The Holocene 7,4 (1997) pp. 489–499

Interdisciplinary investigations of the end of the Norse Western Settlement in Greenland

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Received 22 July 1996; revised manuscript accepted 4 April 1997

A HOLOCENE FORUM ARTICLE

Abstract: The loss of the Norse Western Settlement in Greenland around the mid-fourteenth century has long been taken as a prime example of the impact of changing climate on human populations. This study employs an interdisciplinary approach combining historical documents, detailed archaeological investigations, and a high-resolution proxy climate record from the Greenland Ice Sheet Project 2 (GISP2) to investigate possible causes for the end of this settlement. Historical climate records, mainly from Iceland, contain evidence for lowered temperatures and severe weather in the north Atlantic region around the mid-fourteenth century. Archaeological, palaeoecological and historical data specifically concerning the Western Settlement suggest that Norse living conditions left little buffer for unseasonable climate, and provide evidence for a sudden and catastrophic end around the mid-fourteenth century. Isotopic data from the GISP2 ice core provide annual- and seasonal-scale proxy-temperature signals which suggest multiyear intervals of lowered temperatures in the early and mid-fourteenth century. The research synthesized here suggests that, while periods of unfavourable climatic fluctuations are likely to have played a role in the end of the Western Settlement, it was their cultural vulnerabilities to environmental change that left the Norse far more subject to disaster than their Inuit neighbours.

Key words: Climate impact, fourteenth century, GISP2, historical climatology, Norse Greenland, deuterium isotopic signals, zooarchaeology, Medieval Warm Period, 'Little Ice Age'.

Introduction: the case of Norse Greenland

The Norse colony in Greenland was originally founded by settlers from Iceland around AD 985, and lasted for nearly 500 years. The colony settled in two different locations known as the Western and Eastern Settlements (Figure 1). In this paper, the focus will be primarily on the Western Settlement. On the basis of documentary evidence and radiocarbon dating, the end of this settlement has generally been placed *c.* AD 1350 (McGovern *et al.*, 1983; Andreason and Arneborg, 1992; Halldórsson, 1993; Ogilvie, 1997). The larger and more southerly Eastern Settlement lasted at least until the mid-fifteenth century, but had vanished without any known survivors by the end of the fifteenth century (Nørlund, 1936; Halldórsson, 1993).

Many explanations have been proposed for the loss of the Norse Settlements in Greenland (see, for example, Bruun, 1918; Nørlund, 1936; Roussell, 1936; 1941; Vebæk, 1958; Larsen, 1972; McGovern, 1981; Olsen, 1982; Keller, 1991). These have included Inuit competition, the ravages of pirates, declining trade

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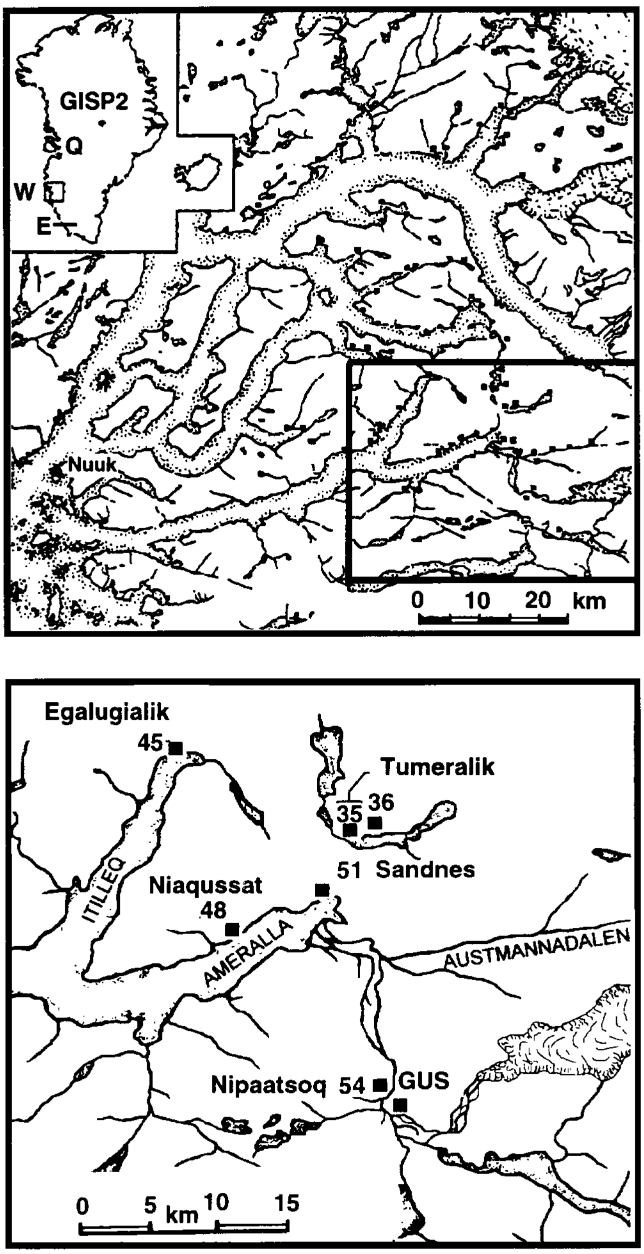

Figure 1 Location maps showing sites discussed in the text. Top: Greenland/Iceland inset: GISP2 = Greenland Ice Sheet Project 2 ice core; W = Norse Western Settlement, with boxed area of enlargement; E = Norse Eastern Settlement; Q = palaeoeskimo site of Qeqertarsuaq, Disko Bay. Enlargement: Norse Western Settlement area. Stippling indicates fjords; thin lines indicate inland ice; dark boxes indicate sites of Norse farms. Norse farms were limited to innerfjord regions by fodder demands of their domestic animals. Bottom: boxed area is expanded again to show farms where palaeoecological research has been done. Sites discussed most frequently in this paper are GUS (Garden under Sandet), V54 Nipaatsoq, and V51 Sandnes. Modified from Buckland *et al.* (1996).

with Europe, and congenital infertility. The most frequently cited explanation has been climate change (for example, Lamb, 1977). However, recent research suggests that the fate of a society is usually not dependent solely on environmental or on social factors, but on an interconnection of influences which require a broad approach to understand it fully (Ingram *et al.*, 1981; Parry, 1981; Ogilvie, 1982; 1984; Kates *et al.*, 1985). Using an interdisciplinary approach, this paper presents new data from historical, archaeological and proxy climate sources in order to investigate possible causes for the end of the Norse Western Settlement.

