global

Snow cover extent (SCE) has decreased in most regions of the Northern Hemisphere since the 1920s with most of the reduction occurring in the 1980s (Fig. 14).

At lower elevations, there is high confidence that mountain snow cover has generally declined in duration (on average by 5 snow cover days per decade) in mean snow depth and accumulated mass since the middle of the 20th century, with regional variations (Hock et al., 2019). In many regions, such as the European Alps, Western North America, Himalaya and subtropical Andes, the snow depth or mass is projected to decline by 25% between the recent past period (1986–2005) and the near future (2031-2050). SCE decreases are largest in spring and the rate of decrease increases with latitude (Déry and Brown, 2007). Average March and April SCE decreased 2.2% per decade over the 1979–2012 period (Vaughan et al., 2013). The NOAA SCE data indicate that, owing to earlier spring melt, the duration of the snow season declined by 5.3 days per decade since winter 1972–1973 (Choi et al., 2010). NHSCE data observed by satellite over the 1967–2012 period showed statistically significant decreases in snow cover in March, April, May and June (Table 1).

In the mountains of western North America, 75% of monitored locations have shown declines in SCE since 1950 (Mote, 2006). At Banff, Alberta it has been estimated that the ski season will be reduced by 7 to 10 weeks at lower elevations and 2 to 14 weeks at higher elevations by the 2050s (Scott et al., 2015). With advanced snowmaking, the ski season in Banff will shorten at low, but not at high, altitudes. The North American snowmobiling industry is more vulnerable because it relies exclusively on natural snowfall. By the 2050s, it is expected that a reliable snowmobile season will have disappeared from most of eastern North America where trail networks have been developed. The decline in the number of former Olympic Winter Games host locations that can remain climatically reliable will depend on the degree of temperature warming (Jacob et al., 2018). Studies from 27 countries consistently project substantially decreased reliability of ski areas that are dependent on natural snow. The process of snow depletion was confidently predicted to continue beyond 2100 (Masson-Delmotte et al., 2018).

Table 1
Least squares linear trend in Northern Hemisphere snow cover extent in millions of km^2 per decade for 1967–2012 (after Vaughan et al., 2013).

Ann	Jan	Feb	Mar	Apr	May	Jun	Jul-Oct	Nov	Dec
−0.40*	+0.03	−0.13	−0.50*	−0.63*	−0.90*	−1.31*	n/a	+0.17	+0.34

* Denotes statistical significance at $p = 0.05$.

