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CLIMATIC AND ANTHROPOGENIC IMPACTS ON AFRICAN ECOSYSTEMS
"CLANIMAE"

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ENERGY
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FINAL REPORT PHASE 1

CLIMATIC AND ANTHROPOGENIC IMPACTS ON AFRICAN ECOSYSTEMS
"CLANIMAE"

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ACRONYMS, ABBREVIATIONS AND UNITS

AD	Anno Domini (years after the birth of Jesus Christ)
BP	Before present (years before AD 1950)
CA	Correspondence Analysis, a common technique in multivariate statistics
Chl a	chlorophyll a, photosynthetic pigment molecule present in most plants and algae
CTD	electronic multisensor probe continuously recording Conductivity, Temperature & Depth
diatom	unicellular or colony-forming alga of the Bacillariophyceae
DIN	Dissolved Inorganic Nitrogen (nitrogen-containing ions available for uptake by biota)
DIVERSITAS	international programme of biodiversity science
DO	Dissolved Oxygen (in lake water)
DSi	Dissolved Si (in lake water)
ESF	European Science Foundation
ESSP	Earth System Science Partnership, coalition of the international environmental-change research programmes DIVERSITAS, IGBP, IHDP and WCRP
GLP	Global Land Programme (an ESSP research programme)
HITE	Human Impacts on Terrestrial Ecosystems (an IGBP-PAGES research programme)
HPLC	High-Performance Liquid Chromatography
ICP-AES	Inductively-Coupled Plasma Atomic Emission Spectrometry
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on global environmental change
IPCC	Intergovernmental Panel on Climate Change
LIMPACS	Human Impacts on Lake Ecosystems (an IGBP-PAGES research programme)
LUCC	Land Use & Land Cover Change (a joint IGBP-IHDP research programme)
LUCIFS	Land Use and Climate Impacts on Fluvial Systems (an IGBP-PAGES research programme)
MC-ICP-MS	Multi-Collector Inductively-Coupled Plasma Mass Spectrometry
PAGES	Past Global Change (an IPCC core research programme)
PEA	Potential Energy Anomaly, a measure of the energy needed to mix the medium
PHAROS	Past Human-Climate-Ecological Interactions (an IGBP-PAGES research programme)
Proxy	an indicator for a climate or ecosystem component preserved in a natural archive
R^2	correlation coefficient
SD	Secchi Disk transparency of the water column
SRP	Soluble Reactive Phosphate (dissolved phosphorus-containing ions available for uptake)
TLi	index for lake trophic status, here defined as Chla/SD
TN	Total Nitrogen (in dissolved and particulate phases, including living biota)
TP	Total Phosphorus (in dissolved and particulate phases, including living biota)
WCRP	World Climate Research Programme
$\delta^{18}O$, $\delta^{30}Si$	ratio of a rare isotope to the most common isotope of resp. oxygen (O) and silicon (S)

SUMMARY

Project background and objectives

The magnitude and geographic reach of human impact on Earth's biosphere has increased rapidly over the last 100 years, in particular in equatorial East Africa where rates of population growth and the intensification of agriculture are among the highest in the world, and where developing economies strongly depend on water and other goods and services provided by natural ecosystems. Economic development with conservation of biodiversity and ecosystem functioning requires spatially and temporally explicit knowledge of the timing and relative magnitude of ancient and modern human impact on terrestrial and aquatic ecosystems to 1) evaluate the current health of ecosystems and their resilience to anthropogenic impact, 2) model the range of their possible responses to future climate change, and from these 3) develop locally optimal strategies for land and water-resource management. CLANIMAE responds to the urgent need of a correct long-term perspective to today's climate-environment-human interactions, by producing simultaneous reconstructions of both past climatic variability and the history of vegetation and water-quality changes through multi-disciplinary analyses of dated lake-sediment records. The integrated paleoecological research method of this project addresses the question of past climate-environment-human relationships at the time scale at which the relevant processes have actually occurred. This allows us to 1) separate the influences of natural climate variability and human activity on East African terrestrial ecosystems, 2) determine the exact timing and relative magnitude of indigenous (pre-20th century) anthropogenic land clearance compared to recent landscape alteration, and 3) determine the severity of lake water-quality losses due to siltation and excess nutrient input directly linked to deforestation and agriculture, compared to those associated with natural long-term hydrological change.

Project results in relation to the work plan

CLANIMAE activities are organized in 14 tasks grouped in 5 work packages dealing with 1) proxy-indicator calibration and validation; 2) reconstruction of past climate variation; 3) reconstruction of terrestrial ecosystem changes; 4) reconstruction of historical water-quality changes; and 5) data integration and causal attribution of past environmental change. A major part of phase 1 activities were concerned with **work package 1**, through comparative study of diverse crater lake ecosystems in western Uganda. We completed 4 field campaigns (Jan-Feb 2007, July-Aug 2007, Feb 2008, Aug-Sept 2008), during which we surveyed a total of 66 lakes. In all lakes we collected basin-morphometric, land use, transparency, and lake trophic status data; samples for analyses of water chemistry, nutrients and aquatic biota (phytoplankton, zooplankton, zoobenthos); and an intact surface-sediment sample for calibration of diverse paleoecological proxies in relation to modern-day environmental gradients and the intensity of human activity within lakes' catchments. For data compatibility, all phase 1 fieldwork surveyed dry-season conditions. To assess seasonal variation in lake function we installed chains of surface- and deepwater temperature loggers in 9 lakes, which by August 2008 had logged 12 or 18 contiguous months of data. Final data downloading in April 2010 will allow assessment of both seasonal and inter-annual variability.

We then selected 18 lakes to study (in Task 1.1) the respective influences of a lake's morphometry (relative depth), physical limnology (e.g., mixing regime) and nutrient budget (TN, TP, SRP, DIN) on its vulnerability to water quality loss when subjected to human exploitation of the surrounding landscape. This study includes CLANIMAE field data and all historical data from Ugandan crater lakes found in the literature or made available by previous workers. Using the trophic status index TLi, our 18 principal study lakes range from oligotrophic (4 lakes) over mesotrophic (10 lakes) and eutrophic (3 lakes) to hypertrophic (1 lake). Marked differences between the nutrient content of surface and deep water in deep (>30 m) lakes point to the importance of mixing-dependent nutrient regeneration from the hypolimnion for supporting lake productivity. Analysis of linked environmental data in the 66-lake dataset revealed significant negative exponential relationships between Secchi transparency and TP and between transparency and Chl *a*. This relationship allows rough estimation of TP or Chl a

in Uganda crater lakes based on Secchi data. There was no significant correlation between transparency and dissolved inorganic nitrogen (DIN). Uganda crater lakes little impacted by human activity tend to be oligotrophic when their depth >90 m, and mesotrophic when their depth <90 m. Lakes with clear anthropic impact can be classified as oligotrophic (depth >90 m), mesotrophic (35 < depth <90 m), or eutrophic/hypertrophic (depth <35 m). Significant land use within a crater basin is likely to raise the trophic level of lakes shallower than ~35 m, whereas very deep lakes remain relatively unaffected. Most probably their important hypolimnia act as a storage for nutrients, and the low frequency of complete lake mixing does not allow much recycling of those nutrients into the surface water where primary production takes place. Our data support the hypothesis that all fresh Uganda crater lakes probably mix completely at least occasionally. Meteorological conditions allowing the mixing of deep lakes (cold air temperature and windy conditions) can be relatively rare, with a frequency of decades for the deepest lakes; these lakes are oligomictic, i.e. circulating less than once a year. Finally, preliminary evaluation of all available historical and recent water-column temperature profiles indicates apparent deep-water warming in the Uganda crater lakes (of a range comparable to that observed in Lake Tanganyika), superimposed on inter-annual variability reflecting notable warmer (e.g., 2002) and colder (e.g., 2007-2008) years.

In Task 1.2, CLANIMAE aims to develop the first diatom-based inference model for past changes in the primary productivity (trophic status) of African lakes. During phase 1, we calibrated diatom species distribution along a wide productivity gradient (measured as TP, TN, dissolved Si, Secchi transparency, Chl *a*) in 48 Uganda crater lakes, through analysis of fossil diatom assemblages in recently deposited surface sediments. Development of this African diatom-based productivity inference model is complicated by the apparent scarcity of diatoms in the living phytoplankton of most Ugandan crater lakes, much of the algal productivity being contributed by other groups (cyanobacteria, desmids, other green algae, etc.). Paired data on total phytoplankton community composition, obtained by HPLC analysis of live algal pigments, discerned associations between individual diatom species (recorded in surface sediments) and prominent types of African phytoplankton community. For the core group of 18 CLANIMAE study lakes the HPLC data were calibrated using semi-quantitative cell counting in preserved phytoplankton samples. Apparent scarcity of diatoms can also be a seasonal phenomenon. Development of the diatom-TP inference model was postponed to phase 2 of the project, pending better understanding of seasonal diatom community dynamics in Ugandan crater lakes based on collections made during the main wet season in April 2009.

Task 1.3 studies environmental controls on the distribution of aquatic macrophyte species in Ugandan crater lakes, similarly to explore their value as environmental indicators in paleoecological reconstructions. Our now completed dataset includes a total of 216 sampling sites (survey plots) in 36 lakes, where a total of 140 terrestrial, semi-aquatic and aquatic plant species were identified from the shoreline to the open water. Individual plant species differ from each other in their habitat requirements, reflected in distinct ranges of distribution in relation to 13 relevant physical and chemical characteristics of their (semi)-aquatic habitat. Clustering analysis revealed 8 major ecological communities (groups), each with particular indicator species. We stress that these plant communities are part of a continuum. ANOVA tests showed significant differences among ecological groups for depth, distance from shore, turbidity, temperature, conductivity and dissolved oxygen. These 8 aquatic macrophyte communities are also distinct in correspondence analysis, with CA axes 1 and 2 together explaining 35% of floristic variability among sampling plots. Between lakes, only pH and TN are significant environmental predictors of aquatic macrophyte distribution.

Task 1.4 and Task 1.5 aim to develop the δ^{30}Si signature of fossil diatom opal as a novel geochemical proxy for paleo-environmental reconstruction, using MC-ICP-MS equipment. During phase 1 we made two important steps to reach this objective. First, the Nu MC-ICP-MS at MRAC (partner 2) was upgraded with an adjustable entrance slit, a stronger primary pump and newly designed sampler and skimmer cones. These settings, combined with the use of collector slits, allowed an isotopic resolution sufficient to overcome interference of ^{14}N^{16}O and ^{14}N$_2$ with the ^{30}Si and ^{28}Si peaks, thus enabling more accurate measurement of both δ^{30}Si and δ^{29}Si. Second, we gathered linked data on DSi concentration, temperature and diatom δ^{30}Si and δ^{18}O in the water column of 15 African lakes situated in climate zones with mild to strongly negative local water balance, and of two Ugandan crater lakes (one oligotrophic, one eutrophic) situated in landscapes with no or intense human impact. Both DSi and δ^{30}Si were found to be fairly homogenous with depth in the water column of these two lakes, a probable consequence of near-complete mixing in these relatively shallow lakes during or shortly before the sampling period. In the impacted lake Katinda, values of 22 ppm DSi and 2.50 ‰ δ^{30}Si may either indicate more important soil leaching and alteration due to deforestation and agriculture (clay formation is known to fractionate Si isotopes) or very high diatom productivity. Since high productivity in Lake Katinda in the sampling period was due mostly to cyanobacteria, data on diatom seasonality gathered in phase 2 may help to explain the observed patterns.

Work package 2 focused on reconstructing past climatic (moisture balance) variation in East Africa during recent millennia. It comprises two tasks, concerned respectively with the reconstructions themselves (Task 2.1) and with their dating (Task 2.2). Climate-proxy data sets from most principal CLANIMAE study sites were already available prior to the start of this project or became available during phase 1 through complementary PhD and MSc projects, and other collaborative projects. New lake-based climate reconstructions from crater lakes in western Uganda, Rift Valley lakes in central Kenya and Lake Challa in southeast Kenya (the latter courtesy of the ESF-EuroCLIMATE project CHALLACEA) confirm the general temporal and spatial patterns documented by published records of climate history over the East African Plateau. CLANIMAE invests significant effort and funds in accurate dating of the studied sediment records, to permit regional correlation of reconstructed climate anomalies between sites, both within East Africa and with other (tropical and temperate) regions (Task 4.1). Focused on Lake Wandakara and Katinda in Uganda, and Lake Challa in Kenya, this helped constrain the timing of pronounced climate change.

Work Package 3 focused on reconstructing past vegetation dynamics based on analysis of fossil pollen (Task 3.1) and phytoliths (Task 3.2). In the last decade, significant progress has been made in documenting the history of terrestrial vegetation dynamics in equatorial East Africa during the last 2-3000 years. However, assigning causation for the documented vegetation changes has often suffered from the difficulty to unambiguously differentiate between climatic and anthropogenic impacts on vegetation in fossil pollen records. CLANIMAE avoids this problem by producing fully coupled reconstructions of past climate, vegetation and water-quality change by extracting them from the same, well-dated and demonstrably high-quality lake-sediment records. In addition we calibrate the magnitude of terrestrial ecosystem response to climate change and human impact as recorded in fossil pollen data. This is done through parallel reconstruction of climate-driven lake-level change and long-term vegetation dynamics in two Ugandan crater lakes situated in a relatively pristine and an anthropogenically disturbed landscape, respectively. To date, CLANIMAE subcontracts produced reconstructions of vegetation history linked to four lake-sediment records: Simbi, Chibwera, Challa and Kanyamukali (partly completed). The Challa reconstruction covers the last 2700 years and can be directly related to the moisture-balance record produced by the CHALLACEA project. The ~800-year vegetation reconstruction for sub-humid western Kenya from Lake Simbi can be linked to the diatom-inferred Lake Victoria lake-level record. The Chibwera vegetation reconstruction for pristine savanna in the Rift Valley of western Uganda covers the last ~250 years, starting with lake desiccation resulting from severe late 18th-century drought. Contrary to the pollen data from Lake Simbi, where relatively modest vegetation response to past climate change is overprinted by strong signatures of human impact (first by pastoralists and later by agriculturalists), Chibwera pollen data indicate a clear dominance of climate-driven vegetation change in this pristine (or at least semi-natural) landscape. We found that even a few decades of mildly wetter weather (5-10% more rainfall), such as occurred during the early 20th century, can reduce grass pollen abundance almost by half (from 75% to 45%). The multiple-proxy Chibwera record further illustrates how solid independent data on climate-driven moisture-balance change can improve the information extracted from pollen data.

Some important African food staples such as banana (*Musa*) produce insufficient pollen to be recorded in pollen preparations, but can be traced by means of their fossil phytoliths. CLANIMAE validates fossil *Musa* phytoliths as paleoenvironmental indicator of banana cultivation by quantifying the relationship between *Musa* phytolith abundance in the surface sediments of 25 Ugandan crater lakes, and the relative cover of banana plantations in their catchments. This test uses February 2007 land-cover surveys which estimated the % land cover occupied by 6 types of natural vegetation, 16 types of cultivated crops or plantations, and 4 types of fallow agricultural land. To quantify the vulnerability of individual lakes to anthropogenic soil erosion and nutrient enrichment (see Task 1.1), these classifications were transformed into a human-impact index (Hi), the summed product of local land-cover fractions and a 'soil erosion susceptibility' factor specific to each type of natural and anthropogenic vegetation. The phytolith calibration study is ongoing: large samples must be scanned to achieve statistically meaningful results.

Work package 4 is concerned with the reconstruction of past water-quality changes. Task 4.1 involves applying our calibrated diatom/productivity relationship (Task 2.1) to fossil diatom assemblages extracted from our target sediment records. This report summarizes fossil-diatom data from Lake Chibwera, a method-validation site in western Uganda. This record shows no evidence of recently increasing productivity or water-quality loss, consistent with the undisturbed condition of savannah vegetation in Queen Elisabeth National Park.

In the absence of human impact, fossil remains of aquatic macrophytes in African lakes reflect episodes of low lake level. When natural vegetation in the catchment of a shallow lake is disturbed by human activity, the macrophytes suffer from reduced water clarity due to influx of eroded soil. Hence, combination of information from sedimentological, fossil diatom and plant macrofossil indicators allows to recognize natural climate-change effects on aquatic macrophyte abundance, and separate the effect of anthropogenic soil erosion on water transparency. Study of the stratigraphic distribution of aquatic macrophyte fossils in lake-sediment cores (Task 4.2) is mostly executed in phase 2 of the project.

Non-pollen palynomorph microfossils (NPPs) are extensively used as paleo-ecological indicators in Europe and North America, but prior to this project their value as such in tropical Africa had not been thoroughly explored. Task 4.3 is concerned with calibrating the ecological indicator value of African NPPs in relation to local landscape variables (vegetation, land use, erosion, burning practices) and lake characteristics (morphometry, productivity) through analysis of their distribution in the surface sediments of 25 Ugandan crater lakes, situated along a landscape gradient from naturally pristine to severely impacted by humans. Current vegetation cover and land use were mapped quantitatively (Task 3.2) and supplemented by population data on domestic herbivores. The NPP analysis has so far yielded 9038 fossils, of which 97% could be assigned to one of 256 distinct morphotypes belonging to spores and other remains of fungi, spores of ferns and mosses, various resting stages of aquatic algae, and microscopic animal remains. This high biodiversity coupled with restricted distribution among sites may indicate high ecological specificity of individual morphotypes; it also requires additional counting to reduce the probability of chance occurrences. Of the common NPP morphotypes, 18 can be assigned to a specific taxon. Comparison of NPP distribution patterns with environmental variables reveals that *Glomus* sp. (a mycorrhizal fungus living symbiotically in plant roots) is positively related to soil erosion from agricultural activity. Direct Gradient Analysis (RDA) of the distribution of 30 major terrestrial NPP morphotypes shows that the distribution of fungal types generally associated with human landscape disturbance indeed all have a significant correlation with environmental variables linked to local human land use, such as annual agriculture and presence of pasture.

In **work package 5**, mostly to be undertaken during phase 2 of the project, patterns of past climate and human impact are integrated in time and space. Studies integrating the effect of anthropogenic vegetation disturbance in East Africa over large regional scales indicate that large-scale stripping of natural vegetation started in the 1920s-1930s when completion of transport infrastructure allowed industrial-scale production of food crops for export. This is supported by CLANIMAE data from Lake Simbi, which show that the onset of sedentary agriculture in this region dates to the 1920s, and was quickly followed by eutrophication (inferred from the appearance of *Spirogyra*) due to enhanced nutrient inputs associated with soil erosion. CLANIMAE analysis of changes in the rate of sediment accumulation in Lake Naivasha (central Kenya) over the past 120 years shows that mineral sediment deposition is exceeding the natural variability associated with climate-driven lake-level change since the mid-1980s, pointing to loss of the vegetation which until then had limited soil erosion in the Malewa River drainage. The resulting lake-water turbidity already has a clear impact on algal and zooplankton communities, and possibly the local fisheries. Reconstruction of past water-balance and vegetation dynamics in this region indicates that significant agriculturalist impact dates back to the 17th century AD, possibly related to population increases following the introduction of maize. New CLANIMAE vegetation reconstructions from drier regions of Kenya do not show clear signatures of sedentary agriculture prior to the 20th century. The Simbi record does show tentative signatures of intensifying land use by pastoralists starting perhaps 600 to 800 years ago. In western Uganda, new CLANIMAE data support previous inferences of significant forest clearing by agriculturalists dating back 900-1000 years at least.

By July 2009 the CLANIMAE project produced 3 publications in print or in press and 7 participations at scientific symposia; we also exploited multiple opportunities of knowledge transfer to the specific stakeholder groups and the public. CLANIMAE data and ideas were featured in the inaugurating workshop for the PHAROS programme, which integrates the IGBP-PAGES programmes HITE, LUCIFS and LIMPACS into the overarching theme Past Human-Climate-Ecosystem Interactions, with links to the ESSP programmes IHDP, WCRP and DIVERSITAS.

Preliminary research conclusions and policy recommendations

1) The vulnerability of Uganda crater lakes to eutrophication and water-quality loss for a given intensity of human land use in the crater basin is strongly related to basin morphometry (most importantly lake depth) and the associated seasonal mixing regime. Lakes shallower than 35 m are highly vulnerable, lakes deeper than 90 m are relatively resistant to eutrophication. Shallow crater lakes are usually mesotrophic, not oligotrophic in their pristine condition.
2) Our study of relationships between the community composition of aquatic macrophytes, diatom algae, zooplankton and zoobenthos with relevant abiotic habitat characteristics across the full gradient of natural and anthropogenic environmental variability significantly increase understanding of how the environment controls the biology of Uganda crater lakes.
3) Our tests of quantitative relationships between assemblages of African plant phytoliths and fungal spores (buried in recently deposited surface sediments of lakes) and environmental parameters related to human impact constitute an important first step towards their rigorous use as paleoenvironmental proxies of ancient land use in the surrounding landscape.
4) We showed that it is possible to produce coherent paired reconstructions of long-term terrestrial and aquatic ecosystem dynamics from the sediment record of Uganda crater lakes with decadal to century-scale time resolution, the time scale most relevant to the history of human impact on the East African landscape, and its future.
5) Multiple-proxy reconstructions in validation lakes revealed major pollen signatures of terrestrial vegetation response to modest historical rainfall variability, and allowed to distinguish large natural variability in aquatic system dynamics from the lake’s response to human impact.
6) Although this raises the bar on identifying evidence of ancient human impact on the African landscape, a combination of pollen, plant phytolith, fungal spore, and biogeochemical analyses will eventually allow to discern such signals with considerable certainty.
7) Preliminary reconstructions of the environmental history of CLANIMAE target sites support the idea that significant human impact on the East African landscape (deforestation, crop cultivation) dates back to ~1000 AD in sub-humid western Uganda, and to ~1700 AD in central Kenya. Semi-arid environments reveal tentative signatures of land use by pastoralists dating back up to 600 years, but the more intense vegetation and soil disturbance typical of crop cultivation, and the resulting water-quality loss, appears limited to the last 70-80 years.

The CLANIMAE project executes priorities of the ‘Science for a Sustainable Development’ (SSD) programme, because it directly addresses an important unresolved research question with critical relevance to the interlinked environmental policy issues of 1) sustainable economic development, 2) managing scarce natural resources, 3) biodiversity conservation, 4) the adaptation of vulnerable communities to global change, and 5) a more humane globalisation. Among the phase 1 results mentioned above, those numbered 1, 4 and 7 are particularly relevant to policy development (by local stakeholders and their government) on water and land resources in tropical Africa.

1. INTRODUCTION

1.1 Context of the research

The magnitude and geographical reach of human impact on the Earth's biosphere has increased rapidly over the last 100-200 years, and rates attained in the last three decades are unprecedented (IGBP-LUCC, 2005). This has resulted in a critical situation of widespread biodiversity loss and ecological damage, which can only be countered by implementing targeted policies which successfully balance the needs of human populations with the space and resources available to them. To help marry the goal of sustainable development with meaningful conservation of natural ecosystems and biodiversity in a rapidly changing world, climate and natural-resource modelers urgently need both spatially and temporally explicit databases of historical land use at regional scales (Lambin & Geist 2001). Specifically, we critically need a long-term historical perspective to modern-day climate-environment-human interactions, in order to 1) properly evaluate the current health of regional ecosystems and their resilience to diverse anthropogenic disturbances, 2) model the range of potential ecosystem responses to future climate change and demographic pressures, and, based on this understanding, 3) develop sound local strategies for ecosystem management and biodiversity conservation. In other words, we need to document the exact timing (onset), trajectory (evolution), and relative magnitude of ancient and modern human impact on the natural environment in specific world regions (HITE, 2002). This is particularly the case for tropical East Africa, where increases in population and natural resource use are among the highest in the world (**Figure 1a**), and developing economies strongly depend on (often scarce) water resources and other goods and services provided by natural ecosystems (**Figure 2**). Although most climate models predict East African rainfall to increase rather than decrease in a greenhouse world (IPCC 2007), its beneficial effect will most likely be lost because large-scale forest clearance has compromised the recharge of aquifers which used to provide a buffer against episodes of prolonged drought (Fischer & Heilig 1997). Large-scale stripping of natural vegetation in both sub-humid and semi-arid African landscapes (**Figure 1b**) also contributed to massive soil erosion, devastating floods, and excess nutrient inputs to lakes and coastal marine habitat. These impacts seriously threaten the natural functioning of terrestrial and aquatic ecosystems, and thus also the services they provide to human society.

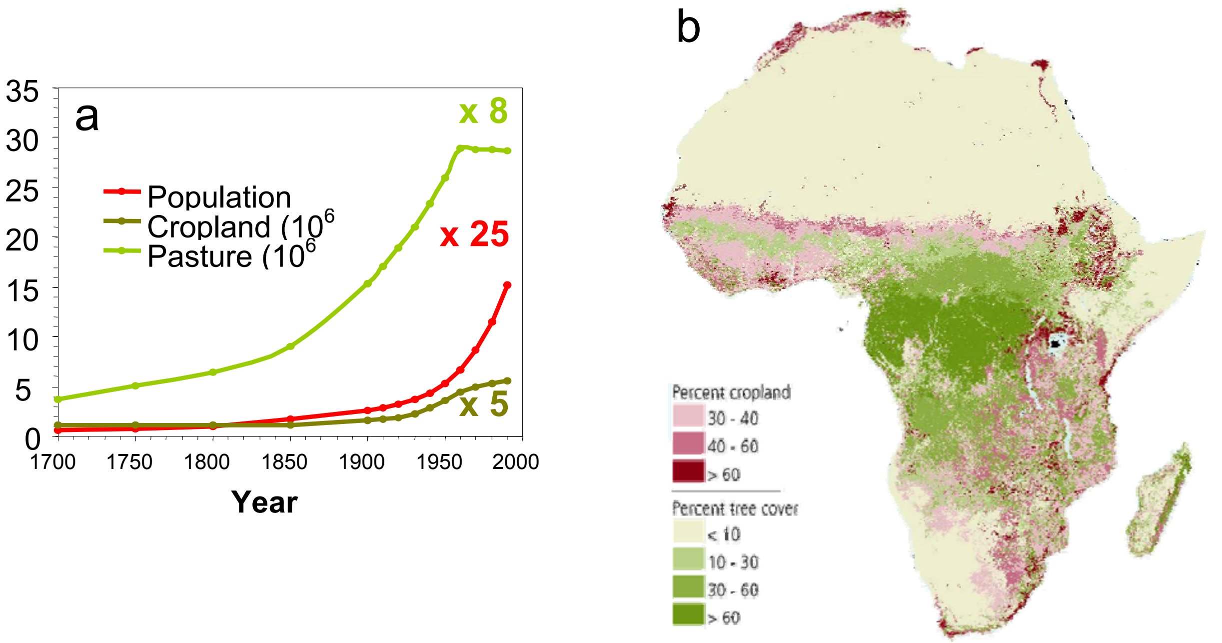

Figure 1. a. Cropland and rangeland (pasture) surface area in equatorial East Africa has multiplied over the past 200 years in proportion to population size, but in recent decades has reached a plateau indicative of limitation of as yet unexploited land in suitable climate regimes and soil condition. Based on data from Klein Goldewijk (2001). **b.** Human impact on the landscape in sub-Saharan Africa is most intensive in deciduous mosaic forest and grass or scrub savannah, located in sub-humid to semi-arid climate regimes.