Much of the earliest research on the settlement of Norse Greenland and the fate of the settlers was based primarily on documentary evidence. This evidence is still vital to our understanding, but it can be augmented by information from other disciplines such as archaeology and isotopic chemistry. Archaeological investigations in Greenland, done primarily in the 1930s and 1940s, have been developed further by an expanding use of a variety of bio- and zooarchaeological techniques. Isotopic data from the Greenland Ice Sheet Project 2 (GISP2), completed in 1993, provide proxy climate information at decadal, annual and even seasonal levels. These high-resolution data enable the establishment of possible links between the settlers and their environment. Even with the availability of seasonal proxy climate data, it is necessary to investigate how the Norse Western Settlers might have been vulnerable to climate dynamics. Thus convincing linkages must be establishd between archaeological, palaeoecological, palaeoclimatic, and historical lines of evidence. The simulation model FARMPACT 5.0 (McGovern, 1995b) was developed partially for this purpose, and is used in this paper.

Documentary evidence: colonization, trade, Inuit contact, climate and the end of the Norse Western Settlement

Historical sources describe the colonization of Greenland from Iceland in the late tenth century, and provide some information on general living conditions as well as matters such as trading and contacts with Iceland, Norway and other European countries, and also relations with the Inuit population. These sources cannot all be considered here, and the discussion will therefore be restricted to information on climate, some details of Inuit contact, and an account of the end of the Western Settlement. All the documents relating specifically to Norse Greenland have been collected in two scholarly works. These are the *Grönlands historiske mindesmærker*, published in three volumes by Finnur Magnússon in 1838 and 1845, and *Grænland í miðaldaritum* by Ólafur Halldórsson (1978). The historical documents relevant to this paper include the medieval Icelandic annals, early works of geographical description, and several letters. A full discussion of these sources and the evidence they contain, as well as an evaluation of their reliability, may be found in Ogilvie (1991; 1997).

Although there are no specific accounts from Greenland regarding weather and climate, there are many such data for Iceland. These mainly concern temperature and precipitation. Accounts of sea-ice incidence off the coasts of Iceland are also of interest as sea ice has value as a proxy climate indicator (Bergthórsson, 1969; Ogilvie, 1992). In comparison with the centuries immediately preceding and following it, there are many data available for the fourteenth century. This period seems to have been rather variable, but it is likely that there were cold years around 1320 and the late 1340s. Much information is available for the 1350s, 1360s and 1370s. Although some mild weather is mentioned, the main emphasis is on cold seasons around these latter decades. The Icelandic sources specifically refer to sea ice reaching the coasts in the years: 1306, 1319 or 1320; 1321; *c.* 1350; and 1374 (Ogilvie, 1991; 1997). The available historical climate data from Iceland are shown in Figure 2.

Because of its comments both on sea ice and its description of the end of the Western Settlement, much discussion has been engendered by the account known as *Ívar Bárðarson's description of Greenland (Grænlandslýsing Ívar Bárðarsonar).* This was almost certainly written in Norway some time during the latter part of the fourteenth century, possibly shortly after 1364 (Jónsson, 1930). The author is unknown, but it is stated in the text that the information he wrote down was told to him by Ívar Bárðarson. Ívar was the steward at the episcopal see of Garðar in the Norse Eastern Settlement in Greenland during the years *c.* 1341 to 1363 (Halldórsson, 1978: 407). It is likely that the

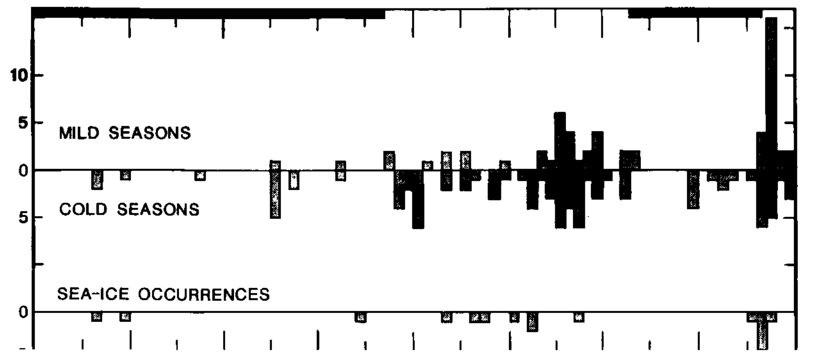

Figure 2 Occurrences of mild and cold seasons and sea ice reported in medieval documents from *c.* AD 865 to 1598. The heavy black lines at the top of the diagram indicate periods of very poor data. A detailed discussion of all the documentary sources of climate data used here may be found in Ogilvie (1991).

account is basically reliable (Jónsson, 1930) but the original document is lost, and the work only survives in a number of seventeenth-century manuscripts (Keller, 1989; Ogilvie, 1997). Two scholarly editions have been published, by Jónsson (1930) and Halldórsson (1978).

Ívar Bárðarson's description of Greenland begins with details of sailing directions and, with regard to the route from Iceland to Greenland, states that the old route can no longer be used due to the increased presence of sea ice. There are two issues of relevance here. One is that it is almost certain that this section of the account is an interpolation, and did not form part of the original, in which case we do not know when it was inserted or what period it applies to. A second issue is that the Icelandic sources already suggest that sea ice was indeed a problem for navigation around the mid-1300s.

Of great interest is the description from this source regarding the end of the Norse Western Settlement in Greenland. It is stated in the text that Ívar was among those chosen by the 'Lawman', or local official, to travel from the Eastern to the Western Settlement to drive away the 'Skrælings'. This derogatory term, meaning something like 'wretch', was the name given by the Norse to their Inuit neighbours. No precise date for the expedition is given in the account, but it is likely to have taken place between 1341 and 1363 (Halldórsson, 1978: 407–408; Ogilvie, 1997). Among other things, the account states that the 'Skrælings have destroyed all the Western Settlement. There is an abundance of horses, goats, bulls, and sheep all wild, and no people neither christian nor heathen' (see Ogilvie, 1997, for a full translation and discussion). The account clearly places the blame for the loss of the Western Settlement on the depredations of the Inuit. However, exactly what did happen appears to have been as perplexing to Ívar as it is to us. The very fact that his expedition took place at all makes it clear that the Norse Greenlanders of the Eastern Settlement had reason to believe that all was not well with their compatriots in the Western Settlement. The implication is also that their concern was fairly recent; otherwise an expedition would have been mounted earlier. If Ívar's account is correct, then the presence of the domestic animals found by them also suggests that the human Norse population had not been gone long, as it seems unlikely that the livestock would have survived more than a few winters without additional food and shelter.

Another interesting account documenting hostility between the 'Skrælings' and the Norse is to be found in one of the Icelandic annals. For the year 1379 it is stated: 'The Skrælings attacked the Greenlanders and killed eighteen men and took two boys into slavery' (translated by Ogilvie from the text published by Storm, 1977: 364). We do not know which settlement this refers to, but if Ívar Bárðarson's account is correct, and his expedition to the Western Settlement took place some time between 1341 and 1363, then it could only be the Eastern Settlement.

