Norse Greenland settlement and limits to adaptation

Andrew J. Dugmore, Institute of Geography, School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, Scotland, UK andrew.dugmore@ed.ac.uk

Christian Keller, IKOS, University of Oslo, P.O. Box 1010 Blindern, 0315 Oslo, Norway christian.keller@ikos.uio.no

Thomas H. McGovern, Hunter Bioarchaeology Laboratory, Department of Anthropology, Hunter College, City University of New York, 695 Park Ave, NewYork City 10021, USA nabo@voicenet.com

Andrew F. Casely, Institute of Geography, School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, Scotland, UK andrew.casely@ed.ac.uk

Konrad Smiarowski, Hunter Bioarchaeology Laboratory, Department of Anthropology, Hunter College, City University of New York, 695 Park Ave, NewYork City 10021, USA nabo@voicenet.com

Abstract.

The end of Norse Greenland settlement is widely associated with the climate changes of the 'Little Ice Age', environmental destruction and an inability to adapt, but there is evidence for both Norse sustainable practice and successful adaptation to climate change. As a result we propose that the choices made during the initial Norse colonization and settlement of Greenland, followed by a rising level of connection, intensification, and investment in fixed resource spaces, social and material infrastructure, increased the effectiveness of adaptation but at a cost of reduced resilience in the face of variation. When confronted by rapid natural, and cultural changes the limitations of the pathway chosen by the Norse seem to have been too great and social collapse could have been the result. The lesson of Norse Greenland is disturbing in a modern context. It is possible to creatively adapt to new environments, build up centuries of community-based managerial expertise, wisely conserve fragile resources for communal benefit, codify the results, maintain century-scale sustainable patterns of life and society- and yet still face ultimate collapse and extinction.

Introduction

The end of Norse Greenland sometime in the mid-late 15th century AD is an iconic example of settlement desertion commonly attributed to the climate changes of the 'Little Ice Age' combined with a generalized failure to adapt (e.g. Diamond 2005). The idea of chronic Norse adaptive failure has been widely accepted, in part because other peoples in Greenland (the Thule Inuit) survived through the period of Norse extinction. Human settlement of Greenland was definitely possible through the climate fluctuations of the 13th to 17th centuries AD., despite increasingly well documented changes in temperature, probable growing season, sea ice, storminess and sea level. . The Inuit achieved sustainability during this period of instability and change, but the Norse did not. It is assumed there must have been some degree of Norse maladaptation or more constrained limits to their adaptations than those of the Inuit, and the Norse are seen to have "chosen extinction". We suggest that the picture emerging from recent and current research is far more complex, and propose that the Norse had achieved a locally successful adaptation to new Greenlandic resources but that their very success may have reduced the long term resilience of the small community when confronted by a conjuncture of culture contact, climate change, and new patterns of international trade.

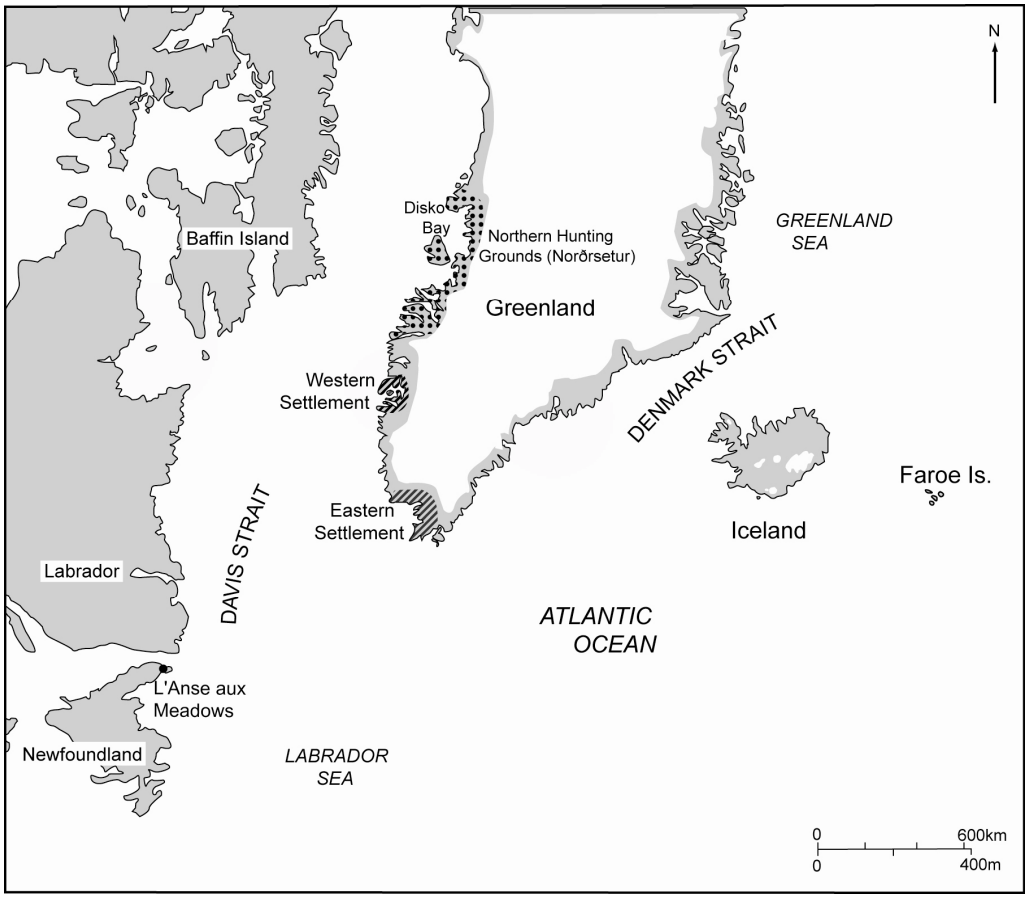

Figure 1: Norse settlement was established on the west coast of Greenland. The larger Eastern Settlement in the south has ca. 400 farms, the Western Settlement has ca. 80 farms. The Norðrsetur (Northern Hunting Grounds) were in the Disko Bay area, c. 800 km north of the Eastern Settlement. Substantial, well furnished churches with stained glass and church bells were built ca. 1150-1300 AD. No more churches constructed after 1300 AD, the Western Settlement was abandoned ca. 1350 AD, the last recorded contact was in 1408 AD and the Eastern Settlement was probably deserted by ca. 1450 AD.

The reasons for the final collapse of Norse Greenland are still incompletely understood, but new data from Greenland and across the North Atlantic, combined with changing ideas and developing cognitive frameworks are refining and deepening our understanding on both adaptation and its limits (McGovern et al 2007, Dugmore et al 2007a).

It is apparent that the Norse in Greenland did adapt to changing conditions, in particular through the increasing utilization of marine mammals (Arneborg et al. 1999). That these adaptations were insufficient to ensure the survival of society may be inferred from the final collapse of Norse settlement, but their limited ultimate effectiveness may be best understood in terms of a failure of *resilience* (' the ability of a system to maintain its structure in the face of disturbance and to absorb and utilize change' (Van der Leeuw 1994)). One possibility is that the initial Norse colonization and settlement of Greenland was followed by a rising level of connection, intensification, and investment in fixed resource spaces, social and material infrastructure which increased the effectiveness of adaptation but at a cost of reduced resilience in the face of variation.