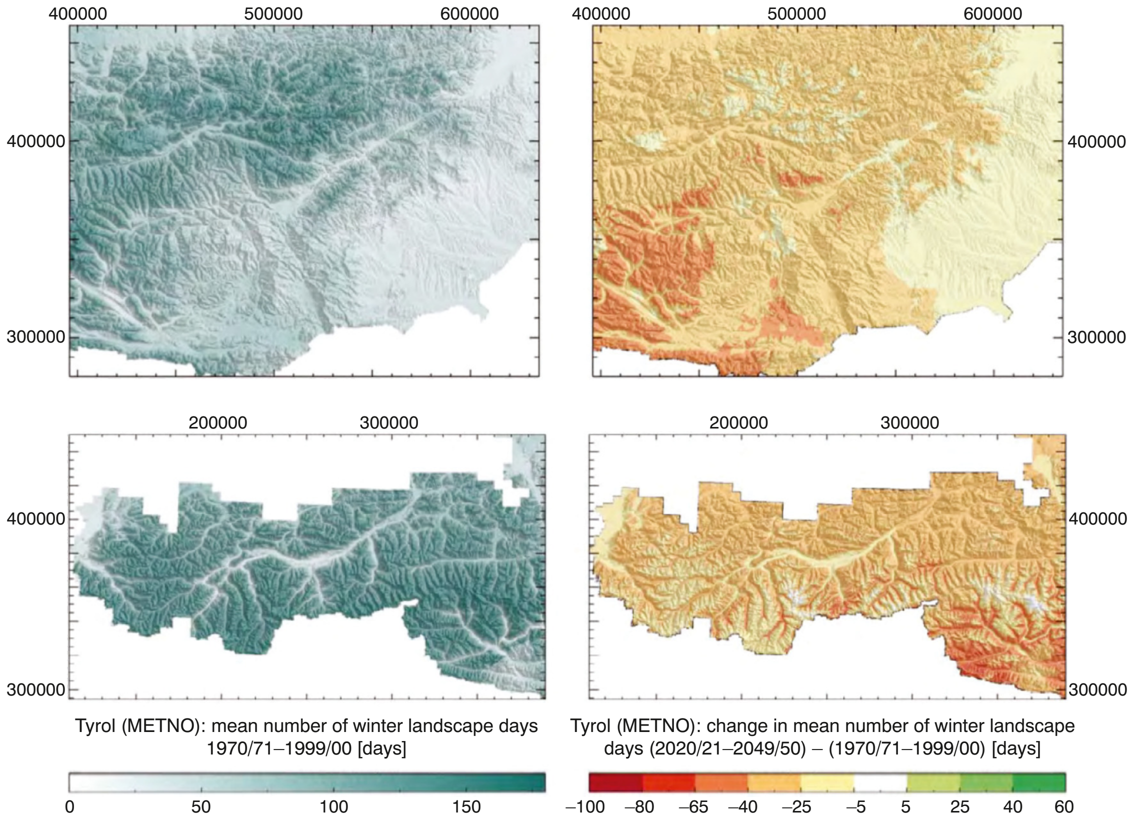


Fig. 15. Left: Mean number of days with a snow water equivalent >15 mm (winter landscape) from November to April in the period 1970/71–1999/2000. Right: expected changes for the period 2020/21–2049/50 compared to the reference period 1970/71–1999/2000. Top panels: Styria, Austria; bottom panels: Tyrol, Austria.
(Source: APCC, 2014)

4.3.2. Snow cover modelling and implications for Austrian winter sports and tourism

Winter sports and tourism are very important for Austria, creating 3.2 to 4.9% of Austrian GDP (Steiger and Abegg, 2011). Snow cover duration and snow depth are highly variable over time and space and are difficult to predict. Much scientific effort has therefore been put into snow cover modelling. Recent declines in snow cover extent (SCE) have been noted in Austria (Fig. 15) as well as in neighboring Slovakia and Switzerland.

In Austria, for example, it is estimated that the number of days with permanent snow cover will decrease especially in regions lying at elevations between 1000 and 2000 m and that the current snow cover (2010) will be shifted by about 200 m towards higher altitudes by the middle of the century (APCC, 2014). Hantel et al. (2000) found that the most sensitive elevation to climate warming in the Austrian Alps was 600 m asl in winter and 1400 m asl in spring. Without snow making, a 1 °C rise in temperature will lead to four fewer weeks of skiing in winter and six fewer weeks in spring.

4.3.2.1. Local cumulative systems control the sustainability of the ski area. In the Austrian Alps, snow depletion and model results demonstrate continuous decline in snow reliable ski areas over time (Fig. 16). A ski area is considered "snow-reliable", if a ski season with a length of at least 100 days (with snow depths of at least 30 cm) in 7 out of ten winters can be provided. This is known as the 100-days rule and is a common indicator for profitable ski operation.

In the reference period 1961–90, 69% of the 228 ski areas could be defined as naturally snow-reliable using the 100-days rule. With artificial snowmaking, nearly all ski areas (96%) are snow-reliable in the reference period. A warming of 1 °C, 2 °C and 4 °C would reduce the share of naturally snow-reliable ski areas to 53%, 28%, and 8%, respectively. Artificial snow making could increase the share of technically snow-reliable ski areas to 81%, 57%, and 18%, respectively. Thus societal impacts are lower when snowmaking is available; however, in a warmer future, current snowmaking technology cannot guarantee technical snow-reliability in an increasing number of ski areas. Available snow making hours (air temperature ≤ −5 °C) may not be sufficient to provide a 100-day season, given the assumed snowmaking capacity (10 cm/day). (Steiger and Abegg, 2013).