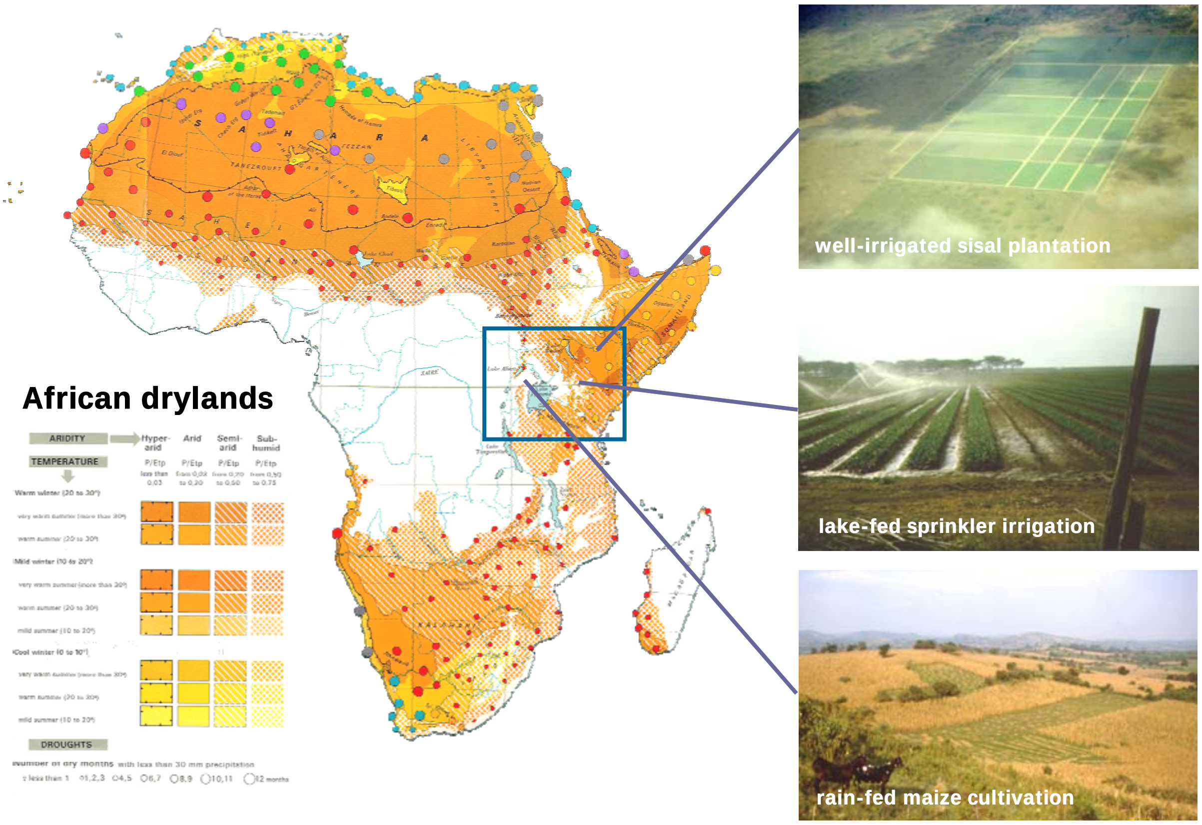

Figure 2. The west-to-east climate gradient across the CLANIMAE study area from a (sub-)humid climate regime in western Uganda to a semi-arid climate regime in eastern Kenya translates into a gradient of agricultural water-use practice, from rain-fed cultivation to irrigated cultivation using surface waters (lakes, rivers) to irrigated cultivation using wells pumping fossil groundwater.

1.2 Project objectives and expected outcomes

The principal objective of the CLANIMAE project is to produce a correct long-term perspective to today’s climate-environment-human interactions in tropical East Africa, through simultaneous high-resolution reconstruction of both past climatic variability and the history of vegetation and water-quality changes through multi-disciplinary analyses of dated lake-sediment records. Climate reconstructions will integrate available information on biological, geochemical and sedimentological proxy indicators of past changes in the water balance of study lakes. Reconstruction of past terrestrial vegetation dynamics will be executed within this project and based on analyses of fossil plant pollen and phytoliths in sediment records from lakes situated along the climatological gradient from (sub)humid western Uganda to semi-arid eastern Kenya. The evolution of water quality through time will be reconstructed using paleoecological analyses of fossil diatoms and aquatic macrophytes, following calibration of diatom and macrophyte species distribution against lake trophic status and turbidity in the modern-day regional lake gradient. Special attention will be given to the validation of silicon isotopes in diatom opal as proxy indicator for past primary productivity, and to the stratigraphy of fossil fungal spores associated with the excrements of large domestic animals as indicators of lake use by indigenous pastoralists.

The essential characteristic of this integrated paleoecological research project is that it addresses the question of past climate-environment-human relationships at the time scale at which the relevant processes have actually occurred. Therefore its principal outcomes will be the sound determination of 1) the separate influences of past natural climate variability and human activity on today’s East African terrestrial ecosystems, 2) the exact timing and relative magnitude of indigenous (pre-20th century) anthropogenic land clearance compared to the more recent landscape alteration, and 3) the severity of lake water-quality losses due to siltation and excess nutrient input resulting from deforestation and agriculture, compared to those associated with natural long-term hydrological change.

2. METHODOLOGY

2.1. The CLANIMAE strategy of integrated paleoecological research

Achieving CLANIMAE's scientific objectives requires an integrated paleoecological research method which includes 1) calibration of new paleo-environmental proxies along modern-day regional East African gradients of environmental variables sensitive to human impact; 2) validation of those and more traditional proxies in the time domain; 3) production of a significant number of new, multi-proxy paleoenvironmental reconstructions from key sites in equatorial East Africa; and 4) regional integration of these site-specific reconstructions to obtain a coherent regional assessment of the timing, magnitude and principal causes of past landscape and water-quality changes. Evidently, this project nor any other research investment can ever achieve a fully complete reconstruction of historical climate-environment-human interactions throughout East Africa at the local scale (i.e., all individual lakes and terrestrial ecotones). To achieve our research objectives, what is important is that 1) the network of selected study sites adequately captures regional gradients in climate (humid to semi-arid) and human impact (long-term versus relatively recent, severe versus benign) and 2) that data from all network sites are of comparable quality and information content. The above-mentioned project tasks are facilitated considerably by substantial previous work by partner 1 on the calibration and validation of climate proxies in African lakes, and (largely in-house, partner 1) availability of an increasingly substantial body of high-quality paleo-environmental reconstructions that are eminently useful for CLANIMAE objectives. Consequently, by filling a number of critical data and knowledge gaps, this project will enable optimal exploitation of those existing reconstruction methods and existing paleoenvironmental data sets. As described below, data production activities funded by this project focus on study lakes in the humid and sub-humid regions of western Uganda. All CLANIMAE fieldwork is conducted with research permission from the Uganda National Council for Science & Technology (UNCST permit NS21) and the Uganda Wildlife Authority (UWA permit TBDP/RES/50).

2.2. Project start-up

The first CLANIMAE field campaign (10/01/07-21/02/07) surveyed 57 crater lakes in western Uganda (33 lakes in the Kasenda-Fort Portal area; 24 lakes in the Kikorongo-Bunyaruguru area) to collect basic basin-morphometric, land use, transparency, and lake trophic status data; and to collect samples for analyses of water chemistry, nutrients and aquatic biodiversity (phytoplankton, zooplankton, zoobenthos). We further collected intact surface-sediment samples from a mid-lake location in each lake for the development or calibration of diverse paleo-environmental proxies in relation to modern-day gradients in ecological conditions and the intensity of human activity within the lakes' catchments. To account for possible trends in the preservation of environmental proxies down-core (and variable mud-volume requirements of each analysis), surface-sediment samples were partitioned in the increments 0-1, 1-3, and 3-5 cm sediment depth, and analyzed separately when needed (see, for example, under Task 1.2).

During this first field campaign we also installed chains of automatic temperature loggers in three lakes (Kasenda, Murabyo and Mirambi) to record seasonal patterns of water-column stratification, supplemented by air temperature loggers near these three lakes and three other locations in and near the Rift Valley. These loggers were first downloaded in August 2008 (yielding an initial 18 months of data) and will be downloaded again in April or May 2010 (yielding ~40 contiguous months of data in total).

3. PROJECT RESULTS IN RELATION TO THE WORKPLAN

CLANIMAE activities are organized in 14 tasks grouped in 5 work packages dealing with 1) proxy-indicator calibration and validation; 2) reconstruction of past climate variation; 3) reconstruction of terrestrial ecosystem changes; 4) reconstruction of historical water-quality changes; and 5) data integration and causal attribution of past environmental change.

3.1 Work Package 1: Proxy calibration and validation

Task 1.1 (partner 2, MRAC Tervuren): Basin-morphometric controls on the sensitivity of Ugandan crater lakes to water-quality loss resulting from human impact (*updated title*)

This task has been expanded into a comprehensive study of the relationship between basin morphometry, physical limnology (mixing regime) and a lake's vulnerability to water quality loss when subjected to human exploitation of the surrounding landscape. During phase 1 we completed four field campaigns (Jan-Feb 2007, July-Aug 2007, Feb 2008, Aug-Sept 2008; originally only two were planned for the first phase of this project), during which we surveyed 48 lakes. To document the seasonality of lake mixing regimes we installed thermistor chains (surface- and deepwater temperature loggers) in a total of nine study lakes (four planned originally), and we dedicated the August 2007 field campaign to combining water-column measurements of temperature, dissolved oxygen, conductivity, and pH with measurements of surface- and deep-water concentrations of essential nutrients (TN, TP, SRP, DIN) and algal biomass (Chl a) in 18 lakes spanning gradients of relative lake depth, mixing regime and land-use intensity.

Data collection and data processing. The second CLANIMAE field campaign (27/07/07-23/08/07) focused on a limnological survey of 18 Ugandan crater lakes along a gradient of relative depth (surface area 4-50 ha; depth between 8 and 156 m) and having drainage basins with contrasting levels of human impact, expressed by the anthropic index Ai (pristine (Ai = 0), cultivated surface <33% (Ai = 1), from 33 to 66% (Ai = 2) and >66% (Ai = 3). In all 18 lakes, we collected the following data and samples:

1) continuous profiles of temperature (°C), specific conductivity (K at 25°C), dissolved oxygen (mg/l) and pH throughout the water column, using *in situ* sensors (CTD19 SEABIRD);
2) Secchi-disk transparency (30 cm diameter) and turbidity (Hach 2100P turbidimeter);
3) Total phosphorus, phosphates, ammonium, nitrates, nitrites, silica, sulfate, hydrogen sulfide and chlorophyll a (~total algal biomass) at four depths in a mid-lake location and of surface water in a nearshore location (Hach DR 2800 field spectrophotometer). Except for TP determination, water was filtered using glass-fibre filters with 0.4 µm pore size; chlorophyll a was retained on Whatman GF-5 filters and extracted overnight with acetone before measurement;
4) Alkalinity and total hardness, by titration following Hach procedures ;
5) Information on the occurrence and frequency of fish kills and lake mixing events collected through interviews with local fishermen or lake-shore inhabitants.

In addition we installed thermistor chains, each consisting of four ONSET Tidbits v2 or VEMCO Minilog 12 temperature loggers, in five lakes (adding to the three chains installed in February 2007); at six sites these were complemented by air temperature loggers. All recorded temperature data will be downloaded during the fourth field campaign, planned for August 2008. As a control on nutrient determinations in the field, phosphate concentrations were also measured on one pelagic surface-water sample from each lake, using ICP-AES techniques upon return in Belgium.

New CTD probe data on water-column parameters were processed using SEABIRD software, with direct advice from SEABIRD company on data processing needed for lakes with strong anoxic profiles. The resulting collection of CLANIMAE field data (from all three field campaigns completed at this time) were added to and compared with the accumulating dataset of historical temperature, oxygen, transparency and algal productivity data from

Ugandan crater lakes (Verschuren et al., unpublished; this includes data previously collected by UGent (2000-2002), Dr. D. A. Livingstone (1994), Dr. L. Chapman (late 1990s) and scarce published data: Beadle, 1966; Melack 1978; Kizito et al., 1993; Chapman et al. 1998) to make a preliminary assessment of the seasonal mixing regime in individual lakes. These assessments were verified in August-September 2008 when 12-18 months of temperature logger data from 9 lakes were downloaded. To investigate lake thermic stability, the potential energy anomaly (PEA or Φ, in J m^{-3}) was calculated according to Simpson ***et al.*** (1982).

Results. The August 2007 field survey targeted the relatively dry and cold mixing season. We indeed found all relatively shallow lakes (<30 m max. depth) in a well-mixed stage, with virtually isothermal temperature profiles and rather uniform oxygen and nutrient concentrations at different depths. In four eutrophic shallow lakes (Nyungu, Lugembe, Saka and Katinda; **Table 1**), anoxic conditions extended to the lake surface at daytime. Considering their low PEA of ~0.1 J m^{-3}, this anoxia is probably due to a recent (partial) turnover of the water column allowing mixing of anoxic deep water. Deeper lakes were generally well stratified at this time (**Figure 3**), with strong gradients in physical (oxygen) and chemical characteristics (diverse nutrients) between the epilimnion and hypolimnion. Note that all 18 principal study lakes, including the ‘shallow’ lakes mentioned above, develop pronounced thermal and oxygen stratification during part of the year; our study excludes true shallow lakes (< 5-6 meter) of which the water column is mixed on a daily basis.

Lake	Max depth (m)	Turbidity (NTU)	NH4-N (mg/l)	NO3-N (mg/l)	NO2-N (mg/l)	DIN (mg/l)	SIO2 (mg/l)	Anoxic depth (m)	TP (mg P./l)	SD (m)	Chl a AV (µg/l)	Chl a surf. (µg/l)	TLI	AI	based on SD	based on av. chla	based on surf chla	based on SD and surf chla (Tli)
Nyungu	25	37.4	1.24	0.01	0.004	1.25	34.2	2.8	0.3	25	34.6	47.1	1.88	3	E	E	H	**H**
Lugembe	19	6.8	0.80	0.00	0.003	0.81	28.9	6.6	0.1	50	22.7	31.1	0.62	3	E	E	E	**E**
Saka	11	74.7	1.15	0.00	0.000	1.15	15.7	3.4	0.4	30		15.9	0.53	3	E		E	**E**
Katinda	17	23.3	0.58	0.01	0.001	0.59	56.2	3.0	0.1	70	20.0	22.9	0.33	3	E	E	E	**E**
Nyabikere	46	4.6	0.00	0.02	0.004	0.02	33.2	3.7		136		17.2	0.13	1	M		E	**M**
Nyahirya	84	6.5	0.70	0.03	0.013	0.74	92.9	7.3	0.1	125	12.5	13.6	0.11	2	M	E	E	**M**
Kasenda	13	6.5	0.43	0.02	0.005	0.45	54.9	6.4	0.0	84	10.3	8.0	0.09	2	M	M	M	**M**
Nkugute	58	3.3	0.58	0.01	0.004	0.59	1.5	12.8	0.1	145	7.6	12.7	0.09	3	M	E	E	**M**
Kyerbwato	13	1.5	0.17	0.02	0.002	0.19	22.7	9.0	0.4	174	13.1	13.1	0.08	1	M	E	E	**M**
Nyanswiga	61	3.8	0.29	0.02	0.005	0.31	21.1	4.0	0.2	150	13.6	9.9	0.07	3	M	M	M	**M**
Bugwagi	85	2.3	0.00	0.01	0.003	0.01	49.6	13.8	0.0	215	10.5	12.5	0.06	3	M	E	E	**M**
Karolero	15	2.3	0.00	0.01	0.005	0.02	22.9		0.1	210	10.5	11.5	0.05	0	M	M	M	**M**
Chiberwa	13	3.1	1.19	0.01	0.012	1.22	7.5	9.2	0.2	160	9.4	6.6	0.04	0	M	M	M	**M**
Kyanga	55	2.1	0.08	0.21	0.003	0.29	12.2	16.9	0.1	220		9.0	0.04	1	M		M	**M**
Mwengenyi	140	1.4	0.06	0.02	0.005	0.09	11.6	13.9	0.2	270	2.8	3.3	0.01	3	O	O	O	**O**
Kyaninga	135	0.9	0.12	0.03	0.001	0.15	24.9	36.0	0.1	470	4.3	5.2	0.01	1	O	O	O	**O**
Katanda	152	1.1	1.20	0.01	0.003	1.21	31.9	21.4	0.0	420	4.6	5.3	0.01	2	O	O	O	**O**
Mahuhura	154	0.6	0.49	0.04	0.014	0.54	59.9	36.0	0.2	635	6.1	8.4	0.01	2	O	M	M	**O**

Table 1. Nutrient concentrations and productivity-related parameters of 18 Uganda crater lakes surveyed during the 2nd CLANIMAE campaign, July-August 2007. Chl a AV: mean Chl a concentration of the mixed layer (water column above the thermocline); TLi: trophic level index = Chl a/SD; Ai: Index of anthropogenic impact on crater basin, from pristine (0) to fully under agriculture (3); Lake trophic status: H = hypertrophic, E = eutrophic, M = mesotrophic, O = oligotrophic. Compare with Figure 4.

Field and laboratory data related to lake primary production are presented in **Table 1**. Classification of lakes according to trophic status has been based on several criteria, most often Secchi disc transparency and chlorophyll a concentration. In addition the range boundaries between trophic categories (oligo-, meso-, eu- and hypertrophic) differ among authors (**Figure 4**, based on Carslon (1977), Forsberg et al. (1980) and Wetzel (1983)). Further, classification schemes developed for temperate-region lakes are not necessarily applicable to other regions (Castagnino, 1982; Huszar et al. 1998). For the Ugandan lakes we alternatively used chlorophyll a and secchi disk transparency (SD) as principal criterion, and also a trophic status index which is a combination of these two parameters (TLi = Chl a/SD).

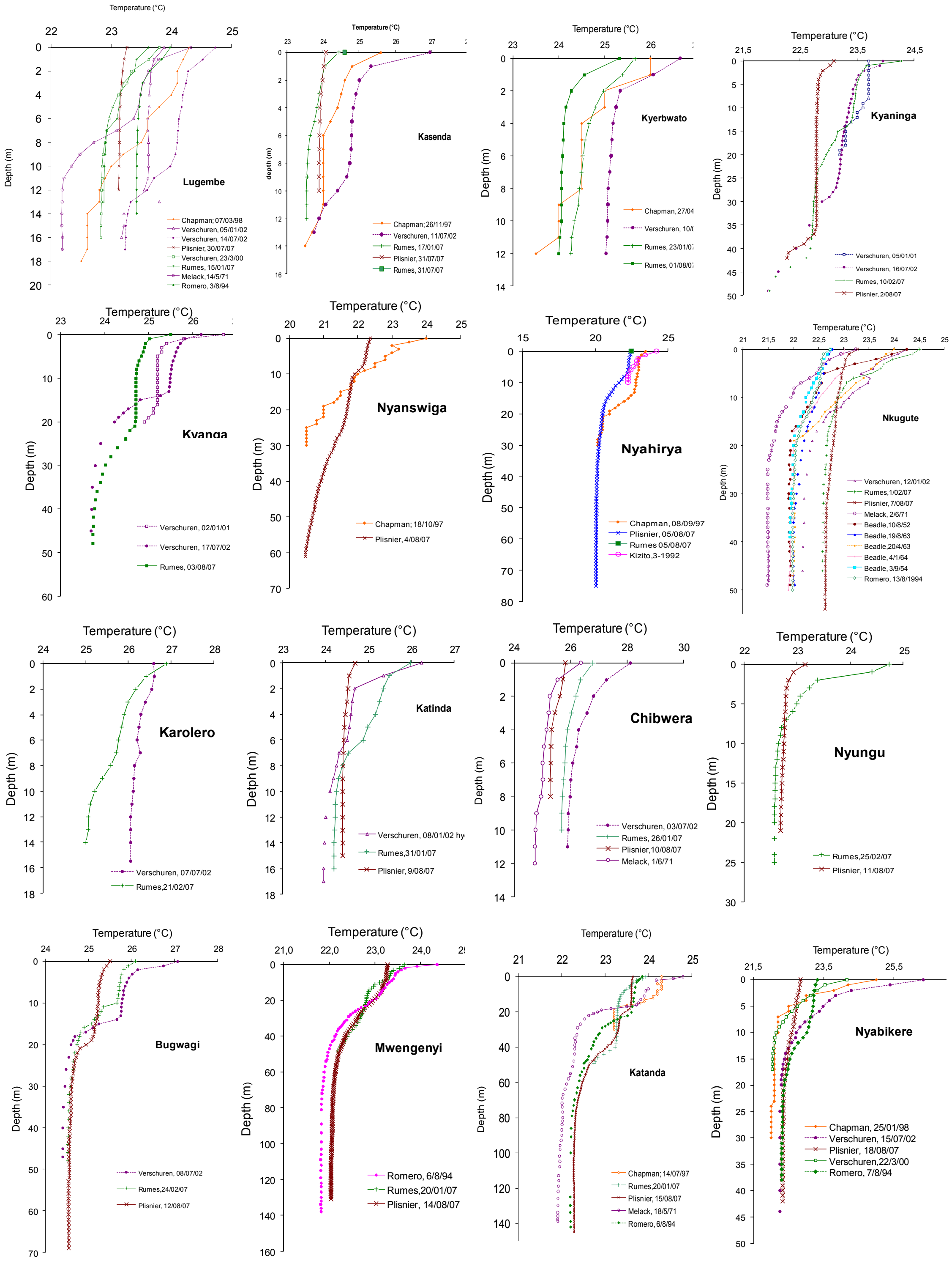

Figure 3. New (CLANIMAE) and existing water-column temperature profiles collected at various times of the year in 16 Uganda crater lakes.

Using this index the 18 surveyed lakes can be separated in four categories: oligotrophic (TLi < 0.025), mesotrophic (0.025 < TLi < 0.25) , eutrophic (0.25 < TLi < 1.5) and hypertrophic (TLi ≥ 1.5). The majority of surveyed lakes are mesotrophic; the four oligotrophic lakes are all deeper than 100 m, and one lake (Nyungu) is hypertrophic. For lakes observed to be stratified in August 2008 (with temperature difference between surface and deep waters often < 1 °C), marked differences between average nutrient concentrations in the epilimnion and hypolimnion (**Table 2**) point to the importance of the hypolimnion for nutrient storage, and the importance of nutrient regeneration from the hypolimnion for lake productivity.

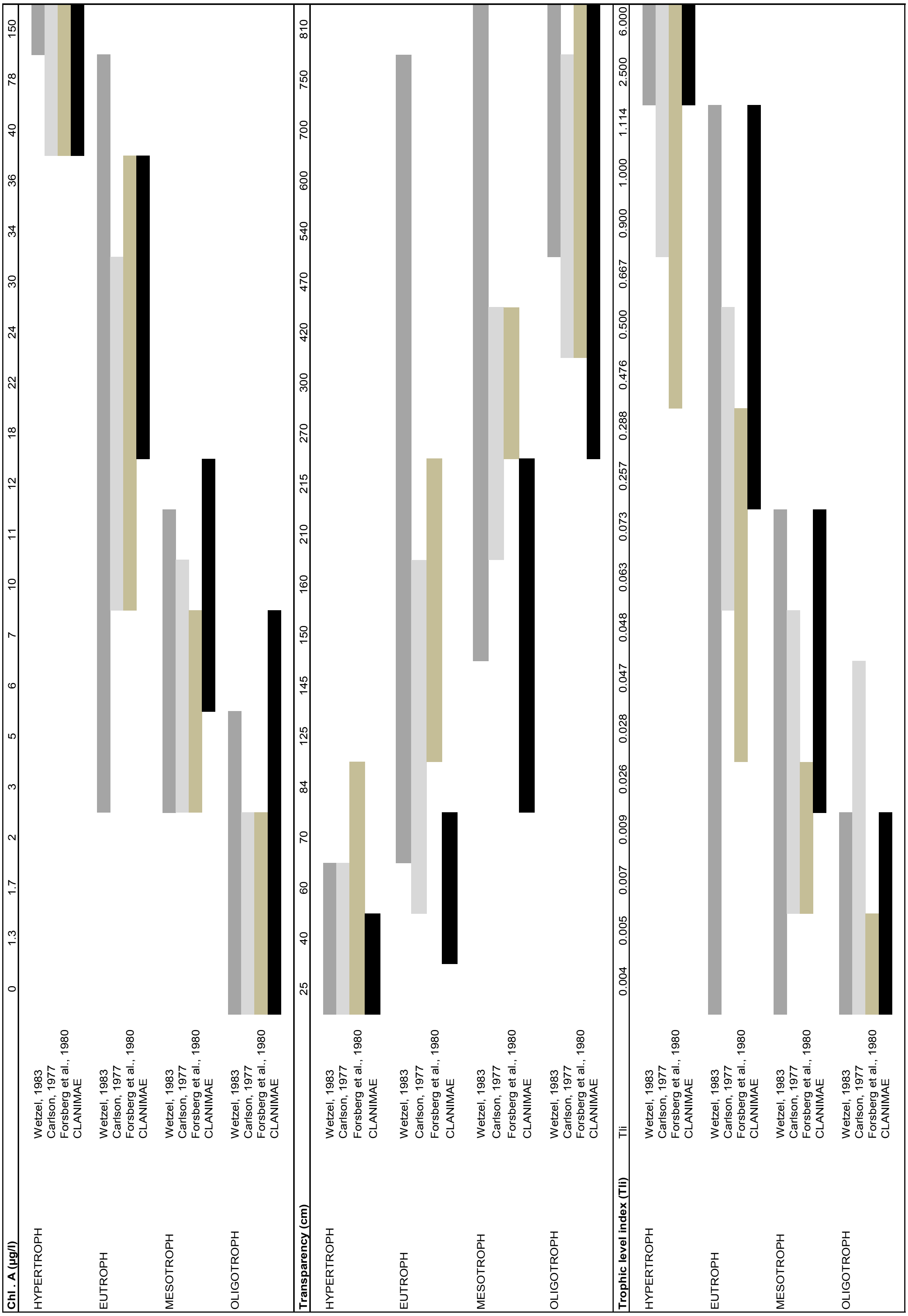

Figure 4. Range of chlorophyll a (µg/l), secchi disk (SD) transparency (cm) and trophic level index (TLi) measured in 18 Uganda crater lakes during July/August 2007 (arranged from left to tight in order of increasing TLi), with trophic status according to criteria used by Wetzel (1983), Carlson (1977) Forsberg et al. (1980) in temperate lakes, and the trophic status proposed by CLANIMAE. Compare with Table 1.

