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Continuity in the face of a slowly unfolding catastrophe: the persistence of Icelandic settlement despite large-scale soil erosion

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Abstract

Since people first settled the Iceland about eleven hundred years ago soil erosion has fundamentally changed some 15-30% of the island's total surface area. This provides a unique case to evaluate the consequences of a slowly unfolding environmental catastrophe that has affected, and is continuing to affect a primary means of subsistence for a whole society. Buffered by the sufferings of regions of Iceland, individual farms and particular social groups, Icelandic society as a whole has endured through subsistence flexibility, social inequalities, and the ability to tap into larger provisioning and economic networks. This demonstrates how an adaptable society can confront challenges through social organisation and by diversifying their impacts on ecosystems. In the medium term—multi-century timescales—this can be an effective, if costly, strategy, in terms of both the environment and society. In Iceland, soil conservation is now a national priority, woodland is returning, and climate warming is opening up more potential for arable agriculture. However, the slow catastrophe of Icelandic soil erosion is still unfolding and with the perspective of the *longue durée* it is evident that decisions made in the Viking Age and medieval period still resonate, constraining future options for resilience and adaptive flexibility.

Executive summary for stakeholders

Within Europe, Iceland has suffered from more soil erosion than any other country. It provides an instructive case study to evaluate the long-term consequences of a slowly unfolding environmental catastrophe that impacts a primary means of food production for an entire nation. Animal husbandry, the basis of the land-based economy in Iceland since the ninth century, coupled with the cumulative effects of land management, climate change and volcanic impact have led to the loss of about 15 - 30,000 km^2 of vegetation and soil cover from the Icelandic landmass. This catastrophic geomorphological change represents a fundamental alteration to some 15-30% of the island's total surface area. Due to the sensitivities of the landscape, soil erosion cannot be reversed by a simple return to the conditions existing immediately before it began, and thus has continued for centuries. Halting erosion requires a fundamental reset in terms of land use, and that is hard to do- especially when the opportunity cost of changing subsistence practices is too great. Buffered by the sufferings of regions of Iceland, individual farms and particular social groups, Icelandic society as a whole endured mostly through flexible subsistence, intensified social inequalities, and the ability to tap into larger marine and overseas provisioning and economic networks. This case demonstrates how an adaptable society can confront challenges through social organisation and by diversifying the ways they impact the ecosystem. In the medium term—the past thousand years or so—this can be an effective, if costly, strategy, but it constrains future options and may fatally undermine human security in the future. A country can be highly eroded, yet still support a resilient agricultural system and develop to support a sophisticated urban society. But the scale of soil loss will generate issues for long term local food security as the potential for future agriculture is limited by the soil erosion of the past. These limitations of local potential currently occur against the background of unprecedented global change and increasing international uncertainty, both of which could dislocate the international networks on with Iceland is heavily dependent. The Icelandic human ecodynamics story is far from over, and the next century will certainly see profound global change and many unanticipated outcomes. The slow catastrophe of Icelandic soil erosion is still unfolding, with the perspective of the *longue durée* it is evident that decisions made in the Viking Age and medieval period still resonate, constraining future options for resilience and adaptive flexibility. Management decisions today will create the landscape heritage of the future. Planners need to be aware that trade-offs among options for enhancing short term resilience can have severe long-term consequences in the context of slowly evolving catastrophic outcomes.

Introduction

In 2009, Sveinn Runolfsson, Director of the Soil Conservation Service, Iceland remarked that *"The strong link between the health of the land and human living conditions has been amply demonstrated over the 1,100 years of Icelandic history…Massive land degradation and soil erosion contributed to the collapse of a once prosperous nation"* (Runolfsson 2009). Runolfsson neatly captures a common view of the consequences of soil erosion in Iceland and elsewhere (e.g Diamond 2005), views that we explore in this chapter.

Soil erosion in Iceland provides a unique case to evaluate the consequences of a slowly unfolding environmental catastrophe that affected and is affecting the primary means of subsistence for a whole society. In Iceland, animal husbandry – the raising of cattle, horses, sheep, and goats and, in the early centuries of settlement, pigs – has been the basis of terrestrial subsistence and land-based trade from initial settlement of the island in the ninth century (*Landnám*) to early modern times. Over the same period, the cumulative effects of land management, climate change, and volcanic impact have led to the loss of about 15-30,000 km^2 of vegetation and soil cover (Arnalds et al. 2001, Arnalds and Barkarson 2003, Crofts 2011, Streeter et al. 2015). This catastrophic geomorphological change represents a fundamental alteration to some 15-30 % of the island's total surface area, and, as about 10% of the island is ice covered, a higher proportion of its usable soils and continuous vegetation cover. Soil erosion in Iceland is in most cases a gradual and cumulative process, developing over multiple decades, if not centuries. Thus, it is not a disaster 'event' as such, but a slowly unfolding catastrophe. The triggering and rate of soil erosion are heavily influenced by the intensity of geophysical and meteorological processes (Arnalds 2000, Ólafsdóttir et al. 2001). However, since the introduction of domestic animals to this sensitive sub-arctic environment, animal husbandry and the management of grazing have had the greatest influence on composition, health and extent of vegetation and soil cover (Runolfson 1978, Thorsteinsson 1986, Arnalds 2000, 2004, Streeter et al. 2015). Historical and palaeoenvironmental evidence of landscape-scale change has been central to understanding the rate and scale of erosion in Iceland. However, the relationship between soil erosion and social vulnerability has received less attention. What were the overall effects of soil loss on Icelandic society?

Soil is the foundation of agriculture, and in Iceland's case, healthy grazing lands are vital for successful animal husbandry. Thus, we might assume that the extreme nature of Icelandic soil erosion has also been a primary driver of large-scale social change (Diamond 2005, Montgomery 2007). From an environmentally deterministic perspective we might infer a connection between large-scale soil erosion and acute social stress, but this is not necessarily so, because societies may choose to innovate and adapt. Icelandic society as a whole has been highly resilient over multi-century timescales, avoiding the fate of the neighbouring Norse colonies in Greenland, despite the compounding effects of socio-political and economic change, environmental degradation, climate change, volcanic eruptions, and outbreaks of disease (Karlsson 2000, Dugmore et al. 2012). Icelandic society has experienced acute social pressures in the centuries since settlement. There have been prolonged limits to population growth and long periods of profound inequality, where substantial proportions of the population were insecure, marginalised and vulnerable, especially during the variable climates of the fourteenth to nineteenth centuries (Vasey 1996, Karlsson 2000). Individual farms have failed as a result of soil erosion, but Icelandic society has endured despite the massive environmental change, and in the nineteenth century entered a prolonged period of growth, increasing human security and wealth, despite rapidly eroding soils and the cumulative effects of a millennium of soil erosion (Karlsson 2000, Crofts 2011, Fig.1).

