Climate change and human disturbance: a multi-lake approach to understanding palaeolimnological responses in western Uganda

1. Scientific objectives

Diatom records from two Ugandan crater lakes spanning the last 50-150 years have been used to compare palaeolimnological records of environmental change and to establish the potential impact of humans on the record of climate history contained within these lake sediments. Specifically, this project aims to:

- Assess if and when major anthropogenic impacts on the lake catchments first become apparent in the palaeolimnological records from western Uganda
- Determine whether varying human influence on lake catchments over the 20th century affect the recent lake-climate record.

2. Background

Current research emphasis in East Africa is focussed upon the comparatively shorter-term (10^1-10^2), more regionally specific aspects of climate variability (Vershuren, 2003). These short-term, regional records of climate in the tropics are directly relevant to human society, in terms of ENSO and monsoonal weather systems (Thompson et al., 2005). There is a lack of relevant, short-term records from the tropics (Nicholson, 2001a; Verschuren, 2003; Barker et al., 2004; Thompson et al., 2005), considering the region is central to studies of climate change (Barker et al., 2004). There is also the potential for such records to provide a context for long-term management plans (Olago and Odada, 2004), especially as major effects of future climate changes in East Africa will be through changes in the hydrological cycle (IPCC, 2007).

Documentary evidence of climate change in East Africa include rain gauge and lake level measurements, observations of glacier fluctuations and ship observations of Indian ocean winds and currents (Hastenrath, 2001). In Uganda, such instrumental records are largely confined to the recent past (c. 100 years; cf. Olago and Odada, 2004, Verschuren, 2004; Endfield et al., 2009). The historical records of tropical African climate began with the onset of European exploration and the influx of Church missionaries (with documentary (anecdotal) records now extending back [in western Uganda] until c. AD 1880 [Endfield et al., 2009]). Similarly, Nicholson (2001b) extended the lake level history of Victoria back to the early 19th century through the use of oral histories. Webster (1979) employed a similar method to reconstruct periods of drought in interlacustrine Africa. The earliest observed (instrumental) climate data in Uganda come from lake levels and rainfall data. For example, Lake Victoria levels from 1896 (Brooks, 1923); Lake Albert, 1904 (Hurst and Phillips, 1933-1946) and rainfall data from 1896 (Entebbe), 1903 (Fort Portal) and the majority of other stations (e.g. Butiaba, Bunyaruguru) from 1910 onwards (Hurst and Black, 1943-1949). The comprehensive instrumental records coincide with the beginning of western colonisation of Uganda and the establishment of the Protectorate (1896).
One of the most widespread proxy records of climate change in East Africa is obtained from lake sediments. These archives have the potential to provide chronologically structured, ecologically integrated and (in some instances) continuous records of both local and/or regional environmental change (Anderson and Battarbee, 1994). Lakes are excellent sensors of environmental change, and sediments that accumulate in a climatically sensitive lake can provide a continuous, high-resolution record of past climate variability (Battarbee, 2000). These lake sediment archives are the principal source of information on the climate history of tropical Africa (Vershuren, 2003). Crater lakes, in particular, have the potential to provide some of the best high-resolution sedimentary records of environmental change (Williams et al., 1993), as these lakes tend to have small, well-defined catchments, simple basin morphology and in several cases rapid sediment accumulation (Lamb et al., 2000). With sedimentation averaging greater than 1 mm yr$^{-1}$ in most East African lakes, (Johnson, 1996; Ssemmanda et al., 2005) and sedimentation rates of c. 10 mm yr$^{-1}$ recorded in Ugandan crater lakes in the recent past (Lakes Kasenda and Wandakara; Ssemmanda et al., 2005; Ryves et al., 2011), sediment cores can be sub-sampled to provide palaeoclimate data with century-scale, decadal or sub-decadal temporal resolution (Battarbee, 2000).

Establishing the level of human impacts on the environment and the nature of feedbacks are one of the most topical issues when attempting to reconstruct palaeoclimatic conditions (Taylor and Robertshaw, 2001), especially in terms of separating natural environmental changes from those which are principally anthropogenic, in lake sediment records (Taylor and Robertshaw, 2001, Anderson, 1995). The use of sediments as proxy records of human activity are based on the assumption that the associated environmental impacts are a result of major changes in human activity, such as introduction or intensification of agriculture, which often leads to, amongst other effects (e.g. changes in pollen, increases in charcoal and increased nutrient inputs), large deposits of catchment material into the sedimentary record. However, many problems remain. For example, the clearance of catchment forests by humans and its replacement by grassland will affect the fossil pollen assemblage; however, it may also be interpreted as a period of increased aridity. As a consequence several lines of evidence are required to disentangle signals of natural and anthropogenic changes.

The exact timing of human impacts in some of the crater catchments of Uganda remains largely unknown. Studies from swamp and lake deposits from south-western Uganda identify ‘human’ impact in the region from pollen, charcoal and sedimentary properties, that date back to the first millennium BC and a second phase a few centuries into the second millennium AD (Taylor and Robertshaw, 2001) as a result of iron working and agriculture. Other phases include a forest disturbance episode c. 1500 AD, and a recent phase dated to c. 200 years BP, the earlier of which correlates with the onset of dry climates of the broadly defined LIA and thus there are uncertainties whether the increase in charcoal is a direct result of human activity or a combination of both natural and human influences (Taylor and Robertshaw, 2001).