In this paper we explore the idea that the Norse were initially well-adapted to life in Greenland with a subsistence economy based upon the seasonal coordination of the labor of dispersed households and with the ability to regulate wild resource exploitation to avoid overuse. The key failure of the Norse settlers in Greenland would thus have been not because of a clumsy or ineffective initial adaptation of European farming and hunting patterns to their new home, but later on in their limited ability to rapidly reconfigure well established and effective mechanisms for adaptation to meet the combined challenges of economic change, culture contact with the Inuit and unanticipated climate change.

New perspectives: Norse adaptation and sustainable practices

Initial adaptation

In Greenland it is apparent that the Norse did not simply apply proven subsistence strategies based on their prior experience, in Iceland or Norway. The early Greenlandic colonists did import cattle, sheep, goats, pigs, and horses and set up farms ultimately tied to the pockets of inner fjord pasture vegetation in the Eastern and Western Settlements (Fig.1) in a dispersed pattern of farms clearly tied to pasture resources. Despite this terrestrial base, zooarchaeology and isotopic study of human bones reveal the importance of marine mammals from the first stages of settlement. Norse archaeofauna in Greenland from the earliest phases have far more seal bones than appear in any of the other North Atlantic bone collections known from the Northern Isles, Hebrides, Faroes, or Iceland (Perdikaris and McGovern 2008, Woollett 2008). Migrating harp (*Phoca groenlandicus*) and hooded seals (*Cystophora cristata*) encountered in Greenland were rare or absent in the rest of the Viking Age North Atlantic, and their huge populations presented a far richer resource less likely to be depleted by large scale exploitation than the small resident harbour/common seal (*Phoca vitulina*) and grey seal (*Halichoerus gryphus*) colonies of Iceland or the British Isles. While the Norse middens do not contain harpoons or the ringed seals (*Phoca hispida*) usually taken with such gear, the Norse Greenlanders were certainly highly competent seal hunters who made use of nets and probably communal boat drives aimed at the millions of migrating seals arriving along the coast of West Greenland in spring. Utilization of the migrating seals may be seen as a key adaptation to provisioning Greenland settlement as the spring seal migration came at the annual low point when other stored food was probably becoming scarce. The seal hunt was critical to the entire community, and archaeofauna from inland sites many hours' walk from the nearest salt water have archaeofauna as rich in seal bones as coastal farm middens. While the spatial organization of Norse seal hunting in Greenland is now under fresh cooperative study, it is already apparent that the spring hunt of the migratory seals was communally organized, probably drawing on the labor of whole districts for intensive

mass hunts timed to catch and widely redistribute this rich seasonal peak in marine resources. It seems likely that the best modern analog to this pattern may be found in the still active Faroese practice of communal drive hunting (*grind*) of the pilot whale. In the Faroes, every step of the grind hunt (from first spotting to final division of meat) is closely regulated by tradition and written law codes extending back to the medieval period. The *grind* today is seen as so critical to community coherence and Faroese social identity as to be totally impervious to outside pressure from influential international anti-whaling groups. Norse seasonal sealing in Greenland certainly played an even more central role in year-to-year survival, and the annual hunt must have played at least as central a role in reinforcing and enhancing community solidarity.

While there is thus far limited evidence for Icelandic-style large scale consumption of marine fish on inland farms, a few marine fish bones have been recovered far inland, as have the bones of sea birds (Enghoff 2003, McGovern 1985, Smiarowski 2008). The sea birds are almost all guillemots (*Cepphus grille*) and murres (*Uria spp.*), who nest communally on cliff sides in several parts of the outer fjords of both settlement areas. The distribution of their bones on distant farm middens again suggests some sort of communal hunting and redistribution, this time probably occurring in late summer when the molting colonies are most vulnerable.

Walrus hunting mainly took place in the Norðursetur district far to the north of the two settlement areas and seems to have involved weeks-long voyages in both directions during the summer months (Dugmore et al 2007, McGovern 1984). The zooarchaeological evidence suggests that this also was a communal activity, as the fragments of bone from around the walrus tusk root chipped off during final finishing (perhaps during the long winter) are found on inland as well as coastal farms in both Eastern and Western Settlements. It would appear that this Norðursetur hunt took boats and active young people out of the settlement areas most summers. Walrus hunting again apparently represents a community-scale effort; this time aimed at securing goods for overseas trade. Fragments of Norðursetur poetry, lost saga references, and the widespread finds of walrus and polar bear amulets carved from walrus post-canines again suggest that this communal effort was embedded in a rich and well-developed cultural matrix.

Sustainable resource management and the maintenance of flexibility

There is growing evidence from Iceland and the Faroes for successful Viking Age and Norse community-level management of seabirds, waterfowl, freshwater fishing, common grazing and woodland (Church et al 2005, McGovern et al 2007, Simpson et al 2002, 2003, 2004, Dugmore et al 2006, 2007b). As we learn more about economy in the North Atlantic, older ideas of widespread and heedless depletion of all forms of natural capital by Vikings-medieval Norse (e.g. McGovern et al 1988) are being replaced by notions of more sophisticated and successful management by well integrated communities capable of regulating access and draw down of potentially vulnerable resources(McGovern at el 2007). Recent results of environmental archaeology and paleoecology have served to underline the historical evidence for conscious and well developed structures for management of communal and private resources found in surviving medieval Icelandic law codes such as Grágás (Dennis et al., 2000) which set limits on hunting of sea birds, seals, and eider ducks, and regulated use of stranded whales and driftwood. Similar law codes and a multi-tiered court *(thing*) system also were set up in Greenland soon after colonization, and while we no longer know the details, a special set of Greenlandic laws is known to have existed to regulate hunting and trips to the Norðursetur. By AD 1300 several centuries of adjustment certainly had produced a complex and well-developed legal structure regulating communal labor deployment and the distribution of catches. Contemporary Icelandic sources note special aspects of Greenlandic law codes (unfortunately without providing details; Gad 1971). By AD 1300, Norse Greenland had

become a small and somewhat isolated corner of medieval Europe that possessed literacy (in both Latin and Norse), law codes, a resident bishop or bishop's steward, a Norwegian royal representative, a monastery, a nunnery, and churches equipped with imported bells and stained glass. While full scale feudalism probably never became established in the Norse North Atlantic, society was certainly stratified at the state level. Rank and precedent played a significant role in the organization of society and economy, as in the rest of medieval Scandinavia. This modest hierarchical structure has been blamed for Norse adaptive failures (McGovern 1981, Diamond 2005), but in many cases the ability to authoritatively regulate and manage communal resource use probably contributed to adaptive successes, particularly in conserving caribou and non-migratory seal populations.

Caribou (*Rangifer tarandus*) were utilized by the Norse throughout their settlement of Greenland.. Along the long and deeply fiord-cut coastline of western Greenland where inlets frequently meet the inland ice, caribou have historically tended to fragment into localized breeding populations subject to different crash-boom cycles driven by climate and modified by differing hunting pressures (Meldgaard 1985). In the Western Settlement area caribou benefit from more closely inter-connected grazing areas and were probably less subject to deadly range-icing in winter than caribou in the Eastern Settlement area (Vibe 1967). Western Settlement area caribou have also proven resilient in the face of sustained human hunting as they survive in substantial numbers today. In contrast, in the entire Eastern Settlement region caribou were driven to extinction by Inuit hunters in the early 19th century AD.