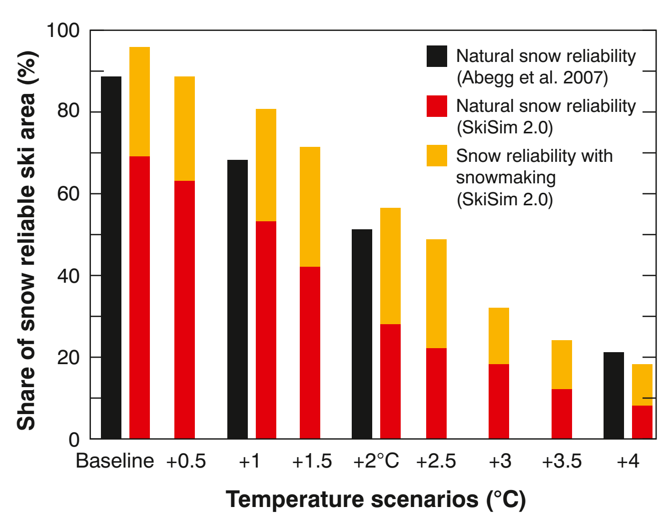


Fig. 16. Snow reliability under various modelled scenarios (after Steiger and Abegg, 2013).

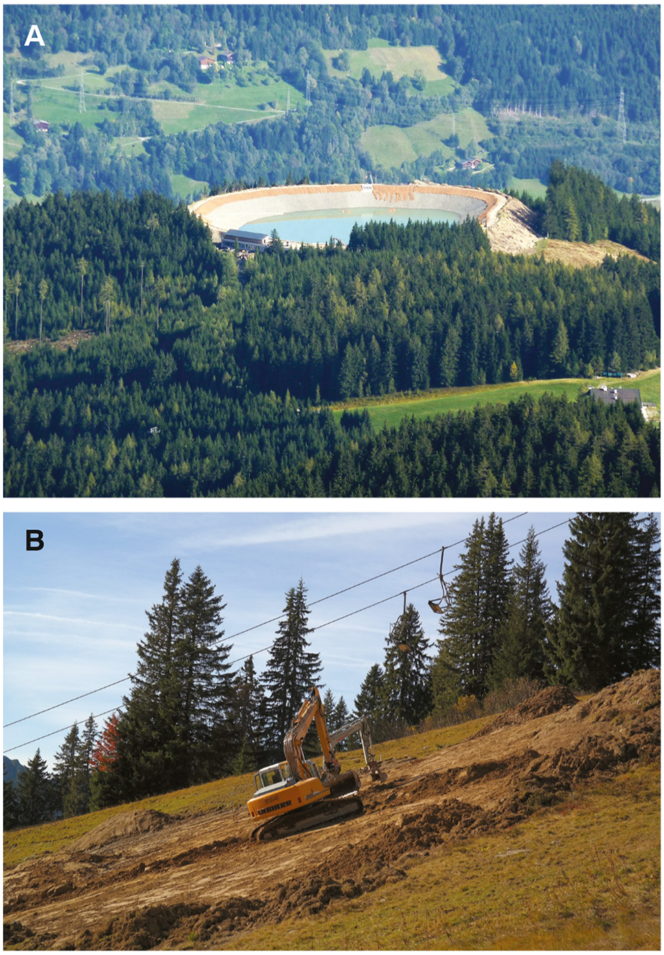


Fig. 17. (A) A water reservoir to give snow-making capacity Source:https://www.sn.at/wiki/images/a/a1/Speicherbecken_unterhalb_Schmittenh%C3%B6he.jpg and (B) a dredger to grade the ski slopes Source:https://pixabay.com/de/photos/baggerarbeiten-baggern-planieren-231825/

The most immediate effects of decreased reliability of snow will depend on a number of local factors, such as the extent to which ski areas are currently dependent on natural snow, increased snowmaking requirements and investment in snow making systems, shortened and more variable ski seasons, a contraction in the number of operating ski areas, altered competitiveness among and within regional ski markets, and subsequent impacts on employment and the value of vacation properties (Steiger et al., 2019).

4.3.2.2. Impact of snowmaking is substantial. Snowmaking also has a strong impact on the landscape as it depends on the installation of water reservoirs and long underground ducts for water and electricity. Costs of snowmaking can be lowered by grading slopes (Fig. 17) but quite often slope instability is created by these construction measures (APCC, 2014). Geomorphological research on these landscape changes and their long-term effects is however scarce. By 2014, Austria Ski slopes covered 23,000 ha, with 66% of them equipped with snow making systems. There are 420 reservoirs associated with snowmaking, and 42 million m^3 of water per year are used for snowmaking (Tschernutter, 2014).

The impact of ski runs on the landscape (Fig. 18) is evidenced by the white bands of snow-covered ski runs cutting through the grey-green mountain slopes in spring. Biologists and soil scientists are aware of the strong impact of snowmaking on the ecosystem and there has been a lot of research during the past three decades, analysing the effects of these impacts and developing counter measures.

