Quaternary Science Reviews 32 (2012) 119–130

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

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

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A R T I C L E I N F O

Article history:
Received 15 July 2011
Received in revised form
9 November 2011
Accepted 15 November 2011
Available online 3 December 2011

Keywords:
Greenland
Norse
Eastern settlement
Landnám
Agriculture
Soil erosion

A B S T R A C T

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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doi:10.1016/j.quascirev.2011.11.014

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).

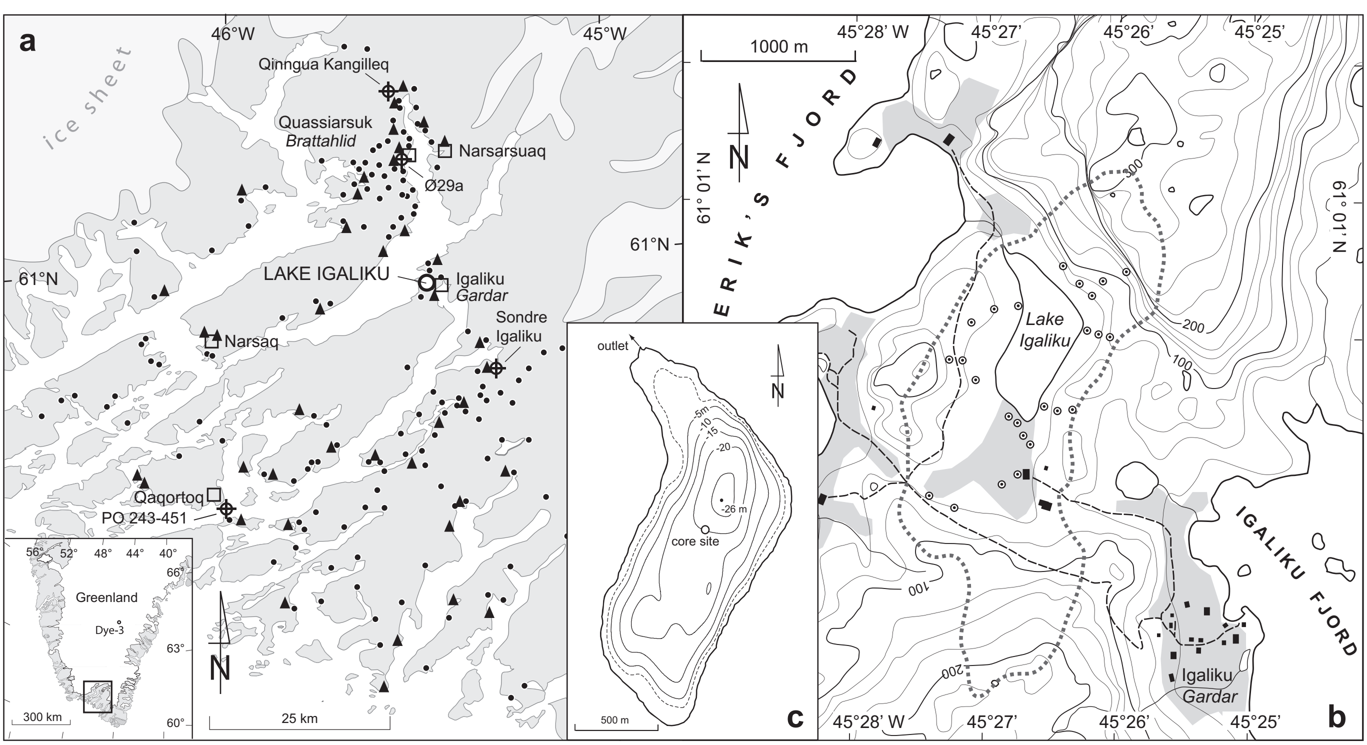

Fig. 1. (a) Map of the Norse Eastern Settlement showing the location of Igaliku/*Garðar*, Norse ruins groups (dots), modern farms (triangles); core PO 243-451 in outer Igaliku Fjord (Jensen et al., 2004; Lassen et al., 2004) and ruin group Ø39 and Ø29b (crossed circles). The inset map displays the regional 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.

The catchment area is 3.55 km^2, without an inlet but a small outlet on the northern shore drains into the Tunulliarfik fjord. The local topography is characterized by a gently sloped large plain (3.1 km^2) surrounded in the western part by a low rounded hill (130 m asl). The slope is considerably steeper to the northeast were the highest relief reaches 300 m asl. The rocks underlying most of the catchment are Proterozoic granites of the Julianehåb batholith (Upton et al., 2003) that are partly covered by arkosic sandstones and lavas of the Mesoproterozoic Eriksford Formation which outcrops on the hills.

The study area is situated in the subcontinental, subarctic climatic and vegetational zone of southern Greenland (Feilberg, 1984). Toward the innermost and sheltered fjords, the climate gradually changes from maritime to more continental conditions reflected in the vegetation by an increase in dwarf-shrub heath or scrub which tends to cover most of the ground. The meteorological standard normals 1961–1990 (Cappelen et al., 2001) at the station of Narsarsuaq (17 km north of Igaliku, Fig. 1a) record a mean annual temperature of 0.9 °C, with a maximum in July of 10–11 °C, 194.8 days/yr with frost and a yearly precipitation of 615 mm. The area is windy, with a mean wind speed of 3.8 m/s, and strong desiccating foehn winds blowing from the Ice Cap are frequent year round.

2.2. History of land use in the Igaliku area

The town of Igaliku – the Norse *Garðar* – is located on a fertile plain at the head of Igaliku Fjord which lies strategically in the centre of the Eastern Settlement. According to the *Groenlendinga Saga* (Saga of the Greenlanders), the area was settled by the daughter of Erik the Red soon after the *landnám* (Gad, 1970; Jones, 1986). *Garðar* became the Episcopal seat of Greenland in 1124 AD, consecrated two years later by the arrival of the first bishop (Krogh, 1967). It is also thought to have been an assembly site of prime importance in the administrative system of Norse society (Sanmark, 2009). For these reasons *Garðar* was a high status farmstead: 52 Norse archaeological structures were recorded, including large byre-barn complexes, animal pens and enclosures, sheep/goat houses and an irrigation system attached to fodder production (Nørlund and Roussell, 1929). The bishop's farms could host over 100 head of cattle, in addition to goats and sheep (Christensen-Bojsen, 1991), probably making *Garða*r, by far, the largest holding of livestock in Norse Greenland. Buckland et al. (2009) showed paleoecological evidence for manuring and irrigation to enhance the productivity of *Garðar*'s infields. As the 15 ha of land at *Garðar* where likely insufficient to raise a large livestock (Christensen-Bojsen, 1991), animals would have been kept from grazing in the infield and the total vegetated landscape of the area would have been utilized. This includes the catchment of Lake Igaliku, although neither ruins nor vestiges of fenced areas have been found.

The last bishop known to have resided at *Garðar* died in 1378 AD (Arneborg, 2007) and the last written account attesting the presence of the Norse in Greenland is a letter dated from 1409 AD that announced a wedding at the Hvalsey church (Fig. 1a) the year before (Gad, 1970). These elements do not allow the exact timing of the abandonment to be determined, but it is generally accepted that it must have occurred sometime in the mid to late 15th century (Dugmore et al., 2009).