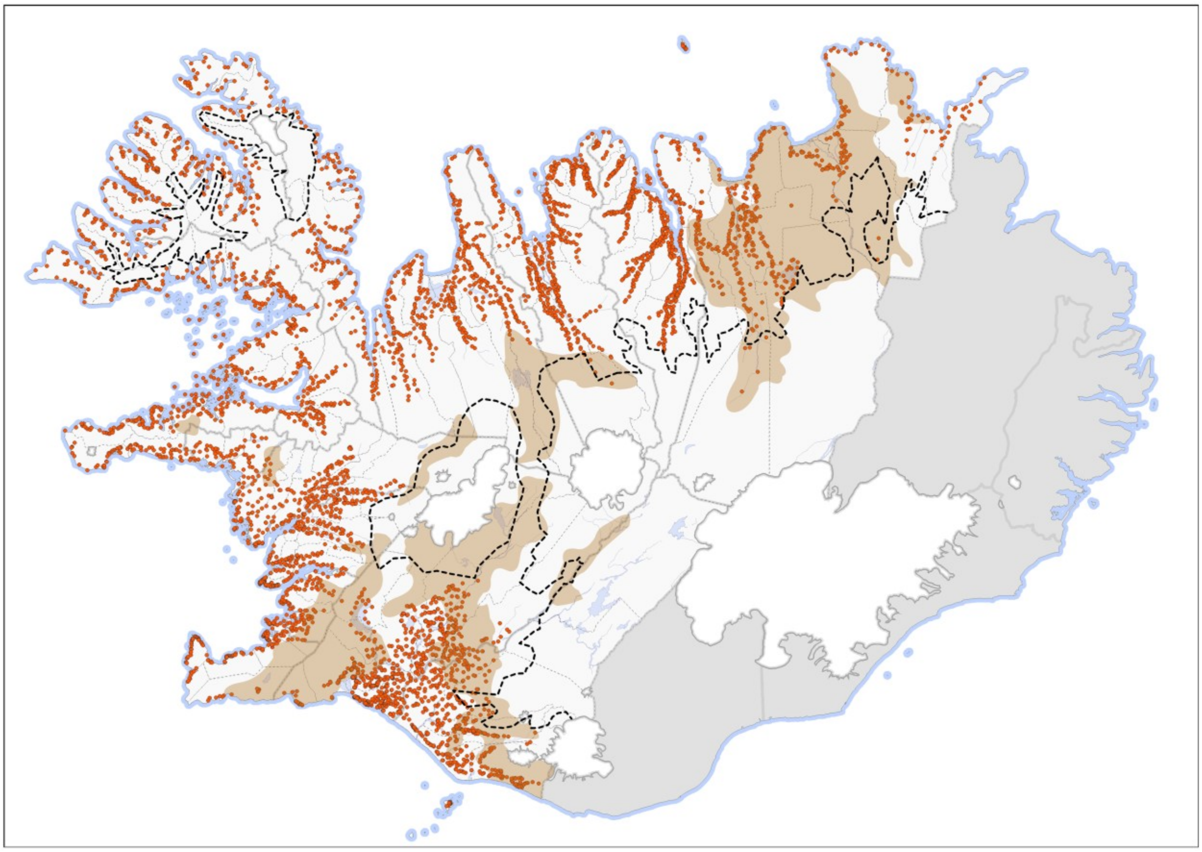

Figure 1: Settlement sites from the 1703 'Book of Farms' (data for the south-eastern part of the Island does not survive). This gives a very good impression of the extent of settlement in the early modern period before the population increases of the nineteenth century and mechanisation. Shaded areas represent districts with significant late twentieth century rangeland degradation, soils erosion and the development of rofabard erosion scarps (Arnalds 2000). The dotted lines in the highlands mark the early twenty-firstt century extent of major areas of very sparsely vegetated zones of poorly weathered vitrisols and lithosols that contain less than 1% organic carbon and are infertile (Arnalds 2008). Island-wide, cumulative soil erosion has a very limited effect on home field areas vital for most terrestrial food production in medieval and early modern times. Degraded areas can be effectively utilised for extensive sheep grazing in the summer time and wool production even though this will exacerbate their deterioration. We argue that persistence of settlement in Iceland was the outcome of adjustments made to the initial subsistence system and subsequent landscape learning that allowed the Norse to take advantage of new opportunities offered by resource systems across Iceland during the Viking Age. Societal resilience in later Medieval Iceland was also a product of social structures that enshrined inequalities, a flexible response to political and environmental change, and the ability to both tap into marine food webs and to capitalise on external economic opportunities. The basis of Icelandic societal resilience (from both engineering and ecological perspectives) was the ability to mitigate impacts of environmental degradation through social and political networks which created flexible resource-use strategies for land, rivers, lakes and sea (Jackson et al. 2018). By displacing vulnerabilities spatially, temporally and socially, the controlling social groups could promote their own resilience with the costs borne by multiple landscapes and lower ranking Icelanders.

Today, societies are also facing another type of slowly unfolding catastrophe driven by anthropogenic climate change. As global average temperatures increase, we are aware of the potential for future problems now, but increasingly severe impacts are only likely in generations to come, and the cumulative effects may be exacerbated by the displacement of vulnerabilities within the entire global system. Global disparities in wealth, access to resources and exposure to the impacts of climate change are likely to widen the capabilities gap in the future (Liechenko and O'Brien 2008). Ecological damage has also become a major threat to global food security. Deforestation and soil erosion are strongly associated with unsustainable land management through intensive grazing and monocultures in many modern contexts (e.g. Foley et al. 2005). Such is the rate of land-use change that the United Nations Food and Agriculture Organisation suggest that there may be as few as sixty harvests remaining (Arsenault 2014). The loss of nutrient-rich top soils is thus a long term, wide reaching problem connecting current global change to the Icelandic case. Slow catastrophes visible in the Icelandic past may shed light on modern global change.

In this paper we draw on sustained international interdisciplinary investigations in Iceland and from across the rest of the Scandinavian North Atlantic. Using an historical ecology framework, we combine landscape-scale data from archaeology, environmental history and geosciences to elucidate evidence of human adaptive strategies that built redundancy into the subsistence and economic base of the Icelanders (Crumley 1994, 2017; Hartman et al. 2017). We utilise records of contemporary soil erosion, tephrochronology and long term aeolian sediment accumulation rates (SeAR) to infer detailed patterns of landscape change over multi-century timescales. This work is based on published and unpublished sources, reinterpretation of established knowledge, and a nuanced philosophical approach to the role of environmental change in human affairs. We do not focus on a single discovery and its implications, an approach that can encourage monocausal and environmentally deterministic emphasis to explanation (Dugmore et al. 2012, cf. Diamond 2005). A belief in reductionism and determinism expresses the view that our future is determined by irresistible forces (Hulme 2011) - that there is indeed *"a divinity that shapes our ends, rough hew them how we may"* (Wm. Shakespeare: *Hamlet,* Act 5, Scene 2). Instead, we choose to evaluate the interplay between the constraints and opportunities presented by the environment, human actions and their consequences. We use a historical perspective to understand how situations developed, with the recognition that alternative outcomes were possible, and that lessons may be learned from the past that can inform contemporary debates about future actions.

The peopling of an island

The colonisation of Iceland by the Norse in the late ninth century marked the initial occupation of one of the last settled places on Earth. Before the arrival of the Norse, the only land mammal on the island was the Arctic fox. There were no indigenous herbivorous mammals. The depauperate, boreo-temperate vegetation of the island was a subset of that of Northwest Europe and lacked endemic species (Dugmore et al. 2005). Woodlands of birch, willow and juniper covered the sheltered and geomorphologically stable areas of the lowlands. Heath lands extended into favourable areas of the central highlands, which were, and still are, dominated by a series of icecaps that cover about 10 % of the island. There is good evidence for a population of over twenty thousand people arriving in Iceland in less than a generation and transforming lowlands and uplands landscapes within this timescale (Vésteinsson and McGovern 2012). Settlement rapidly spread to cover the lowlands up to c. 400 m asl (Schmid et al. 2017). The first settlers introduced cattle, horses, sheep, goats and pigs to form the basis of their farming economy; they cleared woodlands and created field systems to produce fodder and grazing; and they organised a shieling system for seasonal grazing between lowland and upland pastures. Upland pastures were used during the summer months and specific upland areas were utilized as commons grazing land corresponding to each rural municipality (Icel. *hreppur*), while lowland pastures more often had rights connected with specific farms. Historically, sheep have been taken down to lowland pastures in early September and were taken into barns as fall and winter progress. Although the Norse settlement was based on farms and a farming identity, the early settlers also exploited wild birds, walrus, and seal colonies, with marine and freshwater fish providing an increasingly important supplement to the farming economy (Perdikaris and McGovern 2008, Lawson et al. 2007).

The anatomy of an environmental catastrophe

The scale of soil degradation and desertification in Iceland over the last millennia, which has been identified from paleo-environmental evidence, is without parallel in the wider North Atlantic region (northern Europe, the other North Atlantic islands and the eastern part of North America). Iceland is probably the most eroded country in northern Europe, despite its late settlement by people, and the processes that drive Icelandic soil erosion are well known (Arnalds 2000, 2004, 2008).

In modern Icelandic, the noun *uppblástur* is the most common word for wind erosion. It is derived from the Old Icelandic terms for this phenomenon: the verb *blása* (to blow), and the past participle or adjective form *blásinn* (blown). This indicates that wind was considered a primary cause of erosion, and that it was well known in the medieval period. The terms *blása/blásinn* appear a number of times in medieval and pre-reformation texts in different contexts: accounts of Iceland's settlement, sagas, legends and official documents. The multiple references to wind erosion across a number of sources indicates that there was a general awareness of the problem of deflation. However, when viewed in the context of the widespread environmental evidence for soil erosion, references are perhaps less frequent than might be expected.