During recent decades, Lake Victoria has undergone several ecological changes (Vershuren et al., 2002), the most notable of which is the explosion of the Nile perch population and the demise of endemic cichlids (Ogutu-Ohwayo, 1990; Schofield and Chapman, 2000). Observed changes in the phytoplankton community since the 1980s appear to be a consequence of bottom-up excess nutrient loading resulting from long-term, 20$^{th}$ century deforestation and intensified agriculture within the catchment (Hecky and Bugenyi, 1992). In more recent times silica depletion of the lake waters is important as well as a switch in diatom flora from *Aulacoseira* to *Nitzschia* dominated assemblages as a result of increasing anoxia in the lake waters (Vershuren et al., 2002). The timing
of the inferred productivity increase from the diatom data matches the human population growth and agricultural activity in the catchment (Verschuren et al., 2002). The strong chronological link between historical land use and algal production indicates that landscape disturbance is the dominant cause of eutrophication in Lake Victoria.

Similarly a study of the highland crater Lake Saaka (Crisman et al., 2001) in Uganda showed that the lake has been undergoing cultural eutrophication since the early 1970s, based on a variety of measured parameters (conductivity, Secchi depth and DO saturation of surface waters) and the observations of a priest who recorded an increasing number of algal blooms. The eutrophication of the lake appears to be as a result of an expansion of a Ugandan government prison farm along the shore of the lake, where planting against the elevation contours has lead to an increase in erosion, and inorganic and nutrient loading to the lake. In addition to this, wetlands that once lay adjacent to the lake have been drained for agriculture (Crisman et al., 2001).

It is apparent from previous studies that human activity in many lake catchments of Uganda may be traced back a few hundred years, with a marked activity occurring since the end of colonial rule in 1962. A study by Ssemmanda et al. (2005) at Lakes Kasenda and Wandakara recorded pollen of agricultural origin (e.g. eucalyptus and pine) in 20th century sediments (last 50-75 years). The period following the end of colonial rule experienced rapid population growth and a need for increased agricultural expansion that has resulted in the pattern of large-scale deforestation and agricultural conversion (even on the steepest crater walls) that continues to the present day (Crisman et al., 2001; Verschuren et al., 2002). Similar pressures elsewhere in East Africa have resulted in eutrophication of crater lakes (Green, 1986), the waters of which are a major resource for rural populations and degradation of lake ecosystems will continue unless land-management strategies restricting nutrient inputs are implemented (Verschuren et al., 2002).

3. Study Site

In western Uganda, there are over 80 crater lakes in four distinct lake districts (Figure 1) formed in association with the western branch of the East African rift valley system, and straddle the equator at ~30°E from 0° 42’N to 0°19’S. Most have been formed as a direct result of volcanic activity and comprise maars and phreatomagmatic explosion craters (Hutchinson’s lake types 11 and 12, respectively; Hutchinson 1957). The lakes chosen for this study lie in the crater lake cluster of Bunyaruguru, which extend into the southern uplands (975-1250 m asl; Figure 2). The two sites under investigation, Lake Kyogo (0°20’21.4” S, 30°01’7.16” E) and Lake Nyamogusingiri Basin (0°18’55.3” S, 30°01’36.29” E), are situated 6 km apart within the Maramagampo CFR on the ecotone between moist semi-deciduous forest and grass savanna (Langdale-Brown et al., 1964), but differ in terms of the extent of human impact within their catchments (Figure 3). The two lakes also differ in both their physical and limnological attributes (Table 1).

Lake Nyamogusingiri Basin is much larger, with a minimum catchment area: lake (CA:L) ratio of 13.3:1 and a higher conductivity (554 µS cm⁻¹) than Kyogo (CA:L = 1.8:1, conductivity 55 µS cm⁻¹). In addition to this Kyogo has a much higher Secchi depth than Nyamogusingiri, with light penetrating to the bottom of the lake. In terms of direct human impact on the lake system, Nyamogusingiri supports a native fish community (including Barbus neumayeri, Hypoxyanthis deprimus, Clarias gariepinus and several haplochromine cichlids) alongside introduced, non-indigenous species (e.g. Oreochromis niloticus, Oreochromis leucostictus and Tilapia zilli; Bwanika et al., 2004).
### Table 1. Comparison of the physical and chemical variables of Lakes Nyamugisingi and Kyogo (-- missing data / not collected)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Nyamugisingi Basin</th>
<th>Kyogo</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td>0°18’55.3&quot;</td>
<td>0°20’21.4&quot;</td>
</tr>
<tr>
<td>Longitude</td>
<td>30°1’36.29&quot;</td>
<td>30°1’7.16&quot;</td>
</tr>
<tr>
<td>Altitude (m)</td>
<td>984</td>
<td>1120</td>
</tr>
<tr>
<td>Lake Area (km²)</td>
<td>4.28</td>
<td>0.69</td>
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<tr>
<td>Catchment area (km²)</td>
<td>49.75*</td>
<td>1.22</td>
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<tr>
<td>CA:L ratio</td>
<td>13.3:1*</td>
<td>1.8:1</td>
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<tr>
<td>Depth (m)</td>
<td>3.8</td>
<td>3.4</td>
</tr>
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<td>Temperature (°C)</td>
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<td>27.5</td>
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<tr>
<td><strong>Chemical</strong></td>
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<td></td>
</tr>
<tr>
<td>Conductivity (µS cm⁻¹)</td>
<td>554</td>
<td>55</td>
</tr>
<tr>
<td>pH</td>
<td>9.16</td>
<td>7.09</td>
</tr>
<tr>
<td>Oxygen (mg l⁻¹)</td>
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<td>--</td>
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<tr>
<td>Oxygen saturation (%)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Secchi depth (cm)</td>
<td>52.5</td>
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<tr>
<td>TP (µg l⁻¹)</td>
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<td>272.66</td>
</tr>
<tr>
<td>TN (µg l⁻¹)</td>
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<tr>
<td>Chl-a (µg l⁻¹)</td>
<td>--</td>
<td>2.04</td>
</tr>
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</table>