Archaeological evidence: living conditions of the Norse Greenlanders

Investigations in Greenland and in other parts of the Scandinavian North Atlantic have produced a wide range of data on settlement patterns, bioarchaeological collections and a host of specialized environmental studies (see, for example, Bruun, 1918; Nørlund, 1936; Roussell, 1936; 1941; Vebæk, 1958; Larsen, 1972; Fredskild, 1981; 1985; 1988; Olsen, 1982: Sveinbjarnardóttir and Buckland, 1983; Albrethsen and Keller, 1986; Christensen and Vilhjálmsson, 1989; McGovern, 1990; Amorosi, 1992; Bigelow, 1991; Morris and Rackham, 1992; Buckland *et al.*, 1994; 1996).

The Norse Greenland colony was beyond the range of cereal agriculture and survived on a mixed herding and hunting economy. Their diet was based on the milk and meat from cattle, sheep and goats. The settlement map of Norse Greenland suggests that the distribution of pasture plants strongly influenced settlement at all social levels (Albrethsen and Keller, 1986; Keller, 1991), and the pasture area of Norse site territories correlates positively with cattle byre size (McGovern, 1992a). Subfossil beetle faunas from the more recently excavated Western Settlement sites are dominated by introduced synanthropous elements which lived in stored hay, and these underline the need for sufficient fodder to overwinter large numbers of domestic animals indoors (Sadler,1991). Caribou and seal bones regularly outnumber bones of domestic cattle, sheep and goats, especially on less prosperous farms (McGovern, 1985b). From the beginning of their settlement in Greenland, Norse farmers heavily exploited seals. Local common seals and migratory harp and hooded seals regularly make up 30–70% of the bone collections from Norse Greenland (McGovern, 1985b).

A comparison of bone fragmentation rates between Icelandic and Greenlandic archaeofauna suggests that mammal bones on Greenlandic farms were nearly twice as heavily fragmented, presumably for the purpose of marrow extraction. Insect evidence comparing preserved fly fauna from Qeqertarsuaq ('Q' in Figure 1), a Palaeoeskimo site in the Disko Bay region, with fly faunas from the Norse farms in the Western Settlement to the south, reinforces this impression of more thorough marrow extraction by the Norse Greenlanders. Piophilid flies, characteristic of unconsumed fat and bone marrow accumulations, are abundant at Qeqertassuaq, while they are virtually absent in the Norse insect faunas (Amorosi *et al.*, 1994; Buckland *et al.*, 1996). Both Palaeoeskimos and Norse Greenlanders lacked substantial carbohydrate sources and had to consume more fat to allow effective protein metabolism (cf. Speth, 1983). Evidently, the Norse farmers had to process their kills far more completely than the Inuit. This suggests that the Norse Greenlanders were living substantially nearer the limits of their subsistence system than some of their Icelandic contemporaries or the earlier Saqqaq Palaeoeskimos.

Although documentary evidence suggests that fish were eaten by the Norse Greenlanders (Jónsson, 1930), extensive fine-mesh sieving has recovered only a handful of fish remains from any of the excavated Norse sites (Amorosi *et al.*, 1994; McGovern, 1985b; Nyegaard, 1992). Both documentary and archaeological evidence indicate that the Norse Greenlanders attracted transatlantic traders by offering walrus ivory and polar bear skins originating far to the north of the settlement areas (McGovern, 1985a). The hunt for these items began in the tenth century as an element of the Viking Age 'prestige goods' economy, and seems to have continued through the twelfth and thirteenth centuries (Marcus, 1954; McGovern, 1995a) while other Scandinavian communities were shifting to the high bulk staple goods trade in fish. As walrus ivory began to be replaced by enamels in decorative art, and as access to Russian ivory sources improved, the commercial incentive for the long and dangerous trip to Greenland declined (Gad, 1970). By the early fourteenth century, sailings to Greenland were far less frequent than they had been during the first 300 years of the settlement (Ogilvie, 1997). Thus fourteenth- and fifteenth-century Norse Greenlanders had little hope of significant contact from abroad. Both the historical and archaeological evidence for Norse Greenland suggests that economic vulnerability was also a critical factor in the deterioration of the Greenland settlements.

Palaeoecological evidence: the impact of farming

From a rapidly growing body of palaeoecological evidence, it is clear that farming practices in both Greenland and Iceland greatly affected the landscape. In Iceland, evidence of soil erosion dated by volcanic tephra, as well as organic remains such as insects and pollen (dated by tephra and radiocarbon), is combined to reveal widespread impact of human settlement on soils, fauna, and flora (Dugmore and Buckland, 1991; Sadler, 1991; Thórarinsson, 1991; Dugmore and Erskine, 1994). Human settlement and grazing by domesticates began a progressive process of deflation and slopewash that first affected the ecologically marginal uplands and interior and then spread to lower areas. Some estimates place the loss of vegetation at over 40% of Iceland's presettlement total (see, for example: Bjarnarson, 1978; Árnalds *et al.*, 1987; Fredskild, 1992). Research on soils and vegetation suggest a similar pattern of widespread impact by domestic stock in the area of the Norse Greenland Eastern Settlement (Jacobsen, 1991). Jacobsen argues that grazing-induced erosion, not climate fluctuation, would probably have posed the greatest threat to Norse agriculture in his study area. All observers of Norse settlement patterns in Greenland have noted that virtually all patches of potential pasture vegetation had Norse farms on or near them, leaving little unused pasture anywhere in southwest Greenland by the twelfth century (Berglund, 1991; Keller, 1991; McGovern, 1981). Grazing pressure that reduced vegetation cover and soil fertility and triggered erosion is likely to have greatly increased the sensitivity of the area to climate variability. More research on both social organization and human impacts on landscape is required, but it seems clear that, by the beginning of the fourteenth century, the ecological impact of introduced livestock had created significant cultural vulnerabilities to both climate variability and/or an overall lowering of mean temperatures (McGovern *et al.*, 1988).

Zooarchaeological evidence from house interiors: the final phase of Norse occupation of the Western Settlement

Vertebrate evidence

The archaeofauna excavated from Western Settlement sites derive both from middens and from house interiors (McGovern *et al.*, 1983; McGovern, 1985b; Nyegaard, 1992). While the deeply stratified middens provide the best view of long-term diachronic change, the house interiors provide the most interesting data for investigating the final phase of the Norse occupation. The thick flooring of twigs and moss in the Norse house interiors was periodically cleaned out and dumped on the midden surface outside, along with accumulated dung from the cattle byres and sheep pens (Buckland *et al.*, 1994); hence most of the floor contents found inside the houses date to the final phases of occupation, with the last year or so particularly well represented. The following discussion focuses on two sites: V54 Nipaatsoq and V51 Sandnes (V = Vesterbygd, the Western Settlement in the Bruun system of Greenlandic site registration; cf. McGovern, 1991). V54 is a medium-sized centralized farm, defined as having a hall floor area of between 20 and 40 m^2 (McGovern, 1992a), and V51 is a nearby manor. Both locations can be found in Figure 1.