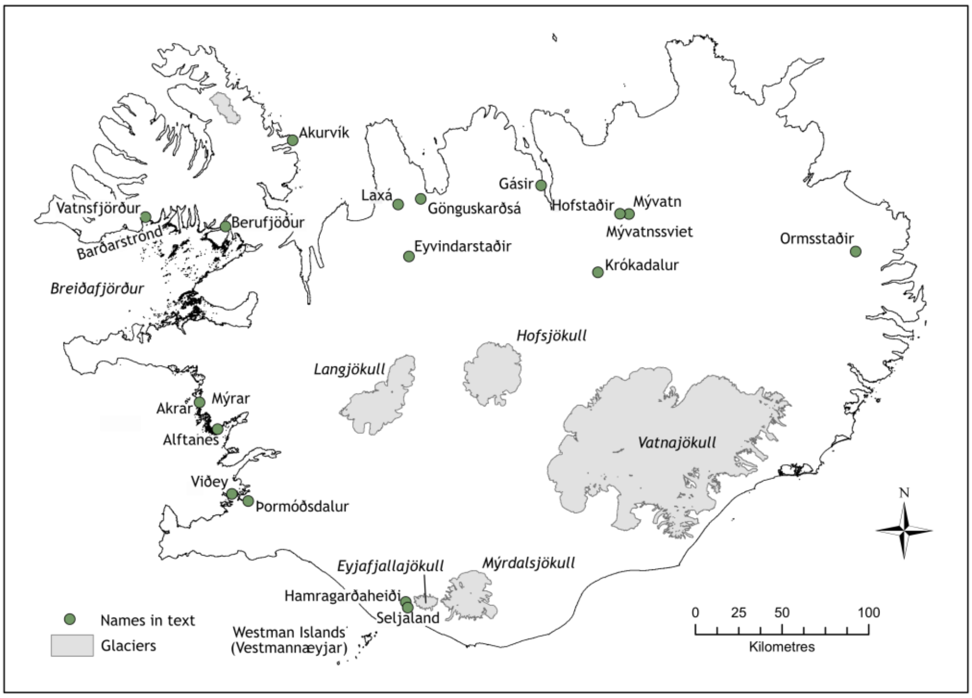

Figure 2: Locations of places mentioned in the text

One example of an early written reference to soil erosion can be found in the Hauksbók version of Landnámabók (The Book of Settlements), compiled by Haukur Erlendsson in the early fourteenth century. This text says that Ormur Auðgi, son of Herjólfur, the first settler of the Westman Islands (Fig. 2), "*bio a Orms stoðvm við Hamar niðri þar sem nv er blasit allt*" (lived in Ormsstaðir down by Hamar where it is all eroded now). (*Hauksbók*, p. 105). In a version of Örvar-Odds saga dated shortly before 1300, erosion appears in an interesting existential or philosophical context, underlining or symbolizing the passing of time (Pálsson and Edwards 1985). When Odd was a young man, a sorceress predicted that he would become three hundred years old, but the skull of the horse Faxi would eventually be the cause of his death. Odd killed the horse and dug it very deep in the ground. After that he travelled all around the world and did not return until three hundred years later to Berurjóður, where he had grown up. "*Þar var þá víða blásit ok jǫrvi, er þá váru hlíðir fagrar*" (it was widely eroded there and gravel was where there used to be beautiful slopes) and a snake came out of the eye of the weathered skull of Faxi and bit Oddur who then died. An eroded grave mound appears in the saga of Saint Olaf (c. 1350-1375), where strong wind had blown the soil off some silver (Johnsen and Helgason 1941). "*Blásinn*" appears once in the Diplomatarium Islandicum, in a document about the Viðey monastery purchasing the abandoned farm Þormóðsdalur in Mosfellssveit (near Reykjavík), "*var jordin adr blasin ok langa tima i eyde. sa þar litil merki til tvna ok tofta oc spiltt at ollv*" (the land was eroded earlier and abandoned for a long time. There were little remains of a homefield and ruins and damaged in every way. (*Diplomatarium Islandicum* VII, 584-585)).

Soil is mobilised when vegetation cover is lacking or breeched, and erodible sediment is exposed to the action of frost, trampling by animals, wind and the action of running water. There are, however, significant differences of opinion over the relative importance of different drivers of vegetation disruption that can lead to soil erosion. The drivers broadly fall into two categories, of human impacts such as deforestation and the (mis)management of domestic animals, and natural processes, such as ash fall from volcanic eruptions, drifting sand, flooding, low temperatures, high rainfall and strong winds (Arnalds and Barkarson 2003, Simpson et al. 2001, Greipsson 2012). Broadly, opinions may be divided into those who think that people are primarily to blame, those who attribute the scale of change primarily to natural forces (while acknowledging some role for human impact), and those who would argue for combined synergistic effect of human actions and natural drivers. Crucially, the importance of different drivers of soil erosion has varied through time and across different regions of Iceland (Streeter and Dugmore 2014).

While authors debate the relative importance of triggers and drivers of soil erosion, the characteristics of Icelandic soils that make them vulnerable to erosion are generally agreed. The soils of Iceland are dominated by loessial andosols, which are derived from volcanic sediments (Arnalds 2015). Discrete layers of volcanic ash (tephra) augment most Icelandic soils. These are the soils subject to greatest erosion. The rapid weathering of fine-grained basaltic tephra (due to a high surface to volume ratio) results in the formation of poorly crystalline clay minerals, such as allophane and imogolite (Arnalds 2015), which lack the cohesive properties of phyllosilicate clay minerals. The ready aggregation of these clay minerals to form stable silt-sized particles, means that Icelandic andosols are particularly vulnerable to wind erosion. In addition, other properties such as high water retention and very low plasticity mean loessial andosols are vulnerable to erosion by rain splash, running water, frost heave and slope failure (Arnalds 2000). Icelandic andosols began to form soon after the decay of the last inland ice sheet, and over the course of the last eight thousand years soil profiles have been thickened through the addition of aeolian sediments derived from unstable sandy areas (Arnalds 2004, Ólafsdóttir and Guòmundsson 2002). Source areas for these wind-borne sediments include the highland deserts, pro-glacial areas and the great outwash plains. In addition, volcanic ash (tephra) from eruptions (in some cases up to several km^3) has been spread over large parts of Iceland several times a century on average. These tephra layers have provided additional sources of fine-grained sediment that may be picked up by the wind and added to soils elsewhere on the island (Larsen and Eiríksson 2008, Larsen Thórarinsson 1977, Larsen 2000, Thórarinsson 1967, 1975). Island-wide there are two main trends in soils thickness and composition. Firstly, thicker soil profiles will tend to contain more tephra layers than thinner soils, because prevailing wind patterns and proximity to active volcanic systems shape the distributions of both aeolian soils and tephra. Secondly, soil cover is older, and generally thicker in lowland areas, becoming thinner and younger in higher, more inland locations (Ólafsdóttir and Guòmundsson 2002).

Un-vegetated Icelandic soils are readily eroded by the wind and may be transported locally and regionally. The eroded sediment can be re-deposited in the surviving areas of soils and vegetation. This means that aeolian sediment accumulation rates (SeAR) can be used as proxy records of the erosion intensity in the surrounding area (Thorarinsson 1961, Dugmore and Buckland 1991, Streeter et al 2012). This is important, as soil erosion in Iceland often leads to the loss of the entire soil thickness, down to the bedrock or lag-deposits (Arnalds 2000). Therefore, enhanced off-site accumulation is the only means of measuring the rates of erosion. Thórarinsson (1961) pioneered the use of tephrochronology to track changes in sediment accumulation rates, and this approach can be used to precisely and accurately track variations in sediment accumulation rates temporally and spatially, and thus infer the intensity and scale of erosion (e.g. Dugmore and Erskine 1994, Dugmore et al. 2009, Streeter and Dugmore 2014).

Thórarinsson (1961) first highlighted the dramatic environmental changes that occurred following the settlement of Iceland, which triggered a shift from an island-wide system characterised by extensive lowland birch forests and low regional rates of sediment accumulation, to one characterised by very limited birch woodland and high regional rates of sediment accumulation (Streeter et al. 2015). In addition to large-scale, island-wide changes, more localised trends exist in the data collected from soil sections. This is because rates of accumulation at any one location represent an amalgamation of the local aeolian sediment flux, which reflects the immediate geomorphological setting, and the regional aeolian sediment flux, which reflects the soil erosion over a wider area. Rates of accumulation will increase, often dramatically, as aeolian erosion develops in the local area (Dugmore and Erskine 1994). The main reasons for the large increase observed in some locations are: 1) increasing proximity to eroding slopes, 2) increasing erosion of nearby, deeper, lowland soils, and 3) a location downwind of actively eroding areas. As proximity to an eroding slope increases, so will accumulation rates, and sites downwind and downslope of eroding slopes will capture more material than sites upwind and upslope (Dugmore et al. 2009). The erosion of shallow soils will generate a comparatively limited sediment flux, but the erosion of deep soils can generate a very large sediment flux (Dugmore et al. 2009). Changes in absolute, normalised and relative SeAR within and between soil sections indicate patterns of nearby erosion (Dugmore and Erskine 1994, Streeter and Dugmore 2014). Increased spatial variability between accumulation rates in soil sections indicates increased levels fragmentation within the landscape, and relative variations of SeAR within a soil section revealed by tephrochronology are important indicators of local change (Streeter et al. 2012, Streeter and Dugmore 2014).

Soil erosion typically begins with the development of small breaks within vegetation cover, known as erosion spots (Gísladóttir 1998, 2001, Arnalds et al. 1987, Arnalds 2000, Dugmore et al. 2009). Either these spots of exposed soil may be re-colonised by plants, or they may erode further, creating persistent deflation patches. These patches will tend to deepen until the resistant underlying substrate is exposed. The denuded areas expand as the eroding fronts eat into the surrounding areas of soil and vegetation, ultimately stripping the landscape of its primary soil cover (Ólafsdóttir 2002). These eroding soil slopes on the margins of vegetated land are a common feature of many parts of the Icelandic landscape and they are named *rofabarðs* in Icelandic (Arnalds 2000). Rofabarðs form a semi-permanent feature of the landscape, as they move at a pace of cm/year or m/century. While the rate of back wearing of the exposed soil slope is an important determinant of the pace of soil cover loss, the most important factor in Iceland is the density of eroding spots or the length of rofabarðs per hectare (Fridriksson and Gudbergsson 1995).