Lake	Date	Epi/Hypo	Depth	Turb,	TP (P)	NH4-N	NO3-N	NO2-N	DIN	SIO2	Chl a	T°	K25	DO	pH
				NTU	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*µg/l*	*°C*	*µS/cm*	*mg/l*	
Kyaninga	02-08-07	E	0 & 10 m	0.9	0.09	0.12	0.03	0.001	0.15	24.9	4.3	22.9	429	4.9	8.2
		H	25 & 56 m	9.8	0.26	1.46	0.02	0.002	1.48	38.2	4.2				
Nyanswiga	04-08-07	E	0 & 5 m	3.8	0.21	0.29	0.02	0.005	0.31	21.1	13.6	22.3	338	1.3	7.8
		H	12 & 35 m	2.4	1.24	9.36	0.02	0.003	9.38	28.0	13.2	21.5	400	0.0	6.9
Nyahirya	05-08-07	E	0 & 7 m	6.5	0.09	0.70	0.03	0.013	0.74	92.9	12.5	22.4	438	1.9	8.1
		H	20 & 75 m	36.2	1.81	12.35	0.03	0.015	12.40	61.5	5.5	20.3	929	0.0	6.7
Nkugute	07-08-07	E	0 & 8 m	3.3	0.06	0.58	0.01	0.004	0.59	1.5	7.6	23.1	123	2.2	7.6
		H	20 & 55 m	3.8	0.26	1.90	0.02	0.005	1.91	15.3	8.5	22.8	145	0.0	7.1
Nyungu	11-08-07	E	0, 4 & 10 m	37.4	0.25	1.24	0.01	0.004	1.25	34.2	34.6	22.9	524	0.3	8.4
		H	20 m	10.7	0.45	2.70	0.00	0.055	2.76	88.1	15.9	22.7	593	0.0	7.6
Bugwagi	12-08-07	E	0 & 7 m	2.3	0.05	0.00	0.01	0.003	0.01	49.6	10.5	25.4	455	4.9	8.7
		H	20 & 50 m	2.6	0.25	0.01	0.01	0.003	0.02	48.9	8.2	24.8	537	0.0	7.7
Mwengenyi	14-08-07	E	0 & 8 m	1.4	0.21	0.06	0.02	0.005	0.09	11.6	2.8	23.3	354	6.3	8.6
		H	25 & 50 m	4.2	0.81	2.56	0.02	0.007	2.58	16.5	3.0	22.5	443	0.0	7.4
Katanda	15-08-07	E	0 & 8 m	1.1	0.04	1.20	0.01	0.003	1.21	31.9	4.6	23.6	419	6.0	8.8
		H	25 & 50 m	1.7	0.44	4.03	0.01	0.005	4.04	47.7	4.2	23.0	494	0.0	7.7
Av.		**E**		**7.1**	**0.1**	**0.52**	**0.02**	**0.005**	**0.54**	**33.4**	**11.3**	**23.2**	**385**	**3.5**	**8.3**
		H		**8.9**	**0.7**	**4.29**	**0.01**	**0.012**	**4.32**	**43.0**	**7.8**	**22.5**	**506**	**0.0**	**7.3**
St.D.		*E*		*12.4*	*0.1*	*0.49*	*0.01*	*0.004*	*0.5*	*28.1*	*10.2*	*1.0*	*120.5*	*2.3*	*0.4*
		H		*11.5*	*0.6*	*4.28*	*0.01*	*0.018*	*4.3*	*24.4*	*4.6*	*1.4*	*235.5*	*0.0*	*0.4*

Table 2. Average values of nutrients and productivity-related parameters measured in the epilimion (E) and hypolimnion (H) of 8 deep stratified lakes during the 2nd CLANIMAE campaign, July-August 2007.

N obs		66	22	59	55	77	67	78	77	78	78	78	77	78	77	76	71	76	51	83
		SD (cm)	*Chla (µg/l)*	*PEA*	*AnoxD-Moy*	*Surf. Area A0 (ha)*	*Max depth Zm (m)*	*Mean Diam (m)*	*Max L (m)*	*ShorelineL (km)*	*L theor*	*Shor dev (L/Ltheor)*	*crater area A (Ha)*	*rim height max (m)*	*rim height min (m)*	*A/A0*	*Diam/Rim height*	*Max L/rim min*	*(Depth/(A/A0)*	*Alt (m)*
66	SD (cm)	1,00																		
22	Chla (µg/l)	**-0,54**	1,00																	
59	PEA	**0,43**	-0,30	1,00																
55	AnoxD-Moy	**0,90**	-0,44	**0,36**	1,00															
77	Surf. Area A0 (ha)	-0,24	0,13	-0,07	-0,12	1,00														
67	Max depth Zm (m)	**0,64**	-0,42	0,71	**0,61**	-0,18	1,00													
78	Mean Diam (m)	-0,25	0,17	-0,04	-0,08	**0,92**	-0,15	1,00												
77	Max L (m)	-0,20	0,15	-0,06	-0,02	**0,94**	-0,14	**0,95**	1,00											
78	ShorelineL (km)	-0,23	0,17	-0,07	-0,06	**0,95**	-0,14	**0,96**	**0,98**	1,00										
78	L theor	-0,22	0,16	-0,04	-0,04	**0,93**	-0,13	**1,00**	**0,95**	0,97	1,00									
78	Shor dev (L/Ltheor)	-0,13	0,11	-0,12	-0,03	**0,37**	-0,12	**0,35**	**0,50**	0,53	**0,35**	1,00								
77	crater area A (Ha)	-0,30	0,23	-0,06	-0,12	**0,91**	-0,23	**0,84**	**0,86**	0,85	**0,84**	**0,35**	1,00							
78	rim height max (m)	0,05	0,28	0,14	0,22	0,01	0,15	0,10	0,05	0,06	0,11	0,01	0,08	1,00						
77	rim height min (m)	0,04	-0,27	**0,39**	0,18	-0,09	0,14	-0,06	-0,08	-0,09	-0,05	-0,10	0,04	**0,64**	1,00					
76	A/A0	-0,18	0,03	0,00	-0,10	-0,14	-0,17	-0,27	-0,21	-0,22	-0,27	0,08	0,01	0,10	0,15	1,00				
71	Diam/Rim height	-0,16	-0,05	-0,08	-0,15	0,71	-0,15	**0,53**	**0,65**	0,59	**0,54**	0,24	**0,54**	-0,23	-0,14	-0,07	1,00			
76	Max L/rim min	-0,23	0,24	-0,18	-0,09	**0,57**	-0,26	**0,58**	**0,60**	0,63	**0,58**	**0,36**	**0,41**	-0,23	**-0,52**	-0,11	**0,33**	1,00		
51	(Depth/(A/A0)	**0,54**	-0,42	**0,62**	**0,59**	-0,07	**0,93**	0,03	0,03	0,02	0,06	-0,02	-0,07	0,18	0,23	-0,30	-0,13	-0,07	1,00	
83	Alt (m)	**0,49**	**-0,39**	0,21	0,32	-0,37	0,43	**-0,43**	**-0,32**	**-0,35**	**-0,43**	-0,03	**-0,47**	-0,12	-0,24	-0,16	-0,17	-0,07	**0,23**	1,00

Table 3. Pearson correlation coefficients for linear regressions between various limnological and topographic parameters of Uganda crater lakes, based on all available data (CLANIMAE and pre-existing). Topographic data derived from maps are available on 78 lakes in total; to date 66 lakes have been surveyed in the field.

Relations between lake morphometry and trophic status. Pearson correlation coefficients between environmental parameters of the Uganda crater lakes, based on pre-existing and new CLANIMAE data, are presented in **Table 3**. Our Uganda crater lake dataset includes a total of 83 lakes, if only by their geographical position and altitude. Basin-morphometric data derived from topographic maps are available on 78 lakes. To date, 66 lakes have been surveyed in the field; listed values for each lake (e.g., secchi-disk transparency) are averages if several measurements are available. The minimum number of observations (number of lakes with data) is 22, for Chlorophyll a. In this dataset we found significant negative exponential relationship both between secchi disk transparency and TP (R^2=0.47, 55 lakes; **Figure 5**) and between transparency and chl a (R^2=0.46, 22 lakes; **Figure 6**). This relationship allows rough estimation of TP or Chl a in Uganda crater lakes based on Secchi disk transparency. There was no significant correlation between transparency and dissolved inorganic nitrogen (DIN), previously documented to be highly fluctuant and not a good indicator of lake trophic status (Barrica, 1990).

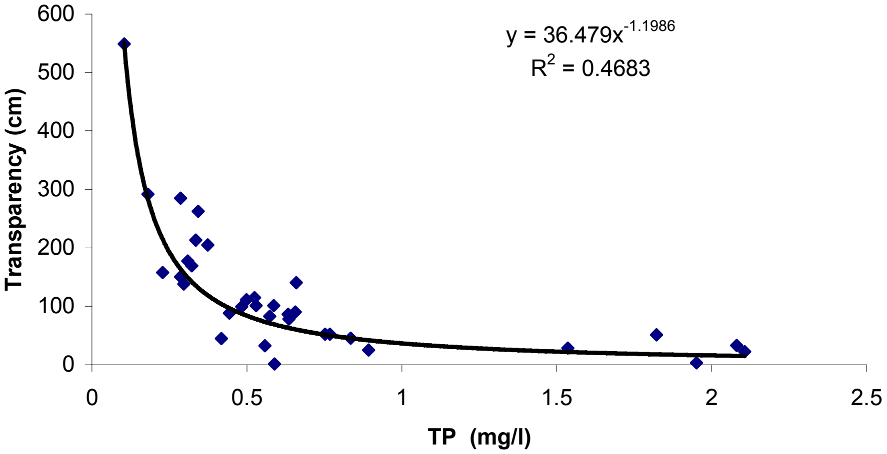

Figure 5. Relationship between secchi disk transparency (SD) and total phosphorus (TP) in 55 Uganda crater lakes.

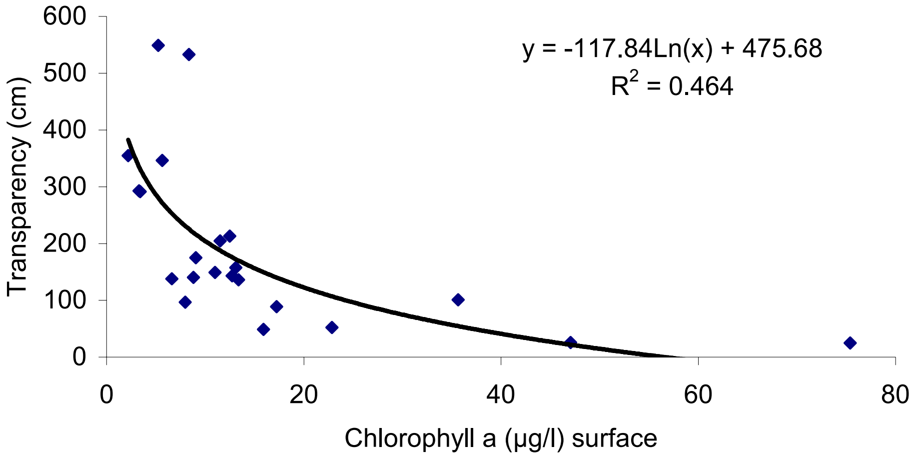

Figure 6. Relationship between secchi disk transparency (SD) and surface-water chlorophyll a in 22 Uganda crater lakes.

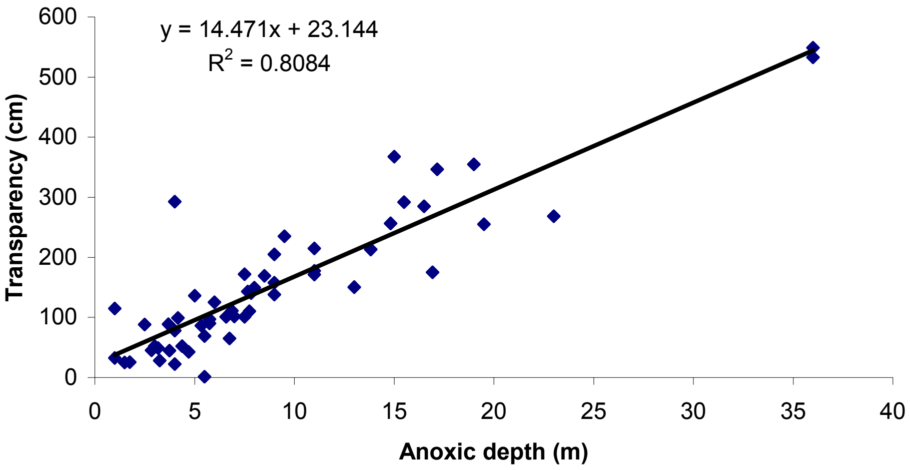

Figure 7. Relationship between secchi disk transparency (SD) and the uppermost depth occurrence of anoxic water in 55 Uganda crater lakes.

We also found a strong, linear and positive relationship between transparency and the depth of anoxic water (defined as the level where DO ≤ 0.5 mg/l) (R^2=0.81, 55 lakes; **Figure 7**). This is because in more productive (less transparent) lakes, deepwater oxygen supplies during the stratified season are used up more rapidly, causing the oxycline to move up towards the thermocline. Other significant correlations were found between transparency and chemocline depth (R^2=0.80), thermocline depth (R^2=0.58) and max. depth (R^2=0.40). The latter relationship occurs because deeper crater lakes generally have steeper bottom slopes, and therefore relatively less recycling of nutrients from shallow-water bottom areas in contact with the epilimnion. Lake trophic status (TLi) is also generally inversely related to lake depth, reflecting the process above but particularly because of a high thermic stability inducing a decreased frequency of deep mixing and nutrient recycling from the hypolimnion.

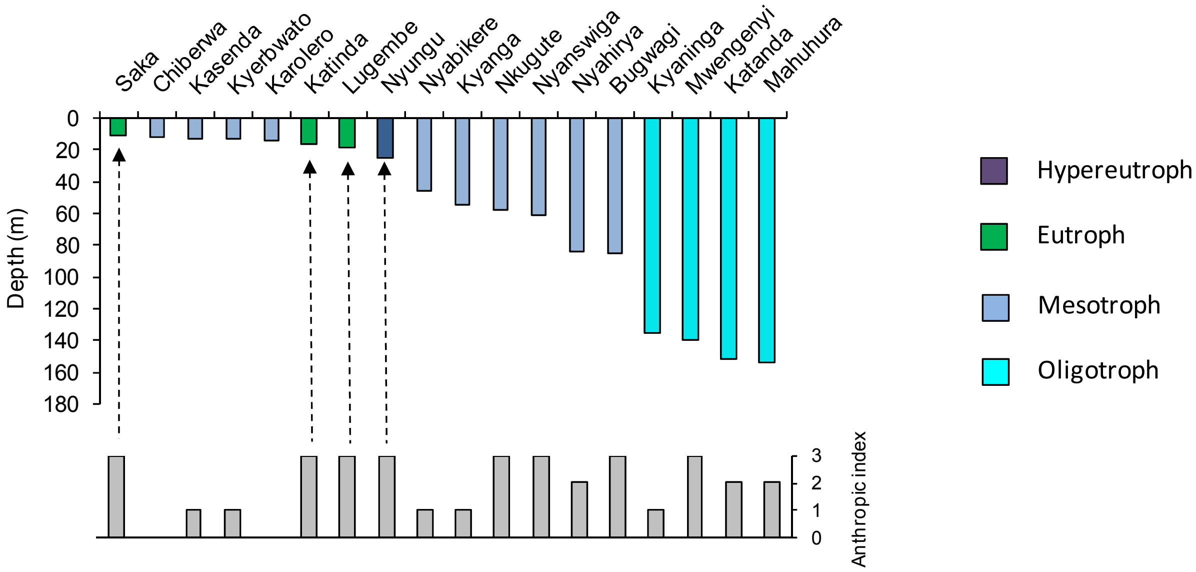

Figure 8. Eightteen principal CLANIMAE study lakes arranged in order of increasing lake depth, colour-coded according to their trophic status. The Anthropic Index Ai ranges from pristine (0) to fully cultivated (3) crater basins. In lakes shallower than ~35 m, human impact has increased lake trophic status; deep lakes (> 90 m) remain relatively unaffected. Note that shallow lakes are naturally mesotrophic (e.g., the pristine forest lake Karolero and the pristine savannah lake Chibwera).

Uganda crater lakes not or little impacted by human activity tend to be oligotrophic when their depth > ~90 m, and mesotrophic when their depth < ~90 m (**Figure 8**). Lakes with a clear anthropic impact can be classified as oligotrophic (depth > ~90 m), mesotrophic (~35 m < depth< ~90 m), or eutrophic/hypertrophic (depth < ~35 m). Our data suggest that significant land use within a crater lake basin is likely to raise the trophic level of lakes shallower than ~35 m, whereas very deep lakes (> 90 m) remain relatively unaffected. The four presently eutrophic or hypertrophic lakes (**Table 1**) had in their pristine state most probably a mesotrophic status. Although the drainage basin of some deep lakes is impacted by human activities (e.g., Mwengenyi), there is no detectable change of trophic status in those lakes. Most probably its important hypolimnion acts as a storage for nutrients, and the low frequency of lake mixing (see below) does not allow much recycling of those nutrients into the surface water where primary production takes place. The PEA calculated for each 5 m depth segment (from 0-5 m to 145-150 m) from all available lake temperature profiles displays an exponential relationship (**Figure 9**). It can be observed that the anthropic impact is mainly observed in the shallower lakes. Those lakes mix more often to the bottom, and the greater nutrient recycling affects more significantly their planktonic biomass and productivity.

Finally, from information on recent or historical fish kills collected during the mission or found in the literature we can also establish a broad inverse relationship between the frequency of fish kills and lake depth (**Table 4**). Since fish kills occur when a large volume of deep anoxic water suddenly mixes with surface water, frequency of fish kills is an indicator of the frequency and seasonality of deep mixing. Although the lake mixing classification indicated in Table M3 remains to be confirmed by the temperature logger data, our data support the hypothesis that all Uganda crater lakes probably do mix completely at least occasionally and with a frequency depending on their depth. It would be coherent with the energy necessary to mix the lakes provided by meteorological conditions (cold air temperature and wind). Meteorological conditions allowing the mixing of deep lakes are relatively rare, with a probable frequency in the ranges of decades for the deepest lakes. Here we use the term oligomictic as defined by Hutchinson (1957), i.e. indicating circulation at frequencies of less than once a year. The term dimictic refers to probable mixing during each of the two dry, colder and windy seasons occurring in this tropical region, although of course one mixing event could be more complete than the other. Dimictics lakes are typical of higher-latitude regions allowing cold surface stratification (<4°C) during winter. The Uganda lakes mixing twice each year remaining in a warm temperature range, hence could be defined as “warm dimictic”.

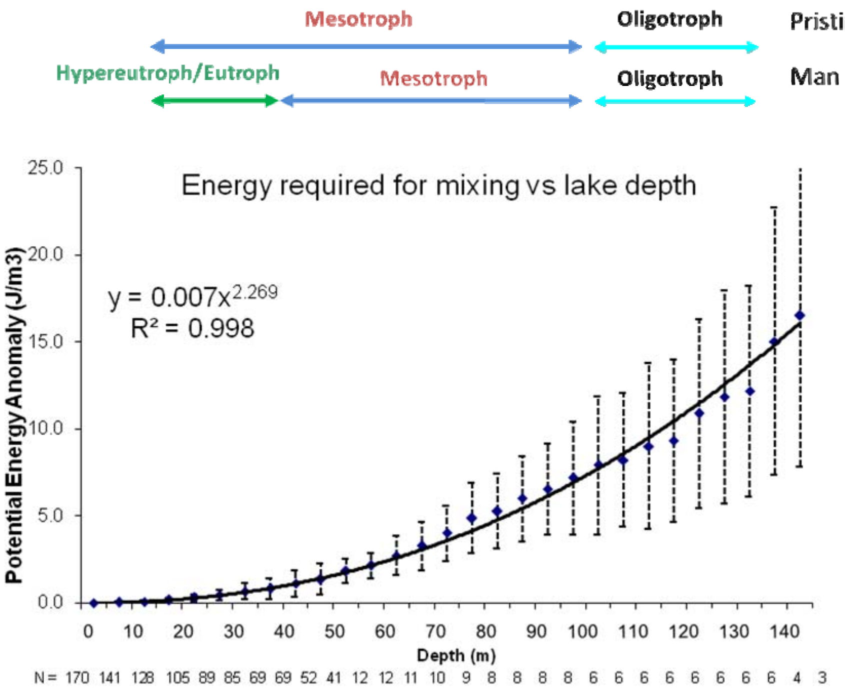

Figure 9. Potential energy anomaly (PEA, in J m-3) calculated for each 5-meter depth segment (0 to 150m) of all 170 water-column temperature profiles currently available from 66 Uganda crater lakes. N = number of observations, only three lakes are 150 m deep. The standard deviation of observed PEA (symbols) increases with depth because the number of available temperature profiles is lower than for shallow lakes. The ranges of lake trophic status is indicated for the situation where human impact is absent or low (Ai 0-2) and for all lakes including heavily impacted lakes (Ai 3).

Lakes	*Depth (m)*	*Prob. mix. type*	*Observations*	*Source*
Katinda	17	dimictic	Fish kill every July and December (3 days)	Pers. com.
Mirambi	21	dimictic	Fish kill every June and November (3 days)	Pers. com.
Nyungu	25	dimictic	Fish kill every July and December (3 days)	Pers. com.
Mbajo.	35	dimictic?	Some dead fish in February 2008	Gelorini & Lebrun, pers.com.
Njarayabana	38	dimictic?	Fish breathing near the surface in Feb 2008	Gelorini & Lebrun, pers.com.
Bunyoni	45	oligomictic	Serious fish kill in 1964	Beadle, 1981
Nyabikere	48	oligomictic	Fish kill +/- 2 years ago (2005?); not every year	Pers. com.
Nkugute	58	oligomictic	Fish Kill 8-7-1956 and some years before	Beadle, 1966
Nyanswiga	61	oligomictic	Fish kill observed (in March or June)	Kizito, 1993
Bugwagi	85	oligomictic	Last fish kill in 1989 (before: every 10 y+/-)	Pers. com.
Kyaninga	58/135	oligomictic	Fish kills every 5 years - Fish kill in 2006	Beadle, 1966 & pers. Com.
Mwengenyi	140	oligomictic	Fish kill in 1998 (2 weeks in July) & every lakes in the region	Pers. com.
Katanda	152	oligomictic	Fish kill in 1998 (2 weeks in July) & every lakes in the region	Pers. com.
Mahuhura	154	oligomictic	Fish kill observed but date not remembered	Pers. com.

Table 4. Information on the frequency of fish kills in 14 Uganda crater lakes (in sequence of increasing depth) in relation to their probable seasonal mixing regime.

A possible global-warming signature in Uganda crater lakes. Preliminary evaluation of all available historical and recent temperature profiles indicates an apparent deep-water warming trend in the Uganda crater lakes, of a range comparable to that observed in upper waters of Lake Tanganyika (Plisnier, 2000), superimposed on inter-annual variability reflecting notable warmer (e.g., 2002) and colder (e.g., 2007-2008) years. Comparison with regional meteorological data is in progress, and will be presented in the final report of the first phase of the CLANIMAE project.

Task 1.2 (partner 4, National Botanic Garden Meise): Diatom-based productivity inference model for East African lakes

We anticipated this task to require data on the modern distribution of diatom species linked to data on nutrient chemistry (TP, TN, SRP, DIN, dissolved Si) and primary production (Chl a) in at least 30 lakes. We now have such data on 48 lakes. In addition, measurement of Chl a by the HPLC technique (courtesy of Protistology & Aquatic Ecology, UGent) has yielded complementary algal-pigment data on phytoplankton community composition in those 48 lakes. For 18 lakes these pigment-derived phytoplankton data are further calibrated against a semi-quantitative assessment of phytoplankton species composition based on cell counting under the microscope. This dataset was further explored with multivariate statistics during the 2nd half of year 2. Development of the diatom-TP inference model had to be postponed to phase 2 pending a better understanding of seasonal dynamics of diatom communities in these Ugandan crater lakes, to be obtained from additional collections made during the main wet season in April 2009.

No diatom-based inference model exists for reconstruction of past changes in the trophic status of African lakes, while such models do exist for lakes in Europe (Bennion et al. 1996) and North America (Hall & Smol 1999). In this project we propose to develop and apply the first such inference model for African lakes, based on calibration of diatom distribution along the wide trophic gradient of Uganda crater lakes. Analysis of sub-fossil diatom assemblages in recently deposited surface sediments from 38 Ugandan crater lakes produced a high-volume reference dataset on the modern distribution of African diatom species in relation to water chemistry, temperature, nutrients (TP, TN, dissolved Si) and other measures of lake primary productivity (SD depth, Chl a) (e.g., **Figures 10-11**). The surface-sediment samples were mostly collected during CLANIMAE campaigns of February and August 2007, supplemented with some samples collected by UGent (partner 1) in 2000-2002. Most samples represent the section 1-3 cm sediment depth, to avoid possible diagenetic effects at the sediment surface. However, in diatom analyses of the 0-1, 1-3 and 3-5 cm depth sections in seven lakes no significant differences were observed in fossil diatom species assemblage, suggesting that data from the sediment surface and immediately below it are interchangeable. This reference dataset on the modern distribution of diatoms in Uganda will be expanded later this year to 48 lakes. Analyses of algal pigments by the HPLC technique (courtesy of the research group Protistology & Aquatic Ecology, Ghent University) on water-filtration residues collected in February 2007 produced data on Chl a and total phytoplankton community composition in the same 48 lakes (not shown). In the context of developing a diatom-based lake productivity inference model (e.g., diatom-based prediction of TP) this will allow a detailed analysis of associations between individual diatom species (recorded in surface sediments) and important types of African phytoplankton communities dominated by other groups of algae (cyanobacteria, desmids, other green algae, etc.). For the subset of 18 lakes surveyed by CLANIMAE in August 2007 and selected other lakes these pigment-derived phytoplankton community data will further be calibrated against a quantitative assessment of phytoplankton species composition based on cell counting in preserved samples. For example, the characteristic phytoplankton community of Lake Kyogo with several common desmid species (e.g., *Staurastrum*, *Closterium*, *Cosmarium*) can be detected only by direct microscopic analysis, because their pigments are identical to those of other green algae. **Table 5** shows the current state of this assessment represented in five abundance classes from sporadic (x) to abundant (xxxxx).

