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A 2500 year record of natural and anthropogenic soil erosion in South Greenland

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ABSTRACT

The environmental impact of the Norse *landnám* (colonization) in Greenland has been studied extensively. But to date, no study has quantified the soil erosion that Norse agricultural practices are believed to have caused. To resolve this problem, a high resolution sedimentary record from Lake Igaliku in South Greenland is used to quantitatively reconstruct 2500 years of soil erosion driven by climate and historical land use. An accurate chronology, established on 18 AMS ^{14}C, and ^{210}Pb and ^{137}Cs dates, allows for the estimation of detritic fluxes and their uncertainties. Land clearance and the introduction of grazing livestock by the Norse around 1010 AD caused an acceleration of soil erosion up to ~8 mm century^{-1} in 1180 AD which is two-fold higher than the natural pre-*landnám* background. From 1335 AD to the end of the Norse Eastern Settlement (in the mid-fifteenth century), the vegetation began to recover from initial disturbance and soil erosion decreased. After an initial phase of modern sheep breeding similar to the medieval one, the mechanization of agriculture in the 1980s caused an unprecedented soil erosion rate of up to ~21 mm century^{-1}, five times the pre-anthropogenic levels. Independently, a suite of biological and geochemical proxies (including Ti and diatom concentrations, C:N ratio, $\delta^{13}C$ and $\delta^{15}N$ of organic matter) confirm that the medieval and modern anthropogenic erosion far exceeds any natural erosion over the last 2500 years. Our findings question the veracity of the catastrophic scenario of overgrazing and land degradation considered to have been the major factor responsible for Norse settlement demise. They also shed light on the sustainability of modern practices and their consequences for the future of agriculture in Greenland.

1. Introduction

Understanding the interactions between climate and human impact on lake sediments has become an important issue of paleolimnology (Dearing et al., 2008; Battarbee and Bennion, 2010). In this framework, the westward migration of the Scandinavian settlers (Norse) across the North Atlantic region during the 8th–10th centuries is an ideal case study for understanding the interactions between human societies and their environment. The absence of established agricultural systems in Greenland before the Norse colonization (*landnám*), well documented by the archaeological and medieval literature, namely "the Sagas" (for a in-depth review see Dugmore et al., 2005 and references therein), provides a unique opportunity to study the human impacts through a rapid colonization of a pristine landscape (e.g. Fredskild, 1973; Gauthier et al., 2010; Schofield and Edwards, 2011). The history of the Greenland settlements (the "Eastern Settlement" in the far south and the "Western Settlement" in modern Nuuk district further north), from the end of the 10th century to the late 15th century, is also an iconic example of the impact of changing climate on human population (McGovern, 1991; Barlow et al., 1997; Dugmore et al., 2007). The chronology of the abandonment is unclear as are its causes. The only consensus is the role of the deteriorating climatic conditions of the 'Little Ice Age' which likely isolated the community and reduced agricultural yields (eg. Dansgaard et al., 1975; Stuiver et al., 1995; Barlow et al., 1997; Patterson et al., 2010).

Among the many reasons proposed to explain the disappearance of the Norse from Greenland, overgrazing and excessive soil erosion may have lead to a dramatic decrease of grassland and fodder production crucial to Norse animal husbandry (eg. Gad, 1970;

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Jacobsen and Jakobsen, 1986; Jacobsen, 1987; Fredskild, 1988; Hansen, 1991; Jakobsen, 1991; Fredskild, 1992; Mainland, 2006). Apart from one exception (Rutherford, 1995), increased soil erosion is documented from all investigations of Norse farming impacts. Severe soil erosion was also observed in a few areas of South Greenland during the 1970s and Fredskild (1988) suggested that the Norse settlers could be responsible for its initiation. Concerned about a possible adverse environmental impact comparable to that postulated for the Norse, the Danish authorities conducted an extensive study of the impacts of sheep grazing on vegetation and soils (Hansen, 1991; Sandgren and Fredskild, 1991; Fredskild, 1992). Afterwards it turned out that the only substantial eroded area (ca. 10 km^2) is situated near Igaliku Kujalleq (Sondre Igaliku, Fig. 1a). Moreover, some authors argued that the extensive sand horizons observed in lakes and soil profiles of this area could be the result of aeolian inputs as well as sediment influx from erosion and transportation in the immediate catchments (Mikkelsen et al., 2001; Andresen et al., 2004; Lassen et al., 2004; Kuijpers and Mikkelsen, 2009).

To assess the problem of soil erosion in Greenland, it must be directly estimated through the calculation of sediment yield, before, during and after the medieval occupation. Lake reservoirs have been widely used in to quantify erosion rates and to determine changes in sediment yield due to agriculture (e.g. Dearing, 1992; Chiverrell, 2006; Enters et al., 2008; Boyle et al., 2011). To date there is no reliable quantification of erosion in the Greenland settlements that could support the mass erosion hypothesis. Fredskild's pioneering work showed strong evidence of soil erosion (Sandgren and Fredskild, 1991; Fredskild, 1992) but poor chronological control does not allow the sediment yield to be estimated. Recent efforts on peat deposits (Edwards et al., 2008; Schofield and Edwards, 2011), soil sections (Buckland et al., 2009) and archaeological trenches (Schofield et al., 2008) have produced high-resolution records of the impact of Norse farming, with reliable chronology through AMS dating of terrestrial plant macrofossils. However, systematic sedimentological hiatuses due to peat cutting or low sediment accumulation rates do not adequately place the records in a late-Holocene palaeoclimatic context. In light of the previous studies mentioned above, nothing definitive can be said as to whether the Norse agricultural practices caused widespread land degradation.