* Catchment area underestimated due to lack of map coverage
Figure 1  Map of East Africa illustrating the Eastern and Western branches of the East African Rift Valley system and the major water bodies associated with this rifting (A). The solid black lines represent the main fracture zones. (B) Map of Uganda. The red boundary shows the location of the field site in the west of the country. (C) A larger scale map of the field study area in the west of Uganda. There are four main crater lake clusters: Fort Portal (FP), Kasenda (Ka), Katwe-Kikorongo (KK) and Bunyaruguru (Bu) following those described by Melack (1978).
Figure 2  Small scale map of the southern field area, indicating the lakes that were sampled for detailed core analyses (X= Kajak and Russian core sampling locations). The map highlights the main land usage across the region. It is worth noting the large scale forest clearance outside of the National Park (NP) and Central Forest Reserve (CFR) boundaries.
Figure 3  Photographs of the lakes and catchment types presented in this study (A) Lake Kyogo, (B) Nyamogisingiri Basin, (C, D) Natural/secondary forest and grass savannah. Photographs taken by K. Mills.
4. Methods

4.1 Sample Collection

Sediment cores were collected from the deepest part of Lakes Nyamugingiri Basin and Kyogo using a HON-Kajak gravity corer (9 cm diameter; Renberg, 1991); the collected cores were 47 cm and 45 cm long, respectively. All of the cores were extruded in the field on a screw-threaded extruding rig at contiguous 0.5 cm intervals. The samples were then bagged, labelled and stored in dark refrigeration (4 °C) until required for analysis.

4.2 Chronology

Samples for $^{210}\text{Pb}$ dating were chemically processed using the following ANSTO methods: ENV-I-044-031 Sedimentation rate determination, ENV-I-044-066 Bulk iron removal by ether extraction, ENV-I-044-023 Polonium analysis and ENV-I-044-027 226Ra analysis. Each dried sediment sample was spiked with $^{209}\text{Po}$ and $^{133}\text{Ba}$ yield tracers. Each sediment sample was subsequently leached with hot concentrated acids to release polonium and radium. Polonium was autoplated onto silver disks after adding the reducing agent hydroxylammonium chloride. Radium was co-precipitated with BaSO$_4$ on a membrane filter source. The activities of the sample sources were determined by spectrometry methods.

Sample sources prepared for alpha spectrometry were counted according to the following ANSTO method: ENV-I-044-001 Alpha spectrometry. Each silver disk ($^{210}\text{Po}/^{209}\text{Po}$ source) and membrane filter ($^{226}\text{Ra}/^{133}\text{Ba}$ source) was counted by alpha spectrometry. The membrane filter was also counted by gamma spectrometry to measure $^{133}\text{Ba}$ tracer activity. Chemical yields recoveries of $^{210}\text{Po}$ and $^{226}\text{Ra}$ were calculated using the recoveries of $^{209}\text{Po}$ and $^{133}\text{Ba}$ tracers.

4.3 Diatoms

Samples for diatom analysis were prepared following the procedure of Renberg (1990). Strewn slides were mounted in Naphrax and at least 300 valves per sample were counted in parallel transects under oil-immersion phase-contrast light microscopy at x1000 using a Zeiss microscope. A variety of general (Krammer and Lange-Bertalot 1986, 1988, 1991a, 1991b) and regional floras (Gasse 1986; Cocquyt 1998) were consulted, and valves identified to species level where possible. Diatom species abundances are expressed as percentages, calculated using total number of valves recorded for each sample.

4.4 Statistical Analyses

Indirect ordination analyses were carried out using CANOCO 4.5 (ter Braak and Šmilauer, 2002) to identify the predominant trends within the data. Initially a Detrended Correspondence Analysis (DCA; Hill and Gauch, 1980) with detrending by segments, and down-weighting of rare species, was used to explore the main patterns of taxonomic variation among sites and to estimate the compositional gradient lengths of the first few DCA axes. The diatom percentage data were transformed using log transformation in an attempt to reduce clustering of abundant or common taxa at the centre of
origin (Leps and Šmilauer, 2003). The gradient lengths allow the determination of the most appropriate response model for further analysis. If the gradients were sufficiently long (>1.5 s.d.), it indicated that numerical methods based on a unimodal response model were most appropriate (e.g. Detrended Correspondence Analysis; CA or DCA; ter Braak and Prentice, 1988). Where gradient lengths were <1.5 s.d. a linear response model (e.g. Principal Components Analysis; PCA) was deemed the most appropriate. The stratigraphical diatom data from each core were divided into assemblage zones using optimal sum of squares partitioning (Birks and Gordon, 1985) by the program ZONE (version 1.2; Juggins, 2002).

5. Results

5.1 Lake Kyogo

5.1.1 Pb-210 chronology

The unsupported 210Pb activities for Lake Kyogo exhibit an overall decreasing profile with increasing cumulative dry mass (Figure 4; Table 2). The sediment ages and mass accumulation rates for this core were calculated using unsupported 210Pb data between 0 and 37 cm by the CRS 210Pb dating model. Sample M624 (40-41 cm) unsupported 210Pb data did not fit the decay profile for this core and was therefore not included in the dating calculation.

5.1.2 Physical properties

The sediments from Kyogo are organic-rich, with loss-on-ignition values generally between 10% and 60%, carbonate values of 2-5% and minerogenic residue accounting for up to almost 80% (in some cases (Figure 5). The organic content is relatively stable and fluctuates 15% in the earliest part of the Lake Kyogo record (45-24 cm; pre-AD 1810-1950). After AD 1950 the organic content increases steadily to a maximum of 60% (at 11 cm; AD 1990 The carbonate content, although fluctuating, between 2-5%, is relatively stable throughout the entire record, with no significant excursions seen in the data.