The substantial engineering required to move ski facilities upslope is well illustrated by the areal extent of land consumption, in both 2000 and 2015, at Saalbach, Austrian state of Salzburg (Fig. 19). This map not only shows the mentioned disturbances of the terrestrial surface but also gives an impression of the areal extent of land consumption for skiing purposes. As of 2020, engineered skiing terrain in many cases crosses watersheds. For instance, in the largest ski area of Austria (7600 ha) 20.6% of the mountainous area has been turned into ski slopes (Ringler, 2017).

4.3.3. Adaptation and human wellbeing

Climate change will have far-reaching consequences for many ski tourism-dependent communities, as economic alternatives to tourism are limited in (mostly) rural mountainous regions. A variety of adaptation measures is available to the tourism industry. These include:

(a) ski resort operators may invest in lifts to reach higher altitudes;
(b) they may invest in snowmaking equipment. Compensating for reduced snowfall by artificial snowmaking is already common practice for coping with year-to-year snow pack variability. This adaptation strategy is likely to be economic only in the short term, or in the case of very high elevation resorts in mountain regions. It may be ecologically undesirable;

Fig. 18. The impact of ski runs on the landscape illustrated by the white bands of snow-covered ski runs.
Source: (after Abegg and Steiger, 2016)

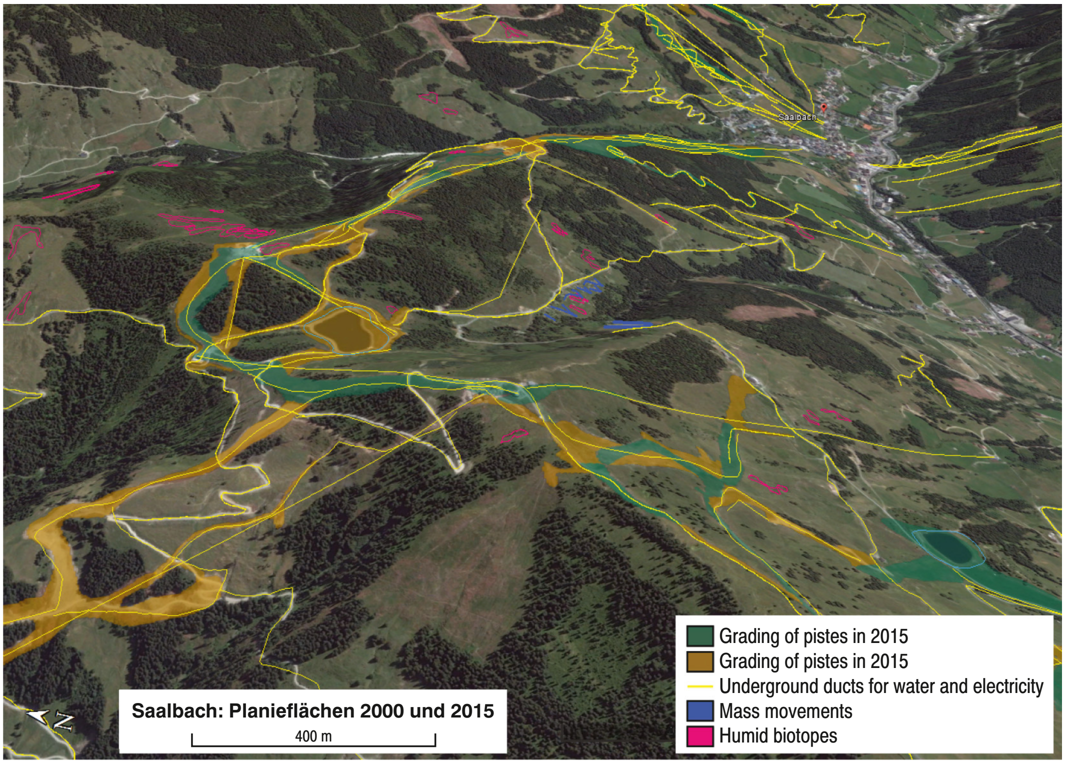


Fig. 19. Extensive and expensive engineered skiing landscape at Saalbach. Work completed between 2000 and 2015 (Ringler, 2017).