The medieval Norse settlers certainly had the capacity to place heavy pressure on the Eastern Settlement caribou herds. They maintained large hunting dogs and probably employed drive systems, as well as keeping substantial numbers of competing sheep and goats in the modern summer caribou grazing areas. (Degerbøl 1934, 1941; McGovern & Jordan 1982, McGovern 1985) . Caribou bones make up a consistent proportion of 2-5% NISP (a simple bone fragment count) of archaeofaunal assemblages from the Eastern Settlement (McGovern and Pálsdóttir 2006). The Western settlement range of is higher at 5-27 % NISP, and the stratified collections indicate no decline in caribou taken through time, despite the climatic variability seen during the nearly 500 years of Norse occupation. This pattern suggests that the medieval Norse settlers in the large Eastern Settlement area were in fact more capable of sustainably managing their inherently more vulnerable local caribou population on the century scale than were the egalitarian Inuit hunters who succeeded them.

The utilization of common seals (*Phoca vitulina*) throughout the Norse occupation at Sandnes in the Western Settlement provides another likely example of a sustainable Norse approach to the management of wild resources in Greenland (Fig. 2). Common seal populations tend to be localized, and over-exploitation results in the extinction of particular pods or forces them to relocate to less accessible hauling out locations. As a result, the long-term (century-scale) utilization of common seals at Sandnes and neighboring farms suggests sustainable exploitation. The notable contrasting decline in common seal utilization in the Eastern settlement is unlikely to be a result of over hunting, but more probably a consequence of climate changes. Common seal pups do not thrive in ice filled waters, and the presence of persistent summer sea ice tends to reduce common seal populations (Woollett et al. 2000). Thus the late 13th century AD transition to modern conditions of increased summer drift ice in southern Greenland that affected the Eastern Settlement area but not the Western, could have forced the reduction in common seal observed in the archaeofauna (McGovern Smiarowski and Pálsdóttir 2006, Jennings and Weiner 1996, Jennings et al. 2001).

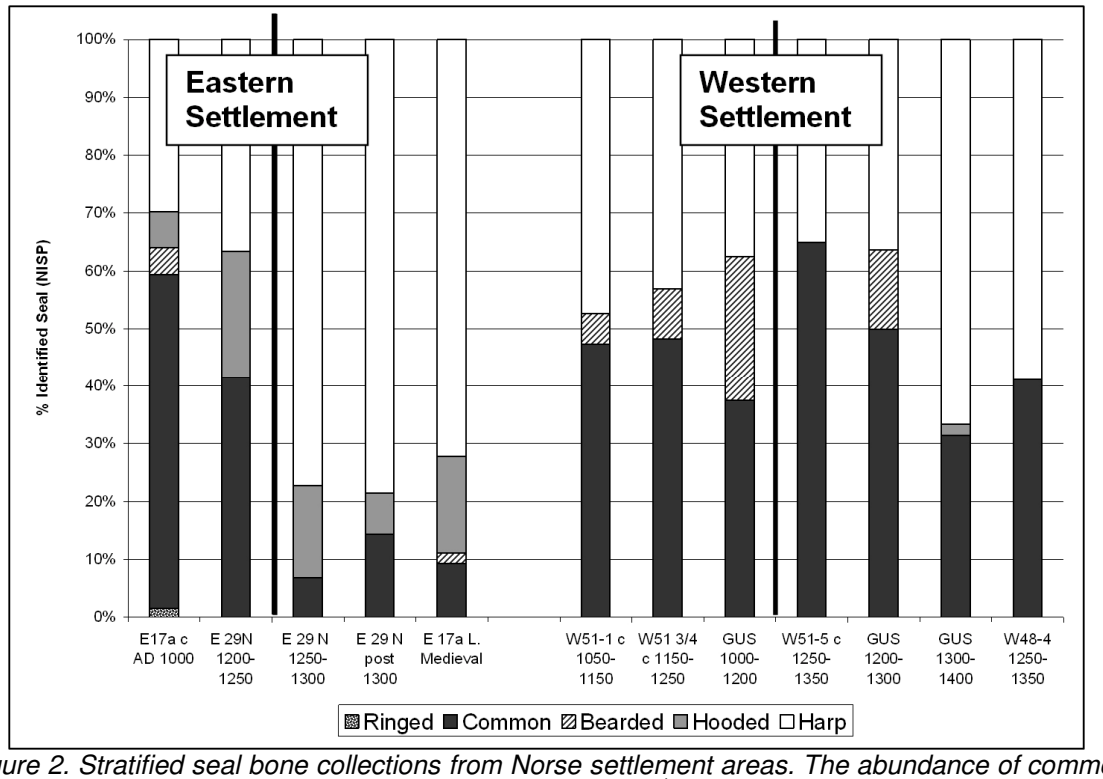

Figure 2. Stratified seal bone collections from Norse settlement areas. The abundance of common seals declines in the Eastern Settlement after the later 13th century. As increases in summer drift ice differentially affect this area it is probable that the change in the archaeofauna is driven by climate. (Data from Enghoff (2003), McGovern et.al. (1996), McGovern et al. (1993), McGovern and Pálsdóttir (2006)).

Details of these Norse strategies of caribou and common seal conservation in Greenland are unclear but we may speculate that it was part of a conscious effort to conserve resilience and flexibility by underwriting the farming economy based on imported stock and the long distance Norðursetur hunt for trade goods. In late medieval and early modern Iceland elements of resilience thinking in a context of recurring labor shortage may be embedded in restrictions on sea fishing. In order to undertake fishing, farm ownership was required, and the development of fishing camps unsupported by agriculture was legally discouraged. The rationale was that fishing alone could not ensure a certain livelihood, and when it failed there would be a burden of poor relief on the wider community if those fishing did not have farming as well. In other words; specialization that could produce a greater short term yield was discouraged because it could potentially compromise the resilience of the wider community through burdens of support during times of fishery failure. Similar rationale may have stood behind the apparent absence of specialized sealing stations in Norse Greenland and the failure to develop substantial fisheries. Despite the growing role of seals in subsistence, even small farms maintained substantial flocks of sheep and goats and at least a few cows- this was a multi-stranded economy which spread risks and coordinated labor on a community scale rather than specialized, individualized subsistence system. Its major limitations were in its inability to accumulate multi-year surplus in the absence of cereal agriculture and the resulting recurring problem of matching high seasonal communal labor requirements with year-round provisioning limits. Even more than in Iceland, medieval Greenlanders faced a year by year zero sum game of allocating scarce adult labor, irreplaceable boats, and a short growing/navigation season among the demands of sealing, birding, caribou hunting, the Norðursetur voyages and farming. Long winters (chess sets are common) were balanced by heavily scheduled summers, and individual and household survival was closely connected to community cohesion and effective deployment of community resources. While a retrospective view of Norse Greenlandic economy and society will inevitably be colored by its final extinction, it is worth emphasizing the extended period of over 450

years during which the Greenlanders successfully achieved their annual balancing act. It seems unlikely that any Norse Greenlander around the year AD 1300 would have sensed changes to come, and unlikely that any modern cultural ecologist would write up the Norse North Atlantic society as a whole as an environmental success story, especially given the scale of soil erosion in contemporary Iceland. Management based upon multi-generational incrementally adjusted legal codes and adjudicated through community court systems backed by top-down secular and religious authority need not be seen as an impediment to effective adaptation or long term resource conservation, and indeed some combination of these environmental management tools are regularly suggested as ways forward today (e.g.Lovelock 2006). There is probably no need to model the Norse Greenlanders as an arctic peasantry oppressed by Eurocentric elites or as poorly adapted to their available resources. Indeed, their problem after 1300 may have been precisely that they had achieved a complex set of well regulated communal adaptations to their arctic homeland.