Figure 3 presents a plan of the main houseblock at V54, with human and animal rooms connected by a winding set of passageways. Rooms of interest are identified as: the hall with hearth and sitting benches; the larder/food preparation area; the cattle byre; and the main sleeping room. Figure 3 (a) shows bone distribution found within this farm complex. An abundance of ptarmigan (*Lagopus mutus*), and Arctic hare (*Lepus arcticus*), represented by their feet and claws, were found in the larder and hall. Hare and ptarmigan bones are unusual in the excavated middens of Western Settlement farms, where alcids and other seabirds normally dominate the small vertebrate assemblages. Also present in the larder were the semi-articulated bones of a lamb and a very young, probably newborn, calf, and the skull of a large hunting dog. The limb bones of what may have been the same dog lay in the passageway between the hall and the bedroom. These bones have small cut marks on their surface, indicating butchery. Assessment of earlier reports of measurements on Norse hounds from the Western Settlement (Degerbol, 1936; 1941) made it clear that the dog bone material all derived from the final floor deposits of excavated farm interiors. The data suggest that the end of the Western Settlement may have occurred in late winter, with hunting parties resorting to the pursuit of hares and ptarmigan, cattle being slaughtered one by one, and, lastly, the hunting dog (McGovern *et al.*, 1983; Buckland *et al.*, 1983).

Insect evidence

The Norse farms in Greenland have been particularly productive of well-preserved fossil insect faunas (Buckland *et al.*, 1983; 1994; 1996; Sadler, 1991). Fly species, in particular, may be especially useful in evaluating abandonment scenarios (Skidmore, 1995). Figure 3 (b) and (c) show occupational (normal) and terminal phase fly distributions for site V54. The fly *Telomerina flavipes* is associated with dark warm conditions and the presence of human or other carnivore faeces. It was unquestionably brought to Greenland by the immigrating Norse and, as a thermophile, could only have survived in the warmest parts of the settlers' homes where it bred in the darkness of fouled twig floors. The samples from the floors of the hall and the sleeping room at V54 are dominated by large populations of *T. flavipes*. The insect fauna of the larder was quite different, dominated by more cold-tolerant heleomyzid fly species. Thus at least two distinct insect faunal communities inhabited the interior of V54, a warmer faeces-centred *T. flavipes* community in the hall and bedroom, and a

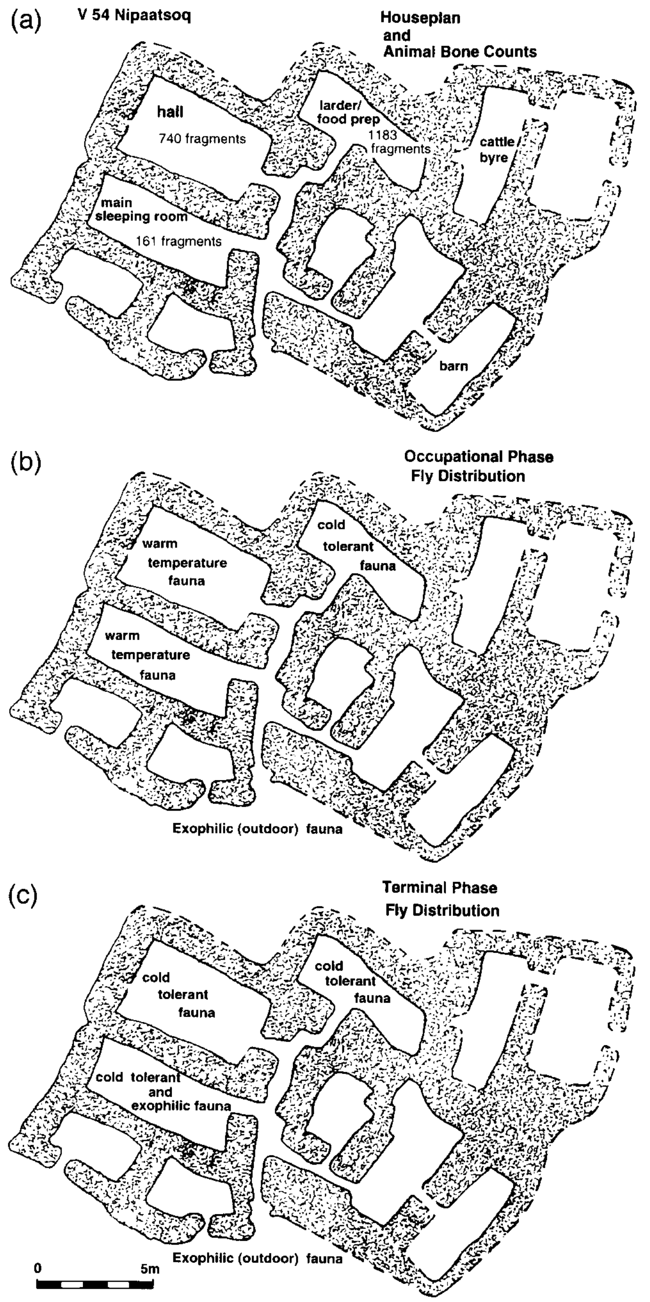

Figure 3 Plan of the main houseblock at V54, Nipaatsoq. Major rooms within the centralized ground plan are identified. (a) Concentration of animal bone refuse within the house. Fragments are identified to species (see text for discussion). In addition to the counts posted, 360 fragments were found in the passages between the larder, hall and main sleeping room, and between zero and five fragments in other rooms. (b) Fly distribution during the last Occupational Phase of V54. *Telomerina flavipes* is associated with warm temperatures and the presence of human or other carnivore faeces and dominated in the hall and bedroom. Cold tolerant, carrion-eating heleomyzid fly species were most abundant in the larder. Exophilic (outside) necrophages were found outside the main houseblock. (c) Fly distribution during the Terminal Phase of V54. Note the absence of warm temperature fly species compared with their distribution in the Occupational Phase, and the presence of exophilic necrophagic fly fauna inside the houseblock.

colder, yet still indoor, carrion fauna in the larder. The uppermost sample from the sleeping room indicates a crash in *T. flavipes* populations and a concurrent explosion in cold-tolerant carrion-eating heleomyzids (Figure 3c). Along with the invasion of the former larder community, there was a massive increase in species diversity of flies, including carrion-eating species from outside the farm complex. These changes in the fly fauna suggest a sudden drop in temperature in the bedroom, and indicate that the farm ceased being an island of artificial warmth, and was now only attractive to carrion-feeders. The testimony of the flies thus appears to support the documentary evidence which suggests that the last occupants of V54 either experienced an abrupt end, or, because no human remains were found, abandoned the site.