5.1.3 Diatoms

The results of diatom analysis are shown in Figures 6a and 6b. Twenty-six samples at 2 cm intervals were analysed from Lake Kyogo. In total 54 species were identified. Five assemblage zones were identified for Kyogo (KYO-1 to 5).

The diatom stratigraphy from Kyogo is dominated by Eunotia pectinalis, which appears to reach a maximum abundance between 18 and 24 cm. The presence of this species is consistent throughout the record and constitutes 35-83% of the total diatom count in all samples. The diatom preservation within the core fluctuates throughout the record, but is generally very good (F index values between 0.8 and 1.0). The occurrence of testate amoeba scales in the Kyogo record is relatively high when compared to other records from the region (Mills, 2009), with the highest counts in the most recent zones (KYO-3 to KYO-5). An unusual feature in the sediments of Lake Kyogo is the presence of
<table>
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<tr>
<th>ANSTO ID</th>
<th>Depth (cm)</th>
<th>Dry Bulk Density (g cm(^{-2}))</th>
<th>Cumulative Dry Mass (g cm(^{-2}))</th>
<th>Total (^{210})Pb (Bq kg(^{-1}))</th>
<th>Supported (^{210})Pb (Bq kg(^{-1}))</th>
<th>Unsupported (^{210})Pb (Bq kg(^{-1}))</th>
<th>CRS Ages (years)</th>
<th>Mass Accumulation Rate (g cm(^{-2}) yr(^{-1}))</th>
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<tr>
<td>M484</td>
<td>0 - 1</td>
<td>0.01 + 0.01</td>
<td>0.01 + 0.01</td>
<td>705 + 16</td>
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<td>916 + 20</td>
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<td>2.2 + 0.3</td>
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<tr>
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<td>0.32 + 0.01</td>
<td>609 + 17</td>
<td>11.7 + 0.9</td>
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<td>464 + 10</td>
<td>10.0 + 0.6</td>
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<td>0.91 + 0.02</td>
<td>462 + 9</td>
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<td>1.29 + 0.03</td>
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<td>12.6 + 1.0</td>
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<td>24.6 + 1.9</td>
<td>79 + 3</td>
<td>51.8 + 0.9</td>
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Figure 4 $^{210}$Pb data for Lake Kyogo. (A) $^{210}$Pb chronology from Kyogo (using linear extrapolation between dated horizons (filled circles). Fallout radionuclides in the Kyogo core showing (B) total and supported $^{210}$Pb and (C) unsupported $^{210}$Pb.
Figure 5 Calculated flux data for Lake Kyogo. (A) Stacked organic and carbonate percentages versus core depth, (B) dry mass accumulation rate (DMAR) calculated using the dry bulk density and $^{210}$Pb rates, (C) organic content displayed as flux (g cm$^{-2}$ yr$^{-1}$) and (D) minerogenic flux (g cm$^{-2}$ yr$^{-1}$). Graphs (B-D) are plotted against calendar years AD.
Chaetoceros spp. in the two upper zones, a feature not seen in other lakes from the area (Mills, 2009).

Zone KYO-1 (44-34 cm; pre-AD 1810-1890), as with the majority of the core, is dominated by the epiphytic Eunotia pectinalis, a species that has a preference for waters with a low mineral content that are slightly acidic (Gasse, 1986). This zone also contains the species planktonic Aulacoseira distans and Staurosira construens var. subsalina which both peak at a maximum abundance of 20% (40 cm; AD 1820). Many of the species in this zone are benthic, aerophilous (e.g. Craticula halophila, Luticola mutica) and epiphytic (e.g. Gomphonema spp.). The testate amoeba: diatom ratio is around 0.2 throughout, and, aside from the basal sample (44 cm), Chaetoceros spp. are not present. Reconstructed conductivity suggests a freshwater lake (400 μS cm⁻¹), but this conductivity is elevated compared to its modern value (55 μS cm⁻¹); Preservation of the valves is very good (F index 0.9-1.0).

Zone KYO-2 (34-24 cm; AD 1890-1950) is again dominated by Eunotia pectinalis, which generally increases towards the top of the zone and reaches a maximum abundance of 70%. The epiphytic Gomphonema parvulum is present at around 10% throughout, as is the benthic Craticula halophila. Pinnularia gibba is also consistently present throughout this zone, although only in very small abundance (3%). The testate amoeba: diatom ratio is still relatively low, but exhibits a small peak at 0.3 (28 cm; AD 1940). Overall preservation decreases a little (0.8) and conductivity is steady at 400 μS cm⁻¹.

Eunotia pectinalis reaches its maximum abundance (80%) in zone KYO-3 (24-18 cm; AD 1950-1970). This zone represents a period of transition in the Kyogo sediments, and many of the species present in the lower zones are no longer obvious in the sedimentary record (e.g. Staurosira construens var. subsalina, Craticula halophila and Luticola mutica). The epiphytic Gomphonema parvulum and Pinnularia gibba are still consistently present, though their abundances are very low (2%). It is during this zone that Pinnularia acrosphaeria, Selaphora laevissima and Navicula lanceolata become more apparent in the record. This transitional zone also sees an increase in the number of testate amoeba scales recorded and a more consistent presence of Chaetoceros spp. The diatom preservation is very good (0.95) and the inferred conductivity remains at an average of 350 μS cm⁻¹.