*Adaptation and the **long dureé***

Isotopic evidence from human remains and a general tendency for the relative percentages of seal bones at archaeological sites to increase through time indicate an increasing marine component in Norse diet in Greenland (Arneborg, et al. 1999, McGovern et al 1996, 2001, McGovern and Pálsdóttir 2006). These changes broadly reflect changes in cumulative measures of climate (Figs. 3a; 3b) suggesting that the progressively more vital role in subsistence played by the seal hunt and other marine foraging could have been motivated by climate changes. Norse migratory seal hunting in Greenland was thus both highly productive and capable of expansion and intensification in response to climate changes. The ultimate cause for failure could however be as a consequence of this increasing utilization and dependence upon marine mammals. When it became the dominant source of subsistence, failure could be catastrophic and the ability to deal with a failure of the seal hunt could be minimal. In absolute terms, boosting alternative sources of subsistence to make good the deficit caused by a failure to adequately harvest the migrating seals could have been extremely difficult and the timing of the shortfall in early spring could have made the situation even worse . If a fishery fails, other options may be available; fishing gear, nets, boats and crews may be re-deployed at other times to target other fish or other fishing grounds. Failure to effectively exploitation of the hooded and harp seals is different. If the spring cull failed because of environmental changes, conflict with the Inuit, or a lack of Norse labour, the making up the shortfall would be a great challenge as there would be no other seal migration the same year. A switch to hunting the harbour seal, which could utilized the same gear as used to hunt hooded and harp seals while possible to some degree in the Western Settlement would not have been possible in the Eastern Settlement (Fig. 2).

Settlement decline

Changing trade

A key motivation for the settlement of Greenland by the Norse was to gain access to walrus ivory and furs; characteristic items of early Viking low-bulk, high value trade in prestige goods. In the late 10^{th}- early 11^{th} centuries AD when the Norse Greenland settlements were becoming established the European market for ivory and fur was buoyant and favourable. Economies changed. The development and expansion of the trade in dried Atlantic cod around 1100 AD was to have widespread economic impacts throughout Europe, which probably did not work to the advantage of the Norse Greenlanders who did little if any fishing. In the Middle Ages Hansa merchants in collaboration with Novgorod and other Russian city states developed the fur trade from the Baltic region northwards into the White Sea; elephant ivory from Africa began to provide unbeatable competition to walrus ivory in European markets and, perhaps most

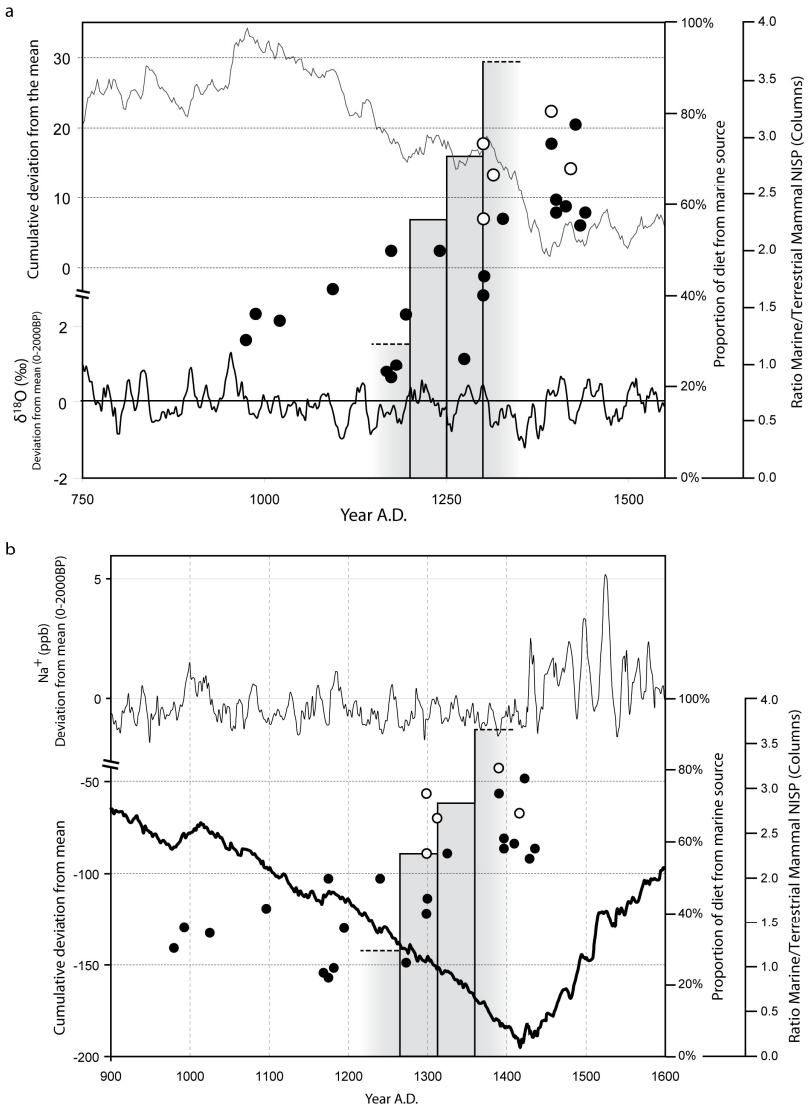

Figure 3: (a) The δ 18O time series from GISP2 (LHS scale), a proxy temperature record, shown against human isotopic data (RHS scale showing proportion of diet from marine sources)(Arneborg et al. 1999; Mayewski et al., 1993; Mayewski and White, 2002; data from Greenland Ice Sheet Project 2. http://www.gisp2.sr.unh.edu/): The lower line is the 5 year running mean of deviations from the long term mean. The upper line is the same data presented as cumulative deviations (Dugmore et al. 2007a). The points represent isotopic data on Norse Greenlanders showing the proportion of marine food consumed. The histograms show the relative proportion of marine and terrestrial bones form the recent excavation at E29N (Brattahlið, Eastern Settlement) (McGovern and Pálsdóttir 2006). The change in the cumulative deviation – marking a shift to cooler conditions- also marks the time of a distinct shift in the isotopic records of diet and changes in the archaeofauna. Closed circles represent data from the Eastern Settlement, open circles data from the Western Settlement.