A Danish farmer settled the site of *Garðar* in the 18th century and a few domestic animals were kept in the region until the early 20th century (Arneborg, 2007). The modern grazing management began in 1915 with 250 sheep (Austrheim et al., 2008) and was intensified in 1924 under the impetus of the Danish government (Hansen, 1991). Until 1976, sheep farming was based on extensive all year round grazing, with small supplements of winter fodder and occasional stabling. The number of sheep in South Greenland increased up to a maximum of 47 800 in 1966 but heavy snow and strong frost during the winter 1966/67 starved to death nearly 60% of the herds. Similar disasters occurred in the winters of 1971/72 and 1976/77 (Greenland Agriculture Advisory Board, 2009). Consequently, a new plan for sheep management was presented (Egede, 1982): henceforth, sheep should graze 5 months on the outlying fields and be stall fed during the 7 months of the Greenland winters, requiring a considerable amount of fodder. Nowadays, there is one single farm in the catchment of Lake Igaliku and the lake surroundings are freely grazed by a few hundred sheep during the summer season. Two areas of land on the south and north shores of the lake are cultivated to produce winter fodder for stabling (Fig. 1b), on which N fertilizer are deployed (200–250 kg ha^{-1} yr^{-1} of N, Miki Egede, personal communication). Also, a small stream drains effluent from the barn into the nearby lake.

3. Methods

3.1. Fieldwork

A 4 m-long sediment succession was sampled from the centre of Lake Igaliku (Fig. 1c) using gravity and piston corers equipped with Ø 63 mm PVC liners (both from UWITEC Co., Austria). The sediment water interface was properly recovered by using the gravity corer (Wagner et al., 2008). The sequence spans the entire post glacial history (ca. 10 000 yrs) but only the top 120 cm are presented here. Twenty five volumetric samples of near-surface soils (upper 5 cm) were taken in the catchment of Lake Igaliku to determine dry bulk density (Fig. 1b). The soil samples were processed for loss on ignition at 550 °C to calculate the bulk mineral content (BMC). An average BMC of 420 mg cm^3 was estimated for the whole catchment.

3.2. Non destructive laboratory analyses

An X-ray radiography was obtained using the Scopix system (Migeon et al., 1999) followed by laboratory X-Ray Fluorescence (XRF) core scanner measurements (Avaatech, Netherlands). Analysis was continuously performed every 2 mm with a counting time of 30 s and a 10 kV acceleration intensity. Because the sediment matrix is characterized by variable water content and grain size distributions the XRF scanner only provides a relative estimation of geochemical variables (e.g. Tjallingii et al., 2007). A normalization of element counts to the total count numbers was operated because it may partially correct drifts (Revel et al., 2010). The relative opal content was assessed using XRF-derived Si:Ti ratio (Peinerud et al., 2001) and compared to diatom valve concentrations (see Perren et al., in press, for methodological details).

3.3. Sampling method

The top 10 cm were sampled in 0.5 cm slices and below 10 cm, sampling intervals were chosen by using the X-ray image to ensure that the varying lithology is well represented and to provide homogenous samples. The subsamples (157) were separated into different sets. Volumetric samples (1 cm^3) were taken with cut plastic syringes, weighed and kept cold for biological analysis (Perren et al., in press; Gauthier et al., 2010). The others were gently dried at 60 °C until constant weight to obtain sediment water content (WC, w/w). The dried sediment was ground to <63 μm with an agate ball micromiller (Retsch, Germany) and homogenized.

3.4. Organic matter, elemental and isotopic analyses

The total organic nitrogen and carbon (TOC) concentrations were determined with a vario MAX CNS analyser (Elementar, Germany) using ~170 mg of dried material. The large sample size led to a relative standard error < 1% for both elements. A subset of 25 samples were also measured for loss on ignition (LOI) at 550 °C and 950 °C to estimate organic matter content (OM), carbonate mineral content and mineral matter content (MM) in sediments (Santisteban et al., 2004). TOC and $LOI_{550°C}$ appeared to be strongly correlated ($LOI_{550°C} = 2.3 \times TOC$, $R^2 = 0.99$, $p < 0.001$). Using this regression (slope = 2.3), OM and MM (100-OM) were estimated on the whole sample set.

About 6 mg of dried sediment of the upper 75 cm ($n = 104$) were loaded in tin capsules and the stable isotopic composition of organic carbon and total nitrogen was determined on an elemental analyser NA 1500 NCS (Carlo Erba Instruments, Milan, Italy) coupled in continuous flow mode to a stable isotope ratio mass spectrometer VG Isochrom (Micromass, Manchester, England). No significant loss of weight at 950 °C revealed that carbonate content is negligible for the Igaliku samples. Therefore, the sedimentary carbon is assumed to be organic and no removal of carbonate carbon was necessary before $\delta^{13}C$ measurements. All subsamples were triplicated and the 95% confidence interval of the mean is reported. Results are expressed in standard delta notation.

3.5. ICP-AES geochemistry and calibration of XRF scanner results

Fifty six samples were processed for inductively coupled plasma-atomic emission spectrometry (ICP-AES) measurements. About 70 mg of accurately weighed sediment were totally dissolved under pressure on a hotplate using a mixture of 1 mL each suprapure grade HCl, HNO_3 and HF (Merck, Germany). After evaporation, the residues were retaken with HNO_3 and appropriately diluted with MilliQ water. Certified reference material (BCR-2, BCSS-1, JSD-1, PACS-1) and 3 duplicates were added to the set of samples. The error of Ti concentration did not exceed ±8%. XRF-normalized Ti contents closely follow those obtained by ICP-AES ($r = 0.83$, $n = 53$, $p < 0.001$). Linear regression parameters were used to estimate Ti content along the whole section.

3.6. Core chronology

The age control of the upper 120 cm of the Igaliku core is based on 18 Atomic Mass Spectrometry (AMS) ^{14}C-measurements on hand-picked and mechanically cleaned plant remains (Table 1, Fig. 2a), carried out at the Poznań Radiocarbon Laboratory (Poland) and at the Lyon Radiocarbon Laboratory (France). The bryophyte date at 66.3–67.3 cm is 310 years too old compared to the result of the two terrestrial macrofossils that closely surround it. This phenomenon is due to a particular reservoir effect which affects arctic lakes due to the in-lake recycling of carbon (Abbott and Stafford, 1996). Thus a reservoir correction of 310 years was applied to all ^{14}C age of aquatic mosses before calibration (e.g. Kaplan et al., 2002; Klug et al., 2009).

The chronology for the last 150 years was established with ^{210}Pb and ^{137}Cs dating (Fig. 2b). The 20 samples from the top 10 cm of the core (~2 g of dried sediment) were measured for ^{137}Cs activity by gamma spectrometry in a calibrated geometry using a high-purity Ge well-type detector. The total ^{210}Pb activity of the top 16.4 cm (14 contiguous samples 1.0-1.6 cm each) was measured using alpha spectroscopy at MyCore Scientific Inc. in Ontario, Canada. Ages were determined using the constant rate of supply (CRS) model, which assumes a constant rate of unsupported ^{210}Pb from atmospheric fallout but allows sediment accumulation to vary (Appleby and Oldfield, 1978). The supported activity was determined from the basal section of ^{210}Pb data (Fig. 2b).

Results from radiocarbon and short-lived radio-isotopes were combined to produce an age-depth model for the whole sequence using a smooth cubic spline model and following the Monte Carlo approach provided by Blaauw (2010). This method ('Clam') allows robust uncertainties to be computed and takes into account the entire probability distribution of the calibrated radiocarbon dates, avoiding any arbitrary choice.