The most recent zone, KYO-4 (18-4 cm; AD 1970-2002) and KYO-5 (4-0 cm; AD 2002-2007) shows a large shift in the diatom assemblage compared to the preceding zones. Eunotia pectinalis remains as the dominant species, although it exhibits a definite decrease towards the top of the zone to around 40%. A number of species are consistently present in abundances ranging from 5-20%. These include a reappearance of the planktonic Aulacoseira distans, and the first appearance of the benthic species Pinnularia acrosphaeria and Pinnularia laevissima and Navicula lanceolata and Navicula subrotundata. In zone KYO-5 (from 4 cm; AD 2002) the first Nitzschia species occur (N. rostellata and N. palea). The testate amoeba: diatom ratio shows a marked increase and remains high throughout the zone (0.4) and Chaetoceros spp. are consistently present, increasing towards the top of the core (maximum of 12). Diatom preservation declines in this zone (0.8), but it should be noted that even these lower values still suggest excellent preservation of diatom valves. The diatom-inferred conductivity shows a small decline, to a recent value of 250 μS cm⁻¹, which does not reflect the measured conductivity of the lake.
Figure 6a  Diatom stratigraphy from Lake Kyogo. All species > 3% in any one sample are displayed. The diatom taxa have been ordered according to their weighted average abundance in the core (descending) and are split into assemblage zones KYO1-4. The ratio of testate amoebae scales to diatoms are displayed alongside the diatom preservation index (F index), diatom concentrations and the axis 1 sample scores from Detrended Correspondence Analysis (DCA). Reconstructed conductivities are based on the crater lake transfer function (Mills & Ryves, in review), a lowess smoother has been added to the reconstruction.
Figure 6b  Diatom stratigraphy from Lake Kyogo. All species > 3% in any one sample are displayed. The diatom taxa have been ordered according to their weighted average abundance in the core (descending) and are split into assemblage zones KYO1-4. The ratio of testate amoebae scales to diatoms are displayed alongside the diatom preservation index (F index), diatom concentrations and the axis 1 sample scores from Detrended Correspondence Analysis (DCA). Reconstructed conductivities are based on the crater lake transfer function (Mills & Ryves, in review), a lowess smoother has been added to the reconstruction.
5.2 Lake Nyamogusingiri Basin

5.2.1 Pb-210 Chronology

The unsupported $^{210}\text{Pb}$ activities for Lake Nyamogusingiri exhibit an overall decreasing activity with increasing cumulative dry mass (Figure 7; Table 3). The sediment ages and mass accumulation rates for the core were calculated using the CRS $^{210}\text{Pb}$ dating model using the data between 0 and 45 cm. The unsupported $^{210}\text{Pb}$ activity at 45 cm is still relatively high, suggesting that equilibrium has not been reached and the entire core is younger than the last 150-200 years (an adjacent core from Nyamogusingiri Crater reached equilibrium at c. 1.5 metres; Mills, 2009).

5.2.2 Physical properties

As with the sediments from Kyogo, those from Nyamogusingiri Basin are also organic-rich, with loss-on-ignition values generally between 20% and 50%, carbonate values of 3-8% and minerogenic residue accounting for up to almost 80% in the lower section of the core (Figure 8). The organic content is relatively, but shows a steady increase throughout the entire record (beginning at 36 cm; AD 1970). After AD 1970, the organic content increases to a maximum of 50% (at 6 cm; AD 2005). The carbonate content, although fluctuating, between 3-8%, is relatively stable throughout the entire record, with no significant excursions seen in the data.

5.2.3 Diatoms

The results of diatom analysis are shown in Figures 9a and 9b. Forty-seven samples at 1 cm intervals were analysed from Lake Nyamogusingiri Basin. In total 115 species were identified. Four assemblage zones were identified for Nyamogusingiri (NB-1 to 4).

The diatom stratigraphy from Nyamogusingiri Basin is dominated by *Cyclotella meneghiniana*, which appears to reach a maximum abundance in zones NB-1 and NB-3. The presence of this species is consistently present in the lower 3 zones, accounting for 20-80% of the total diatom count. The diatom preservation within the core is highly variable throughout the record (F index of 0.5-0.95). The occurrence of testate amoeba scales in the Nyamogusingiri Basin record is relatively low when compared to other records from the region (Mills, 2009), but the ratio does fluctuate throughout the record.

Zone NB-1 (46-38 cm; AD 1950-1965) contains a diatom assemblage dominated by *Cyclotella meneghiniana* which accounts for over 60% of each sample. Also present in this zone are *Nitzschia paelea* which increases towards the NB-1/NB-2 boundary (from <5% to 30%), *Thalassiosira rudolfii* and the epiphytes *Amphora copulata* and *Nitzschia amphibia* and the planktonic *Nitzschia lanceolata* (all occurring at 2-4%). The testate amoeba: diatom ratio is generally low (<0.1) and the preservation of the diatom valves is variable, fluctuating from 0.6 to 0.95 (F index). Diatom-inferred conductivity is also variable, but shows a generally increasing trend from 600 to 900 µS cm$^{-1}$.