(b) The Na+ concentration (sea salt) time series, a proxy record of storminess, from GISP2 shown against human isotopic data - lower RHS scale showing proportion of diet from marine sources; the histograms show the relative proportion of marine and terrestrial bones from the recent excavation at E29N (Brattahlið, Eastern Settlement) (Arneborg et al. 1999; McGovern and Pálsdóttir 2006; Meeker and Mayewski, 2002; data from Greenland Ice Sheet Project 2. http://www.gisp2.sr.unh.edu/): The Na+ in the Greenland icecap derives principally from sea salt in the North Atlantic (Meeker and Mayewski, 2002), so temporal variations in sea salt concentrations in the GISP2 record represent a proxy record for winter storminess in the North Atlantic. The upper line (top LHS scale) is the 5 year running mean of deviations from the long term mean. The lower line (RHS scale) is the same data presented as cumulative deviations (Dugmore et al 2007a). Storminess is an indicator of regional circulation change in the North Atlantic, and the most significant shift occurs within a short time of the final extinction of the Norse settlement. Closed circles represent data from the Eastern Settlement, open circles data from the Western Settlement.

importantly, religious art increasingly moved away from the use of ivory (Roesdahl 2005). The Black Death of 1347-1351 AD and subsequent plagues heavily depleted the population in Europe (Gottfried 1983), and in Norway the loss of 30 - 50 % of the population led to an economic collapse. Other developments could have also further eroded the trade position of the Greenlanders: the development of hemp ropes, for example, may have effectively replaced a market for cables made from walrus hide. Add increasing operational difficulties in Greenland (caused by colder, stormier weather and more sea ice) to a fundamental erosion of the Norse Greenlanders' economic position, then, their situation could have become dire (Dugmore et al 2007a).

Under these circumstances it is probable that the limits of adaptation were defined by the constraints of adaptation through enhancement and intensification of existing activities. In other words, more effort into making established practice better or more efficient could not on its own meet the challenges faced by the Norse in 14th and 15th Century Greenland. Worse still, even their ability to carry on 'business as usual' could have been fatally undermined by population decline.

Limits to adaptation- questions of resilience

Any attempt to devise an integrated model for the range of natural and human transformations affecting Norse Greenland in the 14th and 15th centuries faces a number of challenges, most importantly, how to combine the interactions of fast and slow variables operating over both large and small spatial scales. These variables are both human (including migration and colonization, settlement patterns, subsistence choices, social and economic organization, trade and kinship connections) and physical (including snowfall and sea-ice distribution, storminess, growing season, the populations of marine mammals and their movements). For both human and natural systems the ways in which incremental changes may build through time and their consequences, the nature of cross-scale interactions, the occurrence of meta stable states and the circumstances under which threshold crossing changes may occur are all important factors.

The concept of *resilience* is an idea that adds depth to ideas of adaptation and is a potentially useful aid to understanding the end of Norse Greenland. Gunderson and Holling (2002) have used the *adaptive cycle metaphor* to characterize the behaviour of far-from-equilibrium systems (Fig 4a). Different adaptive cycles can be used to illustrate the behaviour of fast and slow variables operating over varied spatial scales, and they can be grouped in a *panarchy* to explore the interactions between them (Fig.4b) Some aspects of the Greenland story appear to fit the looping heuristic framework of the panarchic formulation (Fig.4) but other aspects do not.

Figure 4a provides a useful summary of the Norse settlement, and one that has a series of bold implications framed within it. Although the cycle is broken within the α (reorganization) and Ω (release) phases, the ribbon form of the diagram implies a pathway of development with an inevitable crisis; on one level this is a simply reflection of the actual record of change through time- there has been just one sequence of actual events. For this case study to have wider implications a key question is what general processes may be identified that may tell us about how transformations occur elsewhere and what are the potential limits to human adaptations to climate change. Here the very constraints of the 'adaptive cycle' highlight the circumstances where events could have followed a different path. Once the Norse established settlements in the inner fiord areas and decided to base a substantial part of their provisioning strategy on the exploitation of migrating seal populations, then a series of other possibilities became harder, if not impossible to realize without substantial and far-reaching transformations (an Ω (release)

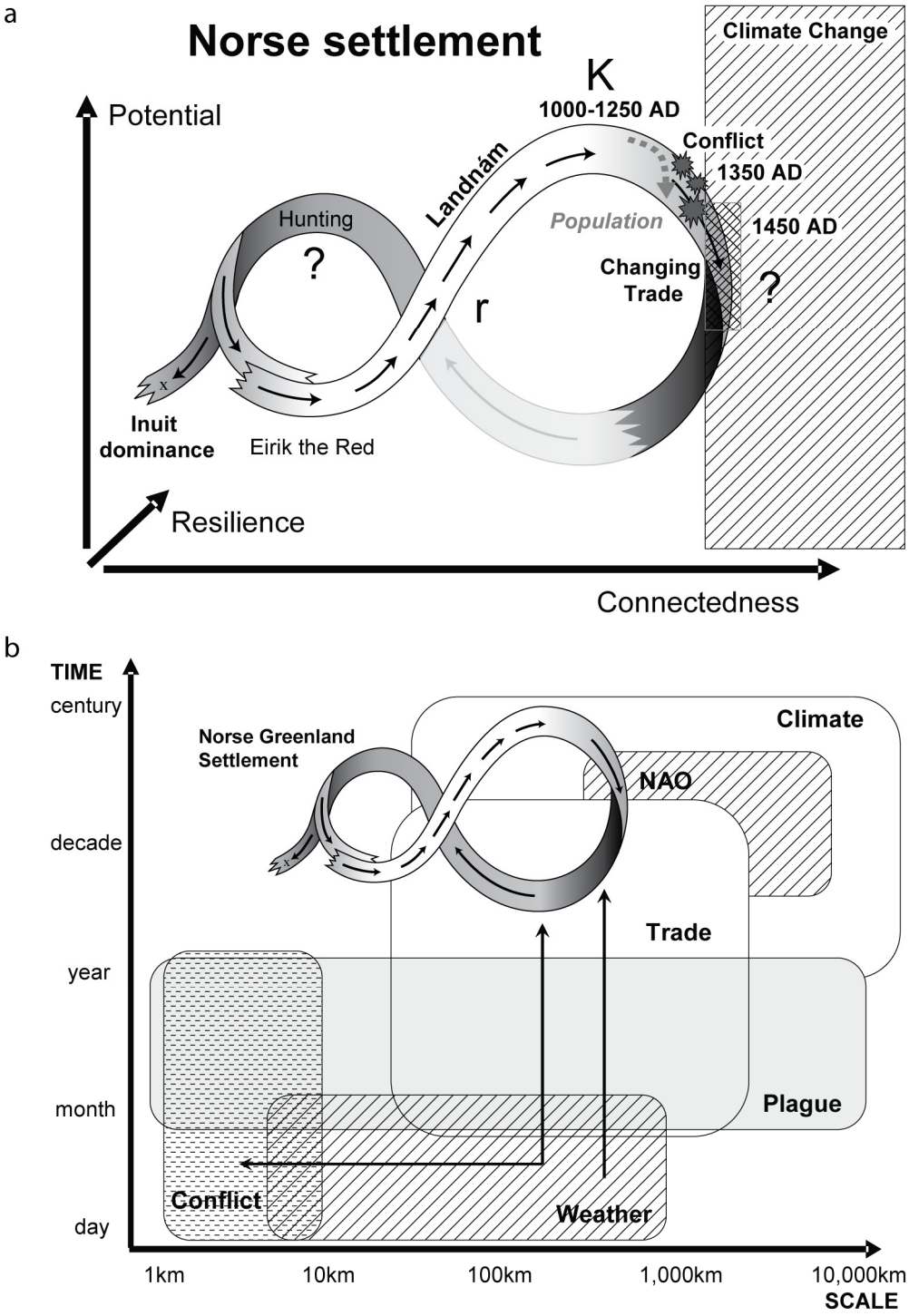

Figure 4a. The Panarchy metatheory (Gunderson and Holling 2002),hypotheses cycles of exploitation (r dominated) to conservation (K dominated) followed by collapse/release (Ω) and reorganization (α): 'connectedness' of the system increases from left to right, 'potential' from bottom to top and 'resilience' reduces into the third dimension (into the page); phases 'r' to 'K' are conceived to involve reduced resilience. The annotation shows how the overall pattern of change in Greenland between the 10th and 16th centuries AD could be described in terms of this conceptual framework as a result of the interplay between fast and slow variables operating at different spatial scales that may be conceived as a 'panarchy' (4b).