3.7. From sediment accumulation rate to soil erosion

The sediment accumulation rate (SAR, expressed in $cm\,yr^{-1}$), as well as its uncertainty, was computed by adapting the 'Clam' function to calculate the first derivative of the n-bootstrapped age-depth models and then, from these multiple SAR, the weighted average and 95% confidence interval. Then, mass accumulation rates of organic and minerogenic matter were calculated as follows:

$$MAR_{org}\left[mg\ cm^{-2}yr^{-1}\right] = WBD\cdot(1 - WC)\cdot OM\cdot SAR$$

$$MAR_{min}\left[mg\ cm^{-2}yr^{-1}\right] = WBD\cdot(1 - WC)\cdot MM\cdot SAR$$

WBD being the wet bulk density ($mg\,cm^{-3}$) assessed using WC, OM and MM (Sugai et al., 1994). Using the obtained MAR_{min}, an

Table 1
Radiocarbon dates from the sediment archive of lake Igaliku. The post-bomb radiocarbon activity (marked*) is expressed as a percentage of modern carbon (pmC).

Depth (cm)	Material	Lab code	C yr BP (±1σ)	Corrected ^{14}C age	Cal BC/AD (2σ range)		Cal BC/AD (weighed mean)
3.5–4.5	Undetermined plant remains	Poz-24707	*107.11 ± 0.36	–	AD	1956 minimum	–
17.4–17.7	Aquatic moss	Poz-31628	680 ± 100	370	AD	1395–1950	1559
27.5–28.5	*Betula* leaf	Poz-31632	620 ± 80	–	AD	1265–1435	1347
30.0–30.7	*Betula* bark fragment	Poz-31629	655 ± 35	–	AD	1280–1395	1337
32.6–33.6	*Salix* leaf	Poz-26852	775 ± 30	–	AD	1215–1280	1248
39.9–40.7	Twig	Poz-31630	945 ± 35	–	AD	1020–1165	1095
51.5–52.5	Wood	Poz-35136	1005 ± 30	–	AD	980–1150	1035
60.7–61.7	1 *Salix* and 2 *Betula* leaves	Poz-38952	1260 ± 40	–	AD	670–870	753
66.3–67.3	Aquatic moss	Poz-30535	1570 ± 35	1260	AD	670–865	749
67.1–67.3	Wood	Lyon-7300	1265 ± 30	–	AD	665–860	739
67.9–68.1	Wood	Lyon-7301	1410 ± 30	–	AD	595–665	631
68.8–69.8	Twig	Poz-35135	1305 ± 30	–	AD	660–770	712
71.0–71.7	*Betula* leaf	Lyon-7302	1450 ± 30	–	AD	565–650	609
78.6–79.8	Leaf	Poz-31633	1580 ± 60	–	AD	345–605	480
89.0–90.0	*Betula* wood	Lyon-31874	1775 ± 40	–	AD	135–380	256
94.2–94.6	*Betula* wood	Lyon-7303	1930 ± 30	–	AD	5–130	73
112.5–113.5	*Betula* leaves fragments	Poz-37363	2250 ± 40	–	BC	395–205	−297
125.8–126.8	Aquatic moss	Poz-30536	2930 ± 70	2620	BC	925–540	−757

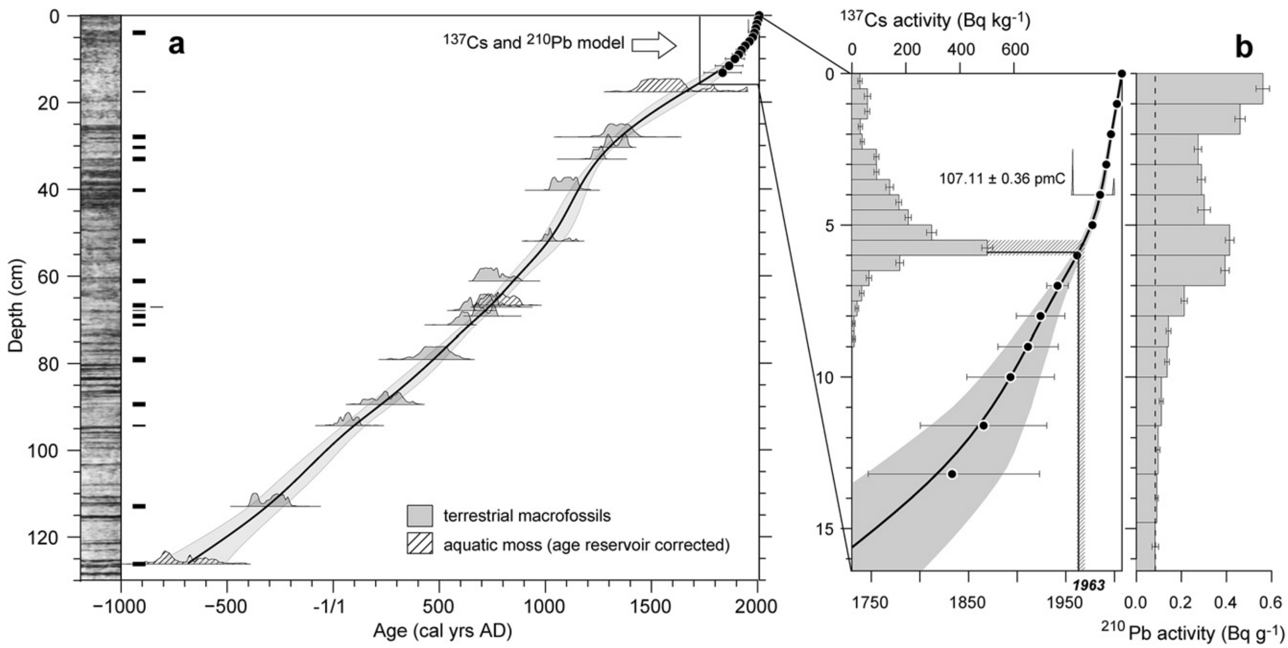

Fig. 2. (a) Age-depth model of the Lake Igaliku core with the probability distributions of calibrated ^{14}C ages and ^{210}Pb age estimates (points). (b) Bulk sediment ^{137}Cs and ^{210}Pb activity plotted on the upper part of the age-depth model. The sample corresponding to the Northern Hemisphere fall-out peak in 1963 AD is marked in grey. The black line marks 1963 AD from the age depth model. Horizontal error bars are expressed as 95% confidence level.

estimation of soil erosion through the calculation of a mean denudation rates (DR) is proposed, basically assuming that the sediment is equally distributed on the entire surface area of the lake (Enters et al., 2008) and with a bulk mineral content (BMC) of 420 mg cm^{-3} for eroded soil (surface horizon):

$$\mathrm{DR}\left[\mathrm{mm\ century}^{-1}\right] = \mathrm{MAR_{min}} \cdot \mathrm{lake\ area}/\mathrm{catchment\ area}/\mathrm{BMC} \cdot 1000$$

4. Results

4.1. Lithology and chronology

The upper 130 cm of the lake Igaliku core are composed of very finely stratified brownish sandy silt with black horizons rich in ferrous iron oxide. From ~5 cm, the sandy silts give way to black clayey silts until water-sediment interface. The X-radiographs reveal a continuous sedimentation with distinct lamina (~6 mm), indicating that sediments were not continuously mixed by bioturbation.

The age-depth model is almost linear until ~1010 AD (Fig. 2a) with a mean SAR of ~0.4 mm yr^{-1}. Then, the SAR continuously rises to a maximum of 0.8 mm yr^{-1}, around 1150 AD, and decreases gradually after that date. A sharp increase in the SAR, up to 1.9 mm yr^{-1}, is noted during the 20th century. Six AMS dates were targeted before 1000 AD to reduce the uncertainty resulting from a plateau in the calibration curve around the *landnám* period (Dugmore et al., 2005). The narrower uncertainty of the ^{14}C part of the model is obtained for the period 1200–1350 AD (±25 yr) with 3 closely spaced dates whereas the ^{210}Pb part of the model is very accurate with an error that range between ±25 to 1.5 yr for the 20th century (Fig. 2b).