Ice core isotopic evidence

The isotopic signal of deuterium (δD) from the GISP2 ice core suggests that, on the century timescale, the fourteenth century was the period of the lowest temperature in central Greenland during the last 700 years (Figure 4). This agrees with the earlier findings for the last 1000 years for Greenland as a whole (Dansgaard *et al.*, 1975), and also with a new composite record of west central Greenland cores (Fisher *et al.*, 1996; Fisher, personal communication, 1996; Figure 4). Although it is preferable to interpret a composite isotopic data set (Fisher *et al.*, 1996; J. White *et al.*, 1997), development of a high-resolution composite record requires that annual dating of each individual record be impeccable. Correlation between data sets to an annual resolution back to the fourteenth century has not been resolved for central Greenland isotopic records, and so the GISP2 record, with an estimated age error of ± 1% (Meese *et al.*, 1994) is the main focus of interpretation here.

Interpretation of isotopic signals at the subannual level is complicated by both physical and methodological influences (Barlow, 1994), and yet has shown correlation with subannual temperature signals (see, for example, Barlow *et al.*, 1993; Shuman *et al.*, 1995; Barlow *et al.*, 1997). Correspondence between the GISP2 isotopic record and the area of the Western Settlement is established through a sign test (Cook *et al.*, 1994) comparing

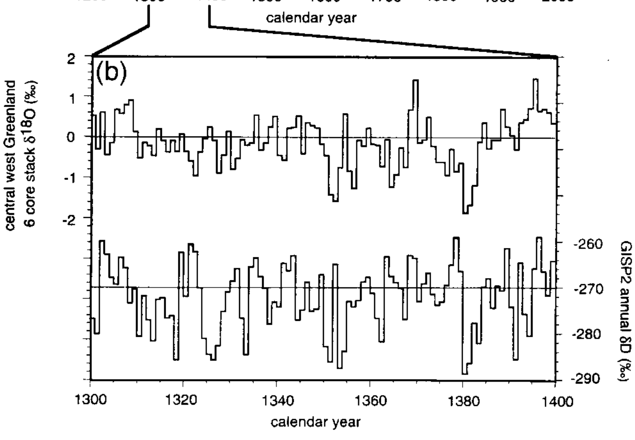

Figure 4 (a) GISP2 decadal deuterium isotopic signal AD 1270–1986 plotted with 100 year means (700 year mean reference of 270‰ is not shown). On the scale of centuries, the fourteenth century is the lowest isotopically. This agrees with earlier findings from other Greenland ice cores by Dansgaard *et al.* (1975). (b) Annual GISP2 deuterium record and six-core stack of central Greenland cores for the fourteenth century (six-core stack from D. Fisher, personal communication, 1996). Although chronologic integrity of the stacking process is tentative, the stack demonstrates a robust negative excursion in the 1340s and 1350s.

Nuuk/Godthåb temperature and GISP2 isotopic excursion directions for the years AD 1868–1986. Data sets were differenced to eliminate the possibility of autocorrelation (Cook *et al.*, 1994), and a chi-squared test was used to establish significance. Differenced annual, summer (JJA; mean of the three highest δD values), and winter (DJF; mean of the three lowest δD values), series corresponded in excursion direction from one year to the next more often than not, with significance at an α-level of 0.05 for annual, between 0.1 and 0.2 for summer, and between 0.2 and 0.5 for winter. Excursions from the mean reference lasting over three consecutive years show fairly good correspondence between GISP2 and Nuuk/Godthåb, particularly in the earlier 60 years when overall temperatures were lower (Figure 5).

Postdepositional effects of snow drift and vapour diffusion in snow and firn damp the original seasonal amplitude of the isotopic signal (Johnsen, 1975; Whillans and Grootes, 1985; Sommerfeld *et al.*, 1991). Simulation of the original seasonal amplitude of the isotopic signal can be attempted through deconvolution (Johnsen, 1975), although deconvolution does not provide a unique solution (D. White *et al.*, 1997). The deconvolved data set used here is discussed in D. White *et al.* (1997). Correlation coefficients for the GISP2 measured data and the deconvolved data for annual, summers, and winters in the fourteenth century are 0.87, 0.69 and 0.65 respectively. Both the measured and deconvolved seasonal isotopic signals are shown in Figure 6.

Within the fourteenth century, dating of the GISP2 core is believed to be ± 1 year, based on the identification of the 1362 volcanic eruption of Öræfajökull in the GISP2 core (Palais *et al.*, 1991). Annual time periods suggested to be particularly low in temperature are AD 1308–18, 1324–29, 1343–62 and 1380–84 (Figure 4). The 20-year time period between 1343 and 1362 corresponds with the time frame of the Bárðarson account. Within this time period, the greatest excursion is seen between 1349 and 1356 in the summer signal (Figure 6). Excursions from the fourteenth-

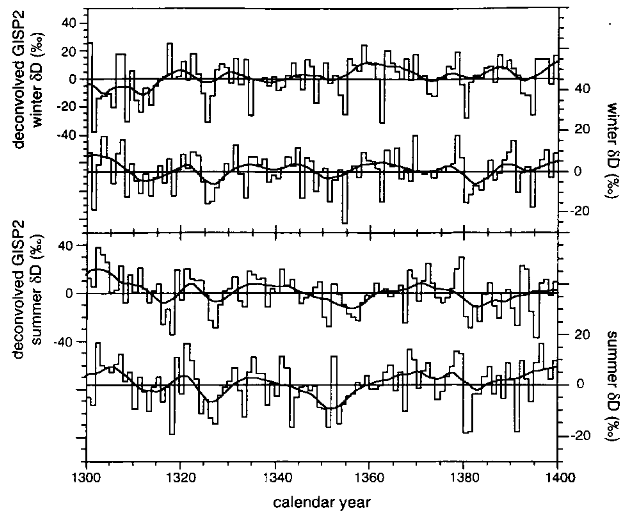

Figure 6 Measured and deconvolved GISP2 seasonal deuterium isotopic signals for AD 1300–1400. Data are referenced to fourteenth-century winter and summer means. For the fourteenth century, the summer isotopic signal in particular shows numerous negative isotopic excursions, suggesting frequent multiyear lower temperature time periods. Note the negative summer isotopic excursion between 1343 and 1362, which corresponds to the time frame of the Bárðarson account, and the years of greater excursion between 1349 and 1356 within this time period.