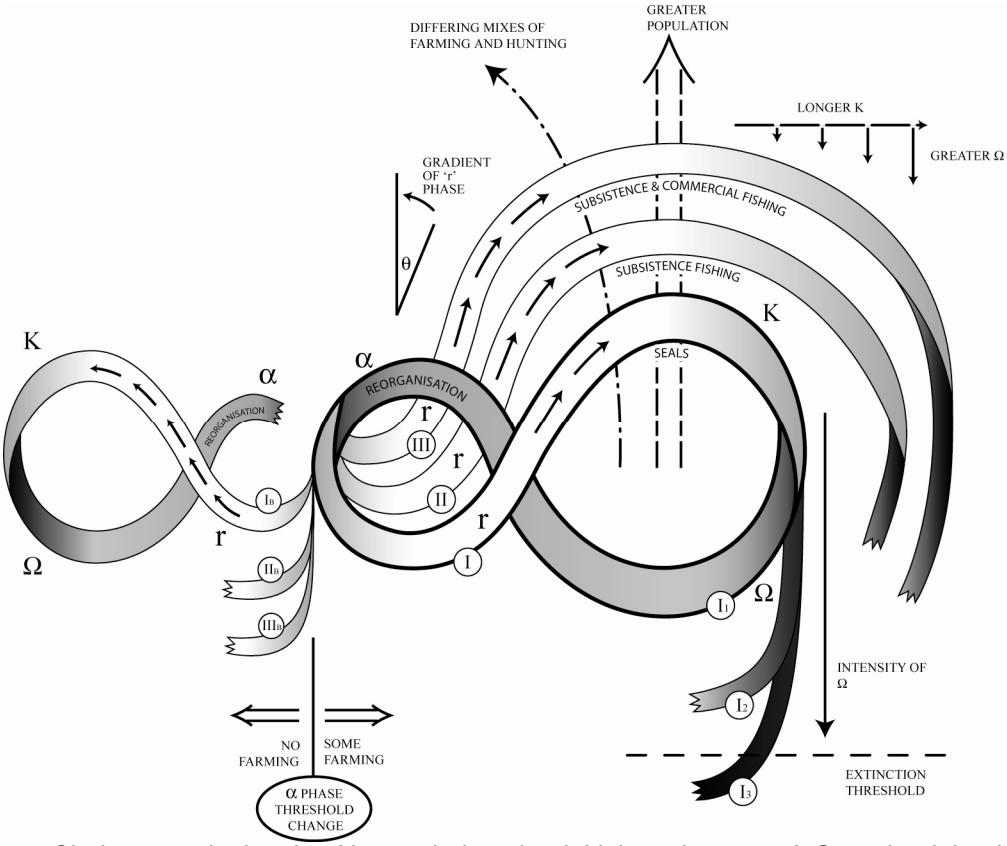

Figure 5. Choices made by the Norse during the initial settlement of Greenland lead to the sequence of events described in Figure 4a and shown here as r I and Ω I_3 pathway. Alternative pathways were possible the 'non-farming' route being the choice of the Inuit, and alternative mixes of hunting and fishing being followed by the Norse elsewhere in the North Atlantic.

phase). As a result the choices made during the initial Norse colonization and settlement of Greenland, followed by a rising level of connection, intensification, and investment in fixed resource spaces, social and material infrastructure, might have increased the effectiveness of adaptation but at a cost of reduced resilience in the face of variation.

The possible alternative pathways that could have been followed by the Norse in Greenland are considered in Figure 5. For each pathway the pace of change will be different (the speed of movement along the pathway)and other adaptive cycles within a more general North Atlantic panarchy are interacting in different ways. For example changes in both regional climate and trade will affect different r-phase pathways in different ways. Cod fishing in Iceland, for example, provided both a means of subsistence and also a commodity to trade, and as a result fishing provided an engine for economic growth in Iceland not available in Norse Greenland.

The possible relation between system resilience and adaptation in the face of climate change for Norse Greenland is explored further in figure 6. Here a key assumption is that the crucially successful adaptive "tool" of the Inuit is not their toggle harpoon, but their mobility, and the adaptive failure of the Norse was a loss of external trade with the decline in the market for prestige goods such as Walrus ivory.. Constraints are imposed progressively from the bottom LHS of the figure and these may be the result of either climate change or conflict that results in access being blocked to resources such as seal migration routes. Population decline for settlements lacking mobility or connectedness could lead to catastrophic threshold crossing events (Ω-phase transformations) as communally-based provisioning systems become non-viable.