(c) ski tourists may adapt independently by changing their recreation behaviour in response to new snow cover conditions; and
(d) operators may diversify their tourism package offer by adding a summer season. (Steiger and Stötter, 2013)

Unfortunately, almost all Austrian resorts are choosing snowmaking, as the revenue from winter tourism is so much higher than the revenue from summer tourism (APCC, 2014). This situation is not helped by the fact that the Austrian government is funding snowmaking. Current snowmaking technology will not only reach climatic limits but also economic limits (increasing snowmaking costs) in the next decades, and the price of ski lift tickets will have to be increased in order to maintain financial viability. Skier behavioural response studies suggest that especially families will no longer be able to afford a skiing holiday and drop out of the market (Steiger et al., 2019). It can be expected that by the middle of the century a number of low-lying skiing resorts will have to give up on winter tourism. In addition, they will be left with a number of unfavorable landscape changes, for instance increased vulnerability to erosion by variable geomorphological processes or an altered drainage network. Areal extent of individual ski areas varies from 1200 ha to 7600 ha. In 44% of the ski areas half of the ski runs have been artificially levelled. The ski slopes of 9% of the ski areas have been strongly affected by mass movements and gully development (Ringler, 2017). It will also be a landscape littered with elements of the former skiing industry like artificial "lakes" or cuttings for ski runs and ski lifts that will prejudice summer tourism, as it can be shown that hikers are very critical of intrusive man-made elements (Hamann, 1994).

5. Conclusions

The following conclusions seem to be important:

(a) Human wellbeing is a critical part of geomorphological systems research. As traditional geoscientists, we are not used to thinking of coastal flooding, permafrost degradation and declining snow depletion as centrally important to our science. But as landscape scientists the inclusion of these and all other components of the cryosphere's interaction with human wellbeing is entirely logical. Geomorphology is important for a complete understanding of landscape, its processes and interactions with human activities. Therefore, geomorphologists should not overlook other landscape dimensions, and geomorphology should not be overlooked by other landscape scientists or managers.
(b) UK has a coastal flooding problem, responding to secular sea level rise and regionally variable glaci-isostatic readjustment which either exacerbate or offset the sea level rise problem; Canada has a permafrost thawing problem responding to the greater than average temperature warming in Canada's North; and the Austrian ski industry is strongly influenced by global snow depletion in alpine regions. But these systemic global changes are only a small part of the story. At this global scale decision making mechanisms and institutions are still too weak to be effective; nevertheless, the IPCC now speaks "with high confidence" that humanity is implicated as the major driver of global warming (Masson-Lemotte et al., 2018; Pörtner et al., 2019);
(c) The spatial and temporal variability of changes at local and regional scales, including the variability that can be attributed to local actors, managers and decision makers, are all cumulative effects that need to be included in assessing the total systemic and cumulative environmental response. Cumulative systems are governed by local, highly variable controls on coastal wetland loss, permafrost thawing, and snow depletion and the ways in which human wellbeing is maintained in dealing with these local sources of instability. Human agency as well as human impacts and variable environmental resistances need to be evaluated in relation to human wellbeing at each distinct scale;
(d) Geomorphology perceived as a landscape science directs attention to all vulnerable spaces and persons and makes the connection between geomorphological process and landscape management self-evident (Vitousek et al., 1997);
(e) Variable local and regional cumulative effects are illustrated by coastal wetland losses, permafrost thawing and snow depletion.

Decision making at zonal, regional and local scales are integral to the way in which geomorphological systems function. Coastal protection ('hard' v. 'nature-based') strategies, forced urban relocation in the Arctic and forced relocation of alpine ski resort sites in the context of rapidly changing landscapes are only a few of the responses that are required in order to provide protection and to achieve improved human well-being; and

(f) In the context of managing changing coasts and cryosphere, an emphasis on sustainability may have to be modified. The goal of environmental sustainability is laudable in principle, but what is it that can be sustained if all around is changing rapidly and continuously towards an unpredictable future? In 2012, in relation to the changing Canadian cryosphere, Slaymaker and French (2012 p.308) argued "that the goal of achieving sustainability should be replaced by a strategy of eliminating manifestly unsustainable practices". This is not a matter of semantics. This argument clearly has wider application. It is up to geomorphology, acting as a landscape science, to provide the underpinning principles that identify landscape-changing actions as being unsustainable and in providing better-informed future pathways away from such actions.

Declaration of competing interest

There are no known conflicts of interest within this text.

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