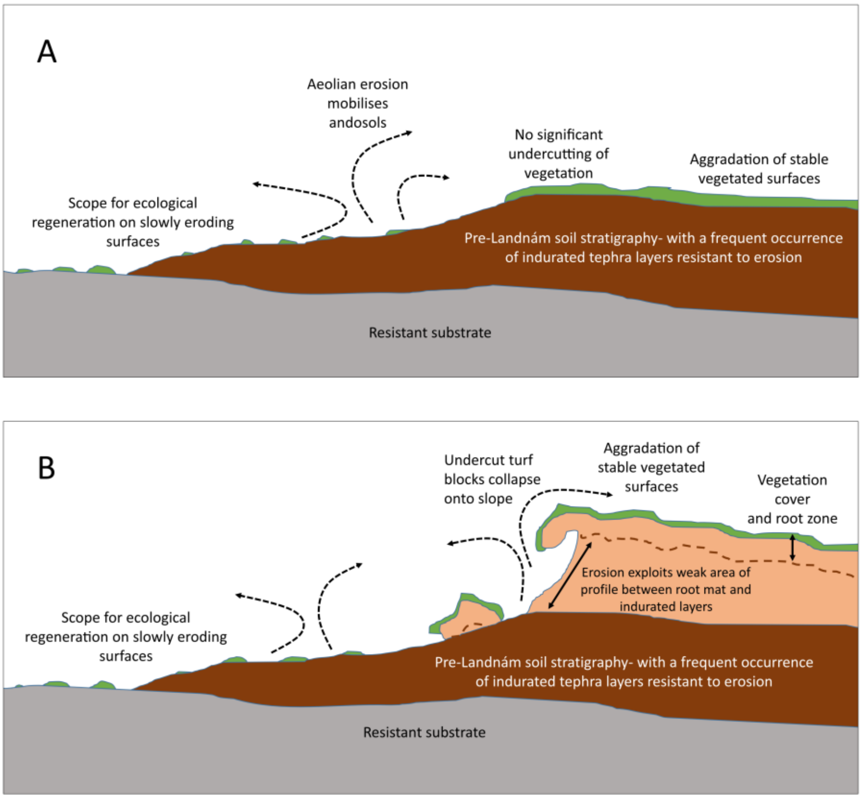

Figure 3: Once rofabarðs form, feedback mechanisms can reinforce their development leading to a slowly unfolding catastrophe. As andosols erode (A), the surviving soil profile thickens (B) and its resistance to erosion changes; thicker soils separate roots from the resistant underlying substrate and create zones more susceptible to back wearing that are formed from more rapidly accumulated, more easily erodible sediment that lacks binding roots. This creates the potential to unzip the soil cover, a process exacerbated by livestock seeking shelter beneath overhanging turf blocks.

The morphology of eroding soil slopes and their vulnerability to degradation will have changed through time (Fig. 3). We have good evidence that the rate of soil cover loss was greater in the past than it is today and yet SeAR are higher now than then (Arnalds et al. 1987, Dugmore et al. 2009). This mismatch can be explained by an early phase of rapid areal loss of thin soils in more marginal upland areas, probably due to a high density of erosion spots across these parts of the landscape and a resulting high density of rofabarðs. More recently, particularly in the last few centuries, the erosion of thick soils in lowland areas has generated much higher levels of SeAR, but because it involves a lower density of rofabarðs per hectare, it results in lower rates of soil cover loss.

Different parts of the eroding slope have varying susceptibilities to erosion depending on the overall thickness of the soil profile, the frequency and degree of weathering of tephra layers contained within the soil, and the depth of the root mat. The basal part of soil profiles may have significant resistance to soil erosion, resulting in low islands of remnant soil scattered across a landscape stripped of soil. This is because pre-Landnám andosols have comparatively low rates of aeolian sediment accumulation (Thorarinsson 1961, Dugmore and Buckland 1991, Streeter et al. 2015). As a result, tephra layers tend to be closer together, and where these tephra are basaltic in composition they are often weathered to form semi-lithified (indurated) layers with a lower susceptibility to erosion. This development of semi-lithified tephra layers within andosol profiles is a function of the presence of tephra layers and their age, but it is also heavily dependent on the weathering environment, which is influenced by rates of profile aggradation. In southern Iceland, we have noticed that where rates of accumulation are low, weathering of basaltic tephra layers is more developed and vice versa.

The presence of semi-lithified tephra layers in the basal parts of soil profiles slows the lateral movement of rofabarðs, resulting in low angle slopes that are more resistant to erosion (Fig. 3). Within the upper parts of the soil profile the root mat offers significant resistance to erosion by wind and water. This is especially true of the dense and thick root mats that develop under well-grazed forb meadows. If the dense root mat penetrates to levels that include semi-lithified tephra layers, overall erosion rates are inhibited. Because of anthropogenic soil erosion, however, the upper parts of surviving post-Landnám soils profiles are characterised by faster accumulation rates than those formed before settlement and the surface root mat is lifted away from both the underlying substrate and the semi-resistant pre-Landnám soil layers. When this happens, the upper parts of the eroding slopes can be undercut and the advance of rofabarðs is dominated by rapid back wearing and turf block collapse. This 'unzipping' of the landscape is difficult to stop, without a physical reshaping of the exposed slopes and proactive re-vegetation.

While certain combinations of ecology, grazing regime and climate will lead to breaks in vegetation cover and initiate soil erosion at a particular place, a partial amelioration of those triggering conditions will not necessarily stop that erosion. This is because the vegetated soil surface, and the exposed, persistently eroding soil surface, represent alternative states which are reinforced by biophysical feedbacks and that can exist under the same external environmental conditions (Marston 2010). While a stable vegetation cover enables plants to grow, and thus perpetuates stability, surface instability inhibits plant growth and that lack of plant growth enhances continued instability. Once rofabarð erosion begins, it will tend to be enhanced as the surviving soils are thickened with locally eroded materials, eroding slopes become more exposed and steeper and the processes of erosion reinforced (Arnalds et al. 1987). This is an example of the positive feedbacks that exist within the Icelandic soil system which promote high and continuing rates of erosion. Very low levels of grazing disturbance reinforced by positive feedback loops can maintain the eroding surface. For example, needle ice formation and cryoturbation in areas of exposed sediments, which disrupt the establishment of seedlings, make it hard for plants to re-vegetate these areas (Arnalds 2015). Thus, the development of rofabarðs represents a cusp bifurcation (Streeter and Dugmore 2013).