The ^{137}Cs peak at 5.5–6.0 cm depth (500 Bq kg^{-1}) clearly represents the main fall-out peak of 1963 AD in the Northern Hemisphere due to atmospheric nuclear weapon tests (Pennington et al., 1973) and is in agreement with the ^{210}Pb CRS model (Fig. 2b). The low ^{137}Cs activity measured before the 1950s can be explained by a slight downward diffusion of the radionuclide in the sediment. The ^{14}C date at 4 cm (Poz-24707, Table 1) gives a clear post-bomb radiocarbon activity of 107.11 ± 0.36 pmC (Fig. 2b). Calibrated with the Bomb04NH1 calibration curve of Hua and Barbetti (2004), it gives a minimum age of AD 1956 which fits with the ^{210}Pb model.

4.2. Mass accumulation rates and sediment composition

As there is no marked change in the sediment composition (Fig. 3), the SAR controls 89% and 97% ($n = 157$, $p < 0.001$) of the total minerogenic and organic MAR variance respectively. Thus, error in MAR is mainly due to lack of accuracy in the core chronology. The two major increases in sediment supply, toward 1150 AD and at end in the 20th century, are characterized by the highest levels of OM with 16% and 19% respectively.

The inferred contribution of biogenic silica is positively proportioned to the diatoms concentration (Fig. 3). There is no significant linear relationship between diatom concentration and MM ($r = -0.02$, $n = 114$, $p = 0.80$) indicating that most of the silica in the sediment is of mineral source. The diatom concentration is inversely proportioned to $MAR_{min,}$ except for the uppermost part of the core where the two parameters reach their maximum values of 74 mg cm^{-2} yr^{-1} and 50 × 10^{9} valves g^{-1} (Fig. 3). However, these high diatom concentrations do not increase the opal content as they are mainly due to a sharp increase in *Cyclotella stelligera*, a small species, which constitute ~60% of the diatom assemblage on this part of the core (Perren et al., in press).

4.3. Geochemical profiles

The Ti profile remains relatively stable before 1010 AD with an average value of 3200 ppm (Fig. 4). The concentration increases then up to 4400 ppm with peak values between 1010 AD and 1335 AD. Then, Ti concentrations fall to an average of 3650 ppm, which is 14% more than the pre-*landnám* baseline. Above ~1960 AD the titanium

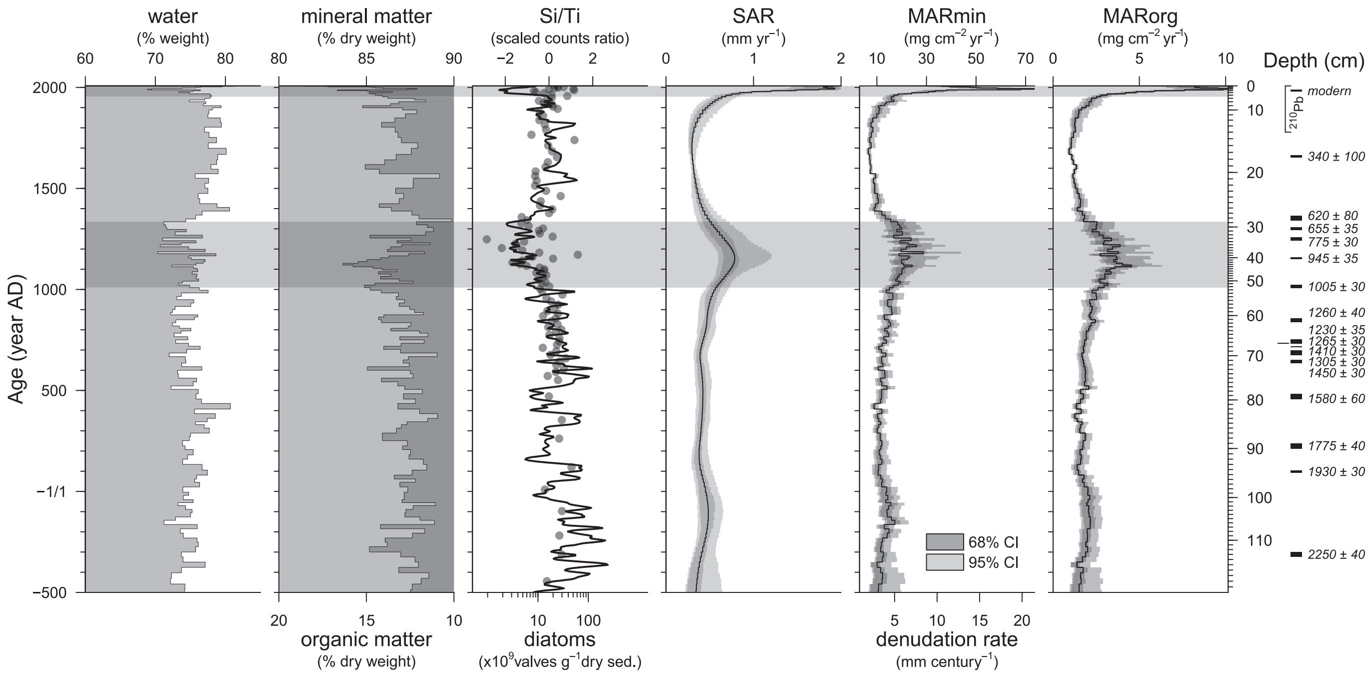

Fig. 3. Water content, organic and minerogenic matter content, diatom concentration and Si/Ti XRF scaled count ratio, sediment accumulation rate (SAR), minerogenic (MAR_{min}) and organic (MAR_{org}) masse accumulation rates plotted versus time (left axis) and depth (right axis). The grey shaded areas mark the periods of medieval (1010-1335 AD) and recent (after 1960 AD) agricultural impacts recorded in the Igaliku core.

content increases sharply to reach the maximum values of the profile around 4600 ppm. C:N ratio coevals greatly with Ti content both for general trends and decadal scale variations, but unlike Ti, the C:N ratio does not show significantly higher values in the period of 1335–1960 AD than before 1010 AD (Student's *t* test, $p = 0.28$). The four uppermost samples, after 1997 AD, are clearly outlying the general geochemical composition of organic matter, and exhibit high $\delta^{15}N$, low C:N ratios and low $\delta^{13}C$ values (Fig. 5ab). Except for these samples, a strong linear and negative relationship links the C:N ratio and the bulk $\delta^{13}C$ ($r = -0.80$, $n = 104$, $p < 0.001$) (Fig. 5b). The relationship between $\delta^{13}C$ and $\delta^{15}N$ is more complicated: the two isotope ratios are negatively correlated ($r = -0.73$, $n = 84$, $p < 0.001$), except for the period 1030–1230 AD during which the correlation is strongly positive ($r = 0.78$, $n = 20$, $p < 0.001$) (Fig. 5a).