Zone NB-2 (38-30 cm; AD 1965-1975) is characterised by a decline in the former dominant taxon *Cyclotella meneghiniana* (to a minimum of 10%) and an increase in the abundance of *Nitzschia paelea* (average abundance of 40%) and *Nitzschia bacillum* (20%). This zone also has the only occurrences of *Aulacoseira granulata var. angustissima, Nitzschia intermedia* and *Nitzschia gracilis*. The ratio of testate amoeba: diatom ratio shows a steady increase throughout the zone, there is little change in
<table>
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<tr>
<th>ANSTO ID</th>
<th>Depth (cm)</th>
<th>Dry Bulk Density (g cm⁻³)</th>
<th>Cumulative Dry Mass (g cm⁻²)</th>
<th>Total ²¹⁰Pb (Bq kg⁻¹)</th>
<th>Supported ²¹⁰Pb (Bq kg⁻¹)</th>
<th>Unsupported ²¹⁰Pb (Bq kg⁻¹)</th>
<th>CRS Ages (years)</th>
<th>Mass Accumulation Rate (g cm⁻² yr⁻¹)</th>
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<tr>
<td>M478</td>
<td>0 - 1</td>
<td>0.01</td>
<td>0.01 ± 0.01</td>
<td>1201 ± 29</td>
<td>37 ± 3</td>
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<td>0.0233 ± 0.0180</td>
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<td>4 - 5</td>
<td>0.03</td>
<td>0.10 ± 0.01</td>
<td>906 ± 21</td>
<td>29 ± 2</td>
<td>877 ± 21</td>
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<td>1050 ± 26</td>
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<td>345 ± 11</td>
<td>59 ± 4</td>
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<td>1.3 ± 4.6</td>
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Figure 7: $^{210}$Pb data for Lake Nyamogusingiri Basin. (A) $^{210}$Pb chronology from Nyamogusingiri Basin (using linear extrapolation between dated horizons (filled circles). Fallout radionuclides in the Nyamogusingiri Basin core showing (B) total and supported $^{210}$Pb and (C) unsupported $^{210}$Pb.
Figure 8  Calculated flux data for Nyamogusingiri Basin. (A) Stacked organic and carbonate percentages versus core depth, (B) dry mass accumulation rate (DMAR) calculated using the dry bulk density and $^{210}$Pb rates, (C) organic content displayed as flux (g cm$^{-2}$ yr$^{-1}$) and (D) minerogenic flux (g cm$^{-2}$ yr$^{-1}$). Graphs (B-D) are plotted against calendar years AD.
the F index (average of 0.85). The diatom-inferred conductivity exhibits a number of excursions in this zone. At the beginning of this zone, the conductivity is c. 1000 μS cm\(^{-1}\) and drops sharply to 500 μS cm\(^{-1}\), most likely driven by the higher abundance of *Nitzschia gracilis*.

*Cyclotella meneghiniana* once again returns as the dominant species in zone NB-3 (30-10 cm; AD 1975-2002), firstly increasing to a maximum of 80% (25-28 cm) before declining towards the top of the zone (to a minimum of 40%). Many of the species that were present in the earlier zones no longer have a significant presence. Rather, the record sees the appearance of a number epiphytic and benthic taxa, including *Sellaphora pupula*, *Gomphonema pumilum* and *Gomphonema gracile* (all <5%). A number of other species increase in abundance through this zone, notably *Encyonema muelleri* and *Nitzschia amphibia*. The preservation during this period is poor (F index of 0.5). Diatom-inferred conductivity holds steady at 600 μS cm\(^{-1}\).

The most recent zone (NB-4, 10-0 cm; AD 2002-2007) sees a decline in *Cyclotella meneghiniana* to abundances <5%, the lowest in the entire record. The dominant species in this zone is *Nitzschia palea* (30%). Many of the taxa that increase in abundance are epiphytic species, such as *Gomphonema gracile* and *Nitzschia amphibia*. It is in this zone that *Cymatopleura solea*, *Synedra ulna*, *Encyonopsis microcephala* and *Achnanthidium minutissimum* occur for the first time. As in the previous zone, the conductivity remains at c. 600 μS cm\(^{-1}\), falling to 570 μS cm\(^{-1}\) in the top sample (which closely matches the modern measurement of 550 μS cm\(^{-1}\)).

6. Discussion

### 6.1 Coherence of lake signals

Climate and environmental (e.g. catchment) changes are external drivers of lake dynamics; however uniform changes in climate across a region can produce a variety of responses in lake ecosystems. This is primarily due to the way in which these different ecosystems filter these signals and alter their expression (Magnuson et al., 2004). Understanding the temporal coherence of lakes at various spatial scales will provide insight into the factors influencing lake dynamics.

Sediments from a range of lakes in the landscape provides an ideal set of temporal and spatial scales to study climate change and lake ecosystems (Magnuson et al., 2004). The ability simultaneously to understand time (such as long-term dynamics) and space (a number of lakes with differing characteristics across a landscape) is becoming increasingly important in (palaeo)limnological studies. This is a particularly pertinent approach when realising that not all lakes respond to external (e.g. climate) forcing in a similar way. Whilst climate change has been shown in the broadest sense to manifest as general trends across regions and continents (and beyond), these are only really apparent and addressed in long-term (e.g. millennial) studies of lake sediments; the dynamics controlling a lake’s response can often overlooked (Magnuson et al., 2004).

The sedimentary records from all lakes highlight several differences in their functioning, which might be expected given the range of lake and catchment morphologies, size and most likely differing land use histories (e.g. Magnuson et al., 2004; Ssemmanda et al., 2005; Ryves et al., 2011). However, despite this, there are several commonalities between the lakes in terms of the diatom assemblage zones. Most of the lakes differ in their diatom assemblages and response, yet independent zoning of the diagrams shows several, significant and regionally important time zones (Figure 10).
Nyamogusingiri Basin