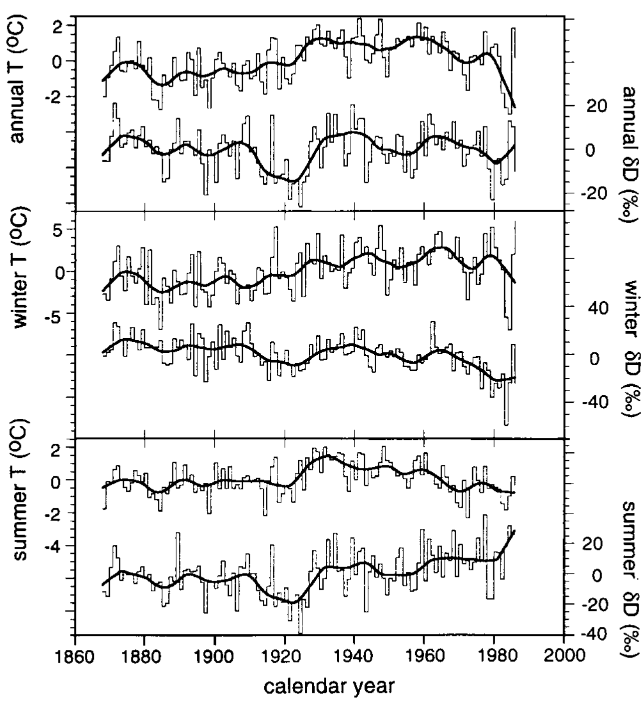

Figure 5 Nuuk/Godthåb temperature compared with GISP2 deuterium isotopic signals for annual, winter (DJF, mean of three lowest deuterium values), and summer (JJA, mean of three highest deuterium values). Data are referenced to the mean for AD 1868–1986. The series have been low-pass filtered to emphasize multiyear trends. Seasonal isotope values from about 1970–1986 reflect near-surface damping of the amplitude of the seasonal isotopic signal due to vapour diffusion, and should not be interpreted as documentable temperature shifts relative to the earlier record.

century isotopic mean for 1349–1356 in the measured isotopic signal are –2.17‰ for winter and –5.57‰ for summer. The deconvolved signal shows excursions of –0.49‰ and –10.25‰, respectively. In order to give a perspective on the possible temperature change associated with these excursions, we apply the modern isotope temperature conversion of 5.6‰/°C (Dansgaard, 1964). Inferred temperature excursion at the GISP2 site in central Greenland for winter and summer for measured data are –0.4 and –1°C respectively. These should be considered minimum values with regard to the damping of the seasonal amplitude by vapour diffusion. The deconvolved signal gives inferred winter and summer temperature excursions of –0.1 and –1.8°C respectively. These temperature values are offered for illustrative purposes only and should not be considered definitive. Although the exact temperature of the isotopic excursion remains elusive, isotopic evidence suggests that lower temperatures can be included as one factor among the complex socioenvironmental stresses of subsistence living at the Western Settlement. At the seasonal level, the isotopic signal shows a greater negative excursion in the summer record. Norse farmers relied as much on summer fodder production to last through the winter as on a timely end to winter conditions. Thus a period of cold summers may have reduced grass production, making the subsistence of the Norse Greenlanders even more precarious.

Approaching linkages: pasture productivity and Norse farm simulation models

Archaeological and historical investigations have demonstrated the dependence of the Norse Greenland farmers on pasture productivity to provide for the overwintering of cattle, sheep and goats. It thus seems reasonable to link possible changes in annual and seasonal temperature to the productivity of these pasture plant communities, following methods already employed by northern agricultural scientists. Using the approach of Parry (1978), a simple accumulated growing-season temperature model was applied to meteorological data, and used to compare potential pasture production vulnerabilities in the Eastern and Western Settlements

(McGovern *et al.*, 1988; Figure 7). Results of this model indicate greater vulnerability of the Western Settlement to changes in summer temperatures.

However, attempts at identification of a single season as the culprit in climate impact in the Western Settlement are hindered because variability in both summer and winter temperature and precipitation could affect the domestic stock. Prolonged periods of poor nutrition have negative effects on milk production, fertility, lamb/calf survival rates, and adult stature (Mount, 1979), but long snowy winters and cold wet springs (especially during lambing) have tended to be the trigger for mass stock mortality in North Atlantic husbandry (Ogilvie, 1982; 1984; Amorosi, 1992). Cold summers and winter-killing of grasses might restrict the amount of stored fodder for the approximately nine months of winter feeding required, and a long cold winter would lengthen winter feeding and further depress the physiological condition of the stock (McGovern *et al.*, 1988; Amorosi and McGovern, 1994).

The Norse farm simulation model FARMPACT (McGovern, 1995b) uses archaeological survey data from the Ameralla region of the Western Settlement (McGovern and Jordan, 1982), and zooarchaeological and architectural data from the same region. The model can be used to estimate fodder consumption rates and productivity of domestic stock, consumption rates of various modelled households, and various levels of rent and tithe payments. Different levels of pasture productivity can be used in the model, and the stocking rates adjusted to compensate for various levels of fodder production. Modelling experiments have produced three important results concerning the probable sensitivity of the Norse colonies.

First, the Norse mixed herding and hunting economy was fairly flexible and resilient. Even with a large modelled human population (*c.* 800–1000 for the Western Settlement) supported by a substantial number of domestic stock (*c.* 500 cattle, 1600 caprines), 30% reductions in pasture productivity could be easily compensated for by moderately increased sealing and caribou hunting. According to the model, the settlement could survive even 60–80% reductions in pasture yields. This level is feasible, as long as a three- to five-year period of more favourable pasture productivity followed a year of low productivity to allow herds and flocks to rebuild, and as long as access was maintained to sealing and caribou hunting territories to compensate for deferred consumption of domestic animal products during the recovery period. However, timing and spacing of climate impacts appear to be nearly as important as the magnitude of the individual impacts. In assessing the frequency of climate-related pasture productivity reductions, the FARMPACT model indicates that the viability of the Norse domestic stock would be more adversely affected by moderate impacts of a frequency of three to five per decade than by a single extreme impact per decade. For northern farming systems, the sequence and spacing of impacts may be the most critical factor in limiting the effectiveness of traditional buffering strategies.

Second, repeated, closely spaced reductions in pasture productivity in the 60–80% range (or permanent loss of 25–35% of farm pasture to erosion) would heavily stress the Norse economy, dropping domestic stock levels close to minimum biological population size for whole communities. Such situations would make minor fluctuations in caribou population or changes in access to migratory seals critical for Norse subsistence security.

Third, late winter/early spring (approximately late May–June) would be the period of maximum stress on household provisioning and livestock feeding. Figure 8 illustrates the modelled impact of changes in temperature patterns on the winter fodder requirements of a medium-sized farm (hall floor area between 20 and 40 m^2) similar to V54. The different pattern of changing fodder demand in the Western and Eastern Settlements may be noted. The longer and colder winters of the Western Settlement region create a greater demand for stored fodder, even for farms of the small scale and stock mix. Western Settlement farms tended to have a higher ratio of hay barn space than do Eastern Settlement farms, perhaps reflecting the need for more winter fodder storage (McGovern, 1992a). Figure 9 illustrates the problem faced by a middle-ranking Western Settlement farmer, like the household at V54, by even minor increases in winter feeding. The difference between a 36-week feeding period and a 38-week period could be in the range of 2–3000 kg of extra fodder. Historical records from Iceland (Ogilvie, 1982; 1984) describe stock disasters triggered by just this sort of shortfall. A two- to three-week variation in snow melt and initial growth of grass could have had a significant impact on the Western Settlement.