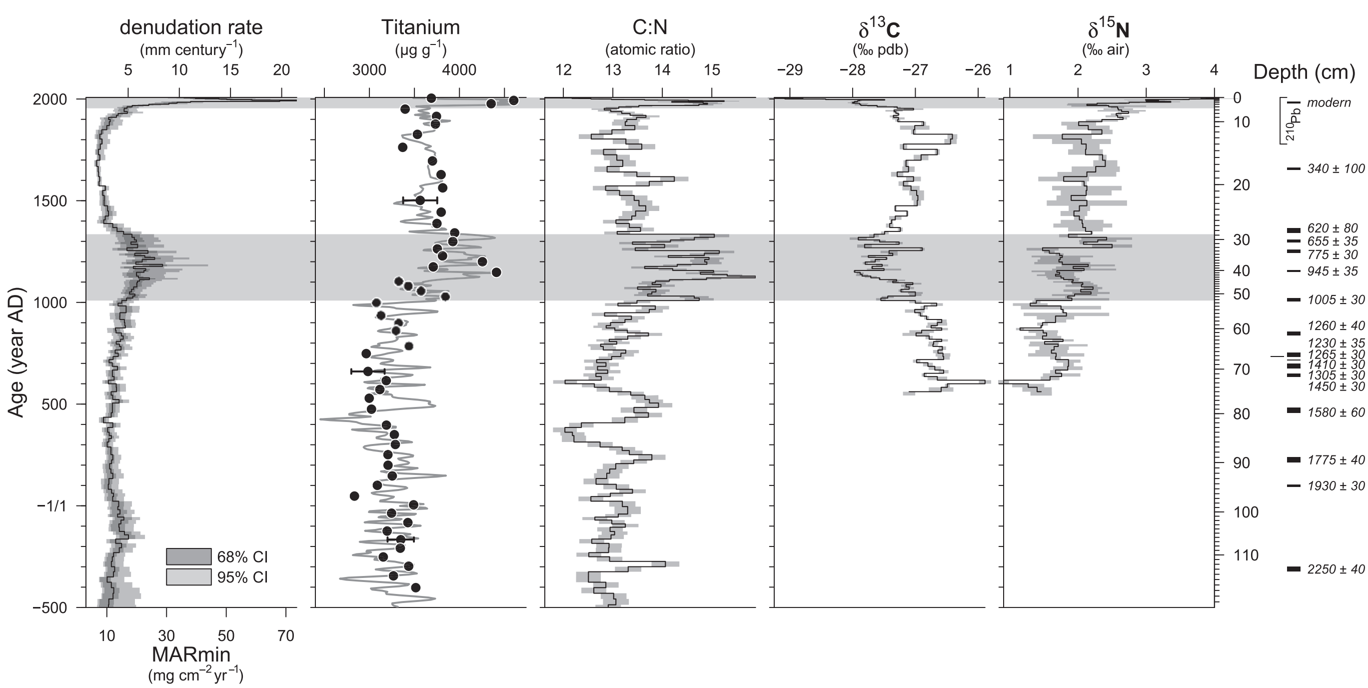

Fig. 4. Mass accumulation rate of minerogenic matter (MAR_{min}), soil denudation rate, titanium concentration measured by ICP-AES (points) and calibrated from XRF scan results (curve), C:N atomic ratio, $\delta^{13}C$ and $\delta^{15}N$ of bulk organic matter from the last 2500 years of the sediment archive of lake Igaliku.

4.4. Assessing soil erosion

The calculated detritic inflows can be biased and overestimated by the presence of autochthonous silica. Especially when considering that in Greenland lakes, biogenic silica can contribute up to 35% of the total minerogenic matter content and can explain more than 40% of its variance (Willemse, 2002). However the absence of significant relationship between MM and diatom concentration indicates that changes in allochthonous MM (linked to soil erosion) drive the total MM fluctuations at the Igaliku Lake. Moreover, the lower diatom concentrations coincide with the periods of maximum sediment yield around 1010–1335 AD and after ~1960 AD which clearly indicate that opal production is diluted by the detritic inputs.

The titanium is a conservative lithogenic element that participates in very few biogeochemical processes (Kauppila and Salonen, 1997; Koinig et al., 2003). So the shifts to higher Ti concentrations in the sediment points to enhanced physical weathering of alumino-silicates in the watershed that can be climatic or due to land use (Kylander et al., 2011). Bulk sediment C:N ratios are widely used in palaeolimnology for assessing the abundance of terrestrial and aquatic components of organic matter (eg. Kaushal and Binford, 1999). For Igaliku, C:N ratios between 11.5 and 16 indicate a mixture of lacustrine and terrestrial contribution to the organic matter pool (lacustrine plants ~6–9, land plants ≥ 20; Meyers and Ishiwatari, 1993). Values above 14 during the period 1010–1335 AD and after ~1960 indicate increases in terrestrial OM input and suggest soil erosion. The consistency of Ti and C:N demonstrate that they constitute two robust proxy of soil erosion and strengthen the significance of the two detritic events described above. It appears that the geochemical parameters provide a very high resolution, but relative, view of soil erosion, whereas the MAR_{min} give an absolute, but smoothed estimate.

Changes in organic matter supplies are also mirrored in the isotopic composition of carbon and nitrogen. The $\delta^{13}C$ of organic carbon produced photosynthetically is enriched with increases in primary production and is used as a proxy for lacustrine productivity (Schelske and Hodell, 1995). However, for the Igaliku core, the strong negative correlation between $\delta^{13}C$ and C:N ratio indicates that the isotopic composition of bulk organic carbon is principally influenced by changes in terrestrial organic matter supplies. Although N utilization associated with productivity variations have been considered the most common cause of changes in sediment $\delta^{15}N$ (e.g. Jinglu et al., 2007), N isotopes are affected to a greater extent by food chain dynamics than are C isotopes (Hodell and Schelske, 1998) and external N inputs from sewage, fertilizers or soil erosion can also contribute to it (Teranes and Bernasconi, 2000; Talbot, 2002; Lu et al., 2010). Thus, $\delta^{15}N$ values are likely controlled both by in-lake mechanisms and allochthonous sources. That may explain its different pattern from that of $\delta^{13}C$.

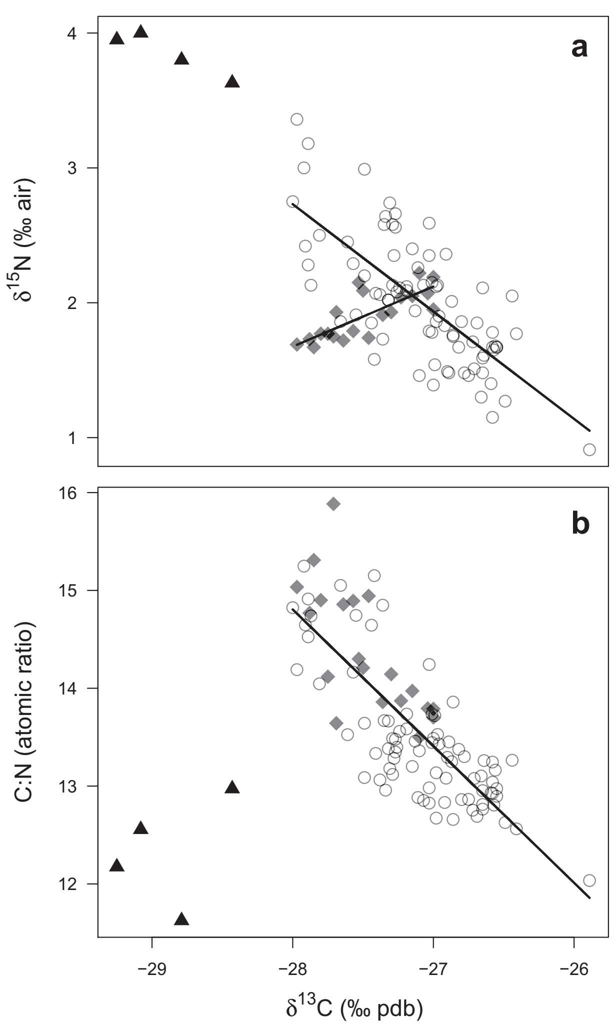

Fig. 5. (a) Cross-plot of $\delta^{15}N$ and $\delta^{13}C$. The isotopic ratios are negatively correlated ($r = -0.73$) except for the period 1030–1230 AD (grey diamonds) where the correlation is positive ($r = 0.78$). (b) Cross-plot of C:N ratio and $\delta^{13}C$. The filled triangles represent the outliers from 1997 to 2007 AD.