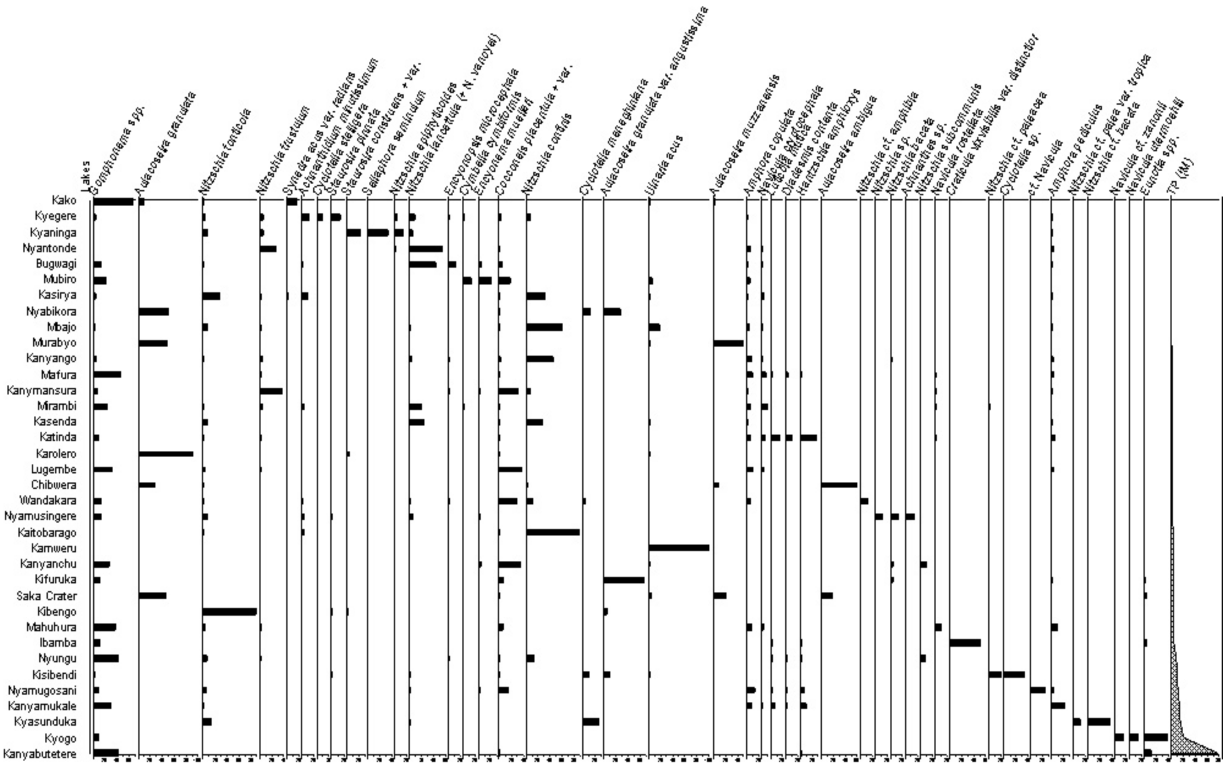

Figure 10. Species composition of diatom algal communities in 36 Uganda crater lakes, as analyzed in recently deposited surface sediments, which integrate seasonal variability. Lakes are arranged from top to bottom in sequence of increasing total phosphorus concentration (TP), a measure of lake productivity.

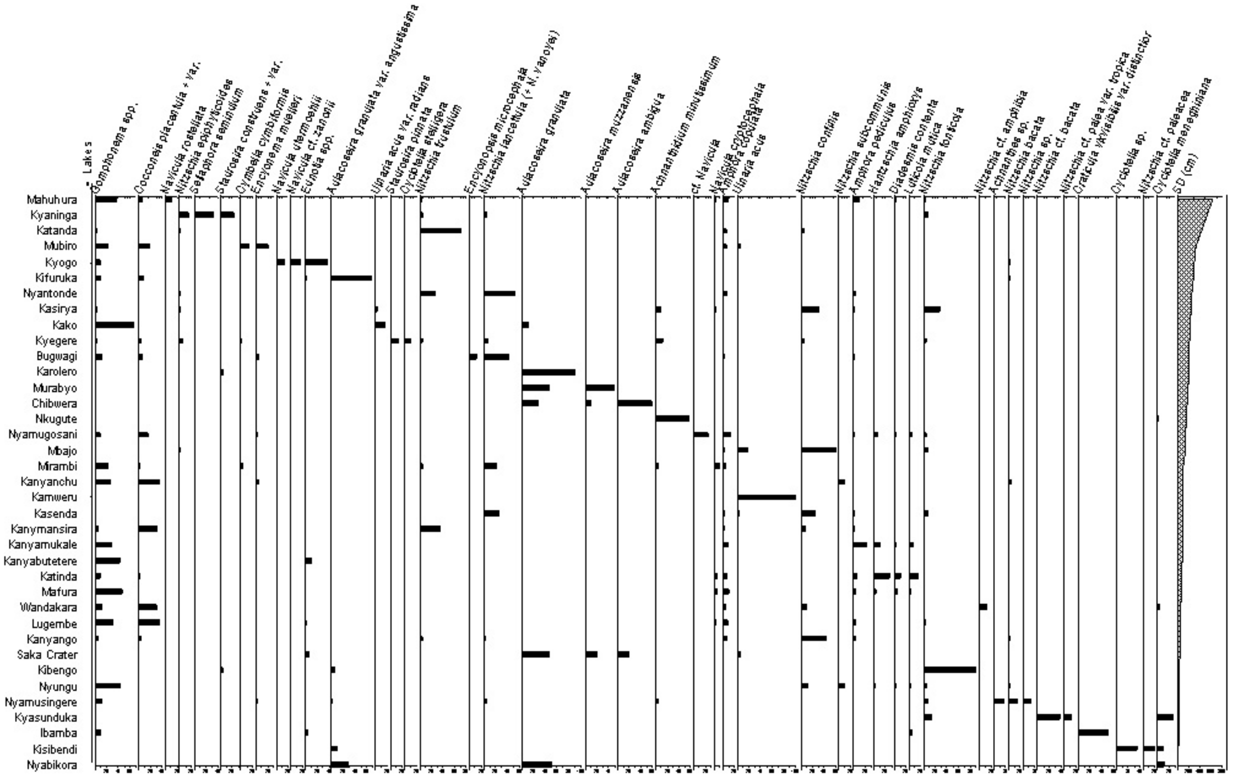

Figure 11. Species composition of diatom algal communities in 37 Uganda crater lakes, as analyzed in recently deposited surface sediments, which integrate seasonal variability. Lakes are arranged from top to bottom in sequence of decreasing secchi disk transparency (SD), a measure of lake productivity.

Lakes	**Katanda**	**Mwengenyi**	**Bugwagi**	**Lugembe**	**Katinda**	**Kyaninga**	**Nkugute**	**Karolero**	**Saka-Crater**	**Mahuhura**	**Kyogo**
Cyanobacteria											
Anabaena cf. verrucosa											
Anabaena sp.						xx	xx	x			xxx
Aphanizomenon flos-aquae						xx					
Aphanocapsa		x	xx		x		x	xxx	x		x
Aphanothece	x		xx	xx			x		x	x	x
cf. Cylindrospermum	xx										
Chroococcales			xx	xx	xxxx		xx				xx
Chroococcus spp.		xx	xx			xx		xx	xx	xx	
Coelosphaerium cf kuetzingianum					x						
Coelosphaerium cf. lacustris			xxx				x	xxxx	xx		
Cylindrospermopsis sp.	xxxx	xx	xx	xxxxx	xx	xx	xxx			xx	
Gomphosphaeria sp.									xx		
Gomphosphaeria cf. aponina											
Merismopedia minima			xx	xx	xxxx	xx	xxxx		xxx		
Merismopedia tenuissima					xx		xx				
Microcystis aeruginosus					x						
Microcystis sp.				x					x		
Oscillatoria agardhii					x				xxxxx		
Oscillatoria sp.			xx								
Planktolyngbya cf. limnetica	x	xx							xxx		
Planktolyngbya contorta			xxx	xx	xxxx	xx	xx	xxxxx	xxx		
Planktolyngbya limnetica	xxxx	xxxx	xxx	xxxx	xxx	xxx	xx	xxx	x	xxxx	xxx
Spirulina sp.				xx							
Synechococcus sp.					xxx				xx	x	
Synechocystis sp.		x									
Chlorophyta											
Chlorococcales (coccoid spp.)			xx	xx							
Actinastrum sp.								x			
Ankistrodesmus falcatus							x				xx
Ankyra sp.							x				
Botryococcus braunii						x			x		
Chlorella sp.	xx	xx	xx		xx	xx	xx	xx	xx	xx	xx
Chodatella sp.			x								
cf. Astroideum sp.									x		
Crucigenia sp.				xx				xx	x		
Crucigeniella crucifera											
Dictyosphaerium ehrenbergianum						x	x				
Dictyosphaerium pulchellum						x	xx				
Dictyosphaerium sp.									x		
Didymocystis bicellularis				xx			xx	xx	xx		
cf. Didymocystis bicellularis		xx								xx	
cf. Eremosphaeria		x					x				
Kirchneriella cf. irregularis		x						xx	xx		
Kirchneriella obesa			x	xx							
Lagerheimia sp.								x			
Monoraphidium cf. arcuatum								x			
Monoraphidium circinale									xx		xx
Monoraphidium contortum		x	xx	xx							
Monoraphidium dybowskii						x					
Monoraphidium flexuosum / irregulare	xxx	xxx	xxx	xx		xxxxx	xx		xx	xxx	xx
Monoraphidium komarkovae	xx	x	x			xx		x	x	xx	
Monoraphidium skujae			x				xx				
Monoraphidium minutum			x				x	x			x
Oocystis sp.											
Pediastrum duplex								x			
Pediastrum duplex var. gracillimum									x		
Pediastrum tetra											
Quadrigula lacustris									x		
Scenedesmus acuminatus							x		xx		
Scenedesmus acuminatus var.									x		

Scenedesmus ecornis							xx	x			
Scenedesmus cf. ginzbergeri											x
Scenedesmus cf. obliquus								x	xx		x
Scenedesmus opoliensis var.									x		
Scenedesmus cf. platydiscus							xx				
Scenedesmus quadricauda									x		
Scenedesmus sp.				xxx			xx				
Schroederia setigera									x		
Tetraedron triangulare			x	x			x		x	x	
Tetraedron minimum	x	x	xx	x		xx	xx	x	x	x	x
Closterium sp.							x				x
Cosmarium spp.	x	x	xx			x	xx				
Staurastrum spp.						x	x				x
Dinophyta											
Gymnodinium sp.	x	x	x	x				x			x
Peridinium cf. africanum			x			x	x	x			xx
Peridinium sp.	x			x	x						x
Euglenophyta											
Euglena sp.						x			x		
Lepocinclis sp.							x				
Bacillariophyta											
Achnanthidium minutissimum							xx				
Amphora copulata										x	
Aulacoseira granulata									x		
Navicula sp.				x		x	x				
Nitzschia cf. gracilis							x				
Nitzschia spp.				x		x					x
Chrysophyta & Cryptophta											
cf. Mallomonas		x									x
Chromulina sp.										x	
Chroomonas sp.		xx									
Ochromonas sp.											x
Dinobryon sp.											xx
unidentified sp. 1				xx							
unidentified sp. 2				xx							
unidentified sp. 3						x					
unidentified sp. 4								x			
unidentified sp. 5											
unidentified sp. 6					x				xx		
unidentified sp. 7											x

Table 5. Species composition of pelagic phytoplankton communities in 11 selected Uganda crater lakes, as sampled in February 2008 (Kyogo) or July/August 2008 (all other lakes). Relative abundance classes range from sporadic (x) over rather common (xx), common (xxx), and very common (xxxx) to abundant (xxxxx).

Task 1.3 (partner 3, FUSA Gembloux): Environmental controls on the distribution of aquatic macrophytes in Ugandan crater lakes

This task similarly requires linked data on modern species distribution and habitat conditions in a set of reference lakes representing the full regional range in bottom slope, substrate type, transparency, circulation regime, and trophic status. Our now completed dataset includes a total of 216 sampling sites (plots) in 36 lakes, i.e. significantly more than the 12 to 15 lakes planned originally. Also its statistical analysis has progressed to near-completion.

Field campaigns, data collection and data processing. Sampling of aquatic macrophytes was carried out in 36 Ugandan crater lakes during two CLANIMAE field campaigns (August 2007 and February 2008). Plant diversity and environmental data were collected in 216 plots (relevés) arranged along transects from the lakeshore to the depth limit of aquatic plant development. Local species abundance was scored visually on the DAFOR scale (Kent & Coker, 1995; Dominant, Abundant, Frequent, Occasional, Rare and Very Rare). Submerged macrophytes in deeper water were sampled using a 4-m long rake. At each plot, water depth, bottom slope, sediment type (soft or compact) and distance from shore were recorded. Turbidity was measured with a Hach turbidimeter. Physical parameters (pH, conductivity, temperature and dissolved oxygen) were measured with a Hydrolab Quanta multi-probe.

Prior to analysis, the floristic data were transformed to ordinal coefficients using the van der Maarel scale (Jongman *et al.*, 1995). The 216 plots were then classified by agglomerative hierarchical clustering to identify distinct ecological groups. This clustering was done with Ward linkage on a squared Euclidian distance matrix. INDVAL (Dufrêne & Legendre, 1997) was used to identify indicator species at each level of the classification. One-way ANOVA and subsequent Tukey's mean separation were used to test the significance of differences in the mean values of environmental parameters associated with each ecological groups as defined by the clustering. With the same objective, a Chi-square test was performed for the nominal variable (sediment type). To improve the normality and homoscedasticity of survey data, values for depth, distance from shore, turbidity and temperature were log-transformed while slope was square-root transformed. Clustering, analysis of variance and statistic tests were performed with Minitab 15 (Minitab Inc., 2006). Correspondence Analysis (CA) ordination was run with CANOCO 4.5 (Ter Braak & Šmilauer, 2002) on the macrophyte and environment datasets at the level of individual sampling plots to assess the influence of environmental factors on floristic variation *a posteriori*. We also conducted a Canonical Correspondence Analysis (CCA) at the lake level to determine the individual importance of 13 relevant environmental factors as predictors of the presence of particular plant communities in Uganda crater lakes. The predictive power of each variable was tested using Monte Carlo tests (999 permutations) at a significance level of 0.05.

Results 1: vegetation structure. A total of 140 terrestrial, semi-aquatic and aquatic plant species were identified from the shoreline to the open water. Individual plant species differ from each other in their habitat requirements, reflected in distinct ranges of distribution (presence-absence) in relation to important physical and chemical characteristics of their aquatic habitat (**Figure 12**). Clustering analysis revealed 8 major ecological groups (communities). Indicator species for each community were classified with their INDVAL value, in descending order (**Figure 13**). Group I is dominated by *Phragmites mauritianus* Kunth and lianas growing in association with it. Group II is characterized by the co-dominance of three emergent aquatic species: *Cladium mariscus* (L.) Pohl subsp. *jamaicense* (Crantz) Kük., *Cyperus dives* Delile and *Cyperus alternifolius* L. Group III is heterogeneous and contains many plots which were difficult to associate to one particular group. It is characterized by lake-edge species (*Phoenix reclinata* Jacq., *Hibiscus diversifolius* Jacq.), recolonisation stage species (*Penisetum purpureum* L., *Hyparrhenia* sp.) and forest species (*Thelypteris dentata* (Forssk.) E.P. St. John, *Nephrolepis biserrata* (Sw.) Schott). The dominant species of Group IV is *Paspalidium geminatum* (Forssk.), an aquatic herb. Submerged vegetation is represented by group V, which is dominated by *Potamogeton pectinatus* L. and *Potamogeton schweinfurthii* A. Benn. Group VI is dominated by the aquatic macrophytes *Nymphaea nouchali* Burm. f. var. *caerulea* (Savigny) Verdc. and *Ceratophyllum demersum* L., and Group VII by *Hydrocotyle ranunculoides* L. f., *Chara setosa* Klein ex Willd. and the rare *Potamogeton nodosus* Poir. Group VIII was largely restricted to Lake Ibamba, occupied by a *Miscanthus violaceus* (K. Schum.) Pilg. swamp with rare *Utricularia* spp. and *Caldesia reniformis* (D. Don) Makino. Other, more common species in this group (*Leersia hexandra* Sw., *Ludwigia leptocarpa*) were sampled in several lakes.

In **Figure 13**, the cluster of groups I-VI includes mostly emergent plant communities except for group V which is a submerged macrophyte community. This could be explained by the wide range of habitat colonised by *Potamogeton* communities, often close to the shore where it is mixed with emergent species like *Cyperus* or the amphibious herb *P. geminatum*. However, *Potamogeton* spp. Are also found with other aquatic macrophytes at greater distance from shore. The second major cluster represents aquatic macrophytes with floating-leaved and submerged species but not exclusively. Indeed, group VIII contains both strict aquatic macrophytes and heliophytes. This means that communities are part of a *continuum* and overlap each other. That is also why the centroids of most groups are very close to group II (**Table 6**). Note that *Cyperus* species and *Cladium mariscus* are able to form rafts floating on water and so extend their zonation to a greater distance from shore.

Results 2: univariate statistics. The ANOVA results show significant differences among the ecological groups for depth, distance from shore, turbidity, temperature, conductivity and dissolved oxygen (**Table 7**). Group I and III share their restriction to shallow water, exemplified by the group I species *Phragmites* which stays above the water table and does not tolerate too much flooding. These groups prevail near the shore, often in relatively cold water (due to shading or higher elevation; needs to be checked). Group I (and IV) further occurs in lakes with relatively high conductivity. Emergent macrophytes of group II can also colonise deeper parts of the littoral zone. This plant community is associated with high pH and turbidity, which in these lakes mostly indicate highly productive systems. The group is exemplified by *C. mariscus*, well known to have high nutrient requirements (Denny, 1985). Group IV (exemplified by *P. geminatum*) is associated with high conductivity in addition to high turbidity and pH.

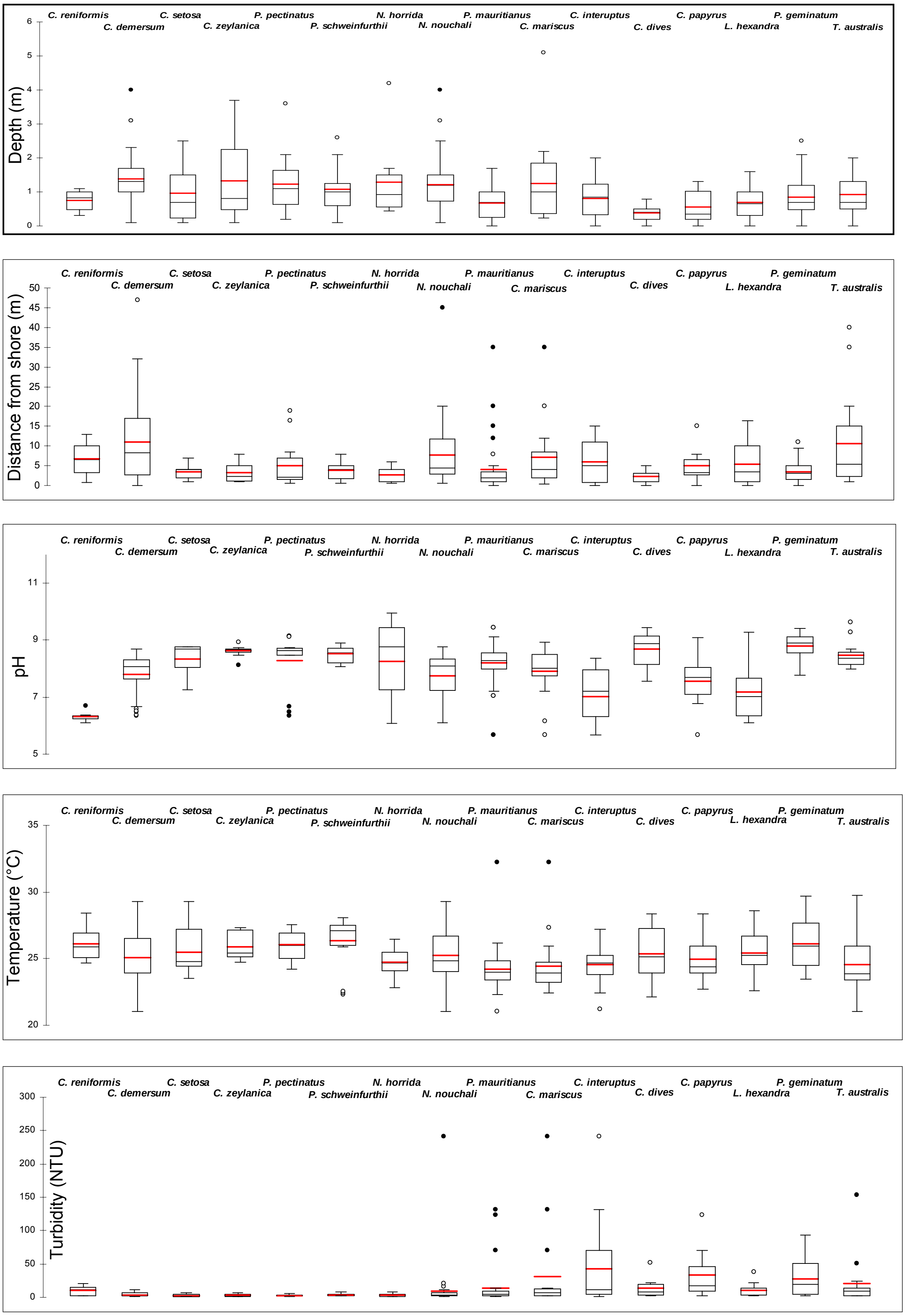

Figure 12. Box plots (mean, standard deviation SD, minimum and maximum values) of the distribution range of 16 aquatic macrophyte species in Uganda crater lakes (n = 36), in relation to the habitat variables (from top to bottom) water depth, distance to shore, water temperature, pH and turbidity.

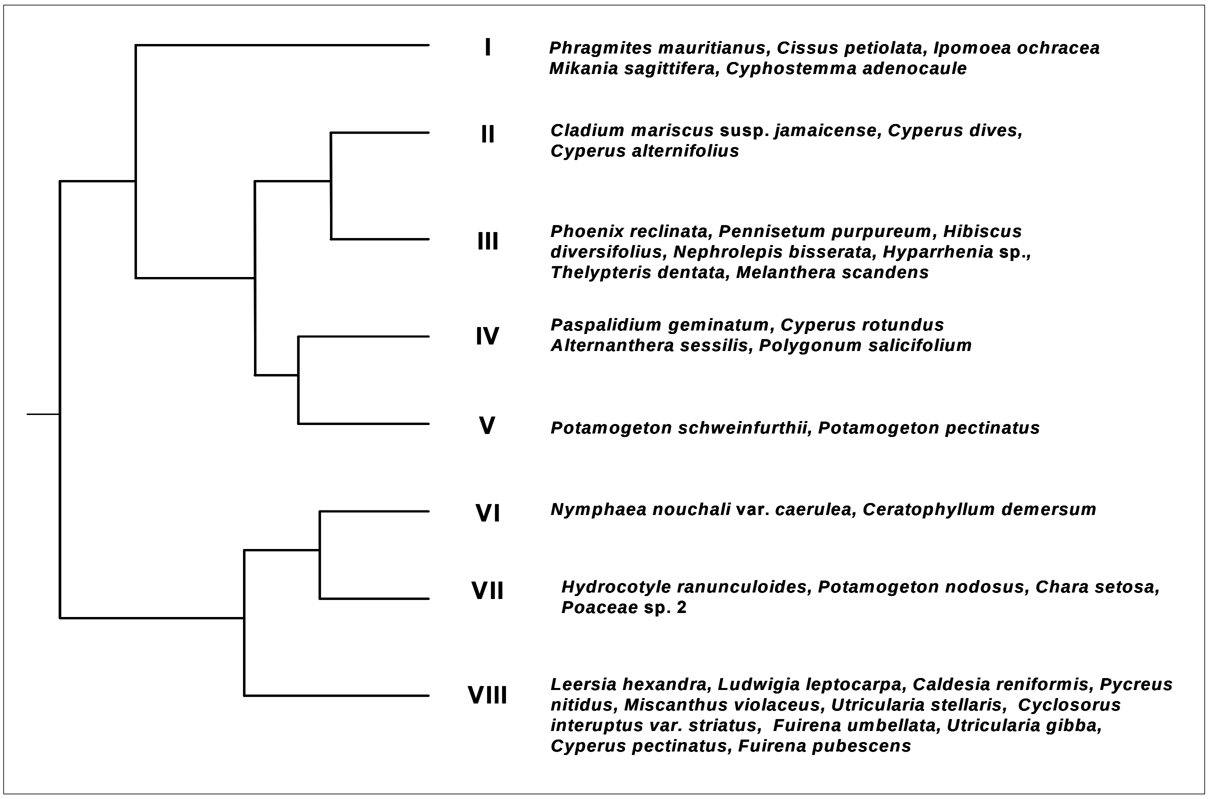

Figure 13. Cluster diagram of 216 vegetation sampling plots in 36 Uganda crater lakes reveals eight distinct communities of aquatic macrophytes (groups I-VIII). Clustering is based on squared Euclidian distance, with Ward linkage. Selection of the listed indicator species is based on IndVal (see text).

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
Cluster 1	0	9.6898	10.3343	12.4678	12.4623	14.7116	12.0247	13.7492
Cluster 2	**9.6898**	0	**7.0096**	**8.3448**	**8.0589**	11.4374	**7.0209**	9.8734
Cluster 3	10.3343	**7.0096**	0	10.3526	10.3693	13.2444	9.5882	11.5142
Cluster 4	12.4678	8.3448	10.3526	0	9.5276	13.7193	10.2867	12.6623
Cluster 5	12.4623	8.0589	10.3693	9.5276	0	12.6629	9.3112	11.9942
Cluster 6	14.7116	11.4374	13.2444	13.7193	12.6629	0	8.2724	12.9276
Cluster 7	12.0247	7.0209	9.5882	10.2867	9.3112	**8.2724**	0	**9.8111**
Cluster 8	13.7492	9.8734	11.5142	12.6623	11.9942	12.9276	9.8111	0

Table 6. Squared Euclidian distances between the centroids (multivariate averages) of the eight clusters (communities) of aquatic macrophytes in 36 Uganda crater lakes. Bold values indicate the smallest distance between each pair of clusters.