Alternative food sources for the Norse in late winter were likely to have been very limited. Potentially, they could have hunted caribou, ringed and bearded seals, hares and ptarmigan, but for

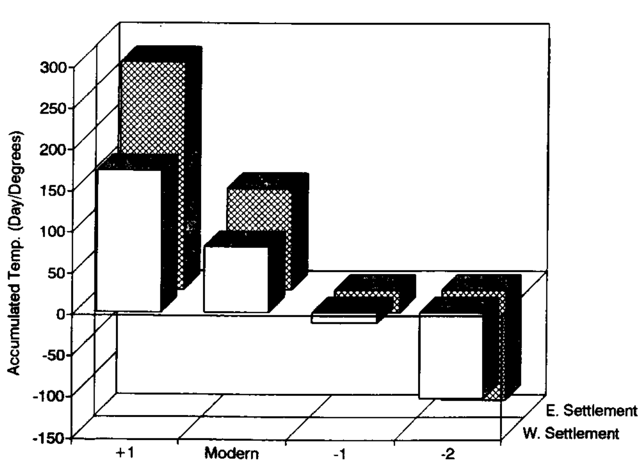

Figure 7 A comparison of the accumulated temperature (measured in day degrees above a sedge/grass community of a minimum of 5°C) during the summer growing season for two modern instrumental stations in the centres of the former Norse Eastern and Western Settlements. Increases or decreases in the summer growing season are graphed with reference to a modern baseline (*c.* 1930–60) for the two stations. Reductions on the order of 1–1.5°C in summer temperatures would have significant impact on the viability of plant communities vital to Norse stockraising.

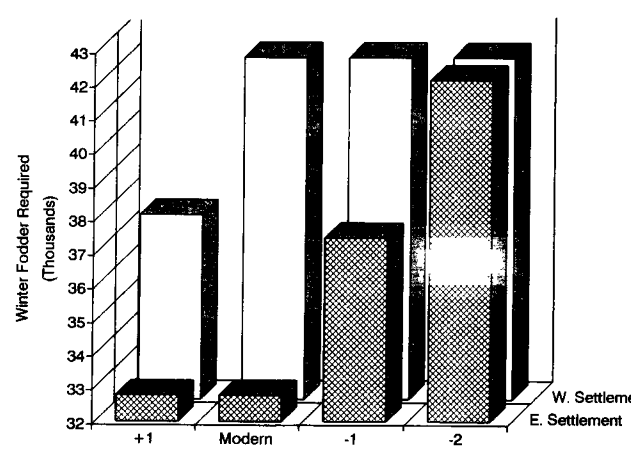

Figure 8 Output of the FARMPACT simulation model illustrates the different winter fodder requirements of the same medium-sized Norse farm, comparable to V54, in the Eastern Settlement and in the more arctic Western Settlement. Changes in temperature from the modern baseline on the order of 1–2°C would increase the winter fodder demand of Norse stock in both settlement areas, but would affect the Western Settlement area earlier and more severely. The excavated Western Settlement farms show a higher ratio of hay barn (for winter fodder) to cattle byre than do the excavated Eastern Settlement farms (McGovern, 1992a).

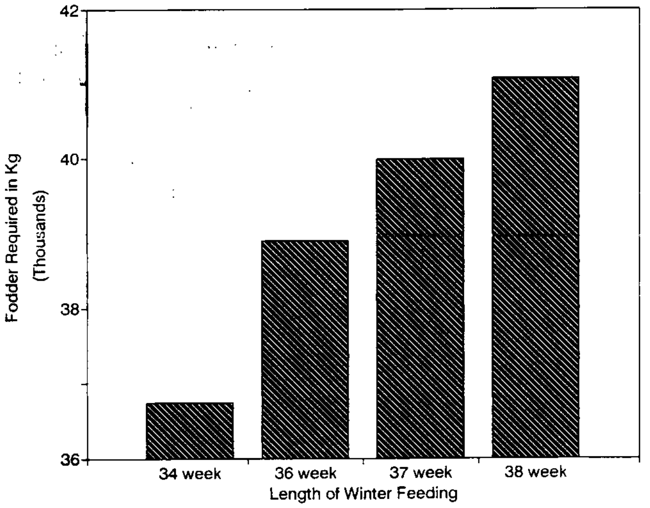

Figure 9 Again using the FARMPACT model output, this figure illustrates the impact of extended byring on the winter fodder consumption of a medium-sized farm in the Western Settlement comparable to V54. Warm early springs might allow a byring of only 34 weeks, while particularly hard winters and late springs (similar to the situation in 1984) would push cattle byring time to 38 weeks or longer. Most Western Settlement farmers would be hard-pressed to supply the extra fodder, especially if preceding summers had been cold, reducing pasture productivity and the autumn hay harvest.

various reasons none of these animals provided significant late-winter nutrition for the Norse. Caribou probably wintered near the coast outside the Norse settlement areas and only began to move back into the inner fjords in May to June (Meldgaard, 1986). Furthermore, dental annuli indicate that the great majority of the Western Settlement caribou were taken in the autumn (September to October) (McGovern *et al.*, 1983). Nonmigratory ringed (*Phoca hispida*) and bearded (*Erignathus barbatus*) seals would be difficult for the Norse to hunt through the ice, as the Norse colonists showed no signs of adopting the harpoon technology used by their Inuit neighbours (McGovern, 1985b). While hares and ptarmigan could be caught close to the farms in winter, they would provide little metabolically useful nutrition by the late winter (Speth, 1983).

The season of the loss of the Western Settlement

Although substantial uncertainty remains, most indicators point to abandonment in late winter or early spring. All excavators encountered thick layers of cattle dung still inside byres and pens (Roussell, 1936; 1941; Andreasen and Arneborg, 1992; Arneborg and Berglund, 1993), most of which would have been cleared out into the midden during the summer. The remains of a newborn calf and lamb on the terminal floor of V54 likewise point to abandonment in May/June shortly after the (still?) birth of these young. Results of the FARMPACT simulation model suggest that any available community reserves were modest in scale and easily exhausted. More reliable than stored surplus in early spring would be the arrival of the migratory seals in the outer fjord sealing grounds, especially the harp seal *Pagophilus groenlandicus* (McGovern, 1985b). Harp seals arrive in the Western Settlement area in mid-May to early June or just before the Norse domestic animals could emerge from their byres. From studies of tooth annuli, we know that most harp seals were killed in spring in the Western Settlement. Figure 10 illustrates the critical timing of the seal hunt relative to the Norse subsistence cycle. As long as the harp seals could be taken in quantity by early June, the subsistence gap would be closed successfully, and another year survived.