5. Discussion

5.1. Natural variability of soil erosion before the Norse arrival (500 BC–986 AD)

The lake Igaliku sediment record documents large fluctuations in mass accumulation rates and geochemical parameters that are consistent with meaningful changes in soil erosion regime. These results can be linked to climate variations and to human activities for the last 2500 years.

The DR is stable for the period 500 BC–986 AD and ranges between 2.5 and 5 mm century^{-1} (Fig. 6a). The main feature of the Igaliku profiles for this period is the large oscillation in Ti, C:N ratio and Si:Ti ratio between 100 and 600 AD which indicate changes in the balance between detritic inputs and in-lake productivity (Fig. 4). The high detritic inputs and low productivity around 250 AD suggests a cooling which corresponds to relatively low temperatures in the Arctic between 165–345 AD (Kaufman et al., 2009). The low C:N and Ti values at ~400 AD indicate low erosion and/or high algal productivity which could be linked to a warm climate. This period is indeed coeval with almost the warmer time interval (375–415 AD) recorded in the Arctic for the last 2000 years (Kaufman et al., 2009). The most detritic period in at 470–550 AD roughly corresponds to a major cooling in the North Atlantic (Bond, 1997) and in the Igaliku Fjord waters (Jensen et al., 2004; Lassen et al., 2004) at ~ 550–650 AD. On the winter $\delta^{18}O$ curve of the Dye-3 ice core (Vinther et al., 2010), which is the closest available glacial record (Fig. 1a), this cold period culminates around 650 AD. The slight discrepancy between the records could be explained by the littoral position of Lake Igaliku which is more influenced by oceanic surface currents than the Dye-3 location (Andresen et al., 2004).

5.2. Impacts of medieval farming (ca. 1010–1335 AD)

The Norse arrived during the relatively warm temperatures of the Medieval Climate Anomaly (Fig. 6b), temperatures that are comparable to those of the 1920s (Vinther et al., 2010). Warm temperatures in the early 11th century results in a reduction of seasonal ice cover in the Igaliku Fjord (Roncaglia and Kuijpers,

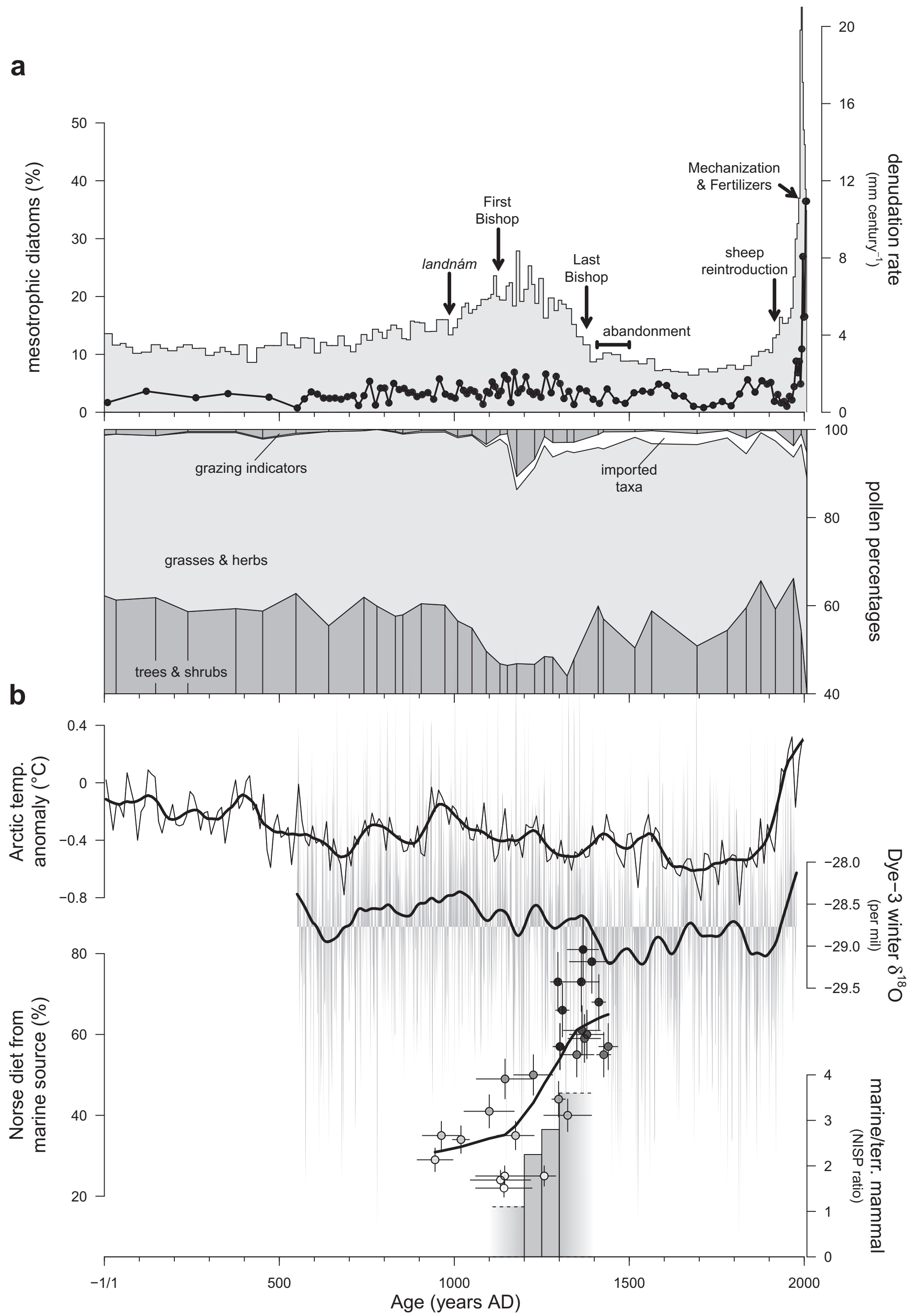

Fig. 6. (a) Reconstruction of past soil erosion rates (grey barplot), lake trophic status (points) and vegetation change for the Igaliku lake system with historical cultural events (black marks). (b) The Dye-3 Winter $\delta^{18}O$ (Vinther et al., 2010) and Arctic temperature anomaly (Kaufman et al., 2009) time series, shown against the estimation of Norse diet (points) from $\delta^{13}C$ of Norse squeletons (Arneborg et al., 1999) and the relative proportion of marine and terrestrial mammals bones from the Norse farm Ø29a (McGovern and Pálsdóttir, 2006). This figure was inspired by the work of Dugmore et al. (2009).

2004) indicating an extension of the growing season which was favorable to Norse farming. Thus, compared with the relatively stable soil erosion rate before the Norse *landnám*, its increase during the period 1010–1335 AD is interpreted as a consequence of agricultural activities in the lake catchment. Soon after the Norse arrival, the land clearance (indicated in pollen data by a decrease in woody taxa) and the introduction of sheep led to a rapid increase in soil erosion to a maximum of 8 mm century^{-1} around 1180 AD, twice the background level (Fig. 6a). The positive phase of correlation between $\delta^{13}C$ and $\delta^{15}N$ between 1030 and 1230 AD as well as maximum values in C:N ratio and Ti suggest a stronger impact of Norse farming during this period (Fig. 5a). Maximum erosion appears a few decades after the appointment of the first bishop when *Garðar* was probably close to its maximum development and activity (Fig. 6a). First land-use erosion around Lake Igaliku also precedes by 100 years the formation of an anthropogenic soil horizon at *Garðar* between ~1110–1370 AD (Buckland et al., 2009) and constitute the older evidence of human impact on the area.