Groups	I	II	III	IV	V	VI	VII	VIII
Number of survey plots	28	51	21	25	21	23	30	17
Depth (m)	0.61^{c}	1.02^{abc}	0.66^{c}	0.82^{bc}	1.13^{abc}	1.50^{ab}	1.22^{ab}	0.78^{abc}
Distance from shore (m)	2.56^{ac}	5.46^{c}	0.67^{a}	4.01^{c}	3.56^{c}	13.12^{b}	5.88^{c}	5.98^{c}
Bottom slope (°)	19.0	18.3	30.1	13.4	19.8	11.6	17.2	12.9
Turbidity (NTU)	15.53^{ac}	34.95^{ab}	14.55^{ac}	30.78^{ab}	3.73^{c}	3.45^{c}	4.38^{c}	11.68^{ab}
Temperature (°C)	24.16^{b}	24.94^{b}	24.81^{abc}	26.31^{c}	26.21^{ac}	25.16^{b}	24.77^{abc}	25.29^{abc}
pH	8.11^{c}	8.37^{b}	8.03^{c}	8.80^{b}	8.61^{b}	7.74^{ac}	8.03^{c}	7.10^{ac}
Conductivity (µS/cm)	633.0^{b}	522.8^{bc}	434.6^{bc}	618.9^{b}	535.4^{bc}	357.7^{ac}	391.5^{c}	208.2^{a}
Dissolved oxygen (mg/L)	3.26^{ab}	5.06^{bc}	4.54^{bc}	6.29^{c}	5.67^{c}	5.25^{bc}	5.13^{abc}	3.68^{ab}

Table 7. Average values for diverse environmental parameters recorded in each of the eight recognized ecological communities of aquatic macrophytes in Uganda crater lakes, as identified by cluster analysis. Averages sharing the same superscript letter are not significantly different (P<0.05, Tukey's test).

The mostly submerged aquatic macrophytes constituting groups V, VI and VII share their obvious need for high transparency (low turbidity); group VIII species tolerate less transparent conditions. Group VI and VIII communities share a requirement for low pH and dilute water chemistry. Among the submerged macrophyte communities, Group VI (with *Nymphaea* and *Ceratophyllum*) tend to occur in habitat with the greatest mean water depth.

Results 3: multivariate statistics. The 8 aquatic macrophyte communities in Ugandan crater lakes identified by cluster analysis are also distinct in a CA ordination (**Figure 14**), with axes 1 and 2 together explaining 35% of floristic variability among individual sampling plots. CA axis 1 mostly reflects the gradient from shallow near-shore to deeper offshore habitat; CA axis 2 appears to reflect the gradient of increasing productivity, temperature and pH. The CCA analysis was run at the lake level, consequently the important nearshore-to-offshore zonation in aquatic-macrophyte communities within lakes was not considered. Between lakes, only pH and TN are significant environmental variables (**Figure 15**), suggesting that these are two important predictors of aquatic macrophyte distribution in Uganda lakes. CCA axis 1 is mostly correlated with pH (0.54); axis 2 with TN (0.51).

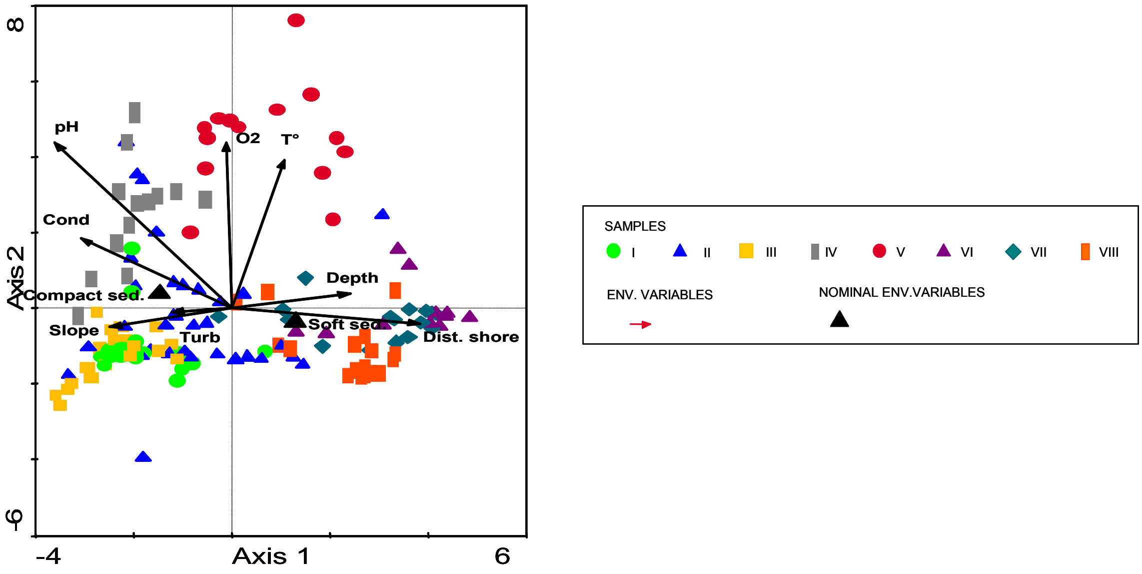

Figure 14. Correspondence analysis of aquatic macrophyte species composition at 216 plots in 36 Uganda crater lakes, colour-coded according the eight ecological groups identified by cluster analysis. Arrows show the main direction of variation in the relevant environmental parameters: CA axis 1 arranges plots along a gradient from nearshore to offshore; CA axis 2 arranges plots along a productivity gradient.

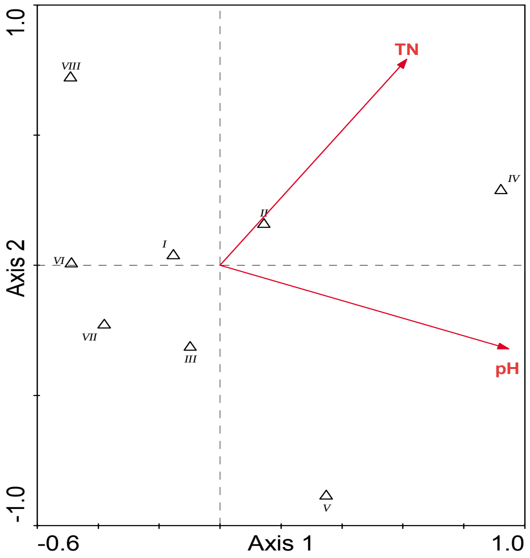

Figure 15. Canonical Correspondence Analysis (CCA) at the lake level identifies total nitrogen (TN) and lake-water alkalinity (pH) as the only two significant predictors of the presence of a particular aquatic macrophyte community (groups I-VIII, as in Figure 12) in Uganda crater lakes.

Task 1.4 (partner 2, MRAC Tervuren): Seasonal variation in diatom δ^{18}O-δ^{30}Si along a water-balance transect

This CLANIMAE component and Task 1.5 aim to develop as novel geochemical proxy for paleo-environmental reconstruction the silicon-isotope (δ^{30}Si) signature of diatom opal, using MC-ICP-MS instrumentation for high-accuracy δ^{30}Si measurements. We showed earlier that Si-isotope fractionation during uptake by diatoms in lakes Tanganyika and Baikal (Alleman *et al.* , 2005; Cardinal *et al.*, 2006) closely follows that observed in tropical marine (De La Rocha *et al.*, 1997) and polar marine diatoms (Cardinal *et al.*, 2005). This fractionation is both species- and temperature-independent (Alleman *et al.*, 2005), making δ^{30}Si measurements in fossil diatoms a potentially powerful tool to quantify past Si utilization (and thus diatom productivity) in lakes. To reach this objective, two preliminary works have been achieved. First, the Nu (MC)-ICP-MS was upgraded with a new adjustable entrance slit, to obtain medium resolution, as well as a stronger primary pump and newly designed sampler and skimmer cones (Abraham et al., 2008). These settings, combined with the use of collector slits, allowed an isotopic resolution to be reached that was sufficient to overcome the ^{14}N^{16}O and ^{14}N$_2$ interferences overlying the ^{30}Si and the ^{28}Si peaks, respectively, in the earlier set-up (Cardinal et al., 2003). This enabled more accurate measurements of both δ^{30}Si and δ^{29}Si (Abraham et al., 2008). Second, another important step was to gather linked data on dissolved silicon (DSi) concentration and diatom δ^{30}Si and δ^{18}O in the water column of lakes situated in climate zones with mild to strongly negative local water balance, and in landscapes with no to intense human impact.

As planned we measured water and diatom δ^{18}O and δ^{30}Si in selected lakes situated in climate zones with mild to strongly negative local water balance, and in landscapes with no to intense human impact. We also engaged Lancaster University (subcontractor SC1, cf. article 5.4 of the contract) for separation and measurements of δ^{18}O, to be followed by δ^{30}Si determinations in surface-sediment samples of five Ugandan study lakes. However, fossil diatom preservation was found to be favourable for this analysis in only two of those lakes, consequently new sites had to be selected for this task. To optimize selection criteria we did this at the end of phase 1 on the basis of the completed 48-lake dataset of diatom species composition (and preservation) in surface sediments.

Data collection and processing. Water samples were collected in August 2007 at different depths in two Ugandan crater lakes (Kyerbwato and Katinda) representing pristine and disturbed ecological conditions. Kyerbwato (sampled at 0, 4, 7 and 10m depth) is a pristine oligotrophic lake, whereas Katinda (sampled at 0, 5, 9 and 15m depth) is a eutrophic lake with heavy human impact (deforestation, soil erosion, etc.). The water samples were filtered immediately after collection through 0.45µm polycarbonate filters and kept in the dark until analyses in the laboratory. Particulate silicon in particles retained on the filters were measured following a double wet-alkaline digestion method (Rageneau *et al.*, 2005) but were found to be under detection limit in both lakes. Consequently the estimation of diatom biomass will be based on diatom counts and chlorophyll ***a*** measures. Si isotopes in the dissolved phase were measured after quantitative coprecipitation using a Triethylamine Molybdate technique (De La Rocha *et al.*, 1996). Isotopic analyses were carried out under dry plasma conditions using a multi-collector mass spectrometer (Nu Plasma) with a desolvator to minimize polyatomic interferences. δ^{30}Si values expresses the observed ^{30}Si/^{28}Si ratio as deviation in ‰ from the ^{30}Si/^{28}Si ratio of the NBS28 standard reference (Cardinal *et al.*, 2003; Abraham et al., 2008).

Results. Both DSi and δ^{30}Si were found to be fairly homogenous with depth in the water column of these two lakes (**Figure 16**), a probable consequence of the deep mixing occurring in these relatively shallow lakes during or shortly before the sampling period. The DSi and δ^{30}Si values in Kyerbwato (no human impact) of around 10 ppm and 2.00 ‰ are close to those found in Lake Tanganyika's surface water (up to 1.91 ‰; Alleman *et al.*, 2005) which was driven by diatom activity. On the opposite, in Katinda (heavy human impact) the values are around 22 ppm DSi and δ^{30}Si around 2.50 ‰ respectively. This last value is very high for a freshwater environment, and could indicate more important soil leaching and alteration due to deforestation and agriculture, as clay formation is known to fractionate silicon isotopes (De La Rocha *et al.*, 2000; Ziegler *et al.*, 2005a, Ziegler *et al.*, 2005b). Very high diatom productivity could also explain this fractionation, but the high phytoplankton productivity in Lake Katinda during the sampling period (high Chl a; **Table 1**) is due mostly to cyanobacteria (*Planktolyngbia*, *Chroococcus*, *Cylindrospermopsis*; **Table 5**). This is the first direct comparison of modern Si isotope mass fractionation patterns in lakes of similar morphology and physical limnology but different human impact. Information about seasonality in diatom productivity may help to explain the observed patterns.

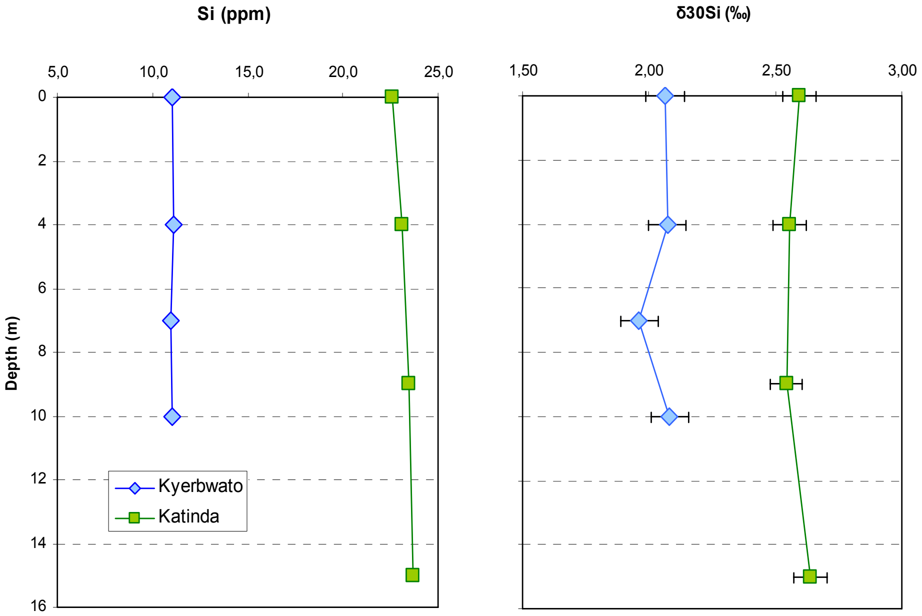

Figure 16. Profiles of dissolved Si concentration and isotopic composition in lakes Kyerbwato and Katinda in August 2007. The standard error (2σSEM) indicated for δ30Si is the cumulated analytical error.

Task 1.5 (partner 2, MRAC Tervuren): Validation of diatom δ^{30}Si as productivity indicator in lake-sediment records

In further preparation of developing δ^{30}Si as diatom paleoproductivity indicator we engaged Lancaster University (subcontractor, cf. article 5.4 of the contract) to prepare surface-sediment samples of five lakes with contrasting algal productivity and human impact for measurement of diatom $\delta^{18}O$ (at the NERC Isotope Geosciences Laboratory, Keyworth, UK) and $\delta^{30}Si$ (at MRAC, Tervuren). This involves sediment treatment to produce a pure diatom isolate (Morley et al. 2004). However, following basic sample treatment with hydrogen peroxide it was found that only two of the selected lakes contained sufficiently high abundance of intact subfossil diatoms and little other opal components (phytoliths, volcanic glass) to be suitable for analysis of fossil diatom isotopes (**Table 8**), despite diatom preservation to be generally very good (% full valves on microscope slides 88-98%). Consequently a new selection of lake sites must be made for this aspect of the project.

Lake		Sampling site		Diatoms		Other Silicon	Quality
Name	Ecological status	Water Depth	Core Interval	Abundance	Preservation		
-		(m)	(cm)		(% full valves)		
Saka crater	eutrophic disturbed (general)	8,5	0-5	high	90,9	mineral	high
Nyantonde	oligotrophic disturbed (general)	38	1_3	medium	95,7	mineral	high
Kisibendi	eutrophic pristine	4,5	0-5	low	87,6	miner + phytoliths	low
Kyogo	oligotrophic pristine	3,4	1_3	low	97,7	mineral	low
Nyungu	eutrophic disturbed (banana)	25	1_3	low		miner + phytoliths	low

Table 8. Quality assessment of fossil diatoms preserved in the sediment of selected Uganda crater lakes with contrasting trophic status and human impact, for use in isotopic analyses of oxygen and silicon.

3.2 Work Package 2. Climate reconstruction: moisture-balance variation inferred from lake-level and water-chemistry changes

Task 2.1 (partner 1, UGent; partner 4, Nat. Bot. Garden): Analysis of climate-proxy indicators in selected sediment records

As explained in the proposal, most climate-proxy data sets (reconstructions) from principal CLANIMAE study sites are already available or will become available during phase 1 of this project, through in-house PhD and MSc research of partner 1 and international collaborative efforts in East African paleoclimatology complementary to this project. Two exceptions are paleoecological moisture-balance reconstructions in western Uganda based on fossil diatom and aquatic macrophyte assemblages, which will be conducted within CLANIMAE but mostly during phase 2 of the project, when calibration and validation efforts (Tasks 1.2, 1.3) have been completed. Exploitation of these proxies as indicators of changes in nutrient supply and transparency associated with human impact is presented under Tasks 4.1-4.2.

Until recently, the only climate reconstructions for equatorial East Africa with at least century-scale resolution and age control were available for the central Kenya Rift Valley (Naivasha, 1800 years; Verschuren et al. 2000a; Verschuren 2001), the northern Lake Victoria region (1000 years; Stager et al. 2005) and the western Rift Valley at Lake Edward (5400 years; Russell & Johnson 2005, 2007) (**Figure 17**). These combined records suggest that equatorial East Africa was relatively dry from about 1000 and 1250 AD and in the late 18th century up to about 1820 AD), and relatively wet from about 1250 to 1500 AD. Between 1500 AD and the late 18th century an interesting climatic gradient appears to have developed over our study region, with drier-than-normal conditions in the west and wetter-than-normal conditions in the east. As a result, during that time the climatic gradient from (sub)humid western Uganda to semi-arid eastern Kenya was less pronounced than today (Verschuren & Charman, 2008).

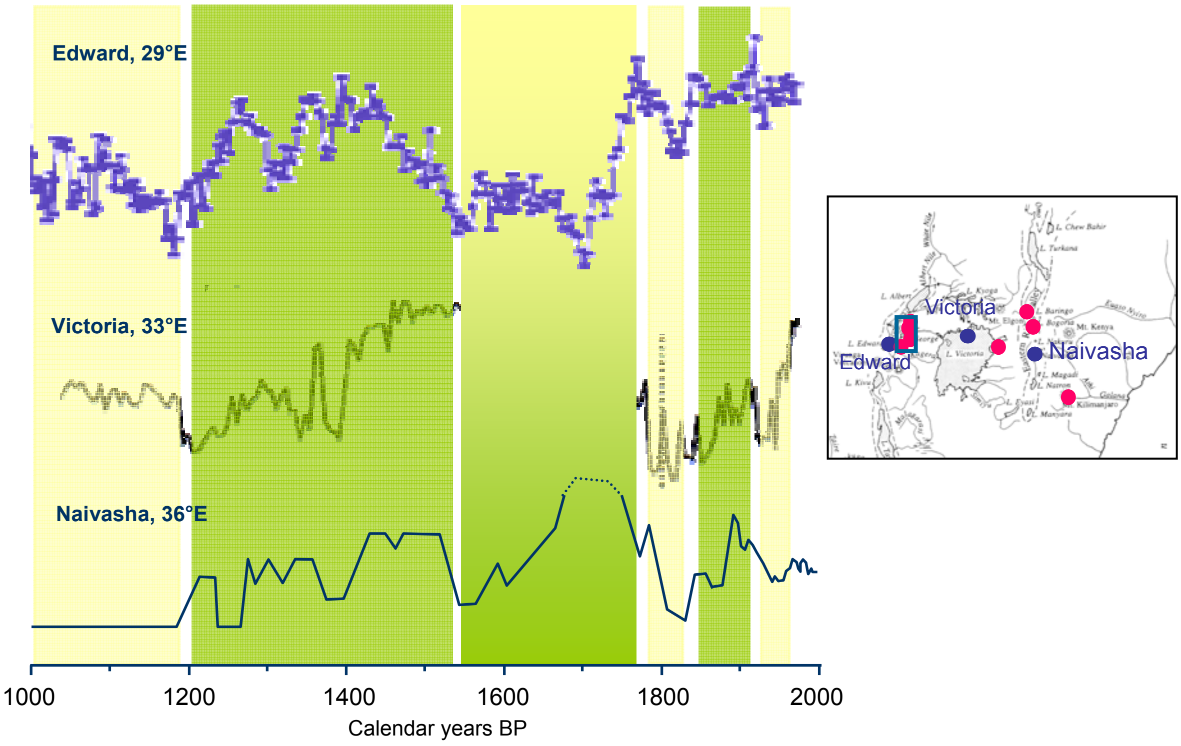

Figure 17. a. Rainfall variation in equatorial East Africa over the past 1000 years reflected in water-balance fluctuations of lakes Edward (reconstructed from %Mg in authigenic calcite: Russell & Johnson, 2007), Victoria (reconstructed from % shallow-water species in fossil diatom assemblages: Stager et al., 2005), and Naivasha (lake level reconstructed from sediment stratigraphy: Verschuren et al., 2000). The shading highlights episodes of widespread drought (yellow) and high rainfall (green); during the main phase of the Little Ice Age (1500-1800 AD), western portions of the East African Plateau were drier than usual, whereas eastern portions of the Plateau were wetter than usual. **b**. CLANIMAE study region in with position of the three lakes shown in a, plus CLANIMAE target sites in western Uganda (grouped within the blue rectangle) and Kenya.

New lake-based climate reconstruction by partner 1 and other workers on crater lakes in western Uganda (Kitagata, Kibengo: Russell et al. 2007; Kasenda, Wandakara, Katinda: Bessems 2007), Rift Valley lakes in central Kenya (Bogoria, Baringo: Bessems 2007; Loboi swamp: Ashley et al. 2004; Driese et al. 2004) and Lake Challa in southeast Kenya (Verschuren et al., ESF CHALLACEA unpubl. data) confirm these general temporal and spatial patterns, indicating that the Lake Edward and Lake Naivasha moisture-balance records correctly describe the long-term climate history of respectively western Uganda and the eastern part of the East African Plateau. The new Lake Challa moisture-balance record also confirms the widespread occurrence of late 18th-century drought throughout the East African Plateau (Bessems et al. 2008), which was more severe than any drought in recorded history and most probably the most severe drought in at least the last 800 years (Verschuren 2004).

Task 2.2 (partner 1, UGent): Improving the chronology of lake-sediment records used in regional reconstruction if East African climate history

An essential component of our integrated paleoecological research method is that sufficient effort and investment is allocated for accurate dating of all studied sediment records (and the paleoenvironmental information contained in them). This is essential to permit regional correlation of reconstructed decadal and century-scale climate anomalies between sites, both within the study region and between East Africa and other (tropical and temperate) regions (Task 4.1). Adequate time control will be based on multiple radiocarbon (^{14}C) dating supplemented by alpha-spectrometric ^{210}Pb-dating of the youngest (<150 years) deposits. Exploratory ^{14}C and ^{210}Pb-dating executed during initial core quality screening already produced skeleton age models for all target study sites, however dating of a significant number of additional intervals is required to constrain the timing of individual events and episodes of pronounced change. Because high-quality terrestrial plant macrofossils tend to be rather scarce and their stratigraphic distribution erratic, the optimal ^{14}C-dating strategy involves rather labour-intensive sieving and visual scanning of sediment cores.

CLANIMAE investment in additional sediment dating has so far been focused on lakes Wandakara (Russell et al. submitted) and Katinda (M. Blaauw & D. Verschuren, unpubl. data). The project also greatly benefits from substantial investment in accurate dating of the Lake Challa climatic moisture-balance record for southeastern Kenya.

3.3 Work Package 3: Vegetation reconstruction based on pollen & phytolith analysis

Task 3.1. Pollen analysis of past vegetation dynamics

We originally planned that the Belgian palynologist hired on the project by partner 1 would analyze both fossil pollen of terrestrial vegetation and so-called non-pollen palynomorphs (NPPs), the former after receiving training in African pollen taxonomy at the York Institute for Tropical Ecosystem Dynamics (partner 5). However the taxonomic aspects of the pioneering NPP study (Task 4.3) are so complex that we decided to allow the UGent analyst to dedicate most of her time to the NPPs, and to tender all planned pollen analytical work to sub-contractors 2 & 3 at the National Museums of Kenya and Makerere University (Uganda).

In the last decade, significant progress has been made in documenting the history of terrestrial vegetation dynamics in equatorial East Africa during the last 2-3000 years (e.g., Marchant & Taylor 1998; Taylor et al. 2000; Lamb et al. 2003; Ssemmanda et al. 2005). However, assigning causation for the documented vegetation changes has often suffered from the difficulty to unambiguously differentiate between climatic and anthropogenic impacts on vegetation in fossil pollen records; and use of independent moisture-balance reconstructions from other sites for guidance to determine the impact of climate is compromised by insufficient dating control on either record to determine synchronicity of events between them (Verschuren 2004). A critical aspect of the CLANIMAE project, therefore, is that we produce fully coupled reconstructions of past climate, vegetation and water-quality change at selected study sites by extracting them from the same, well-dated and demonstrably high-quality lake-sediment records, such that changes are observed against the same time axis. In addition, CLANIMAE aims to calibrate the magnitude of terrestrial ecosystem response to climate change and human impact as recorded in fossil pollen data. This is done through parallel reconstruction of climate-driven lake-level change and long-term vegetation dynamics in two Ugandan crater lakes situated in a relatively pristine and an anthropogenically disturbed landscape, respectively. The two lakes selected for this purpose are Lake Chibwera in the Kyambura area of Queen Elisabeth National Park, and Lake Kanyamukali in the southern Kasenda district.

To date, CLANIMAE subcontracts to Kenyan and Ugandan pollen analysts (Dr. Immaculate Ssemmanda, Makerere University, Kampala; Stephen Mathai Rucina, National Museums of Kenya, Nairobi) produced reconstructions of vegetation history linked to four lake-sediment records: Simbi (**Figure 18**), Chibwera (**Figure 19**), Challa (**Figure 20**) and Kanyamukali (partly completed, not shown). The Challa reconstruction for semi-arid southeastern Kenya covers the last 2700 years, and can be directly related to our climatic moisture-balance record for the same time interval produced by the ESF CHALLACEA project. Pending availability of a high-quality moisture-balance record from Lake Simbi, and improved dating of its ~800-year sediment record, the Simbi vegetation reconstruction for sub-humid western Kenya can be linked appropriately to the diatom-inferred Lake Victoria lake-level record (Stager et al. 2005; **Figure 17**). The Chibwera vegetation reconstruction for the pristine savanna presently occupying the floor of the Rift Valley in western Uganda covers the last ~250 years, and starts in a phase of lake desiccation resulting from severe late 18th-century drought. Its record of regional vegetation history can be related directly to reconstructions of lake-level change based on sedimentological characteristics (Bessems et al. 2008) and the local aquatic invertebrate community (e.g., for Lake Chibwera: **Figure 21**).

Below we describe in more detail the pollen records from Simbi and Chibwera. For both studies, preparation of sediment samples for pollen analysis followed Faegri *et al.* (1989). Scanning and counting of pollen and spores was done using a compound microscope at 400x and 1000x magnification. The relative abundance of plant species in the landscape is expressed as percentages of the pollen sum, which besides plant taxa found in the crater catchment and near surroundings also includes a varying degree of long-distance pollen from plant species occurring farther away. Aquatic plants and ferns are excluded from the pollen sum due to local over-representation in lake environments; their abundance is expressed as a % of the pollen sum, hence can exceed 100%.

Lake Simbi vegetation reconstruction. The Simbi pollen diagram (**Figure 18**) comprises three vegetation zones (Sim I-III) that can be related to relatively minor vegetation disturbances caused by climate-driven moisture-balance changes and historical land-use practices. In Sim I (140-104 cm core depth) the pollen assemblage is characterised by high abundance of grasses (Poaceae: ~ 80%) and *Podocarpus* (~20%). Pollen from other trees and herbs (*Acacia*, *Artemisia*, *Juniperus*, *Myrica*, *Olea*) are barely present. This suggests open savanna vegetation typical of a rather dry climate regime. The relatively high *Podocarpus* abundance result likely through long-distance pollen dispersal from wetter highland regions (Lamb *et al.* 2003; Ashley *et al.* 2004), in this case the Mau Range and Nandi Hills.