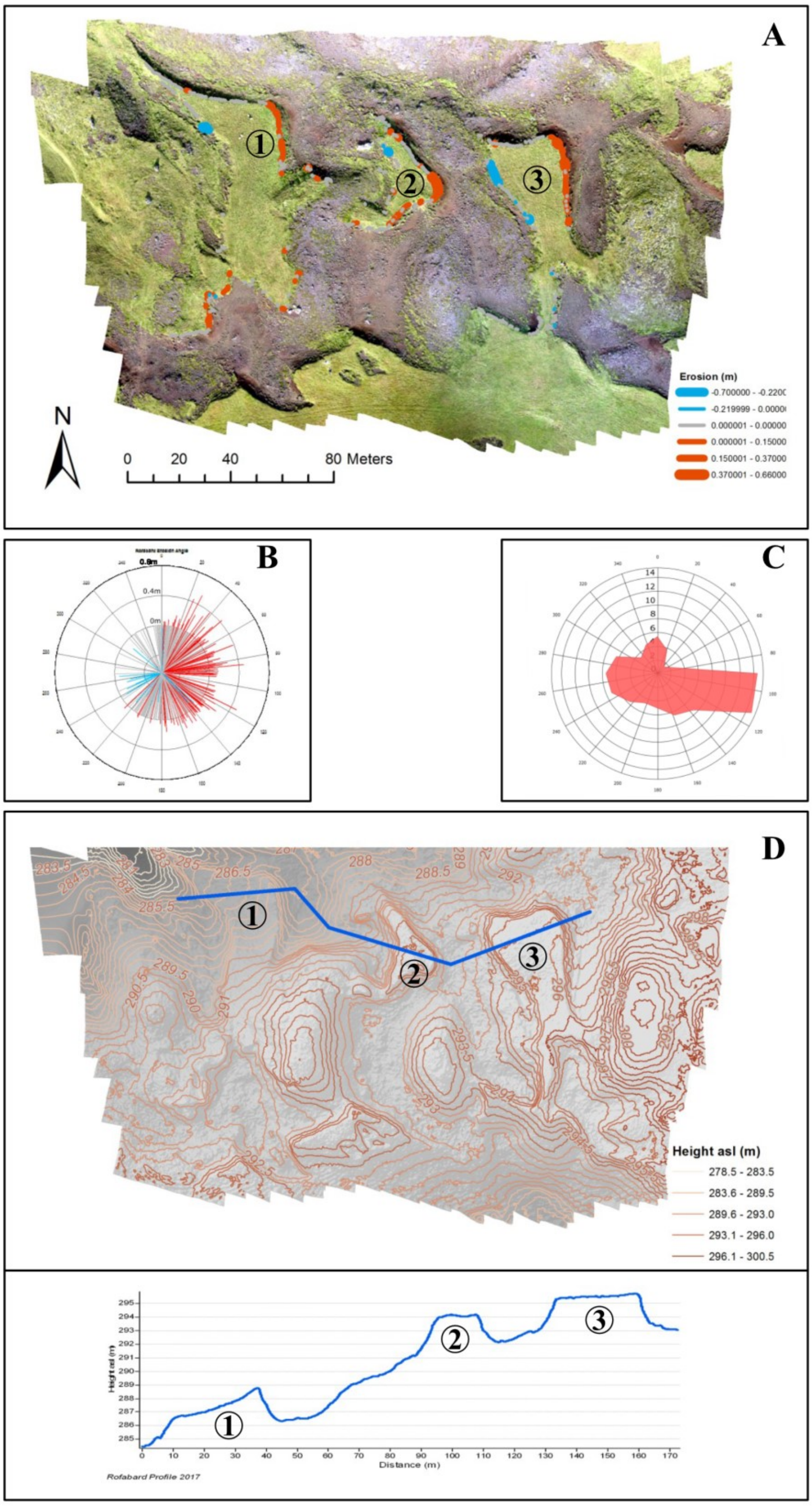

Figure 4: Analysis of rofabarð erosion over a two year period using aerial imagery. Orthophotos and digital elevation models were derived using UAV photography, corrected with differential GPS, via the structure from motion software Agisoft Photoscan. Rofabarð margins for 2015 and 2017 are delineated and differences measured manually using ArcGIS v10.1 (measurement accuracy ~0.05m), to indicate erosion (red) and accretion (blue) (A). The aspect of each rofabarð margin, and its associated level of erosion/accretion (B) is compared to the prevailing wind direction (data from nearby Vestmannaeyjar) (c). A topographic representation of the site is shown (D) which displays the transect used for creating profiles of rofabarðs (1), (2) and (3). The rofabarð cross profiles (E) are created using ArcGIS 3D analyst.

Once past land management (or indeed mismanagement) led to the creation of eroding surfaces, the prevailing climate became the dominant factor determining the pace of geomorphological change as this is driven by a combination of earth surface processes such as aeolian erosion, needle ice formation, raindrop impacts, overland flow, rill formation and gullying (Arnalds 2000). The lifespan of rofabarðs will depend on their spacing in the landscape and rate of movement, but where they have become established tens-to-hundreds of metres apart in thick soil profiles they can persist over multi-century timescales. Close to the farms of Seljaland in south Iceland for example, changes in the spatial patterns of SeAR coupled with coarse sediment transported by overland flow indicates that the rofabarðs present on hillsides today initially formed in the fourteenth century (Dugmore and Erskine 1994).

The spatially complex interplay of grazing impacts and earth surface processes is illustrated by recent rofabarð development on the sheltered slopes of Hamragarðaheiði in southern Iceland (Fig.4). Here, at about 200 m asl, rofabarðs consist of prominent upstanding patches of soil and vegetation tens of metres across, separated by lower-lying denuded areas of approximately the same scale. Locally, grazing intensity has declined since the late twentieth century, reflecting national trends. On Hamragarðaheiði, vegetation growth during the summers of 2014 to 2017 was strong, which combined with modest grazing allowed a lush and deep herbaceous ground cover to grow each year. A partial recolonization of some bare soil slopes has taken place, with the seasonal appearance of 'horsetails', Equisetum spp. Despite signs of ecological recovery on slopes facing the west and south, rofabarð slopes facing the east continued to retreat at rates of cm/yr over this period. This is probably because of prevailing easterly winds that dry exposed soils and then erode exposed particles (Fig. 4B). This effect is probably enhanced as these winds pass over the nearby mountain ice cap of Eyjafjallajökull. The pattern of change on Hamragarðaheiði illustrates how environmental drivers can maintain active areas of soil erosion centuries after the erosion was originally triggered, despite modern grazing pressures that are in of themselves currently sustainable.

In addition to the *environmental* feedbacks that act to maintain soil erosion once it has been initiated, *social and cultural* drivers have also been important in maintaining as well as triggering soil erosion. Traditions of land use, vested interests and displaced impacts have also acted to reinforce established grazing practices, even when changing circumstances may have rendered them unsustainable and environmentally-destructive. For example, revealing details about the management of the uplands and the drivers to maintain grazing there despite environmental degradation, are contained in documents from the fifteenth and sixteenth centuries, and references to events of the fourteenth century.

> *„2. okt. 1464 á Svínavatni. „... Kærði Egill það til Magnús að hann hefði ekki rekið lambfé sitt á Eyvindarstaða heiðar eður toll goldið eftir gömlum vana ... nefndur Egill lét lesa þar transkriptarbréf af úrskurði Einars Gilssonar lögmanns norðan og vestan á Íslandi með heilum og ósködduðum góðra manna innsiglum svo látanda að fyrr nefndur Einar hefði úrskurðað alla bændur í milli Gönguskarðsár í Skagafirði fyrir vestan vötn og Laxár á Skagaströnd fyrir norðan Blöndu þá sem eiga tíu lömb eður fleiri frjálslega í heimild að reka sinn lambfénað um sumar á Eyvindastaðaafrétt en lúka að hausti eitt lamb af rekstri Eyvindarstaðamönnum er af fjalli kemur svo fram sem þeir vilja forðast ... sekt ...*" (*Diplomatarium Islandicum* V : 433).

This passage refers to a court order from Einar Gilsson, Lawman of Iceland 1367 to 1369. The order requires all farmers between Gönguskarðsá in Skagafjörður west of the water divide and Laxá in Skagaströnd north of Blanda river, who owned ten or more lambs, to drive all their lambs to Eyvindarstaðaheiði (an area of upland grazing), and pay a fee of one lamb to the farmer at Eyvindarstaðir, or be fined if they failed to do so. There are several court cases from the period after 1500 where farmers in various areas were also ordered to drive their lambs into the highlands or be fined for failing to do so. In these circumstances the farmers who owned access rights had a powerful incentive (backed by law) to require a continued use of the uplands, even though the grazing quality was failing due to changing climates and land degradation. In the case of Eyvindarstaðaheiði, it was not until the nineteenth century that the landowners were able to restart mountain grazing by tenants and profit from it, but at the cost of enhanced soil erosion (Júlíusson 2019).

In the early modern period widespread tenancy, combined with insecure leases, did nothing to promote practices of landscape conservation, and probably acted to greatly exacerbate impacts (Jonson 1993). Short leases of one to two years, combined with widespread 'tenancies of will' and no incentives or rewards for investing in the land, encouraged tenants to focus their meagre resources in livestock, and maximise offtake rather than tackling soil erosion. In addition, tenants moved frequently from region to region, thus inhibiting the development of local environmental knowledge and nuanced understanding of how best to manage the land (Vasey 1996).

Environmental catastrophe vs societal resilience.

So far, we have discussed the anatomy of the slowly unfolding environmental catastrophe following the rapid colonisation and expansion of farming throughout Iceland, but what affects did deforestation and erosion have on society as a whole? For Jared Diamond and Sveinn Runolfsson, soil erosion had devastating impacts on the prosperity and subsistence of Icelandic society. Studies have since challenged these narratives to provide a complex and contrasting account of the relationship between early settlers and resource use (McGovern et al. 2007, Kristinsson and Júlíusson 2016). Narratives of Norse settlers surpassing the carrying capacity of the environment, overexploiting common resources or indeed developing strategies to sustainably exploit resources to meet local needs, echo broader theoretical frameworks used to study population and resource use. The contributions of Thomas Malthus (1766-1834), Ester Boserup (1910-1999), Garrett Hardin (1915-2003) and Elinor Ostrom (1933-2012) have had significant influence on contemporary research frameworks for reconstructing human resource use in the past—and studies of environmental degradation in particular.

Malthus (1798) observed a cyclical relationship between population growth and food production: as population increased, a greater number of labourers were available to utilise resources, but this growing population would eventually surpass the capacity of the environment to support subsistence. Critically, Malthus observed that human population grows geometrically—or exponentially—whereas food production follows an arithmetic—or linear—growth trajectory (Rowley-Conwy and Leyton 2011). This has informed so-called neo-Malthusian fears that exponential population growth, coupled with overconsumption and the degradation of common-pool resources, will eventually surpass the carrying capacity of the planet (Hardin 1961). Others argue that a global food shortage could even trigger the collapse of global civilization (Ehrlich and Ehrlich 2013, Diamond 2005).