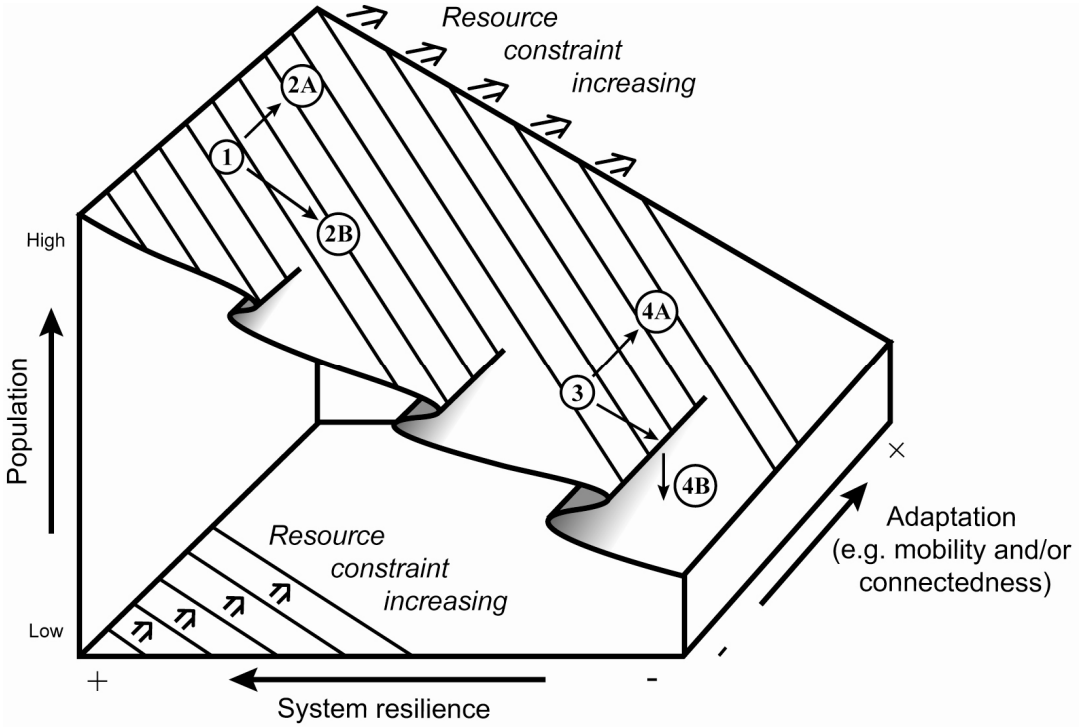

Figure 6. This figure combines ideas of resilience (x-axis) and adaptation (z-axis) with population (y-axis) and resource constraints (defined by diagonal lines). Non linear, threshold changes are defined by catastrophe cusps in the upper 3-D surface. In the example (1) increasing resource constraint (caused by climate change or conflict) may result in adaptive change and a maintenance of population (route 1-2a) - this could be achieved by greater mobility or increased connectedness (trading links). If these adaptive changes are not possible, population may be forced to decline (route 1-2b). Population decline in settlements lacking mobility or connectedness may result in threshold crossing events of a progressively more severe nature. These thresholds may be localized and avoided (route 1-2b) or they may be catastrophic (route 3-4b).

Conclusions

In Norse Greenland successful subsistence strategies were developed and underpinned a well-integrated settlement. Ultimate failure may be attributed to limited resilience and the interplay of cultural, economic and environmental changes at local, regional and continental scales compounded by hostile cultural contacts.

Applications of adaptive cycle thinking at a range of different spatial and temporal scales, and the organization of these cycles in a panarchy provides a bold framework with which to explore limits to adaptation.

The choices made during the initial Norse colonization and settlement of Greenland, followed by a rising level of connection, intensification, and investment in fixed resource spaces, social and material infrastructure, increased the effectiveness of adaptation but at a cost of reduced resilience in the face of variation. We propose that the limits of the Norse Greenlanders ability to adapt to climate change was caused by a series of interrelated factors; firstly the success of the provisioning strategy based on seal hunting was such that initial changes in climate could be met with an intensification of existing practice (but at a hidden cost of reduced resilience).

The rich web of community connection and centuries of legal tradition which provided regulation of resource use, brought inland labor to coastal resource zones and marine food to inland farms, and maintained the long distance walrus hunt in the Norðursetur may also have represented a formidable barrier to individual experimentation and innovation in the face of change. Certainly the adoption of winter ringed seal hunting by

individual hunters whose catch could only provision their own households would represent a major tear in the social and economic fabric of a society centered on spring communal seal hunting and wide distribution of harp seals to those far from the fjord-side. The barriers to the ready adoption of Inuit technology may not necessarily have been imposed from above, especially when traditional communal sealing methods still proved apparently effective. The social danger of undermining the legal and ritual aspects of communal cooperation in Norse Greenland may have appeared to outweigh the flexibility potentially provided by "just another" approach to seal hunting. If problems were perceived, one rational choice might be to avoid measures undermining the very communal solidarity that had seen Norse Greenland through so many hard times in the past, and certainly any widespread collapse of the social underpinnings of the richly interwoven subsistence network would be correctly perceived as the most immediate threat to the society as a whole.

Unpredictable shifts in local climate and sea ice could have compromised both terrestrial resources and raised the costs and hazards of the utilization of marine mammals. The progressive Inuit expansion from Northwestern Greenland into the coastal areas of western and south western Greenland resulted in new cultural contacts and the potential for conflict to disrupt key Norse activities such as access to the Northern Hunting grounds and the spring seal migrations. The communal organization of seal hunting and probably many other subsistence activities in Norse Greenland effectively buffered individual households against shortfall and occasional loss of life at sea, but carried with it the potential for an extreme disaster producing cascading labor shortages encompassing the whole community. Given the small size of the Norse community and the multiple demands upon labor and boats, any set of factors increasing cost and risk had the potential for exceeding buffering limits. The lack of effective multi -year food storage, the recurring shortage of active adult labor, the demands of the (increasingly unprofitable) Norðursetur and the diffuse or direct competition from the locationally flexible Inuit would certainly have posed daunting challenges to the Norse annual managerial balancing act. If even a few ambitious and able Greenlanders did emigrate back across the Atlantic their absence may have been disproportionately felt by the dwindling community left behind, and imported disease need not have been terribly virulent to have damaged this fine balance of producer and consumer.

When faced with rapid changes in a combination of both natural and human factors the limitations of the pathway chosen were probably too great and social collapse was the result. Certainly any reduction of the total population past a minimum threshold needed to carry out effective communal seal hunting would have triggered a terminal subsistence crisis, and any widespread breakdown of law and community cohesion would probably have been equally fatal. Transition to lOmega phase may have been very rapid, and it is possible that no credible management strategy could have averted extinction past the tipping point. The wider lessons of Norse Greenland and the limits to human adaptation to climate change may thus be more complex than we once believed. The Norse Greenlanders did not perish because they were foolishly unwilling to adapt to arctic conditions or because of irrational economic choices. Their real lesson may be far broader and far more frightening in the modern context. It is possible to creatively adapt to new environments, build up centuries of community-based managerial expertise, wisely conserve fragile resources for communal benefit, codify the results, maintain century-scale sustainable patterns of life and society- and yet still face ultimate collapse and extinction.

Acknowledgements

We would like to acknowledge support from the Leverhulme Trust (Footsteps of the Edge of Thule) and funding from the US National Science Foundation Office of Polar Programs Arctic Social Sciences under grant number 0732327 as part of the International Polar Year Humans in the Polar Regions project "IPY: Long Term Human Ecodynamics in the Norse North Atlantic: cases of sustainability, survival, and collapse". This publication is a product of the North Atlantic Biocultural Organization (NABO) cooperative.

References

Arneborg Jette, Jan Heinemeier, Niels Lynnerup, Henrik L. Nielsen, Niels Rud and Arny E. Sveinbjornsdóttir
1999 Change of diet of the Greenland vikings determined from stable carbon isotope analysis and C14 dating of their bones. *Radiocarbon*, 41: 157-168

Church, M. J., Arge, S. V., Brewington, S., McGovern, T. H., Woollett, J., Perdikaris, S., Lawson, I. T., Cook, G. T., Amundsen, C., Harrison R., Krivogorskaya, K. and Dunbar, E.
2005 Puffins, Pigs, Cod, and Barley: Palaeoeconomy at Undir Junkarinsfløtti, Sandoy, Faroe Islands. *Environmental Archaeology* 10, 179-197

Dennis, Andrew, Peter Foote and Richard Perkins
2000 *Laws of Early Iceland: Grágás II. The Codex Regius of Grágás with material from other manuscripts*. Translated and edited by Andrew Dennis, Peter Foote, Richard Perkins. Winnipeg, Manitoba: The University of Manitoba Press.

Degerbøl, Magnus
1934 Animal Bones from the Norse ruins at Brattahlið, *Meddelelser om Grønland* 88:149-155.