Figure 9a  Diatom stratigraphy from Nyamogisingiri Basin. All species > 3% in any one sample are displayed. The diatom taxa have been ordered according to their weighted average abundance in the core (descending) and are split into assemblage zones NB-1-4. The ratio of testate amoeba scales to diatoms are displayed alongside the diatom preservation index (F index), diatom concentrations and the axis 1 sample scores from Detrended Correspondence Analaysis (DCA). Reconstructed conductivities are based on the crater lake transfer function (Mills & Ryves, in review), a lowess smoother has been added to the reconstruction.
Figure 9b  Diatom stratigraphy from Nyamogisingiri Basin. All species > 3% in any one sample are displayed. The diatom taxa have been ordered according to their weighted average abundance in the core (descending) and are split into assemblage zones NB-1-4. The ratio of testate amoebae scales to diatoms are displayed alongside the diatom preservation index (F index), diatom concentrations and the axis 1 sample scores from Detrended Correspondence Analysis (DCA). Reconstructed conductivities are based on the crater lake transfer function (Mills & Ryves, in review), a lowess smoother has been added to the reconstruction.
The reason for the variation in system responses to shared external forcing almost certainly arises from the complexity of lake ecosystems in their response to these drivers. For example, a model presented by Magnuson et al. (2004) suggests that lakes have several levels of filters that allow them to respond uniquely (Figure 11). A lake’s response to external forcing is governed by factors such as its morphometry, chemistry, local hydrology (e.g. groundwater) and ecology. The model outlined by Magnuson et al. (2004) suggests that lakes may amplify, attenuate, delay or extend the climate signal.

6.2 Core trajectories

One approach for trying to unravel changes in the diatom records through time is to compare the diatom responses from the lake cores directly to the surface sediments and selected environmental variables used in the Ugandan diatom transfer function (Mills and Ryves, in review). A canonical correspondence analysis (CCA) with forward selection was used to define which environmental variables influenced the diatom distributions and abundances in the modern calibration data set. The statistically significant environmental variables $p \leq 0.05$ (with Bonferroni adjustments) that were included were depth, conductivity and total nitrogen (Mills, 2009). The down-core diatom samples were then fitted as passive samples into the CCA ordination space (Velle et al., 2005). Figure 12 shows the results of this ordination, illustrating the time-trajectories from the two sediment cores (B, bottom; T, top) in an attempt to try and assess the long-term patterns in the development of the fossil assemblages with reference to the diatom–environmental relationships in the modern calibration set. This technique can help to identify which environmental variables have influenced the down-core diatom assemblages through time (Birks et al., 1990).

The results indicate that Lakes Kyogo and Nyamugusingi Basin have responded in a different manner over time. Nyamugusingi Basin clearly oscillates along the total nitrogen variable, with the mid section of the core related to elevated nitrogen levels in the system which are most likely driven by the presence of Nitzschia palea, a nitrogen heterotroph, a species which under increasing levels of phosphorus (which is not limiting nutrient in many Ugandan lakes; Mills 2009) can fix its own nitrogen. The Basin shows a decline in total nitrogen towards the top of the core, which has a measured total nitrogen value of 245 $\mu$g L$^{-1}$, which is a low value when compared to other lakes in the region (e.g. Lake Nyamirima total nitrogen value of 203 $\mu$g L$^{-1}$).

Lake Kyogo seems to exhibit minor changes in conductivity, and perhaps depth to some extent, through time. Lake Kyogo is located at the fresher end of the conductivity scale throughout the last 150 years. The apparent fluctuations in ‘depth’ at Lake Kyogo may also be linked to changes in the clarity/turbidity of the water column, and changes are likely driven by the fluctuating abundances of benthic and epiphytic diatoms species, which may increase in abundance either as a result of increasing clarity in the water column, or via the inwash of littoral sediments as a result of catchment disturbance.

6.3 Cultural and Environmental Changes

As part of this research, the general trends in the sediment flux data from a single core in each lake basin were reconstructed. These core data can provide an integrated record of sediment accumulation (Anderson, 1990a; 1990b). The accumulation of sediments in a lake basin is often highly heterogeneous, due to the variability of depositional processes both spatially and temporally
Figure 10  Schematic diagram comparing the age of statistically significant zones between the two short core sequences: Lake Kyogo and Nyamogusingiri Basin.
Figure 11 Diagram illustrating possible responses of a lake system to an environmental driver (X; e.g. climatic perturbation, catchment disturbance etc). The various lake filters would modify the strength and timing of the lake response to that environmental driver. (Redrawn from Magnuson et al. [2004]).
(Davis, 1976; Dearing et al., 1981; Davis and Ford, 1982; Anderson, 1990a; 1900b). Sediment distribution is affected by a number of factors including: topography, shelter and limnological processes that can be influenced by climate (e.g. the process of stratification; Anderson, 1990a). In many cases, accurate and precise chronologies are rare (especially when based on $^{14}$C dates). In addition, the reconstruction of trends in the sediment data is more useful, especially when using accumulation rates from a single long core (Dearing, 1994).

A significant and large change in the diatom and sedimentary data is observed in all lakes after AD 1970 and throughout the twentieth century. In terms of the diatom records, in all lakes there is a declining trend in the number of planktonic species (and an increase in the abundance of diatoms with a preference for benthic habitat (or those that are facultatively planktonic). The sedimentary records all record an increase in the dry mass accumulation and hence an inferred increase in the amount of organic and minerogenic material being delivered to the lake system.