Adopting a neo-Malthusian view, Diamond (2005) outlines a general framework for population overshoot and collapse. The rapid colonisation of Iceland and the increasing utilisation of marginal lands as the population increased, coupled with the degradation of vegetation cover, soil erosion, conflict and disease appear to follow this 'grand narrative' closely. The problem with Diamond's account is that he does little to explain how the Norse adapted subsistence strategies in light of terrestrial environmental degradation. Rather than blindly persisting with their initial strategies, they intensified their subsistence system, utilising wild resources to supplement short-falls from animal husbandry and to capitalise on opportunities to trade wool and dried fish overseas.

As Kristinsson and Júlíusson (2016) explain, there is limited evidence to suggest the Norse Icelanders diminished their resource base in the upland region through deforestation and overgrazing. Estimates from settlement surveys also indicate that the population was not close to carrying capacity at any time between the twelfth and fifteenth centuries (Karlsson, 2000). The human population has declined at various times in Iceland, but it has always remained above thirty thousand people (Vasey 1996). There have been acute but comparatively short-lived demographic contractions, most notably following the fifteenth century plagues, the smallpox epidemics, and the early eighteenth and late eighteenth century famines that were driven by impacts of climate cooling (in 1755) and volcanism (in 1783) (Vasey 1996). Yet even after the eighteenth century—also known by historians as the '*century of misery*'—the Icelandic population was able to recover after each of these shocks. A younger recovering population are likely to have taken on farms that had been abandoned throughout the famine and disease of the 1780s (1783 to 1786); annual population growth averaged 1.32% from 1791 to 1795 and increased to 1.67% in the late 1790s. By the 1801 census, the population had recovered to 47,240—an increase of eight thousand on late 1780s levels (Karlsson 2000).

Characterisations of early Icelandic agricultural systems as rigid or conservative seem misplaced. Kristinsson and Júlíusson (2016) argued that Icelandic agriculture should be viewed through Boserupian theoretical framework. In contrast to Malthusian and neo-Malthusian approaches, Boserup (1965) argued that population growth is likely to stimulate technological and adaptive innovations that allow the population to increase food production. This does not, however, rely on an exponential trajectory of innovation in the techno-optimist sense. Rather, population pressure is eventually felt by a law of diminishing returns. A well-known application of this model in archaeology is Tainter's (1988) seminal work, *The Collapse of Complex Societies*. As he argued, societies collapse in a cyclical process of complex build-up—investment in socio-political complexity required to managing societal problems—and fragmentation—complexity leads to marginal returns and the destabilization, decline and fragmentation socio-political institutions. This follows the Boserupian law of diminishing returns, as the increasing complexity of an expanding society demands increasing energy to sustain its size and complexity. This model fits the Icelandic system in the sense that the Norse settlers demonstrated adaptiveness, but there is increased hierarchy with the emergence of magnates and the demise of independent farmers.

Unlike the Scandinavian colonies in Greenland, settlement in Iceland has endured and survived the multiple environmental, political, economic and social challenges of the last millennium (Dugmore et al. 2007, 2012, 2013). Despite the demonstrable scale, and acute local impacts of soil erosion, in Iceland there was no societal collapse, in either a Diamond-esque or Tainter-esque sense. It should be acknowledged that long-term vulnerability to acute climate variation does increase in the mid fourteenth century especially and has been associated with the abandonment of multiple upland farms in the northern highland valley of Krókdalur, for example (Vésteinsson et al. 2014, Nelson et al. 2016). This would suggest that many settlers walked a fine line between resilience and (household) collapse, but at the island-wide scale the population managed the potential impacts of political-economic complexity and environmental overshoot. Missing from these models is the identification of resource flexibility and governance required to endure times of hardship. Kristinsson and Júlíusson (2016) emphasise that strategic subsistence adaptations were essential to survival in Iceland.

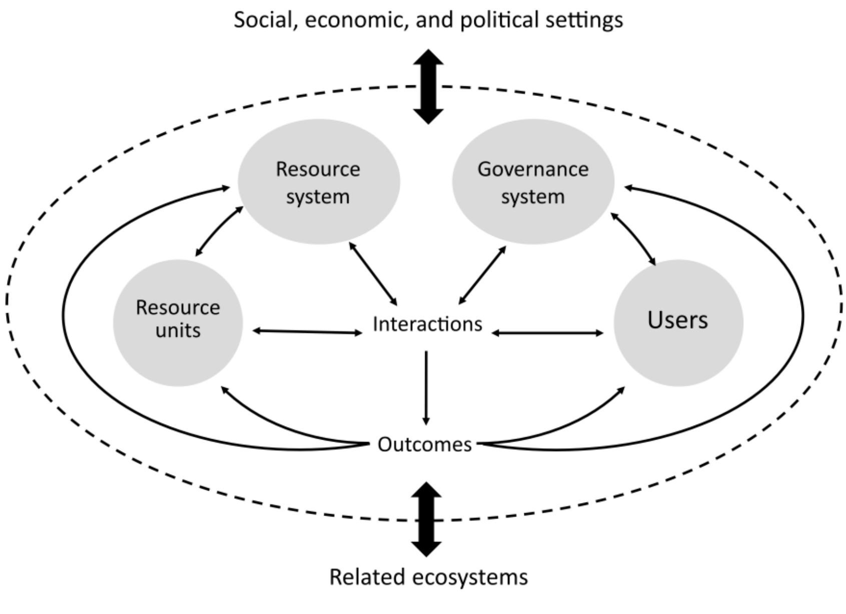

Figure 5: Ostrom's 2009 model for assessing sustainable social-ecological systems. This diagram divides the social-ecological system into four subsystems, comprising resource units, the resource system, systems of governance and users (After Ostrom, 2009).

The Boserupian model can be taken further, however, using Ostrom's influential economic model for managing common-pool resources and assessing the sustainability of social-ecological systems (Ostrom 2015, 2009). Ostrom, who builds on Malthus, Hardin and Boserup, saw value in each of their theories of resource-use, but argued that they largely focused on extremes rather than the various modes of collective action, cooperation and trust that are observed in all societies (Ostrom, 2015). This approach can be summarised in Ostrom's (2009) framework for analysing sustainable social-ecological systems (Fig. 5), and incorporates four subsystem elements: resource units, the resource system, systems of governance and users. The resource system and units comprise what resources fall within the system that are utilised by user groups and over what timescales and spatial extents they are abundant. Governance and users include how human resources are organised and what rules are imposed on exploiting the resource system (Ostrom 2005, 2007, 2009). Understanding the relationship between each of these subsystems can provide a clearer understanding of how the Medieval Icelandic political economy functioned over the *longue durée*, and what impacts the organisation of social groups and collective and private resource had on resource use and local environmental change.

Sustained research in the north and central uplands of Iceland have challenged existing narratives that assumed the early settlers had 'immediate and severe' impacts on the local environment through deforestation and intensive grazing of highland pastures (McGovern et al. 2007). While insufficient settlers' knowledge of the sensitivity of Icelandic ecosystem and volcanic soils in particular could have triggered some episodes of erosion (Dugmore et al., 2006), these knowledge limits do not apply to all settlements (cf. Vésteinsson et al. 2014).

The Medieval Subsistence Economy of Iceland

With the possible exception of some very minor short-lived settlement by Irish hermits before the early eighth century, Norse settlers would have arrived in a culturally blank landscape. Settlement and organisation of subsistence was therefore based entirely on an imported agricultural niche from the Scandinavian homelands to the east (Jackson et al. 2018, Vésteinsson et al. 2002, Vésteinsson 2000). To accommodate the Norse agricultural economy, birch and willow scrub were removed to create grasslands for animal grazing and prime land was reserved to produce hay fodder for stalled winter livestock (Amorosi et al. 1997). The accumulation of environmental knowledge about wild resources would have been an essential strategy from the outset of settlement (Amorosi et al. 1997, Dugmore et al. 2007). In the highland region of Mývatn, extensive multi-disciplinary investigation has revealed a diverse seasonal resource strategy that incorporated animal husbandry with the hunting and gathering of a wide range of local wild resources (McGovern et al. 2007). This has existed from the early tenth century and involved the integration of long-distance economic networks linking inland farms with winter fishing stations on the coast (Perdikaris and McGovern 2009).