At the start of Sim II (104-22 cm) some minor changes occur. *Acacia*, Asteraceae, *Euphorbia*, *Juniperus* and *Olea* become more prominent, Asteraceae and *Olea* in particular. Grass pollen continues to dominate, but at a slightly lower mean abundance of ~75%. The pollen % of presumably mostly aquatic Cyperaceae increases to high but strongly fluctuating values (100-250%). The greater prominence of montane forest taxa, *Juniperus* and *Olea*, and very high peaks in Cyperaceae may reflect an overall improvement of regional moisture balance (higher rainfall) during the period represented by Sim II, however with much temporal variability. The rise in Asteraceae pollen may also be related to improved moisture, but since its onset is situated within the drier period preceding Sim II, we favour the alternative possibility that it reflects increasing vegetation disturbance due to more intense land use by pastoralists. The exact timing of this increasing human occupation of the Simbi area is uncertain, pending ^{14}C dating of the lower section of the record. Judging from average sedimentation rates in the ^{210}Pb-dated upper section, we surmise that the Sim I-II zone boundary correlates with the climatic transition which ended the medieval drought episode (about 1000-1250 AD) now known to have affected much of the East African Plateau (Verschuren & Charman, 2008).

Sim III (22-0 cm), which covers the last 60-70 years, records marked vegetation changes which likely result mostly from intensifying human impact. Pollen of cultivated cereals already appear slightly below the Sim II-III zone boundary at 28 cm depth, dated to the early 20th century. Also characteristic is the appearance around this time of *Spyrogira*, a cyanobacterium (blue-green alga) indicative of high nutrient availability and thus possibly reflecting the soil erosion resulting from the clearance of natural vegetation for crop cultivation. Intensifying anthropogenic vegetation disturbance is also indicated by the rise in Amaranthaceae/Chenopodiaceae (ruderal plants; pollen from these families are hard to differentiate). The marked reduction in Poaceae pollen from ~70% at 12 cm depth (~1980) to ~35% at the surface (1999) should not be interpreted as a drastic reduction in grassy ecosystems in recent decades. It is mainly due to a parallel increase in *Podocarpus* pollen from ~15% to 45%, which may reflect current forest management practices in which *Podocarpus* trees are protected from cutting. Other montane forest taxa, such as *Juniperus* and *Olea*, decrease from the base of zone III, consistent with relatively dry climatic conditions in Kenya since the 1930s.

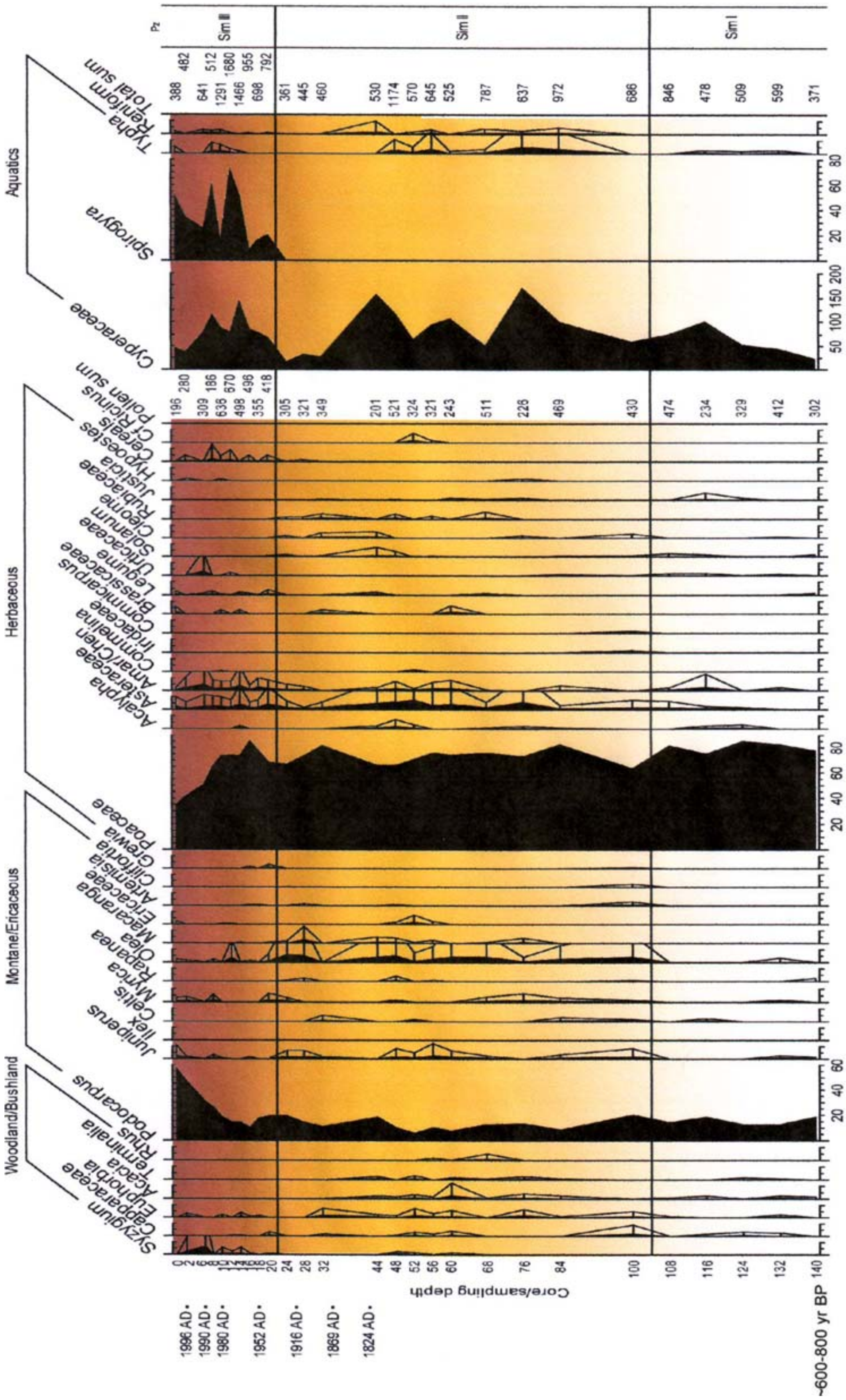

Figure 18. Fossil pollen record of Lake Simbi, showing vegetation shifts near the shore of Lake Victoria in western Kenya over the last 600 to 800 years (precise pre-19th century chronology is pending). Natural, climate-driven vegetation shifts are hard to discern, except for a greater proportion of moist indicator plant taxa in pollen zone Sim II than in zone Sim I. The increase in Asteraceae starting halfway zone Sim I may reflect increasing pastoralist impact on the landscape (orange highlight). Onset of sedentary agriculture in the early 20th century (brown highlight) is clearly marked by arrival of cereal grasses and increase in Amaranthaceae/Chenopodiaceae. Development of *Spirogyra* blooms since the 1930s reflects enhanced nutrient influx associated with soil erosion. Increase in *Podocarpus* trees since the 1970s reflects recent forest management practices. Pz: Pollen Zonation.

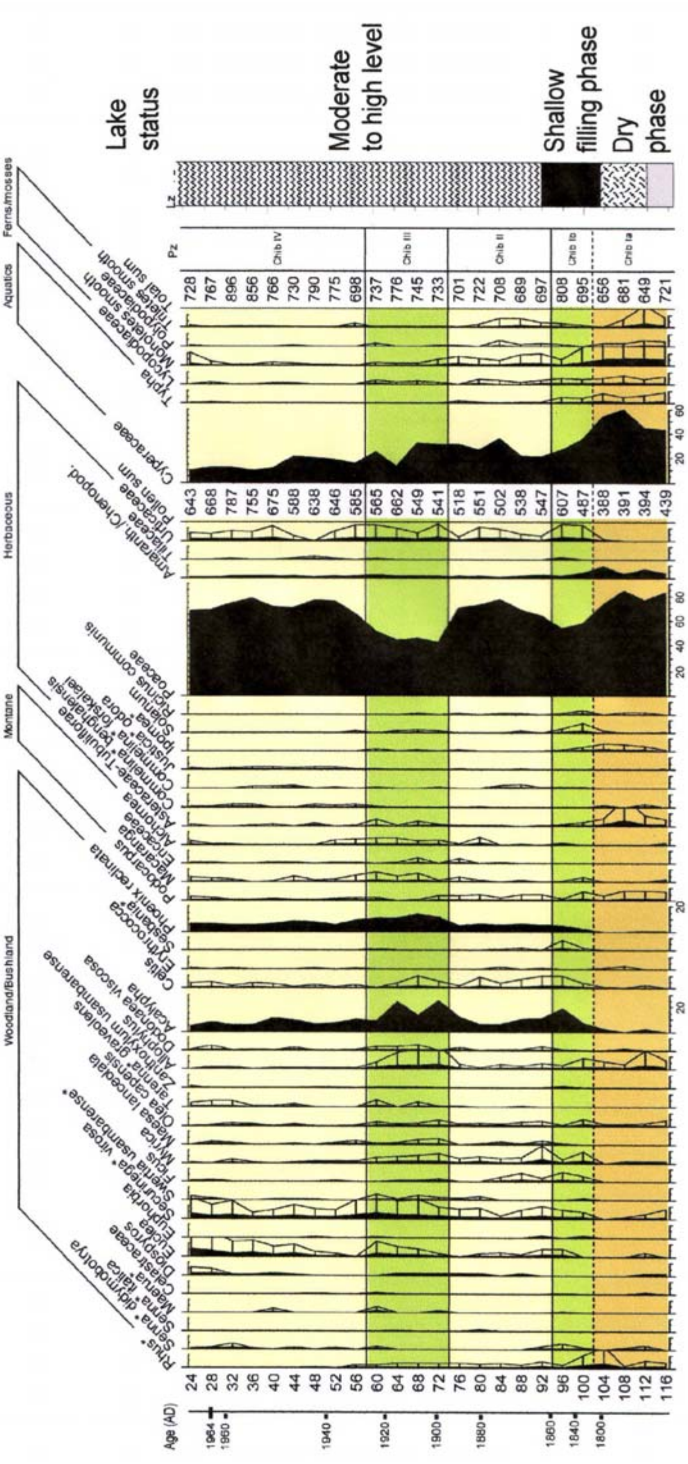

Figure 19. Fossil pollen record of Lake Chibwera, showing vegetation shifts in the southern Lake George area of western Uganda between the late 18th century and ~1970 AD (most recent sediments still to be analysed). Lake Chibwera dried out completely during severe late-18th century drought (brown highlight). Since then, wet episodes during ~1810-1860 AD and ~1890-1930 AD (green highlights) have alternated with modestly dry episodes (yellow highlights). Pz: Pollen Zonation; Lz: Lithological zonation.

Lake Chibwera vegetation reconstruction. The dated sediment record of Lake Chibwera is the subject of a multiple-proxy paleo-environmental study aiming to find direct causal links between past climate change and the long-term dynamics of lake hydrology (lake level, water chemistry; Bessems *et al.* 2008), aquatic biology (**Figures 21-22**), local aquatic and surrounding terrestrial vegetation (**Figure 19**), and water quality (see Task 4.1) in a pristine natural savanna landscape. This sediment record covers the last ~250 years with high temporal resolution, consequently it can be exploited to assess how well the response of regional vegetation to known 20th-century climate variability is recorded in the composition of fossil pollen assemblages. Here we focus on vegetation response to the end of severe late 18th-century drought, and to the early 20th-century period (~1890-1930) when climatic conditions in equatorial East Africa were substantially wetter than today, on average (Verschuren 2004). At present our vegetation reconstruction (**Figure 19**) ends around 1970; data from recent decades (the upper 22 cm of the core) are pending.

As in the Simbi record, high grass pollen abundance (Poaceae mostly >70%) reflects a grass savanna environment persisting in the southern Lake George area throughout the past 250 years. Pollen zone Chib I (116-94 cm) is divided in two sub-zones. Zone Chib Ia (116-102 cm), which represents the late 18th century period when Lake Chibwera stood dry, is characterised by high abundances of both Poaceae and Cyperaceae pollen. In Zone Chib Ib (102-94 cm), representing the ensuing period ~1800-1860 AD of lake filling under a wetter climate regime, these two dominant pollen types decrease, in contrast to palms (*Phoenix reclinata*) and a diverse assemblage of woodland trees, shrubs and herbs (*Acalypha*, *Celtis*, *Euclea*, *Ficus*, *Myrica*, Urticaceae, etc.) which all increase markedly above the Chib Ia-Ib boundary. In zone Chib II (~1860-1890 AD) grass pollen abundance rises again from ~ 60% to 80%, at the cost of woodland species (*Acalypha*, *Euclea*, Urticaceae). Also the Cyperaceae increase in abundance, though less prominently than in Zone Chib Ia. Zone Chib III (74-58 cm) covers the historically wet period from the late 19th century to the 1920s. It is characterised by a very conspicuous fall in grass pollen percentage (Poaceae: from ~80% to 50%), again accompanied by rises in woodland/bushland taxa such as *Acalypha*, *Allophylus and Euclea*.

Finally, in Zone Chib IV (58-24 cm) Poaceae pollen increase again to ~80%, consistent with the comparably dry climatic conditions prevailing during the mid-20th century. At the very top of the sequence we find some indication of the documented return to wetter weather in the late 1960s and 1970s, but this remains to be confirmed by pollen data representing the last three decades. However, given the long protected status of the Kyambura area as game reserve, absence of pollen from cereals in our record indicates that at least in the last 250 years (and most probably before that time as well), no significant agricultural activity occurred in the vicinity of Lake Chibwera. Yet the date palm (*Phoenix reclinata*), present throughout the pollen record, was most probably introduced by humans.

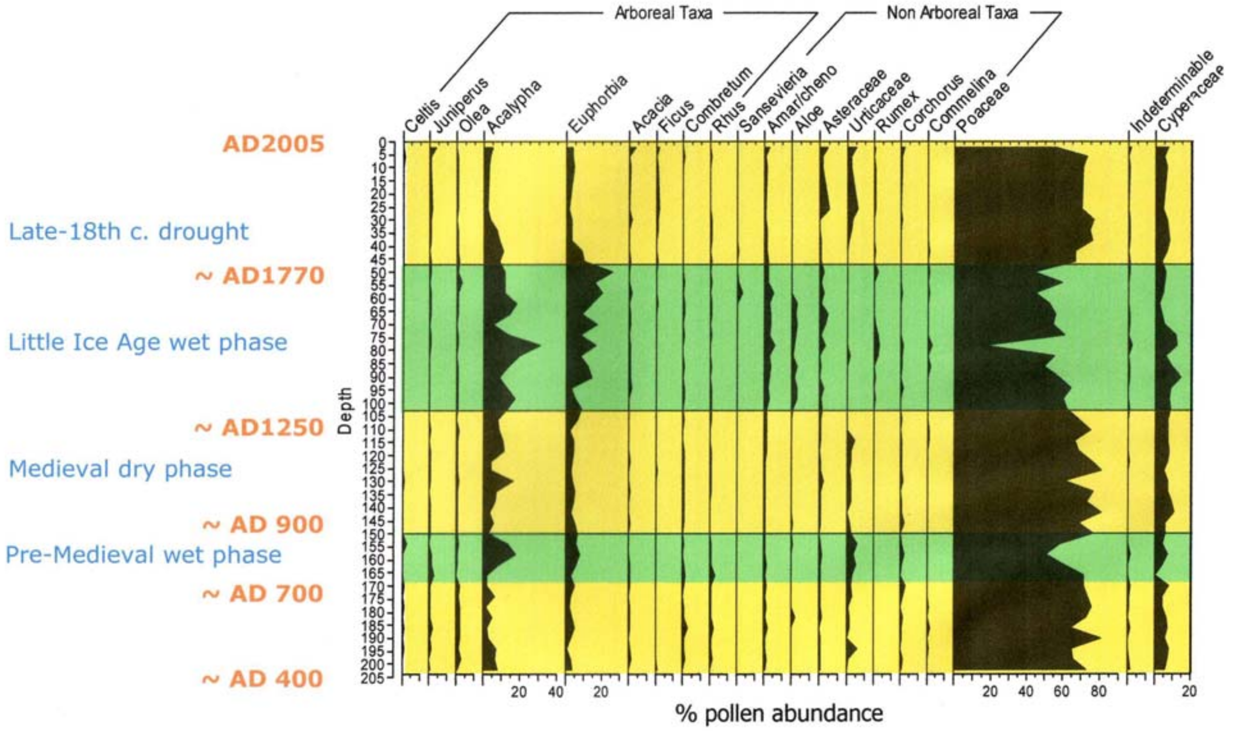

Figure 20. Preliminary vegetation reconstruction (1600 cal year BP to Present) for southeastern Kenya based on the % abundance of 19 selected plant taxa, as recorded in fossil pollen assemblages preserved in sediments of Lake Challa (Taita-Taveta district).

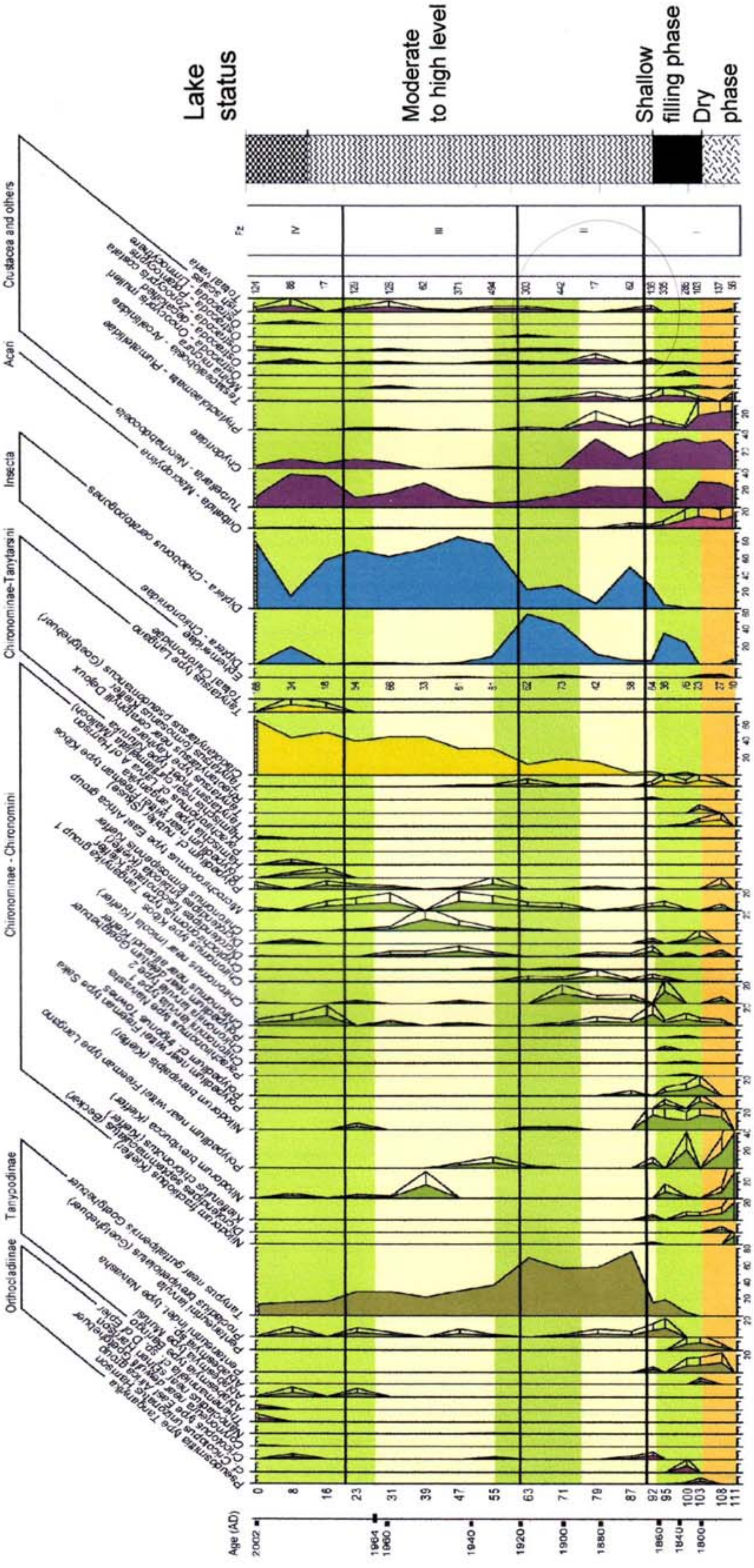

Figure 21. Fossil record of aquatic invertebrate communities in the pristine Lake Chibwera in the southern Lake George area of western Uganda, between the late 18th century and the present (2002). Highlights as in Figure 16. During and shortly after the late 18th-century drystand the local aqutic fauna was dominated by species inhabiting freshwater swamps and ephemeral lakes and ponds. Faunal response to moisture-balance variation since that time appears to be partly overprinted by a trend in lake development. Fz: Faunal Zonation.

Contrary to the pollen data from Lake Simbi, where relatively modest vegetation response to past climate change is overprinted by strong signatures of human impact (first by pastoralists and later by agriculturalists), Chibwera pollen data indicate a clear dominance of climate-driven vegetation change in this pristine (or at least semi-natural) landscape. Interestingly, even within the grass savannah landscape of the western Rift Valley, a few decades of mildly wetter weather (5-10% more rainfall), such as occurred during the early 20th century, can reduce grass pollen abundance almost by half (from 75% to 45%).

The multiple-proxy Chibwera record further illustrates how availability of solid independent data on climate-driven moisture-balance change can improve the information extracted from pollen data. For example, the herb *Solanum* appears to be naturally scarce in the Chibwera area, reaching significant abundances only during brief episodes of unusually wet conditions (zones Chib Ib and Chib III). It may thus be considered a trustworthy indicator of such conditions in an East African grass savannah habitat.

In contrast, Asteraceae reached peak abundances both during a known dry period (Zone Chib Ia) and a known wet period (Zone Chib III), suggesting that this pollen type comprises species with contrasting ecological requirements. If true, this would limit the use of this pollen type as a paleo-environmental indicator of specific habitat conditions. The families Amaranthaceae and Chenopodiaceae include many ruderal species, hence their common use as indicators of vegetation disturbance by humans. However, in the Chibwera record considerable restriction of the Amaranthaceae/Chenopodiaceae pollen type to Zone Chib Ia suggests that these plants responded naturally to severe late 18th-century drought by colonising the dry lake bed.

Task 3.2: Phytolyth analysis of ancient human impact on vegetation

Due to budget constraints on personnel, partner 4 has limited its contribution to fossil-diatom analyses (primarily Tasks 1.2 and 2.1). The phytolith analyses planned in CLANIMAE are now being executed by phytolith expert Dr. Julius Lejju of the Mbarara University of Technology (Uganda), at limited cost to this project.

Some important African food staples such as banana (*Musa*) produce insufficient pollen to be recorded in pollen preparations, but can be traced by means of their phytoliths (Lejju et al. 2005), which are preserved in fossil-diatom preparations. CLANIMAE aims to validate the use of fossil *Musa* phytoliths from lake-sediment records as paleoenvironmental indicator of banana cultivation, by quantifying the relationship between *Musa* phytolith abundance in the surface sediments of 25 Ugandan crater lakes, and the relative cover of banana plantations in their (small) catchments. This test is conducted by phytolith specialist Dr. J.B. Lejju of Mbarara University of Technology (Uganda), using surface-sediment samples collected in February 2007 and contemporary land-cover surveys within the crater catchments by CLANIMAE staff. These quantitative surveys estimated the % land cover occupied by 6 types of natural vegetation, 16 types of cultivated crops or plantations, and 4 types of fallow agricultural land (**Table 9**).

3.4 Work Package 4: Reconstruction of past water-quality changes

Task 4.1: Fossil diatom analyses

This task involves application of the newly developed calibration of the diatom/productivity relationship (Task 2.1) to fossil diatom assemblages extracted from the sediment records of our target study sites. Application of the new diatom-based phosphorus inference model will reveal both natural and anthropogenic changes in lake trophic status. Indeed, in relatively shallow fluctuating African lakes also natural, climate-driven lake-level decline tends to increase primary production and thus lake trophic status, either because new nutrient imports from the catchment are concentrated in a smaller water volume (Harper et al. 1993), or because of improved nutrient recycling from the hypolimnion and lake bottom (Verschuren et al. 1999), and decreased PEA (this report). CLANIMAE again exploits the paired 250-year reconstructions from Ugandan crater lakes Chibwera (pristine) and Kanyamukali (impacted by agriculture) to better differentiate the response of lake biology to such natural and anthropogenic eutrophication. This improved understanding can then be applied to the reconstruction of long-term water-quality changes in impacted lakes during the past 3000-3000 years. In Uganda, our principal target study site for this long-term reconstruction is Lake Katinda (Bunyaruguru district), where sedimentological proxies (Magnetic Susceptibility, % mineral matter) suggest human occupation dating back to ~1800 years BP.