Both climatic and cultural factors offered possible threats to Norse access to the best harp sealing grounds in the outer fjords. It is now known that Thule-culture Inuit had moved into Greenland from arctic Canada after AD 1100 and had set up winter house settlements in the outer fjords of the Western Settlement by *c.* 1300 (Gullov, 1983). While the Norse and Thule Inuit may have been in contact for as long as 250 years by the time of the end of the Western Settlement, little is known about the nature of relations (Andreasen and Arneborg, 1992; Arneborg and Berglund, 1993). Archaeological data indicate that the Inuit acquired metal and a range of curios from the Norse, while the Norse seemed reluctant to acquire Inuit skin boats, winter clothing or the toggling harpoon technology that allowed Inuit hunters ready winter access to the widespread ringed seals (McGovern, 1985b). Both historical documents and Inuit legends report situations of conflict. If the mid-fourteenth century was indeed a time of hostilities between Norse farmers living in the inner fjords and Inuit hunters living in the outer fjords, the Inuit would be well placed to interdict seasonal Norse access to their harp sealing stations. Certainly warfare between the two groups would greatly complicate the tightly scheduled Norse subsistence round, and could have contributed to a late-winter subsistence crisis.

Local climate effects may also have critically impeded access to the outer fjords. The very cold winter and late spring of 1984 may provide a model for earlier hard winters. Mean monthly temperatures for January and February 1984 at Nuuk/Godthåb to the west of the Western Settlement were 10°C lower than average for the reference period 1868–1986, while the months of March through June 1984 were between 0.7 and 4°C lower. An overflight of the inner Ameralla area of the Western Settlement on 2 June 1984 showed that the only snow-free area in the southern half of the former Western Settlement was the small valley surrounding the manor at V51 Sandnes. A plug of densely packed ice and two areas of lighter pan ice also obstructed the Ameralla and Itilleq fjords, effectively cutting off the Norse settlements along the Ameralla from access to the outer fjords, and could have seriously endangered spring harp sealing. While such late fjord ice is rare in modern times, contemporary local Inuit report that it is a regular feature of extremely cold winters. When the V51 Sandnes site was reached in late June of 1984, no fjord ice was present, but grass growth was minimal even around V51 Sandnes, and the lake Tungmeralik area near V35 remained ice-choked and impassable into July. The monthly mean temperature for July 1984 at Nuuk/Godthåb was close to the average value. However, August was 2°C lower than average. If exceptional years like 1984 have many similarities with the conditions regularly encountered by the Norse in the mid-fourteenth century, then there would seem to be a good case for substantial climate culpability in the loss of the Norse Western Settlement.

Conclusions

Although our conclusions on the fate of the inhabitants of the Western Settlement remain speculative, as no human remains have been discovered, new high-resolution proxy climate data and new detailed palaeoecological data have increased our understanding of the combination of adverse conditions experienced by the Norse Greenlanders of the Western Settlement. We have presented evidence that begins to achieve the linkage between climate and human economy which is called for by modern interdisciplinary approaches. Intensification of agricultural production in an economy already making maximum use of traditional resources, while ignoring others, might well have caused serious problems for Norse Greenland even in the absence of significant

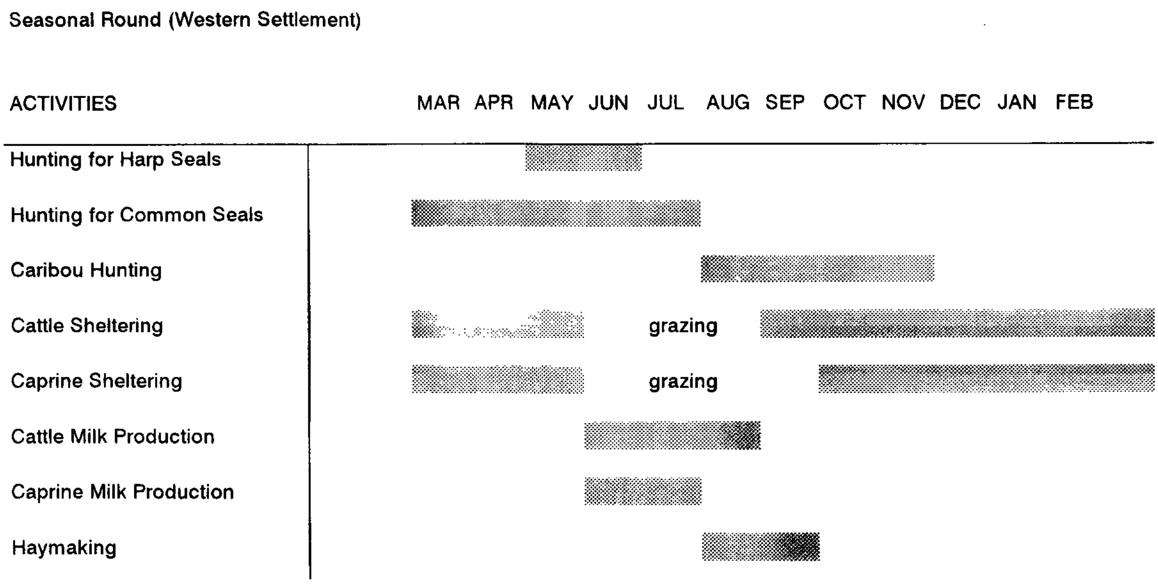

Figure 10 Based on seal and caribou tooth annuli recovered from excavated bone collections, ethnographic analogy with mediaeval Iceland, and modern patterning in plant growth and animal migration in West Greenland, a seasonal round for the Norse Western Settlement can be reconstructed (discussion in McGovern, 1985b). While there was probably considerable interannual variation in the precise timing of activities, the reconstruction serves to illustrate the potential for a late-winter subsistence gap between the exhaustion of stored meat and dairy produce and the beginning of the spring sealing. From McGovern, 1994.

climate variability. It was economic, political and ideological structures that confined the Norse of the Western Settlement to the pastures of the inner fjords. The apparent decision to suppress innovation coming from the Inuit was ideological and political, not environmental. Had the Norse adopted toggling harpoons and other Inuit ice hunting technology, they could have taken ringed seals all year long, and the possibility of a crisis in late winter/early spring might have been avoided. Without these innovations, the onset of lower temperatures and less stable climatic conditions, especially the combination of a string of lower temperature winters and summers in the mid-fourteenth century, may have made a difficult situation fatal for the Norse Greenlanders of the Western Settlement.

Acknowledgements

The authors gratefully acknowledge support from the North Atlantic Biocultural Organization (NABO) program funded by the National Science Foundation, USA, Arctic Social Science and ARCSS Programs (Grant no. OPP-9222956), as well as the American-Scandinavian Society, the National Geographic Society, and the Wenner-Gren Foundation for Anthropological Research. The initial study of entomological material from sites in the Western Settlement was supported by the Leverhulme Trust (Grant no. F94M). In addition, L.K. Barlow wishes to acknowledge the support of the National Science Foundation, USA, ARCSS Program (Grant no. OPP-9418845) and an NSF grant supporting the GISP2 project (J.W.C. White, Principal Investigator). A.E.J. Ogilvie also acknowledges the support of the NSF grant OPP-9418845 as well as the Leverhulme Trust (Grant no. F204L). Part of her work on this paper was done at the Stofnun Árna Magnússonar at the University of Iceland. Thanks are due for their hospitality. We are grateful to Philip Buckland for his work on a number of the figures. We also thank our reviewers for their constructive comments.

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