Degerbøl, Magnus
1941 The Osseous material from Austmannadal and Tungmeralik, *Meddelelser om Grønland* 89:345-354.

Diamond, Jared
2005 *Collapse: How Societies Choose to Fail or Survive*. London: Allen Lane.

Dugmore, Andrew J., Christian Keller and Thomas H. McGovern
2007a Reflections on climate change, trade, and the contrasting fates of human settlements in the North Atlantic islands, *Arctic Anthropology*, 44, 1, 12-36

Dugmore, Andrew J Mike J. Church, Kerry-Ann Mairs, Thomas H. McGovern,, Sophia Perdikaris and Orri Vesteinsson
2007b Abandoned farms, volcanic impacts and woodland management: revisting Thorjsardalur, the Pompeii of Iceland. *Arctic Anthropology* 44,1 1-11.

Dugmore, Andrew J., Mike J. Church, Kerry-Ann Mairs, Thomas H. McGovern, Anthony J. Newton, and Guðrún Sveinbjarnardóttir.
2006 An over-optimistic pioneer fringe? Environmental perspectives on medieval settlement abandonment in Thorsmork, south Iceland. In Arneborg, Jette and Grønnow, Bjarne (eds.), *The Dynamics of Northern Societies*. PNM, Publications from the National Museum, Studies in Archaeology and History, Volume 10. Copenhagen: 333-344

Enghoff, I. B.
2003. Hunting, fishing, and animal husbandry at the Farm Beneath the Sand, Western Greenland: an archaeozoological analysis of a Norse farm in the Western Settlement, *Meddelelser om Grønland Man & Society* 28. Copenhagen

Gad, Finn
1970 The History of Greenland Volume 1. London: G. Hurst and Co.

Gottfried, Robert S.
1983 *The Black Death: Natural and human disaster in Medieval Europe*. New York: Free Press.

Gotts, N.M.
2007 Resilience, Panarchy and world systems analysis. *Ecology and Society* 12 (1) 24 online http://www.ecologyand society.org/vol12/iss1/aer24

Gunderson, Lance H. and Holling, C.S.
2002. *Panarchy: understanding transformations in human and natural systems.* Washington DC: Island Press.

Jennings Anne E and N. J. Weiner
1996 Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen Fjord 68N *The Holocene* 6/2:179-191

Jennings, Anne E., S. Hagen, J. Harðardóttir, R. Stein, A. E. J. Ogilvie, and I. Jónsdóttir.
2001. Oceanographic Change and Terrestrial Human Impacts in a Post A.D. 1400 Sediment Record from the Southwest Iceland Shelf. In A. E. J. Ogilvie and T. Jónsson (eds.) *The Iceberg in the Mist: Northern Research in Pursuit of a "Little Ice Age"*. London: Kluwer Academic Publishers.

Lovelock, J.E.
2006 *The revenge of Gaia*. London: Allen Lane

McGovern, T.H.
1985 Contributions to the Paleoeconomy of Norse Greenland, *Acta Archaeologica*, 54 : 73-122.

McGovern, T.H. and R. H. Jordan
1982 Settlement and land use in in the inner fjords of Godthaab District, West Greenland *Arctic Anthropology* 19(1):63-80.

McGovern, Thomas H., Bigelow, Gerald F., Amorosi, Thomas, and Daniel Russell
1988 Northern Islands, human error and environmental degradation: a view of social and ecological change in the Medieval North Atlantic. *Human Ecology* 16:225-270.

McGovern, T.H., G.F. Bigelow T. Amorosi, J. Woolett and S.Perdikaris
1993 Animal bones from E17a Narsaq, In: C.L.Vebaek Narsaq- A Norse Landnama Farm *Meddelelser om Grønland Man & Society,* 18

McGovern T.H., Amorosi T., Perdikaris S. and Woollett J.W.
1996 Zooarchaeology of Sandnes V51: Economic Change at a Chieftain's Farm in West Greenland, *Arctic Anthropology* 33(2)94-122.

McGovern T.H., Sophia Perdikaris and Clayton Tinsley
2001 Economy of Landnám: the Evidence of Zooarchaeology, in A. Wawn & Thorunn Sigurdardottir (eds) *Approaches to Vinland*, Sigurdur Nordal Inst. Studies 4 Reykjavik. 154-165.

McGovern, Thomas H. and Albina Pálsdóttir
2006 Preliminary Report of a Medieval Norse Archaeofauna from Brattahlið North Farm (KNK 2629), Qassiarsuk, Greenland *NORSEC Zooarchaeology Laboratory Report* 34, 1-22.McGovern, T. H., Vésteinsson, O., Friðriksson, A., Church, M. J., Lawson, I. T., Simpson, I. A., Einarsson, A., Dugmore, A. J., Cook, G. T., Perdikaris, S., Edwards, K. J., Thomson, A.M., Adderley W.P., Newton, A. J., Gavin Lucas, Ragnar Edvardsson, Aldred, O. and Dunbar E.
2007. Settlement, sustainability, and environmental catastrophe in Northern Iceland. *American Anthropologist* 109 (1) 27-51.

Meeker, Loren D., and Paul A. Mayewski
2002 A 1400 year long record of atmospheric circulation over the North Atlantic and Asia. *The Holocene* 12:257-266.

Meldgaard, Jørgen
1965 *Nordboerne i Grønland*. Copenhagen. Munksgaard.

Perdikaris, Sophia and Thomas H. McGovern
In press Codfish and kings, seals and subsistence: Norse marine resource use in the North Atlantic. In *Human impacts on marine environments*. Torben Rick and Jon Erlandson, eds. Berkeley: UCLA Press Historical Ecology Series.

Roesdahl, Else
2005 Walrus Ivory- demand, supply, workshops, and Greenland, in: Andras Mortensen and Simun Arge (eds.) *Viking and Norse in the North Atlantic: Select Papers from the Proceedings of the 14th Viking Congress, Tórshavn 2001*. Annales Societatis Scientarium Faeroensis XLIV, Tóshavn Faroe Islands, pp 182-192.

Simpson, Ian A., Adderley, W.P., Guðmundsson, G., Hallsdóttir, M., Sigurgeirsson, M.Á., and Snæsdóttir, M. (2002) Land management for surplus grain production in early Iceland. *Human Ecology* 30, 423-443.

Simpson, Ian A., Orri Vésteinsson, W. Paul Adderley, and Thomas H. McGovern
2003 Fuel resources in landscapes of settlement. *Journal of Archaeological Science* 30:1401-1420.

Simpson, Ian A., Garðar Guðmundsson, Amanda M. Thomson and Jon Cluett
2004 Assessing the role of winter grazing in historic land degradation, Mývatnssveit, north-east Iceland. *Geoarchaeology* 19:471-503.

Van der Leeuw, S.
1994 Social and environmental change. *Cambridge Archaeological Journal* 4, 130-139.

Vibe, Christian
1967 Arctic animals in relation to climatic fluctuations. *Meddelelser om Grønland* 170(5).

Woollett, James W., Anne Henshaw, and Cameron Wake
2000 Palaeoecological implications of archaeological seal bone assemblages: case studies from Labrador and Baffin Island, *Arctic* 53(4):395-413.