Lake	**Kifuruka**	**Nyantonde**	**Kanyanchu**	**Kanyango**	**Mubiro**	**Kaitabarago**	**Ekikoto**	**Kanyamansira**	**Wandakara**	**Wankenzi**	**Kanyamukali**	**Mbajo**	**Njarajabana**	**Katinda**	**Mirambi**	**Kyasunduka**	**Nyamunsingere**	**Kyogo**	**Kako**	**Murabyo**	**Ibamba**	**Nyungu**
palm trees	-	-	40	-	-	-	-	8*	-	-	-	-	-	-	-	-	*few*	*few*	-	*few*	-	-
other trees	-	-	40	-	-	-	-	87	-	-	-	-	-	-	-	82	100	100	-	100	-	-
shrubs	-	-	13	-	-	-	-	8*	-	-	-	-	-	-	-	-	*few*	*few*	-	*few*	-	-
lianas	-	-	5	-	-	-	-	8*	-	-	-	-	-	-	-	-	*few*	*few*	-	*few*	-	-
ferns	-	-	2,5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*few*	-	*few*	-	-
grass savannah	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	8	-	-	-	-	-	-
pristine or secondary vegetation	**20**	**18**	**100**	**33**	**40**	**75**	**70**	**95**	**0**	**55**	**18**	**59**	**60**	**5**	**10**	**90**	**100**	**100**	**0**	**100**	**0**	**0**
banana	25	8	-	6	-	-	-	-	15	11	3	3	-	15	40	-	-	-	10	-	58	60
cassava	4	1	-	1*	2	-	-	-	*few*	-	-	-	-	2*	1*	-	-	-	30	-	2*	4
maize	4	40	-	2	1	-	-	-	17	10	1	2	5	8	9	1	-	-	4	-	2*	1*
potatoes	1*	1*	-	1*	-	-	-	-	5	1	*few*	-	-	2*	1*	-	-	-	20	-	2*	-
tea	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
gabbage	-	1*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
beans	1*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*few*	-	-	-
Eucalyptus	1	2	-	1	-	-	*few*	-	-	5	15	1	-	-	-	-	-	-	4	-	5	-
pine	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-
sugar cane	-	-	-	-	-	-	-	-	8	3	*few*	-	-	-	-	-	-	-	-	-	-	-
papaya	-	-	-	-	-	-	-	-	*few*	-	-	-	-	-	-	-	-	-	-	-	-	-
coco yam	-	-	-	-	-	-	-	-	-	-	*few*	-	-	-	-	-	-	-	-	-	2*	1*
cotton	-	-	-	-	-	-	-	-	-	-	-	-	-	45	-	4	-	-	-	-	-	-
sorghum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*few*	-	-	-
millet	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
coffee	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2*	-
cultivated crops +plantations	**35**	**52**	**0**	**11**	**3**	**0**	**0**	**0**	**45**	**30**	**19**	**6**	**5**	**70**	**50**	**5**	**0**	**0**	**70**	**0**	**65**	**65**
elephant grass/shrubs	39	*few*	-	45	20	-	-	-	55	-	45	25	34	25	30	5	-	-	25	-	20	35
recently cleared	5	22	-	8	-	16	-	5	-	14	-	-	1	-	10	-	-	-	-	-	13	-
burned	1	8	-	*few*	-	8	*few*	-	-	1	-	-	-	-	-	-	-	-	-	-	2	-
pasture	-	-	-	3	37	1	30	-	*few*	-	18	10	-	-	-	-	-	-	5	-	-	-
fallow land	**45**	**30**	**0**	**56**	**57**	**25**	**30**	**5**	**55**	**15**	**63**	**35**	**35**	**25**	**40**	**5**	**0**	**0**	**30**	**0**	**35**	**35**

Table 9. Percent land use/land cover in 22 Uganda crater lake basins, recorded in Aug. 2007 or Feb. 2008. This considerable detail allows Dr. Lejju to also calibrate the distribution of phytolith types derived from other cultivated plants (e.g., maize, oil palm) and natural vegetation difficult to differentiate in pollen preparations (e.g., Phragmites). Secondly, these land-cover data will be used to quantify the vulnerability of individual lakes to anthropogenic soil erosion and nutrient enrichment (a contribution to Task 1.1). For this purpose, the land-cover classifications are transformed into a lake-specific human-impact index (Hi). This index, a more detailed version of the anthropic index used in task 1.1, is the summed product of local land-cover fractions and a 'soil erosion susceptibility' factor specific to each type of natural and anthropogenic vegetation. The phytolith calibration study is pending: large numbers of phytoliths must be counted to achieve statistically meaningful results on the phytolith types of greatest interest.

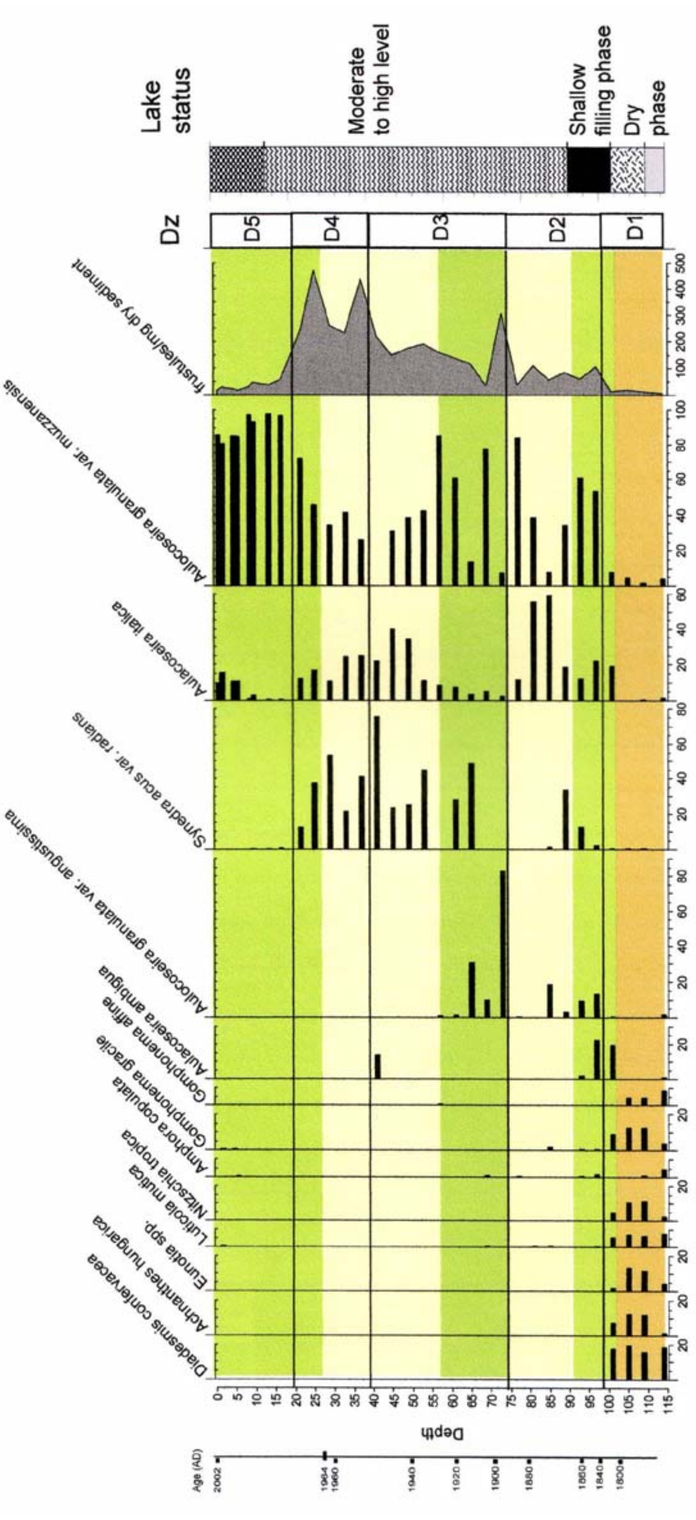

Figure 22. Fossil record of diatom communities in the pristine Lake Chibwera (southern Lake George area of western Uganda) between the late 18th century and the present (2002). Highlights indicate wet and dry episodes as in Figure 17. During the late 18th-century (near-)drystand the local diatom flora was dominated by epiphytic species inhabiting freshwater swamps and ephemeral ponds. Since then the diatom flora has been dominated by planktonic species, indicating a large open-water area. Diatom response to moisture-balance variation since that time is characterised by species turnover within the genus *Aulacoseira* (see text). Dz: Diatom Zonation.

In Kenya our target study site for long-term reconstruction is Lake Challa in southeast Kenya (CHALLACEA project, unpublished data). We will also strive to apply our diatom-based productivity inference model to existing fossil diatom records produced for climate reconstruction: Lake Naivasha in central Kenya (Verschuren et al. 2000a), Lake Victoria (Stager et al. 2005), and crater lakes Kasenda and Wandakara in western Uganda (Ssemmanda et al. 2005). At all these sites, parallel application of the Gasse et al. (1995) diatom-based salinity inference model will simultaneously reveal climate-driven changes in lake level and water chemistry.

Here we summarize fossil-diatom data from one of our method-validation lakes, the pristine savannah lake Chibwera, covering the last ~250 years (**Figure 22**). Diatom zone Chib D1 at the base of the Chibwera sequence, deposited during severe late 18th-century drought, is characterized by a diverse community of benthic-epiphytic diatoms (taxa belonging to *Diadesmis*, *Achnanthes*, *Eunotia*, *Luticola*, *Gomphonema*), consistent with a swampy remnant aquatic ecosystem surviving through this drought in the centre of a dried-out lake bed. Immediately following the early 19th lake-filling phase (starting ~1810 AD) most of these benthic-epiphytic diatoms either disappeared or reduced to very low abundances, indicating that Lake Chibwera never came close to drying completely again. In the past 200 years (diatom zones Chib D2-D5), the local diatom flora has been dominated by planktonic species (*Synedra ulna* var. *radians* and *Aulacoseira* spp.). Most notably we document a striking succession of species within the genus *Aulacoseira*, with *A. granulata* (sum of vars. *muzzanensis* and *angustissima*) fully dominant during known episodes of wetter climate (1890s-1930s; 1960s-1980s), and *A. italica* usually less common but approaching co-dominance during known episodes of drier climate (1870s; 1940s-1950s). A third species, *A. ambigua*, inhabited Lake Chibwera only during the early phase of early 19th-century lake filling, and again briefly in the 1950s, possibly coincident with the driest weather conditions of the 20th century. The Chibwera diatom record shows no evidence of increasing productivity or water-quality loss in recent decades, consistent with the undisturbed condition of savannah vegetation in Queen Elisabeth National park. Note that the relatively wet climate of the 1960s-1980s reflected in the dominance of *A. granulata* predicts that expansion of woodland/bushland vegetation at the expense of grasses will be recorded in the uppermost section of the pollen-based vegetation reconstruction (which is not yet available: **Figure 19**). Analysis of fossil-diatom assemblages covering the last ~250 years in the sediment record of the impacted lake Kanyamukali (not shown) has been completed, but interpretation awaits completion of the pollen-based vegetation reconstruction to permit proper distinction between pre- and post-impact periods.

Task 4.2: Stratigraphic analyses of aquatic plant macrofossils

The use of aquatic plant macrofossils for paleoenvironmental reconstruction in African lakes is still uncommon (Birks 2001), although many characteristic components of the African flora (*Ceratophyllum*, *Potamogeton*, *Najas*, and charophyte algae *Chara* and *Nitella*) are the same as in north-temperate lakes with similar habitat requirements of depth, transparency and nutrient availability. In the sediment record of fluctuating African lakes in the absence of human impact, fossil remains of aquatic macrophytes reflect climate-driven episodes of low lake level, when gently sloping shallow-water habitat amenable for macrophyte colonization expanded (Verschuren et al. 2000b; Verschuren 2001; Gouder de Beauregard et al. 2002). When the drainage basin of a shallow lake with well-developed aquatic macrophyte community is impacted by anthropogenic vegetation disturbance, the macrophytes are prone to suffer from reduction of water transparency due to enhanced influx of mineral soil. In reconstructing lake response to human impact, combination of information derived from sedimentological, fossil diatom and plant macrofossil indicators allows to control for natural water-balance effects on aquatic macrophyte abundance, and separate the effect of anthropogenic soil erosion on water transparency.

Identification of eight distinct aquatic macrophyte communities of in the Uganda crater lakes (the completed Task 1.3) establishes the ecological indicator value of the component species and is thus an important step in their application as paleo-environmental indicators of past habitat conditions. Considering the large sample requirements of plant macrofossil analysis, we plan to limit the study of their stratigraphic distribution in lake-sediment cores to selected episodes in the history of CLANIMAE target lakes, and work as much as possible with the sieved organic residue remaining after analysis of aquatic invertebrate fossils. Consequently, this task is mostly executed in phase 2 of the project.

Task 4.3: Paleoenvironmental calibration and stratigraphic analyses of non-pollen palynomorph microfossils (NPPs), including fossil fungal spores (*updated title*)

Non-pollen palynomorph microfossils (NPPs) are extensively used as paleo-ecological indicators in paleo-environmental reconstructions from peat deposits, lake sediments and archaeological features in Europe and North America, but to date their value as such has never been thoroughly explored for palaeoecological research in tropical Africa. In this project Task we aim to calibrate the ecological indicator value of African NPP morphotaxa in relation to local landscape variables (vegetation, land use, erosion, burning practices) and lake characteristics (morphometry, productivity, water chemistry) by means of an analysis if their diversity and distribution in the surface sediments of Ugandan crater lakes. The 25 CLANIMAE study lakes selected for this purpose are situated along a landscape gradient from naturally pristine or recently reforested to severely impacted by human land-use practices. Current vegetation cover and land use within each crater basin were mapped quantitatively (Table 9; see also under Task 3.2) and supplemented by data on the relative population density of large wild and domestic herbivores and other patterns of human occupation.

A first round of surface-sample analysis in the 20 study lakes yielded 9038 NPP fossils, of which 8749 (97%) could be assigned to one of 256 distinct morphotypes belonging to one of four major taxonomic groups: spores and other remains of fungi (218 morphotypes), spores of ferns and mosses (26 morphotypes), various resting stages of aquatic algae (12 morphotypes) and microscopic animal remains (13 morphotypes). This exceptionally high biodiversity (the fungal spores in particular) contrasts with the more modest number of NPP morphotypes that was found in at least three lakes. This may indicate a relatively high ecological specificity of individual morphotypes, and a need for additional counting to reduce the probability of chance occurrences. **Table 10** lists the most common 33 NPP morphotypes, of which at this time 18 can be assigned to a specific taxon at the genus or species level; other morphotypes have been assigned a code name pending more accurate identification. Preliminary comparison of NPP distribution patterns with environmental variables reveals that the occurrence of *Glomus* sp. (a mycorrhizal fungus living symbiotically in plant roots, occasionally with detrimental effects on plant growth) in lake sediments is positively related to soil erosion from agricultural activity, indicating its common association with cultivated crops.

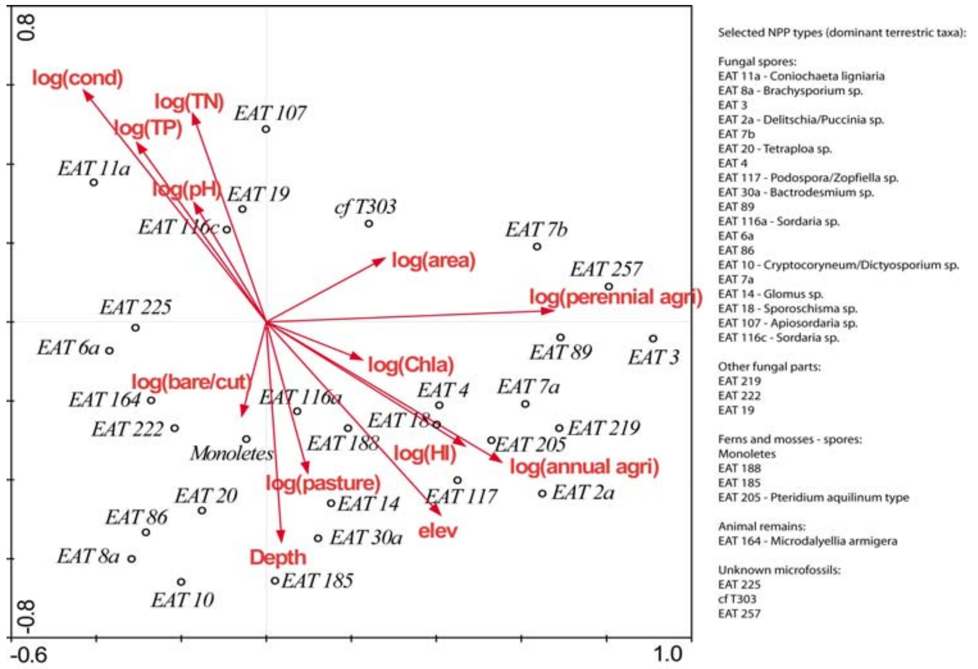

Figure 23. Direct Gradient Analysis (RDA) of the distribution of 30 major terrestrial NPP morphotypes in relation to diverse lake and landscape environmental variables, based on the composition of NPP assemblages extracted from surface sediments in 20 study lakes in western Uganda. RDA Axis 1 mainly captures variation in perennial/annual agriculture and general human impact (HI). Axis 2 captures variation in variables related to lake trophic status: total nitrogen (TN), total phosphorus (TP), conductivity and depth.

Direct Gradient Analysis (RDA) of the distribution of 30 major terrestrial NPP morphotypes in relation to diverse lake and landscape environmental variables (**Figure 23**) shows that the distribution of fungal types generally associated with human landscape disturbance (e.g. cattle breeding, crop cultivation, soil erosion), such as *Sordaria* sp. (EAT 116a, EAT 116c), *Podospora/Zopfiella* sp. (EAT 117), *Apiosordaria* sp. (EAT 107), *Delitschia/Puccinia* sp. (EAT 2a), and *Glomus* sp. (EAT 14), indeed all have a significant correlation with environmental variables linked to local human land use, such as annual agriculture and presence of pasture. They are also strongly associated with lake variables indicating high nutrient inputs, such as nitrogen (TN) and phosphorus (TP). *Coniochaeta ligniaria* (EAT 11a), common on decayed wood and animal excrements, can be linked to both phosphorus (TP) and lake-water conductivity.

Table 10. Overview of non-pollen palynomorph (NPP) microfossils extracted from the mid-lake surface sediments of 20 Uganda crater lakes spanning a large environmental gradient of water chemistry, terrestrial vegetation and intensity of human impact.

Fungal spores	**6328**
EAT 11a - *Coniochaeta ligniaria*	4288
EAT 8a - *Brachysporium* sp.	243
EAT 3	134
EAT 2a - *Delitschia/Puccinia* sp.	85
EAT 7b	84
EAT 20 - *Tetraploa sp.*	82
EAT 4	71
EAT 117 - *Podospora/Zopfiella* sp.	58
EAT 30a - *Bactrodesmium sp.*	55
EAT 89	47
EAT 116a - *Sordaria*sp.	46
EAT 6a	39
EAT 86	39
EAT 10 - *Cryptocoryneum/Dictyosporium* sp.	31
EAT 7a	29
EAT 14 - Glomus sp.	27
EAT 18 - *Sporoschisma* sp.	27
EAT 107 - *Apiosordaria* sp.	26
EAT 116c - *Sordaria* sp.	25
Other fungal parts	**336**
EAT 219	195
EAT 222	51
EAT 19	26
Ferns and mosses - spores	**626**
Monoletes	278
EAT 188	87
EAT 185	64
EAT 205 - *Pteridium aquilinum* type	81
Animal remains	**107**
EAT 164 - *Microdalyellia armigera*	64
Unknown microfossils	**209**
EAT 225	84
cf T303	53
EAT 257	33
TOTAL TERRESTRIC NPPs	**7606**
Algae zygospores-coenobia	**1143**
EAT 172 - *Botryococcus* sp.	730
EAT 174 - *Coelastrum* sp.	112
EAT 178 - *Pediastrum boryanum* var. *longicorne*	112
TOTAL AQUATIC NPPs	**1143**
Undetermined specimens	**289**
TOTAL NPPs	**9038**

This study is the very first direct calibration of the paleoecological indicator value of NPP morphotaxa, through a comparison of NPP abundance data from lake surface sediments with actual land-use and vegetation cover data. Its results may help to better distinguish between African vegetation changes caused by past human impact and natural, climate-driven vegetation dynamics.

3.5 Work Package 5: Data integration and valorization

Task 5.1: Geographical patterns of past climate and human impact

Scientists studying global patterns of past land use and land-cover change assume that prior to 300 years ago human impact on the East African landscape was limited, mainly because of very low population density (on average ~3% of today's value; Klein Goldewijk 2001). Also after AD 1700 the area of land under agriculture is thought to have expanded only very gradually. Strongly exponential increase in additional land clearance is a phenomenon of the past 60-70 years (Ramankutty & Foley 1999), primarily associated with the post-independence redistribution of land ownership and explosive population growth in recent decades (**Figure 1a**). This contrasts with the position held by many archaeologists and paleoecologists (e.g., Runge 1996; Robertshaw et al. 2004), who situate the start of anthropogenic forest clearance in equatorial East Africa about 2500 years ago, linked to the introduction of iron smelting by Bantu-speaking immigrants. Their evidence would suggest that the procedure of land-use researchers to hind-cast past land-use patterns in tropical countries using (poorly constrained) historical population estimates (e.g., Houghton 2003; IPCC 2007) must be re-evaluated.

However, many pollen-based vegetation reconstructions that were claimed to indicate early anthropogenic deforestation in East Africa are ambiguous, because analysts failed to adequately consider the possibility that natural, climate-driven episodes of prolonged drought would also reduce forest cover and expand grassland (Verschuren 2004; Ngomanda et al. 2005). Now that this natural climatic variability in rainfall and drought over the past several thousand years has been documented for both eastern and western portions of the East African plateau (Verschuren et al. 2000; Stager et al. 2005; Russell & Johnson 2005, 2007; **Figures 17-18**), we can, using the integrated paleoecological research method adopted by CLANIMAE, attempt to separate the effects of past human activities and natural climate variability on the terrestrial and aquatic ecosystems of East Africa.

Studies integrating the effect of anthropogenic vegetation disturbance in East Africa over large regional scales, such as the geochemical record of soil erosion in the Athi-Sabaki river drainage preserved in corals along the Indian Ocean coast (Fleitmann et al. 2006; **Figure 24**) or the fossil-diatom record of excess nutrient inputs to Lake Victoria (Verschuren et al. 2002; **Figure 25**) indicate that large-scale stripping of natural vegetation is indeed a relatively recent phenomenon, which started in the 1920s-1930s when completion of transport infrastructure (railroad network) allowed industrial-scale production of food crops for export. These results are supported by CLANIMAE data from Lake Simbi near Lake Victoria (**Figure 18**), which show that the onset of sedentary agriculture in this region dates to the 1920s, and was quickly followed by eutrophication of Lake Simbi (inferred from the appearance of *Spirogyra* cyanobacteria) due to enhanced nutrient inputs associated with soil erosion.

In the semi-arid eastern Rift Valley of central Kenya, major changes in aquatic productivity and water quality associated with natural water-balance fluctuation (Harper et al. 1993; Verschuren et al. 2000b) has long complicated the identification of unique human impacts on lake nutrient dynamics (Kitaka et al. 2001). A CLANIMAE analysis of changes in the rate of sediment accumulation in Lake Naivasha over the past 120 years (**Figure 26**) shows that since the mid-1980s mineral sediment deposition at the mid-lake coring site is exceeding the natural variability associated with climate-driven lake-level change, pointing to a general loss of the vegetation buffers which until then had limited soil erosion in the Malewa River drainage. Bessems (2007) presents similar data on drastically increased soil erosion in the Lake Baringo drainage basin, further north in the Kenya Rift Valley, in recent decades. In Lake Naivasha, the resulting enhancement of lake turbidity (decreased water transparency) already has a clear impact on local algal and zooplankton communities (Mergeay et al. 2004), and possibly its fisheries (Hickley et al. 2001).

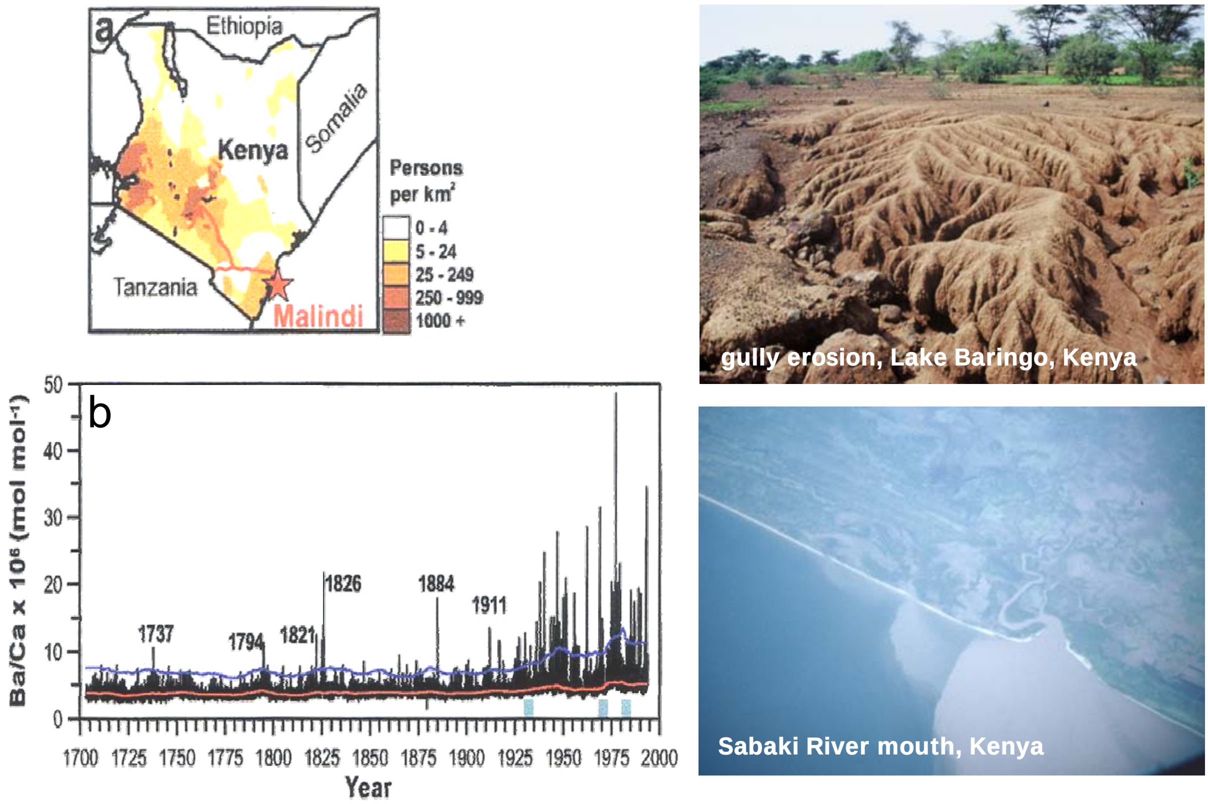

Figure 24. Barium/Calcium ratio in a *Porites* coral growing near the mouth of the Sabaki River in Malindi (Kenya) shows episodes of increased soil erosion in the relatively densely populated Athi-Sabaki River watershed, initially only during high rainfall events terminating climatic drought (e.g., the 1820s) but since the early 20th century mostly reflecting increasing demographic pressure and unregulated land use. From Fleitmann et al. (2007).

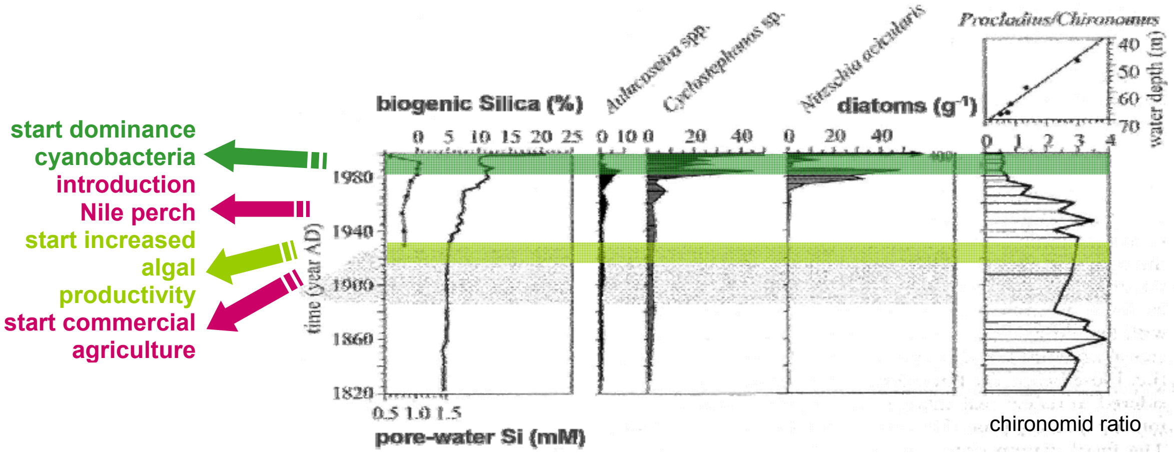

Figure 25. Sedimentary record of the eutrophication of Lake Victoria in relation to human impact on the lake and its drainage basin. Algal productivity (indicated by biogenic Si in fossil diatoms) started to increase in the 1930s in conjunction with human population growth (Figure 1a), and ~20 years before the introduction of Nile perch in the 1950s. Development of anoxic bottom waters started in the 1960s, as indicated by a shift towards anoxia-tolerant benthic insect larvae (Chironomidae). The switch to cyanobacteria (blue-green algal) dominance in the pelagic phytoplankton occurred in the mid-1980s when the dissolved Si concentration in Lake Victoria water dropped to limiting levels for new diatom growth, due to ~50 years of excess diatom burial in bottom sediments. From Verschuren et al., (2002).