Soil erosion is perfectly synchronized with the grazing pressure recorded by the amount of coprophilous fungal spores (grazing indicators, Fig. 6a) which are typically found on animal dung (Gauthier et al., 2010). The grazing pressure and associated soil erosion still remain high until 1335 AD with high levels and large amplitude fluctuations of the C:N ratio indicating a destabilization of soils in the watershed (Fig. 4). Surface horizons of *Garðar*'s soils are high in organic matter (~25%) because of the short growing and decomposition periods (Rutherford, 1995). Thus, erosion of surface horizons could result in a rapid increase in soil organic matter input that could explain the simultaneous increase of OM accumulation rates and high sediment organic contents (Fig. 3) as well as the marked changes in elemental and isotopic composition of OM (Figs. 4 and 5). Indeed, although allochthonous input does not seem to have caused substantial changes in trophic status of the lake, indicated by a relatively stable abundance in mesotrophic diatoms (Perren et al., in press, Fig. 6a), a reversed slope in linear relationship between C and N isotopes has already been observed in Lake Ontario and interpreted as a change in phosphorus loading to the basin (Hodell and Schelske, 1998). At Igaliku, high inflows of soil organic matter made the sediment composition remain relatively stable during erosion phases. Other sedimentary sequences, close to the archaeological remains, may have recorded a more localized and intense erosion which was able to cause noteworthy change in the sediment composition (Sandgren and Fredskild, 1991; Edwards et al., 2008; Schofield et al., 2008; Buckland et al., 2009; Schofield et al., 2010).

After 1335 AD, the grazing pressure decreased as indicated by a return of coprophilous fungal spores to pre-*landnám* background values (Gauthier et al., 2010). At the same time the dwarf-shrub community recovered and soil erosion level decreased to reach pre-anthropogenic values (Fig. 6a). Our data indicate a substantial decline of agro-pastoral practices around the lake of Igaliku well before the end of the Norse Eastern Settlement. This decline occurred a few decades before the death of the last bishop known to have lived at *Garðar* (Fig. 6a) suggesting that the activity was already reduced before this historical evidence of decline.

5.3. Adaptation versus destruction

Land degradation and mass erosion leading to a serious decline in agricultural yield is supported by many authors (e.g. Gad, 1970; Jacobsen and Jakobsen, 1986; Jacobsen, 1987; Fredskild, 1988; McGovern et al., 1988; Jakobsen, 1991; Fredskild, 1992; Diamond, 2005; Edwards et al., 2008; Schofield and Edwards, 2011). Coupled with worsening climate conditions of the 'Little Ice Age' and the refusal to drastically change their sedentary lifestyle, what Barlow et al. (1997) called 'cultural intransigence', the overexploitation of the environment would have been a major cause of the collapse of the medieval Norse society in Greenland. Archaeology nonetheless provides evidence that might oppose this theory. The Norse were only partly dependent upon agriculture (Krogh, 1967) and studies of the archaeofauna from several Norse farms have demonstrated a change of the dietary habits giving more and more importance to hunting, especially sealing (McGovern and Bigelow, 1984; McGovern et al., 1996; Enghoff, 2003). This is illustrated in Fig. 6b by the increasing relative proportion of marine mammal bones during the different phases of activity at a major farm of *Brattahilð* (Ø29a, Fig. 1a) (McGovern and Pálsdóttir, 2006) and by human isotopic data showing an increasing proportion of diet from marine source over the five centuries of the Greenland settlement (Arneborg et al., 1999).

The modern farming developments (section 2.2) demonstrate that cold years in such a marginal area as southern Greenland can have dramatic consequences for livestock. Soon after 1000 AD, a regime of more extreme climatic fluctuations was inferred from the outer Igaliku Fjord core with, since ~1245 AD, stronger advections of the cold East Greenland Current, more sea ice and lower summer temperatures (Jensen et al., 2004). A succession of harsh winters is also noted in the Dye-3 winter $\delta^{18}O$ record toward the end of the 12th century (Fig. 6b). It suggests that climate deterioration was likely the main driver of the evolution of the Norse subsistence pattern (Dugmore et al., 2009). This may have led to a decrease of sheep herds and related grazing pressure early before fully entering the 'Little Ice Age' indicated, in the early 15th century, by a negative shift in the Dye-3 winter $\delta^{18}O$ record (Vinther et al., 2010; Fig. 6b) and by the culmination of a cooling in the Igaliku fjord at ~1405 AD (Lassen et al., 2004).

While Sandgren and Fredskild (1991) argue that the most severe erosion seems to have taken place at the end of the Norse era, our observations bring strong evidence of reduced agropastoral pressure a least one century before the abandonment, perhaps since 1230 AD as indicated by the isotopic ratios of N and C, in accordance to the climate deterioration and the changes in Norse diet. An early decrease in grazing intensity was also demonstrated close to a large Norse farm complex (Ø39, Fig. 1a) of the Eastern Settlement (Schofield and Edwards, 2011). The Igaliku record showed no continuous increase of soil erosion until the end of the Eastern Settlement, which contradicts the idea of catastrophic erosion due to overgrazing as the ultimate cause of the collapse of the Greenland Norse society. Moreover, the highest level of Norse soil erosion recorded at Igaliku, 8 mm century^{-1} (2 sigma range of 6–12 mm century^{-1}) could even be considered as characteristic of conservation agriculture (12.4 ± 2.2 mm century^{-1}) (Montgomery, 2007).

5.4. Incomplete recovery of the Igaliku lake system (ca 1450–1915 AD)

Pollen assemblages indicate that the vegetation did not completely recover from Norse impacts (Gauthier et al., 2010). As for other studied sites (Fredskild, 1973, 1978) the most obvious footprint of Norse farming on vegetation at Igaliku is the persistence of Norse apophytes like *Rumex acetosa* and *Ranunculus acris* type which are widespread today around ruins of medieval farms (Fig. 6a). C:N ratio and $\delta^{13}C$ to natural values and indicate a cessation of soil erosion associated with agriculture. Higher concentrations of titanium after the abandonment could be interpreted as a legacy of more than four centuries of Norse farming which could have altered the physicochemical properties of soils for a long time. However, a well documented change in climatic conditions occurred at the onset of the Little Ice Age. Initiated close to the end of the Norse Eastern Settlement ca. 1425 AD (Dugmore et al., 2007), this period was characterized by cold and dry air masses above the North Atlantic with increased wind speed and storm frequency which caused an enhanced deposition of eolian material (O'Brien et al., 1995; Christiansen, 1998; Willemse et al., 2003; Jackson et al., 2005). This is also apparent in the rise of sea salt spray in a peat bog deposit from Qinngua Kangilleq (Fig. 1a) located 50 km north from Igaliku (Schofield and Edwards, 2011). A shift to dry and windy conditions may have brought more aeolian dust to the Igaliku Lake basin and, with a possible persistent modification of soils properties due to Norse farming, it could contribute to higher Ti concentrations.