The rapid settlement of Iceland is likely to have been sustained by an influx of settlers seeking wealth and status on newly available lands at a time when west Norwegian chieftains were losing power to King Harald Finehair (Fitzhugh 2000, Raffield et al. 2016). Settlers could make a name for themselves by claiming land in Iceland and awarding land to a loyal following (Vésteinsson et al. 2002). This strategy is captured in accounts of early settlers such as *Skallagrim*, in Egil's Saga:

> *Skallagrim was an industrious man. He always kept many men with him and gathered all the resources that were available for subsistence, since at first they had little in the way of livestock to support such a large number of people. Such livestock as there was grazed free in the woodland all year round. […] there was no lack of driftwood at Myrar. He had a farmstead built on Alftanes and ran another farm there, and rowed out from it to catch fish and cull seals and gather eggs, all of which were in great abundance… Whales beached there, too, in great numbers, and there was wildlife there for the taking at this hunting post: the animals were not used to man and would never flee. He owned a third farm by the sea on the western part of Myrar. […] and he planted crops there and named it Akrar (Fields). […] Skallagrim also sent*

> *his men upriver to catch salmon. He put Odd the hermit by Gljufura to take care of the salmon fishery there […] When Skallagrim's livestock grew in number, it was allowed to roam mountain pastures for the whole summer. Noticing how much better and fatter the animals were that ranged on the heath, and also that the sheep which could not be brought down for the winter survived in the mountain valleys, he had a farmstead built on the mountain, and ran a farm there where his sheep were kept. […] In this way, Skallagrim put his livelihood on many footings.* (*Egil's Saga*, ch. 29. Transl. Bernard Scudder, 1997. Vol. 1)

This is a model strategy; Skallagrim took claim of land from the uplands down to the sea. He grants land to his kin as a retainer of resourceful land and he then exploits multiple resource spaces for seasonal grazing, haymaking and fishing (Vésteinsson et al., 2002). This is in stark contrast to the account of Raven Floki, who fails to utilise a range of resources upon settlement in Iceland.

> *Floki and his crew sailed west across Breidafjord and made land at Vatnsfjord in Bardastrand. At that time the fjord was teeming with fish, and they got so caught up with the fishing they forgot to make hay, so their livestock starved to death the following winter.* (Book of Settlement: *Landnámabók*, ch. 5. Transl. Pálsson and Edwards, 1972)

These contrasting narratives can be understood as allegories for sustainable subsistence. The strategy of organising a communal labour force that could be pooled to utilise seasonally abundant resources provided a diversity of resources, building redundancy into the system to buffer against less productive years.

There is evidence of farm abandonment across marginal areas in Iceland—possibly as a result of localised environmental degradation and isolation from supplementary resources—but far from being viewed as examples of failure, recent research has suggested that attempts to occupy marginal land should be viewed as opportunities to create social capital. As Vésteinsson and colleagues (2014) have explained, the occupation of marginal upland environments, such as Krókdalur, should be viewed in the context of the Norse status system. The availability of land in the uplands would have allowed settlers to increase livestock and with this their reproductive rights and social status (Vésteinsson et al. 2014). In other upland areas, such as Mývatnssveit, the early subsistence system is understood to have been sustainable and resilient. Initially, subsistence farming was buffered by marine resources and then, after the fourteenth century, by a wider network of external trade and exchange. So, while conventional narratives viewed upland areas like Mývatnssveit as marginal, archaeological and palaeoenvironmental evidence has revealed a diverse and sustainable strategy that placed rules on exploitation and networked between different resource areas (McGovern et al. 2007).

From the ninth to eleventh centuries, subsistence was largely organised at the household scale, in a peasant mode of production that yielded a minimal surplus that could be stored for hard times or shared with other farms in the district (Wickham 2005, Jakobsson 2013). Inland farms utilised marine resources of fish, marine mammals and sea birds from the earliest times. Chieftains maintained status not through coercive control akin to Feudalism but through honour and loyalty delivered by an allied following. Medieval Iceland underwent a political and economic transformation in the twelfth and thirteenth centuries. In this time, the economy transitioned from a peasant mode of production to manorial tenant system comprising greater taxation and commercial exports (Jakobsson 2013). The transition to a manorial tenant system is significant because it moves the population from a more even distribution of resilience to a generally resilient population, but with significantly more uneven distribution. Izdebski et al. (2018) describe this observed historical phenomenon as the social burden of resilience. This is an outcome of the reorganisation of the economy from reciprocity (more sharing) under a peasant mode of production to redistribution (less sharing from elite to lower social classes) under the new manorial system of accumulated power by the church and elite families.

This transition in political and economic power also lead to a reorganisation of control over the means and spatial organisation of production. Vésteinsson (2016) argues that this transition from a political economy of reciprocity to a manorial system where magnates and the church controlled surplus production could be a key factor in the expansion of commercial stock fishing in the thirteenth century. Under this system, the elite received their status from the support of the Norwegian royal court rather than a loyal following (Jakobsson 2013). By controlling land and the means of production—and therein its surplus—the elite could maintain a lifestyle that would have included obtaining status goods from abroad and attending the royal court in Norway (Karlsson 2000, Vésteinsson 2016). This entailed the specialisation of existing elements of the Norse production system. Extensive research at Hofstaðir and the surrounding farms in the Mývatnssveit reveals an early connection between inland farms and coastal fishing stations (McGovern 2009, McGovern et al. 2007). From the fourteenth century, bulk staple goods including dried cod (stockfish) and woollen cloth (vaðmál) were being exported from Iceland to the European sites. Seasonal trade centers, such as the north-eastern site of Gásir in Eyjafjördur, became points of cultural contact between Icelanders and European traders (Harrison et al. 2008). This entailed the specialisation of cloth production from artisanal production (ninth to thirteenth centuries) to standardisation and specialisation from the thirteenth to fourteenth centuries onwards (Hayeur-Smith, 2014). Sites such as Akurvík and Gásir show evidence of the increased control and manipulation of stockfish markets by elite groups from the fourteenth century onwards (Amundsen et al. 2005).

The transition from a relatively equal distribution of subsistence resources during the Viking Age to a system of tenancy, taxation and specialisation would have created higher levels of material inequality. The overall level of resilience across society as a whole would have remained relatively stable. But this masks the underlying vulnerability and inequalities that were created as powerful magnates exploited labour and rent from materially impoverished farms. In his research on the economy of the Skálholt bishopric in southern Iceland, Hambrecht (2011) demonstrated that the extraction of rents from their tenants by the bishopric in the form of food, driftwood and other resources from a variety of environmental niches secured the elite site and buffered it from the significant environmental variability of the eighteenth century. This security would have come at the expense of impoverished farms that were already suffering the consequences of famine and smallpox.

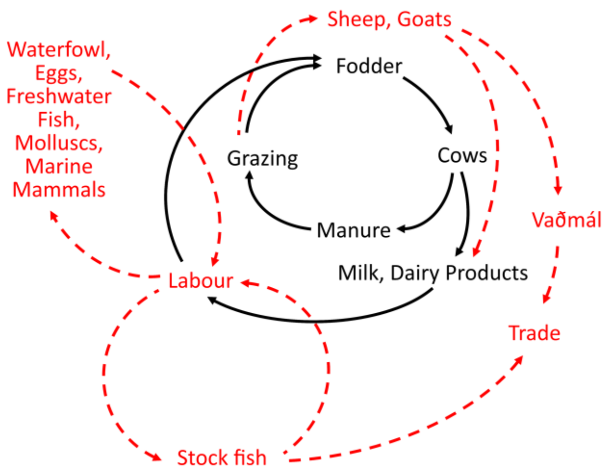

Figure 6: Thomas Malthus' example of the relationship between resources, labour and productivity in Alpine Switzerland (in black). The population will reach a dynamic equilibrium as population is balanced against the available resources and productivity. Overgrazing through mismanagement—which could be related to population growth—will cause environmental degradation and thus reduces the productivity of the environment. However, broader subsistence networks (in red), including hunting and gathering strategies, would allowed the utilisation of resources between upland and lowland grazing areas and marine resources. (Edited from Rowley-Conwy and Layton, 2011).

A Sustainable Social-Ecological System?

Access to a diversity of resources would have allowed farms to modulate between sources of subsistence and trade depending on their seasonal and inter annual availability. If we consider an inflexible agricultural system based solely on grazing, then as soon as erosion is triggered and the size of rangelands declines, there would be little option other than to intensify (Fig. 6 *in black*). This would soon lead to an overshoot and abandonment scenario (cf. Diamond 2005). Many — including Diamond — have considered erosion in Iceland to be a significant challenge for the human population. However, this logic fails to take into account economic networks and modularity built into the Norse Icelandic subsistence system (Fig.7). Broad subsistence networks, hunting and gathering strategies, and management of livestock numbers, plus developing local and regional networks allowed the Norse to utilise resources across upland and lowland grazing areas and from the sea (Fig.6 *in red*). The modularity and heterogeneity of the resource system meant the Norse were able to adapt to local stresses created by soil erosion (Scheffer et al. 2012). The upland areas also never reached carrying capacity, meaning erosion would have had little impact on livestock grazing other than in localised areas that were already marginal or slowly became overwhelmed by the scale of erosion.