All of the core analyses exhibit an increase in the sediment flux over successive time zones, reaching a maximum between AD 1930 and AD 1990, and a declining to a surface minimum. Although high, these accumulation rates can perhaps be considered estimates and whole basin fluxes (using multiple cores) would need to be calculated to understand the sediment fluxes to the lake and changes in sediment focusing over time (Anderson, 1990b). However, the increases in sediment flux in most lakes manifest as a double peak (Figure 5; Lake Kyogo, the record from Nyamugusingiri is too short to record this change. The record from Kyogo matches many more from the region [Mills, 2009]). This is a signature seen in many other lakes around the world affected by human intervention; the occurrence of sediment pulses may indicate substantial environmental impact during initial settlement stages, with the first peak related to the removal of catchment vegetation, and the second related to the onset of agriculture (cf. Oldfield et al., 1980; Fisher et al., 2003; Anselmetti et al., 2007). Marchant et al. (1997) observed substantial wet-season erosion of sediments from forested hillsides around Mubwindi Swamp. The destabilisation of these slopes as a result of vegetation removal, either naturally (fire) or more recently as a result of anthropogenic clearance for agriculture, would lead to the exacerbation of this erosion, especially at times of enhanced precipitation (Marchant et al., 1997).

Catchment disturbance in western Uganda during the last 150 years may be attributed to the exploitation of resources during the early colonial period and the influx of people to the west of Uganda following the onset of political instability (Taylor and Robertshaw, 2001). The impact of human activity on lake catchments over the last 200 years has been highlighted by a number of other studies outside Africa. For example, research on Frains Lake in Michigan, illustrated the erosional impact of catchment vegetation clearance from AD 1800 (Davis, 1976). The clearance of catchment woodland caused increases in erosion rates to almost 80-times the pre-settlement rates (Davis, 1976). However, there are few studies based on sediment flux from the tropics (Deevey et al., 1979; Dearing, 1994; Anselmetti et al., 2007), thus the results presented here are amongst the first data from tropical East Africa relating to sediment yields over this time period.

In many of these lake records, the evidence for catchment disturbance occurs as an increase in the input of sediments to the lake system (Oldfield et al., 1980; Worsley and Oldfield, 1988). The disturbance in these lakes often falls into two discrete periods separated by a period of relatively low impact. In most cases, the first period of disturbance is related to initial forest clearance which increases sediment influx to lakes. The latter period of increased sedimentation rates is likely a result of an increase in the intensification of cultivation (Worsley and Oldfield, 1988; Deevey et al., 1979;
Figure 12 Trajectories for the core samples. (A) CCA of surface-sediment diatom samples and the 3 forward-selected variables (Mills & Ryves, in review). (B) Core trajectories from Lake Kyogo and Nyamogusingiri Basin. Core samples are plotted as passive samples over the surface-sediment CCA. T and B indicate the top and Bottom core samples.
Anselmetti et al., 2007). These patterns are mirrored in the Lake Kyogo record (Figure 5) with peaks in AD 1920 and AD 1940.

The increase in the delivery of sediments to the lake systems is also likely to have caused an increase in the amount of nutrients delivered to the lake system. Increasing nutrients can lead to the deterioration of lake water quality, largely through eutrophication. Many lakes in the developing world are experiencing eutrophication, salinisation and pollution as a consequence of increasing human pressure, and problems with surface water quality is one of the twentieth century’s largest and most widespread environmental problems (Smith, 1998; Dong et al., 2008).

Cultural eutrophication of lake waters occurs as result of human activity within the lake’s catchment that increases the nutrient input to the aquatic ecosystem, which can in turn increase algal productivity and can lead to water quality issues and deep water anoxia (Smith, 1998; Ekdahl et al., 2004). Whilst many studies have shown that early societies have modified catchments (e.g. removal of vegetation for agricultural purposes) and therefore water chemistries of lakes in Europe (Fritz, 1989; Renberg et al., 1993; Bradshaw et al., 2005), tropical America (Deevey et al., 1979; Anselmetti et al., 2007) and North America (Ekdahl et al., 2004), the study of human impacts of lacustrine ecosystems and the onset of cultural eutrophication in East Africa, has been limited to the larger lakes, such as lake Victoria (Hecky, 1993; Verschuren et al., 2002) and Malawi (Hecky, 2000; Puchniak et al., 2005). The only exception to this is a comparative study of data over a 30-year span (1971-2000) at Lake Saaka, near Fort Portal, which suggested that eutrophication had occurred over the time period in question. Although this study was based on one dataset collected in 1971 (Melack, 1978) and compared to data collected during monthly monitoring between 1995 and 1998, it indicated that the lake had been undergoing cultural eutrophication since the 1970s. This eutrophication was attributed the enlargement of a prison farm and agricultural expansion on the flanks of the crater as well as the introduction of Nile perch in the 1970s which would have caused alterations to the food web, leading to the observed increase in trophic state (Lates niloticus; Goldschmidt et al., 1993; Crisman et al., 2001).

7. Summary

- Two short (44-46 cm) sediment cores spanning the last c. 150 years were retrieved from lakes across a landscape (contrasting catchment types of pristine to impacted) in western Uganda.
- Multiproxy analyses (\(^{210}\)Pb, organic content and diatoms) were completed on the two core sequences.
- Whilst both lakes differ in their overall diatom species composition and their response to both external and internal factors, they do share some common features.
- The ‘pristine’ Lake Kyogo, reveals very little variation in its diatom assemblage since AD 1870 due to the dominance of a single species (Eunotia pectinalis), however a switch in the assemblage occurs c. AD 1955 (24 cm). Conversely, ‘impacted’ Nyamugasiringi Basin indicates significant shifts in the diatom species assemblages over the last c. 50 years, with a change in habitat from a planktonic to a benthic dominated system.
- Many of these major changes in the diatom flora are coincident with an increase in the delivery of sediment to the lake system.
- The sedimentary records the two lakes demonstrate an increase in sediment flux to the lakes in the last 50-100 years. This similar response across all lakes suggests that a regional driver is
responsible for the observed recent changes in the record, perhaps related to the onset of human activity, overprinted on known regional climatic fluctuations.

References


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