5.5. Impacts of modern agriculture (since 1915 AD)

From the beginning of the 20th century to ~1960 (±5 yr) no sedimentary parameter reveals any significant increase of erosion around the lake of Igaliku (Fig. 7a) suggesting that sheep grazing around the lake was minimal before that date. Since ~1960 the grazing pressure, once again revealed by a decline in woody taxa and a rise in coprophilous fungi (Fig. 6a) caused a progressive increase in soil erosion which started gently as indicated by subtle changes in all parameters except Ti. Soil erosion accelerated in 1969 (±4 yr), with a sharp increase in Ti and C:N ratio, to reach ~11 mm century^{-1} in 1988 (±2.5 yr), slightly more than the medieval period (Fig. 7a). The year 1969 also marks the beginning of a steady increase in δ^{15}N for the remainder part of the profile. It may partly reflect an increase in primary productivity due to enhanced nutrient loading and also external contribution from enriched sources like animal dung (Teranes and Bernasconi, 2000).

Around 1988, major earthworks and digging of drainage ditches were carried out in both hayfields (Fig. 1b). At the same time, soil erosion increased dramatically, up to 21 mm century^{-1}. After 1997 (±2 yr), the erosion rate decreased continuously and may mark the stabilization of the material remobilized by the drainage works. This phase also corresponds to the four outliers in the organic matter geochemical composition (Fig. 5a and b). Despite the high level of soil erosion, the C:N ratio continuously decreased due to the highest N concentrations of the core (>0.6%). The +1‰ offset in δ^{15}N could be attributed to the loss of ^{14}N stimulated by greater primary production and deposition of nitrogen-rich organic matter (algal) due to the input of N fertilisers and barn effluents into the lake. This is supported by the sharp increase in the relative abundance of the mesotrophic diatom, *Fragilaria tenera*, from 10% to 36% after 1997 (Fig. 6a). However, early diagenesis effects on isotopical and elemental composition (Meyers and Ishiwatari, 1993; Lehmann et al., 2002), such as the preferential degradation of lake derived organic matter (Gälman et al., 2008), cannot be ruled out.

These two periods of soil erosion, 1960–1988 and 1988–2007, are consistent with the two modern agricultural phases of South Greenland (Fig. 7b) discussed in section 2.2. The former corresponds to the first phase of free-ranging sheep whereas the later is the expression of intensified practices and hay-field management that followed the agrarian reform of 1982. Consequently, the Igaliku lake system is undergoing the most important environmental changes of the last 2500 years, with soil erosion is 3-fold the Norse level. Even if soil loss inferior to 10 mm century^{-1} could be tolerable (Montgomery, 2007), the mean denudation rate refers to the whole catchment area of lake Igaliku (355 ha) and erosion on the plowed 30 ha hay-fields must be much higher.

6. Synthesis and conclusion

This study is the first quantification of soil erosion from a lake deposit of South Greenland. The results demonstrate that the Igaliku lake system is very sensitive to the human land use and permits a high resolution reconstruction of the history of agricultural impacts on the landscape. The estimation of sediment yield from an accurate core chronology as well as the use of geochemical parameters (C:N, Ti, δ^{15}N, δ^{13}C) turned out to be two valuable and independent methods to investigate past soil erosion in subarctic lake systems.

Although other studies of lake sedimentary archives are needed before generalizing about the fate of the Greenland Norse settlements, our findings question the veracity of the catastrophic scenario of overgrazing and land degradation considered to have been one of the major factors responsible for their demise. The mutations of subsistence practices toward hunting and fishing have probably contributed to the reduction of grazing pressure and associated soil erosion which is recorded in the sediments of Lake Igaliku long before the end of the Eastern Settlement and therefore is unlikely to have been the prominent cause of its abandonment.

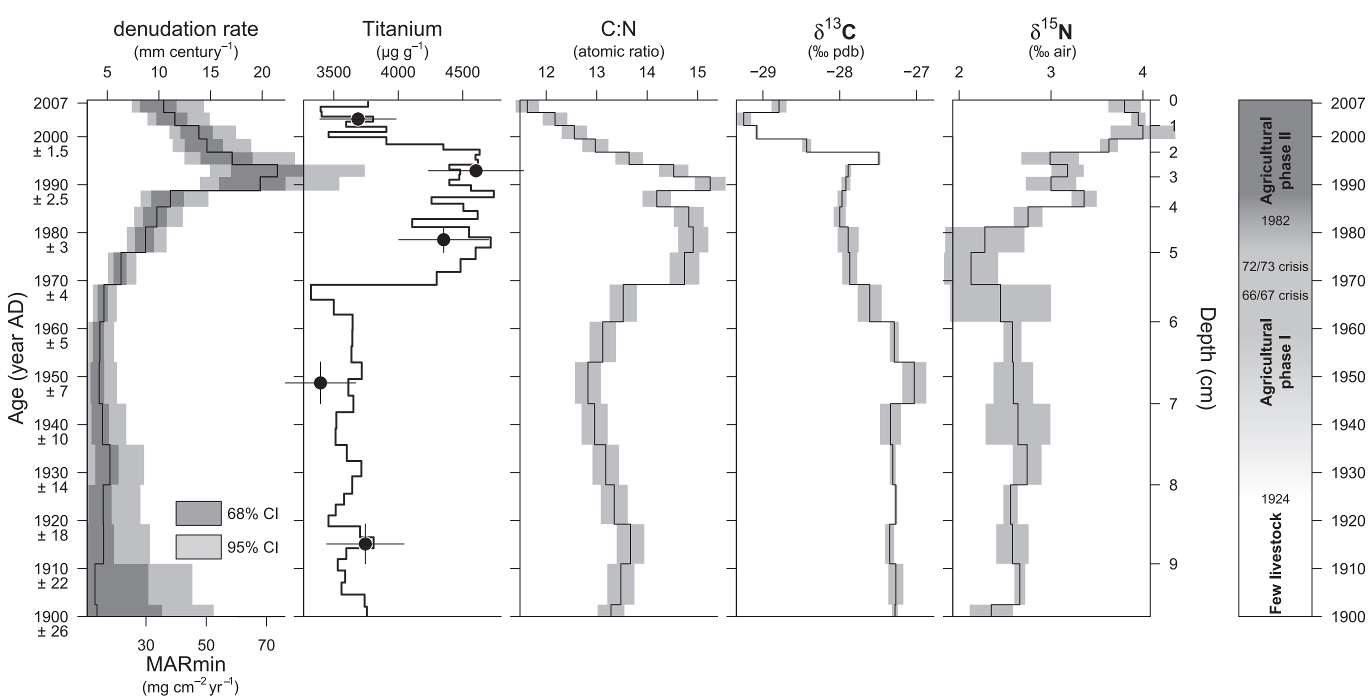

Fig. 7. Mass accumulation rate of minerogenic matter (MAR_{min}), soil denudation rate, titanium concentration measured by ICP-AES (points) and calibrated from XRF scan results (curve), C:N atomic ratio, δ^{13}C and δ^{15}N of bulk organic matter from the recent sediment archive of lake Igaliku (1900–2007 AD). The left diagram represents the recent agricultural phases in South Greenland.

Due to technological evolution, the medieval and modern farmers have followed diametrically opposed pathways in adaptation strategies to climate changes. Thus medieval and modern agricultures are not true analogues. In response to the succession of harsh winters, modern farmers have mechanically and chemically intensified their fodder production on the sparse arable lands to protect their livestock from other agricultural disasters. This caused unprecedented soil erosion that could have consequences for the future of Greenland agriculture which is expected to benefit from warming future climate.

Acknowledgements

This study is part of Charly Massa's PhD thesis (University of Franche-Comté). Coring campaign and analysis were supported by grants from the University of Franche-Comté, the University of Burgundy (France), the French Polar Institute (IPEV) and the ANR CEPS "Green Greenland" project. Hervé Grisey, Michel Campy and Boris Vannière provided invaluable assistance during the field work, which we gratefully acknowledge. Thanks also to Michel Magny and two anonymous reviewers, whose comments and suggestions improved the manuscript.

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