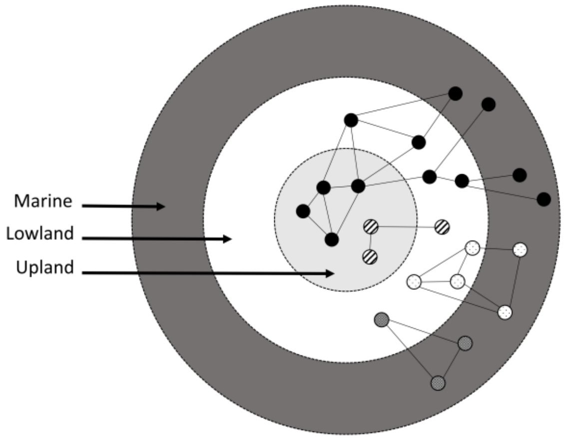

Figure 7: A conceptual diagram showing three different resource systems (upland, lowland and marine) and four different economic networks in Medieval Iceland. Farms are show as small circles, and they are joined by lines representing resource networks. The ability to network across multiple resource spaces would have built redundancy into the subsistence system. Those with limited access to the full range of lowland, upland and marine provisioning systems are more likely to fail and can fail in isolation. This provides scope for incremental changes, as opposed to a critical transformation of the whole system. In resilience thinking, redundancy allow resource users to modulate between areas where the resource system has been impacted and areas that remain unaffected.

From the earliest days of settlement, access to rich marine food webs provided buffering to climate and demographic shocks. The external trade and exchange that developed from the thirteenth century onwards provided wider network linkages, but these were associated with elite management and increased hierarchy, and so, over the *longue durée*, landscape damage and social inequality were linked. In the face of soil erosion, the subsistence system remained resilient through a flexible resource-use strategy—rather than managing the variability of local resources (cf. Carpenter et al., 2014). In other words, the buffering capacity (i.e. resilience) of the seasonal round, plus their ability to tap into the large-scale food webs presented by marine resources (principally fish supplemented by marine mammals), and trade overseas (principally wool and stockfish), allowed them to maintain a large safe operating space through periods of environmental and climatological change. However, these buffering abilities came at a significant social cost of enhanced inequality, and would only be available if stresses did not coincide. If marine resources did not arrive while other pressures were being felt, this would have had dramatic impacts on the Icelandic people. Attempts to mitigate erosion would have created huge opportunity costs because the erosion represents the crossing of a fold bifurcation (catastrophe cusp) and thus requires a non-linear management response to reverse it - strict controls over grazing regimes, and/or reductions in grazing intensity are required to promote ecological regeneration. An environmentally conservative strategy focussed on minimising soil erosion could have consumed significant domestic resources through investment of time and labour and promoted homogeneity and reduced the modularity of resource systems (i.e. diversity of alternative resources in the seasonal round).

The implication is that rangeland soil erosion was not, in of itself a critical problem in the resource system because the Norse were flexible in terms of their utilisation of grazing animals (for meat and milk or wool production), access to wild resources and the extent and diversity of the provisioning system and trade links.

The story of Norse farming should not, however, be viewed simply as a positive example of a resilient society that was impervious to the impacts of soil erosion. Redundancy was built into the Icelandic subsistence economy from the beginning of settlement, but the ability to overcome local impacts also set Icelandic society on a slow and unrelenting path towards the extensive soil erosion now found across Iceland and the depleted fish stocks in the North Atlantic today.

Implications and Lessons

Decoupled Social-Ecological Change in Medieval Iceland – A caution in resilience

Karl Butzer (2012) acknowledged contemporary society's pressing need to transform toward sustainability (see O'Brien 2012, Pelling 2011), but notes that historical examples are needed to offer a deep time basis to test resilience with the caution that "*what is logical in contemporary perspective may be unpredictable in light of good field, archival or other primary sources for historical time*." (p. E2032, Butzer and Enfield 2012).

The declining quality and productivity of the Earth's biophysical systems is a 'grand challenge' for society in the twenty-first century (NRC 2001). The search for parallel challenges in past societies has been plagued with erroneous monocausal and deterministic claims that 'suck in' or 'smear' historical data (Baillie 1991). 'Grand narratives' of collapse are a case in point; often disregarding complex multi-scale changes that contributed to societal stress (Butzer 2012, Butzer and Enfield 2012). The rate and scale of soil erosion in Iceland has been severe since the tenth century (Thorarinsson 1961, Crofts 2011, Streeter et al. 2015), but the impacts of environmental degradation on societal resilience have been overestimated. Large-scale and correlated impacts cannot be equated to simple cause-effect relationships (Oppenheimer 2015, Butzer 2012). Many researchers now caution over-reliance on physical indicators that cannot show direct effects on human populations that could have been resilient to such changes (Redman 2005, McAnany and Yoffe 2010, Middleton 2017, Riede 2017).

We recognise that soil erosion in Iceland operates as a slow variable. It has persisted over the last eleven hundred years, albeit at varying rates (Dugmore et al. 2009). As we have discussed, societies such as Iceland have been and can be resilient to the impacts of soil erosion through the efficient and flexible subsistence strategies that tap into multiple resource systems combined with social systems that enshrined inequalities. Despite social and environmental costs, group survival was ensured. However, at a broader spatial scale, and over longer periods of time the system is under threat, and there is a significant danger in simply arguing that societies can be resilient to the effects of centuries of soil erosion without a cost. In the past, soil erosion may not have driven transformative change to Icelandic society, but at a broader scale, environmental degradation has destroyed natural capital of soils and vegetation that could prove to be vital in the future, if Iceland is thrown back on its own terrestrial resources for food production. Societies may be so flexible and oblivious to costs that they fail to identify the slow decline of local resources and become increasingly dependent on resources brought in along extensive but increasingly destructive networks that erode other resources outside the system.

Conclusions

Iceland is an exemplar of the rate and scale of ecological impact that humans can cause to their environments. Over eleven hundred years, animal husbandry has unzipped the landscape—as localised threshold-crossing events exposed soils to erosion. Buffered by the sufferings of regions of Iceland, individual farms and particular social groups, Icelandic society as a whole endured through subsistence flexibility, social inequalities, and the ability to tap into larger provisioning and economic networks.

Our case study from Iceland demonstrates how an adaptable society can confront challenges through social organisation and by diversifying the ways in which they impact the ecosystem. In the medium term—the past thousand years or so—this can be an effective, if costly, strategy, in terms of both the environment and society. Without conservation and alternative resource-use strategies, revealed in archaeological and palaeoecological studies, the soils could have been even more eroded, and long-term effects may have further compounded vulnerabilities. With unchecked soil erosion, farming on Iceland would be compromised. Likewise, with increasing exploitation of marine resources the marine food web could collapse, further amplifying exposure to risk.

Human exposure to risks can be studied as natural experiments of the past. By focusing on the biophysical processes of soil erosion and the changing social, economic and political organisation of Icelandic society it is possible to map human vulnerability over space, time and between social groups. This of course requires the input of multiple disciplines to reconstruct an accurate account of the connections between socio-cultural and environmental processes (Hartman et al. 2017). The past can be understood in this sense as a laboratory— revealing an experiment on the influence that soil erosion had on society (Curtis et al. 2016). This permits a diachronic perspective linking the evidence for vegetation change and soil erosion with the economic and legal history governing land-use and the household/catchment-scale processes that show evidence of agricultural management (see for example McGovern et al. 2007).

The Iceland case study shows that a country can be highly eroded and still support a resilient agricultural system, and can develop a sophisticated urban society centred on modern Reykjavik and surrounding communities. While Iceland is today an internationally popular tourism destination and is ranked amongst the best places to live in the world, concerns remain about long-term food security (Bailes and Jóhannsson 2011**)**. Soil conservation is now a national priority (Crofts 2011), woodland is returning, and climate warming is opening up more potentials for Icelandic arable agriculture, but future geographic expansion is limited by the soil erosion of the past. While Iceland is positioned to profit from new trans-polar shipping enabled by melting sea ice, much of its modern infrastructure is near sea level and vulnerable to rising tides and increasing storminess. The Icelandic human ecodynamics story is far from over, and the next century will certainly see profound global change and many unanticipated outcomes. The slow catastrophe of Icelandic soil erosion is still unfolding, with the perspective of the *longue durée* it is evident that decisions made in the Viking Age and medieval period still resonate, constraining future options for resilience and adaptive flexibility.

Acknowledgements

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Árni Daníel Júlíusson
Árni Daníel Júlíusson is an Icelandic historian. He has a PhD from the University of Copenhagen. Árni Daníel has written and edited several books, among them the Icelandic Historical Atlas (three volumes, 1989), the Agricultural History of Iceland (four volumes. 2013) and the monograph *Af hverju strái*, (2018) about the environmental history of pre-modern Iceland. He is a specialist at the University of Iceland and is presently active in several international research projects on the environmental history of Iceland.

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Richard Streeter (PhD 2011 The University of Edinburgh)uses layers of volcanic ash (tephra) to date and reconstruct past environmental change. One of his main focusses over the last decade has been understanding past environmental change in Iceland, particularly the interaction between soil erosion, changing climate and a fluctuating population. Recently, he has also started to use aerial images to quantify patterns of erosion in Iceland, with the aim of enhancing our understanding of the underlying biological and physical processes which control soil erosion patterns, in order to better predict the response of Icelandic eroded landscapes to future global change.

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Thomas McGovern
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