Here, we present a quantified reconstruction of past soil erosion based on the analysis of a well dated lacustrine sediment record from Igaliku, near the major archaeological site of *Garðar*, in South Greenland. The objective of the present study is to estimate soil erosion within the catchment area of Lake Igaliku using the detritic and organic inputs into the lake. The reliability of our estimate is controlled by a set of geochemical and ecological parameters including, titanium content, bulk organic matter geochemistry and diatom valve concentration. As sheep farming was reintroduced at a large scale in the area during the 1920s, we have also compared medieval and recent soil erosion to place the Norse impacts in a modern context. Both erosion rates and sedimentological proxies were interpreted in the context of past arctic climate and historical land-use. This work builds on paleoecological data obtained from the same core (Perren et al., in press; Gauthier et al., 2010) and constitutes a comprehensive reconstruction of human impact on an area of prime importance during the Norse period.

2. Study area

2.1. The Igaliku lake system

Lake Igaliku (unofficial name, 61°00′N–45°26′W, 15 m asl) is located in a low valley between the head of Igalikup Kangerlua (Igaliku fjord) and Tunulliarfik fjord (Erik's fjord) (Fig. 1a,b). It is a north-south oriented lake with a surface area of 34.6 ha (Fig. 1c).

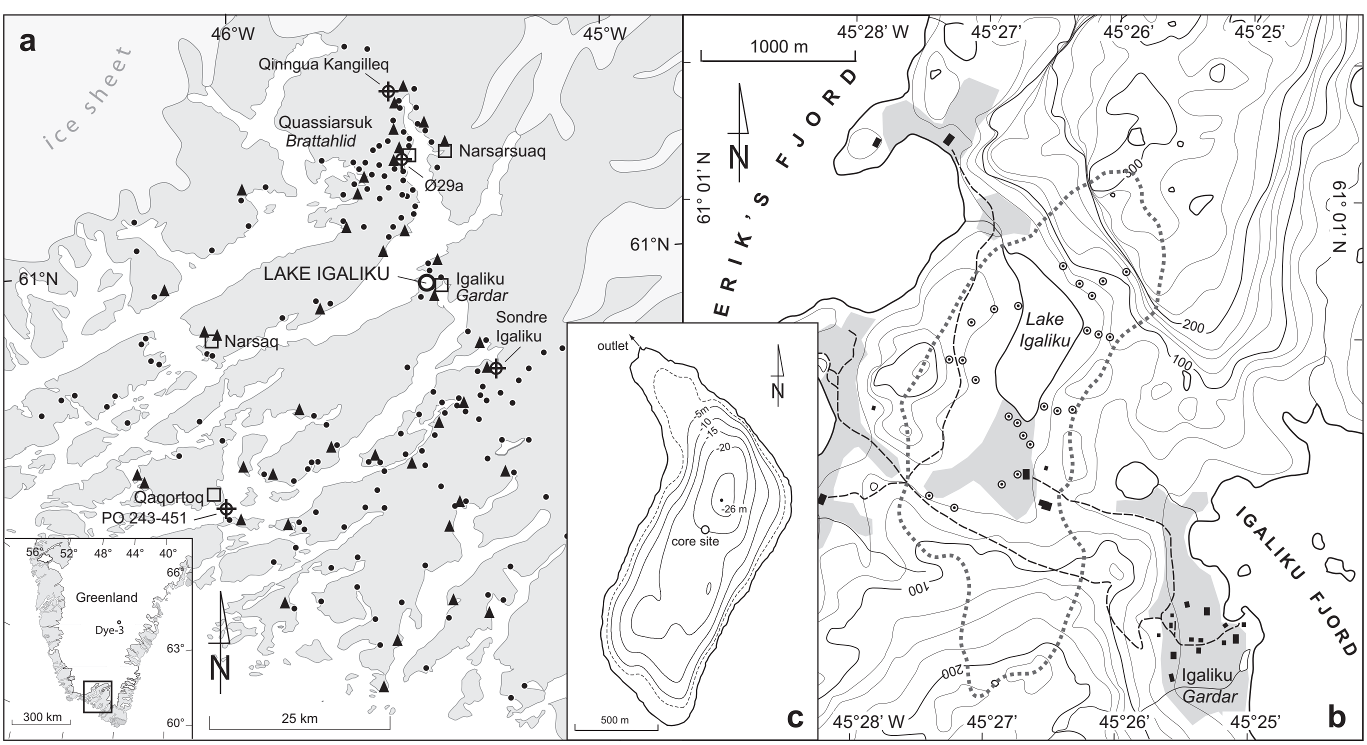

Fig. 1. (a) Map of the Norse Eastern Settlement showing the location of Igaliku/*Garðar*, Norse ruins groups (dots), modern farms (triangles); core PO 243-451 in outer Igaliku Fjord (Jensen et al., 2004; Lassen et al., 2004) and ruin group Ø39 and Ø29b (crossed circles). The inset map displays the regional setting of the study area and the location of the Dye-3 ice core (modified from Mikkelsen et al., 2001). (b) The region around Lake Igaliku including roads (dashed lines), buildings (black rectangles), current hay fields (shaded area), the soil samples (dotted circles) and the archaeological site of *Garðar*. The catchment delimitation is drawn in dotted line. (c) The bathymetry of Lake Igaliku and coring location.