However, pollen-based reconstruction of past vegetation dynamics in the Kenya Rift Valley (Lamb et al. 2003; **Figure 27**), coupled with the climatic water-balance reconstruction from Lake Naivasha (Verschuren et al. 2000; bottom panel in **Figure 17**) indicates that significant agriculturalist impact on regional forested landscapes (presumably mostly on the humid Rift Valley shoulders, e.g. the Kinangop Plateau) dates back to the 17th century AD, and was possibly related to population increases following the adoption of imported maize as a new staple food.

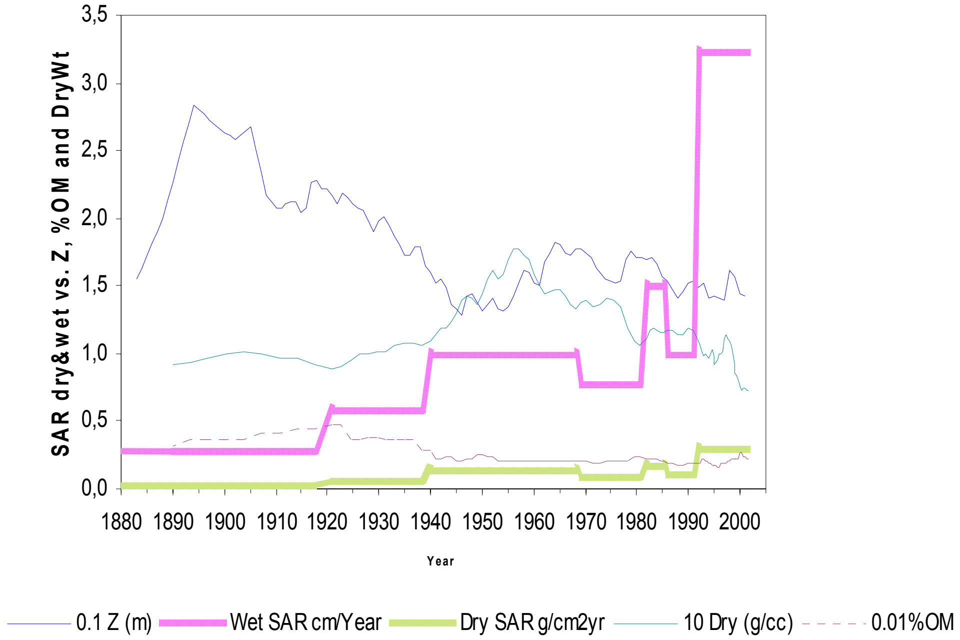

Figure 26. Dry and wet (i.e., linear) sediment accumulation through time in Lake Naivasha (Kenya) in relation to 20th-century lake-level fluctuation. Natural lake-level fluctuation (thin blue line) causes major variability in sedimentation rate (and turbidity), due to greater sediment focusing during lowstands (e.g., 1950s peak sedimentation). Sediment accumulation has exceeded natural variability only in recent decades, due to intensifying agriculture and removal of soil-erosion barriers in the Malewa River drainage.

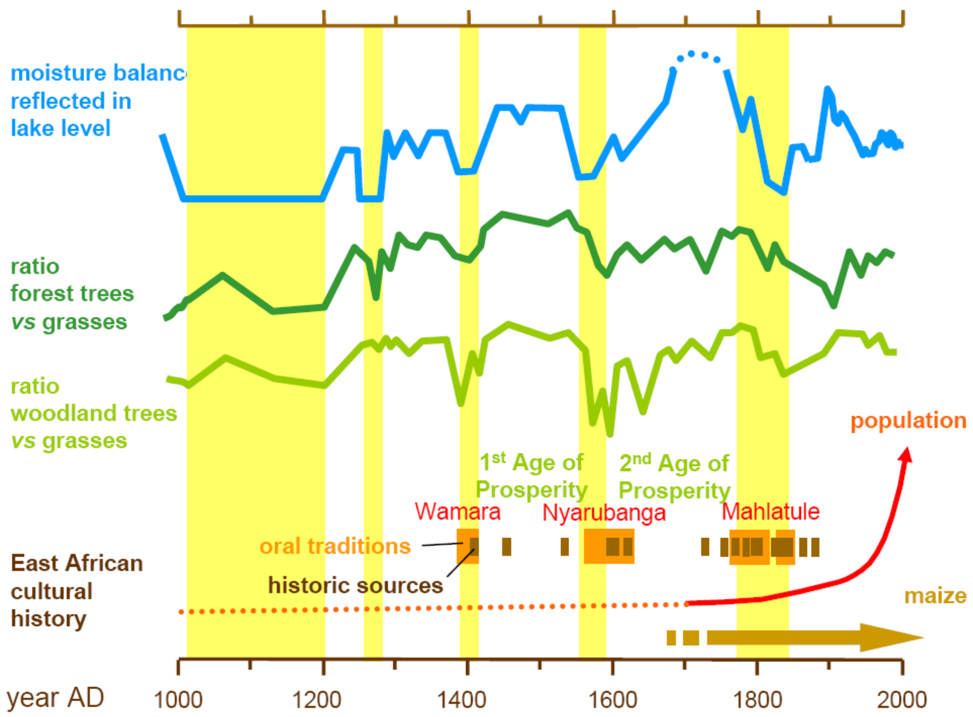

Figure 27. Environmental history of the central Kenya rift valley during the last 1000 years documented by lake-level and vegetation reconstructions at Lake Naivasha, in relation to the cultural history of the region. It can be seen that the wooded-to-grass savannah ecotine (light green line) is highly sensitive to decadal episodes of climatic drought (yellow vertical shading), and that the positive relationship between relative forest area (dark green line) and moisture balance (blue line) breaks down in the 17th century, approximately coincident with the first evidence of maize cultivation. Modified from Verschuren et al. (2000) and Lamb et al. (2003).

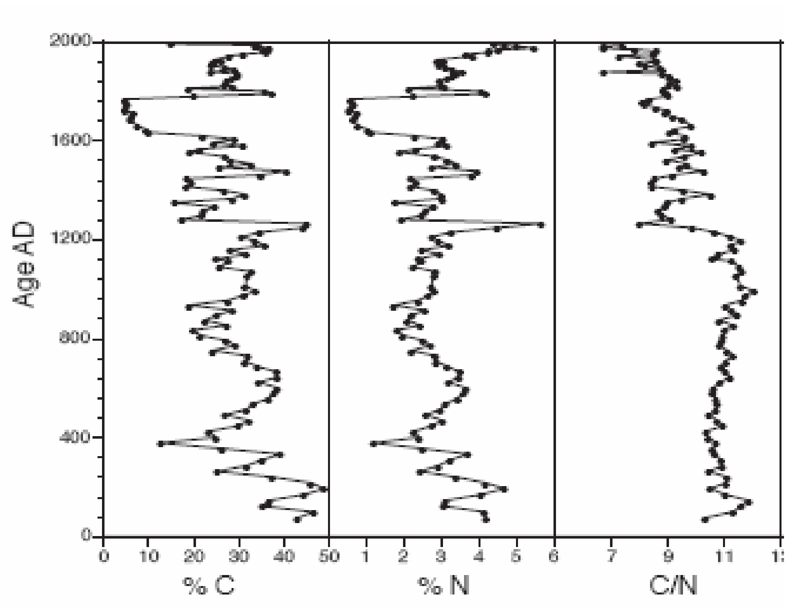

Figure 28. Percent organic carbon and nitrogen in the sediments of Lake Wandakara (Uganda) over the past 2000 years broadly reflect the concentration of organic matter, which is primarily influenced by effects of climate-driven lake-level fluctuation on organic preservation. The C/N ratio is primarily determined by the balance between aquatic algae and different types of terrestrial vegetation as the principal source(s) of this preserved organic matter. In this case, the marked shift to lower C/N values ~1150 AD is interpreted to indicate the shift to dominance of grasses and cultivated cereals marking the onset of human occupation of the crater basin. From Russell et al. (in press).

New vegetation reconstructions from CLANIMAE study sites in drier regions of Kenya (Simbi, Challa) do not show clear signatures of sedentary agriculture prior to the 20th century. The preliminary pollen diagram from Lake Challa (**Figure 20**) shows the evident dominance of climate-driven moisture-balance changes on the semi-arid, and until recently sparsely populated landscape of southeastern Kenya. In the Lake Simbi record (**Figure 18**) from western Kenya such climatic forcing of long-term vegetation dynamics is less evident, perhaps because the local terrestrial ecosystem was buffered against episodic drought by the shallow groundwater table surrounding Lake Victoria. What we do see are tentative signatures of intensifying land use by pastoralists starting perhaps 600 to 800 years ago (more precise dating is pending).

In sub-humid regions of western Uganda, significant forest clearing by agriculturalists has been established to date back 900-1000 years at least (e.g., Taylor et al. 2000, Ssemmanda et al. 2005). New data by CLANIMAE collaborators at Brown University (USA), based on biogeochemical proxies extracted from the sediment record of Lake Wandakara in the Kasenda lake district (Russell et al., submitted; **Figure 28**) support this timing, and highlight the relatively abrupt switch from pristine to heavily impacted vegetation in the immediate vicinity of this crater lake. Additional reconstructions from CLANIMAE target study sites in western Uganda planned during phase 2 of this project will permit evaluation of the significance of the documented patterns of vegetation change on a broad regional scale, as well as of the effects of this long history of human settlement on the aquatic ecosystem functioning and water quality of the Ugandan crater lakes.

Task 5.2: Project workshops, valorization, publication

To date the CLANIMAE project has resulted in three publications in print, in press or submitted and seven active participations at national or international scientific symposia. To help mobilize the African paleoscience community around the study of climate-human-ecosystem interactions, project leader Dr. Dirk Verschuren presented CLANIMAE's research objectives at the inaugural meeting of the East African Quaternary Association (EAQUA), held in Kampala (Uganda), 06-08/06/2007. CLANIMAE data and ideas also featured significantly in the contribution of the project leader to a 'think-tank' workshop inaugurating the international PHAROS research programme, which aims to integrate the existing IGBP-PAGES programmes HITE, LUCIFS and LIMPACS into the single overarching theme Past Human-Climate-Ecological Interactions, with new links to the ESSP core programmes IHDP, WCRP and DIVERSITAS. The PHAROS workshop was held in London (UK), 7-8/07/2008.

In the first 18 months of the project, the partners have organized 7 project meetings/workshops for exchange of research data, presentation of project results, and planning of field campaigns. These meetings were held at the following dates and locations:

20/12/2006: National Botanic garden, Meise (partner 4): planning meeting
02/02/2007: Limnology Unit, Ghent University, Gent (partner 1)
22/5/2007: Royal Museum of Central Africa, Tervuren (partner 2)
4/7/2007: Royal Museum of Central Africa, Tervuren (partner 2)
12/10/2007: FUSA Gembloux (partner 3)
30/05/2008: Limnology Unit, Ghent University, Gent (partner 1)

4. PRELIMINARY RESEARCH CONCLUSIONS

Research conducted during phase 1 of the CLANIMAE project permits the following conclusions:

8) We documented a significant relationship between morphometric parameters of the Uganda crater lakes (most importantly their depth), the associated seasonal mixing regime, and their vulnerability to eutrophication and water-quality loss for a given intensity of human land use in the crater basin. Specifically, lakes shallower than ~35 m are highly vulnerable, whereas lakes deeper than ~90 m are relatively resistant to eutrophication. Shallow Uganda crater lakes are usually mesotrophic, not oligotrophic in their pristine condition.
9) We documented the relationships between community species composition of aquatic macrophytes, diatom algae, and pelagic phytoplankton (partim) on the one hand, and relevant abiotic habitat characteristics on the other, across the full gradient of natural and anthropogenic environmental variability observed in freshwater Uganda crater lakes. Together with similar data on diverse groups of aquatic invertebrate fauna (Verschuren 1997, Rumes et al. 2005, Eggermont et al. 2006), these data allow increasingly complete understanding of environmental control on the biology of the Uganda crater lakes.
10) We have shown the feasibility of testing quantitative relationships between assemblages of plant phytoliths and fungal spores (buried in recently deposited surface sediments of African lakes) and a diverse range of environmental parameters related to human impact. This is an important first step towards their rigorous use as paleo-environmental proxies of ancient land use in the surrounding landscape.
11) We have shown that it is possible to produce mutually coherent reconstructions of long-term terrestrial and aquatic ecosystem dynamics from the sediment record of Uganda crater lakes. These reconstructions have a decadal to century-scale time resolution, the time scale most relevant to the history of human impact on the East African landscape, and its future.
12) Through multiple-proxy reconstructions of the 250-year environmental history of calibration lakes (pristine versus impacted), we have demonstrated the feasibility to i) reveal major pollen signals of terrestrial vegetation response to relatively modest 20th-century rainfall variability; and ii) distinguish between large natural variability in aquatic ecosystem dynamics and the lake's response to human impact.
13) Although these results raise the bar on identifying ancient evidence of modest human impact on the African landscape, documentation of terrestrial ecosystem changes by a combination of pollen, plant phytolith, fungal spore, and biogeochemical analyses will eventually allow to discern such signals with considerable certainty.
14) Preliminary reconstructions of the environmental history of CLANIMAE target sites thus far support isolated published data that significant human impact on the East African landscape (deforestation, crop cultivation) dates back to ~1000 AD in sub-humid portions of western Uganda, and to ~1700 AD in sub-humid portions of central Kenya. Semi-arid environments reveal tentative signatures of land use by pastoralists dating back up to 600 years, but the more intense vegetation and soil disturbance typical of crop cultivation, and the resulting water-quality loss in regional lakes, appears limited to the last 70-80 years (i.e., starting in the 1920s-1930s).

5. POLICY RECOMMENDATIONS

The CLANIMAE project meets both strategic and operational priorities of the 'Science for a Sustainable Development' (SSD) programme, because it directly addresses an important unresolved research question with critical relevance to the interlinked environmental policy issues of 1) sustainable economic development, 2) management of scarce natural resources, 3) biodiversity conservation, 4) the adaptation of vulnerable communities to global change, and 5) a more humane globalisation. Of CLANIMAE project results obtained in month 1-18, we consider the following most directly relevant to the strategic development of policy (by local stakeholders and their government) on water and land resource management in tropical Africa:

1) The significant relationship between morphometric parameters of Uganda crater lakes (most importantly their depth and the associated seasonal mixing regime) and their vulnerability to eutrophication and water-quality loss for a given intensity of human land use in the crater basin.
2) Our demonstration that it is possible to produce mutually coherent reconstructions of long-term terrestrial and aquatic ecosystem dynamics from the sediment record of African lakes, with two important quality aspects: i) the reconstructions have a decadal to century-scale time resolution, the time scale most relevant to the history ***and*** future of human impact on the African landscape; and ii) multi-proxy reconstructions permit clear separation of past natural and human impacts on ecosystems, offering clues to distinguish between the effects of those natural and human impacts as they are happening today.
3) CLANIMAE results support the isolated data previously available that significant human impact on the East African landscape (deforestation, crop cultivation) dates back to ~1000 AD in sub-humid portions of western Uganda, and to ~1700 AD in sub-humid portions of central Kenya. Semi-arid environments reveal tentative signatures of land use by pastoralists dating back up to 600 years, but the more intense vegetation and soil disturbance typical of crop cultivation, and the resulting water-quality loss in regional lakes, appears limited to the last 70-80 years (i.e., starting in the 1920s-1930s).

6. PUBLICATIONS / VALORISATION

6.1. Publications of the teams

Cocquyt C. & D. Verschuren (2007). De bijdrage van fossiele diatomeeën aan multidisciplinair onderzoek naar de lange-termijn dynamiek van Afrikaanse aquatische ecosystemen onderhevig aan klimaatverandering en historische antropogene invloed. *Diatomededelingen* 31: 29-32.

Lebrun J., Mahy G. (in press). Etude de l'écologie des communautés macrophytiques en vue de fournir des indicateurs paléo-environnementaux pour les lacs-cratères d'Afrique de l'Est. *Actes du colloque Ecoveg 4.*

Russell, J.M., S. J. McCoy, D. Verschuren, I. Bessems, M. Blaauw, Y. Huang (in press). Human Impacts, Climate Change, and Aquatic Ecosystem Response during the past 2,000 years at Lake Wandakara, Uganda. *Quaternary Research*.

Manuscript in advanced stage of preparation:

Audenaert L., Eggermont H., Cocquyt C., Baetens V., Rumes B., Verschuren D. (in prep). Aquatic ecosystem response to historical climate change and human impact in two shallow crater lakes in western Uganda. *Journal of Paleolimnology*.

6.2. Co-publications

Manuscripts in advanced stage of preparation:

Plisnier P.D., D. Verschuren, B. Rumes, C. Cocquyt, H. Eggermont, J. M. Russell, H. Hughes & L. André (in prep). Trophic levels and mixing of Ugandan crater lakes. *Limnology & Oceanography.*

Plisnier P.D., B. Rumes, C. Cocquyt, L. André & D. Verschuren, in prep. Recent warming recorded in Uganda crater lakes. *Hydrobiologia*.

6.3 Other research output

Active contributions to national and international research conferences:

Cocquyt C. & D. Verschuren, 2007. De bijdrage van fossiele diatomeeën aan multi-disciplinair onderzoek naar de lange-termijn dynamiek van Afrikaanse aquatische ecosystemen onderhevig aan klimaatverandering en historische antropogene invloed. Lecture presented at the Annual meeting of "Nederlands Vlaamse Kring van Diatomisten". Waternet, Amsterdam, The Netherlands, 8-9 June 2007.

Cocquyt C., Verschuren D., Eggermont H. Plisnier P.-D., 2008. Diatoms in Ugandan crater lakes as a tool to reconstruct past lake nutrient dynamics in East Africa. Lecture presented at the 20th International Diatom Symposium, Dubrovnik, Croatia, 7-13 September 2008.

Gelorini V., Verschuren D. & Van Geel B., 2007. Non-pollen palynomorphs as palaeoecological indicators for human impact on the East African landscape. Poster presentation at the Gents Afrika Platform Symposium 'Heritage and/as reproduction in Africa: outcomes and limits', 18 december 2007, Gent.

Gelorini, V., D. Verschuren en B. van Geel, 2008. Evaluating modern non-pollen palynomorph diversity in East African lake deposits: a potential palaeoecological tool for tracing human and climatic impact through time. Poster presentation at the 3rd International workshop on Quaternary Non-Pollen Palynomorphs, 25-28 juni 2008, Università degli Studi di Padova, Padova (Italy).

Lebrun J., Mahy G., 2008. Etude de l'écologie des communautés macrophytiques en vue de fournir des indicateurs paléo-environnementaux pour les lacs-cratères d'Afrique de l'Est. Oral communication at the Ecoveg 4 meeting, march 2008, Rennes (France).

Verschuren D., André L., Mahy G., Cocquyt C., Plisnier P.-D., Gelorini V., Rumes B., Lebrun J., Bock L., Marchant R., 2007. CLANIMAE: Climatic and Anthropogenic Impacts on African Ecosystems. BBPF conference on Biodiversity and Climate Change, 21-22/05/07, Brussel.

Verschuren D., André L., Mahy G., Cocquyt C., Plisnier P.-D., Gelorini V., Rumes B., Lebrun J., Bock L., Marchant R., 2007. CLANIMAE: Climatic and Anthropogenic Impacts on African Ecosystems. Poster presentation at the Gents Afrika Platform Symposium 'Heritage and/as reproduction in Africa: outcomes and limits', 18 december 2007, Gent.

7. PHASE 2 PLANNING & PERSPECTIVES

7.1 Work Package 1. Proxy calibration and validation

Task 1.2: Diatom-phosphorus inference model

Further exploration of the 48-lake dataset of modern diatom species distribution in relation to nutrient chemistry (TP, TN, SRP, DIN, DSi) and algal productivity (chl a) using multivariate statistical methods, with consideration of the relative importance of diatoms in local phytoplankton communities. Refinement of the diatom-based inference model for TP and/or chl a, as proxies for total primary productivity (lake trophic status). Using complementary datasets on phytoplankton composition and algal pigment spectra, identification of diatom indicators for algal communities dominated by other primary producers (cyanobacteria, green algae) that preserve less well in lake sediments.

Task 1.3: Environmental controls on aquatic macrophyte distribution

Based on multivariate statistical analyses of the 36-lake aquatic macrophyte dataset completed in phase 1, calibration of aquatic macrophyte species distribution in pristine versus impacted Ugandan crater lakes, so that the presence/absence and relative abundance of species in fossil assemblages can be used as proxy indicators of past trophic status and water transparency (~turbidity).

Task 1.5. Silicon and oxygen isotopes as environmental proxy

The heavier δ^{30}Si signature for higher Si contents observed in the disturbed Lake Katinda compared with the pristine lake Kyerbwato can not be explained by Si uptake by diatoms, suggesting an imprint of land use on Si fluxes to the lake. This is in agreement with the observation of only few diatoms in most Ugandan lakes (unpublished CLANIMAE data, partner 4), and in accordance with δ^{30}Si results on Cameroon banana fields suggesting that agriculture is likely to have an impact on the δ^{30}Si signatures of continental waters (Opfergelt et al., in press). In the soil-plant system δ30Si are driven both by formation of pedogenic clays (weathering) and preferential uptake of 28Si by plants, leading to the formation of opal phytoliths (e.g., De La Rocha et al., 2000; Ziegler et al., 2005; Georg et al., 2006; Opfergelt et al., 2006). It is therefore very likely that any change in land use by human activities (tree cutting, agriculture...) will modify the extent of biological and weathering Si isotopic fractionation. We propose to check this hypothesis by analysing surface and bottom water in a significant number (12) Ugandan lakes under a wide range of anthropogenic pressure (scheduled for sampling in August 2008). Both δ30Si and Ge/Si will be analysed since Ge has also be found to be discriminated by plant uptake and accumulated in clays (Derry et al., 2005; Blecker et al., 2007). This will allow us to better quantify the likely anthropic impact on silicon isotopes in lake DSi.

7.2 Work Package 2. Climate reconstruction: moisture-balance variation inferred from lake-level and water-chemistry changes

Task 2.1: Analysis of climate proxies in selected lake-sediment records

Partner 2. This task involves coupled measurements of δ18O (measured by the subcontractor Dr. P. Barker, U. Lancaster), δ30Si and Ge/Si on diatoms from Ugandan lake sediment records. Oxygen isotope analyses on these diatoms will provide insights on precipitation, evaporation and indirectly temperature which can be used to look into climatic controls on the Si cycle (Lamb et al., 2005; Mackay et al., 2008). As further isotopic enrichment takes place through preferential uptake of 28Si by diatoms (e.g. De La Rocha et al., 1997; Ding et al., 2004; Alleman et al., 2005), the Ge/Si ratio (which is not modified during incorporation by diatoms; Froelich et al, 1992) will be used as tracer to distinguish fractionation related to diatoms productivity from that s induced by anthropogenic activities. These analyses will be done on sediment cores from Ugandan lakes, selected on the basis of the results from Task 1.5 during phase 1). Comparative study can possibly be done on cores from lakes Challa in Kenya (Ge/Si; material made available by partner C), Tanganyika and Masoko (possible partnership with A. Cohen, U. Arizona or L. Bergonzini, U. Paris 9) which like the CLANIMAE project lakes have been extensively studied for paleoclimate and/or anthropogenic impacts (e.g. Barker et al., 2003; Cohen et al, 2005 and 2006; Delalande, 2008; CHALLACEA, unpublished data). Effort will be concentrated on the last 200 years in order to follow as close as possible the often significant anthropogenic impacts during this period. If diatoms are very well preserved in available Ugandan cores, this study will be extended to the last 2 millennia to contribute to the research question whether or not anthropogenic impact had an early start in eastern Africa.

Partner 3. Analysis of macrofossils of aquatic plants in function of climate reconstruction will concentrate on selected time zones in selected long lake records, to better characterize aquatic habitat conditions during lowstands. In the absence of human impact, fossil remains of aquatic macrophytes in deep crater-lake records reflect climate-driven episodes of low lake level, when gently sloping shallow-water habitat suitable for macrophyte colonization expanded. Combination of diatom, lithological and macrophyte data will allow to control for such water-balance effects on macrophyte abundance in more recent time slices, and hence separate the effect of anthropogenic soil erosion on water transparency.

Partner 4. Fossil diatom analysis of the sediment records of the calibration/validation lakes Chibwera and Kanyamukali has been completed during phase 1. Phase 2 will focus on long sediment records from selected lakes that are either still pristine (e.g., Karolero) or potentially possess a long history of human impact (e.g., Katinda, Simbi). As for the other records, 500 diatom valves will be counted per sediment horizon to permit quantitative treatment of species and community changes through time.

Task 2.2: Sediment dating, chronological framework

Extraction of high-quality ^{14}C dating targets from lake-sediment cores is labour-intensive, and will be de by a trained research technician (partner C) funded by this project. Using core scanning data on plant macrofossils from (Task 2.1, partner 3) as a guide, she will systematically scan and extract large plant macrofossils (>250 µm) from selected records, in order to construct the best-possible chronological framework for the long-term paleo-environmental reconstructions, and focusing on sites and episodes with the most critical need of additional age control. Preference is given to macrofossils of terrestrial plants or emerget aquatic macrophytes, which incorporated ^{14}C in equilibrium with the atmosphere. If unavailable, dating on bulk organic matter (primarily derived from aquatic algae) will be supplemented by paired terrestrial-bulk dating in selected time intervals in order to constrain the lake-carbon reservoir age, to be subtracted from all ^{14}C dates on bulk organic matter.

7.3 Work Package 3: Vegetation reconstruction

Task 3.1. Pollen analysis of past vegetation dynamics

Pollen analysis on the long-term sediment records of the Uganda lakes Katinda (disturbed) and Karolero (pristine forest) will be executed by subcontractor 3, under supervision of partner C; the invested man-months are for data quality control, interpretation in function of long-term vegetation dynamics, and presentation. If the sub-contracting budget allows, we also plan pollen analysis on a 250-year record from Lake Baringo (Kenya) by subcontractor 2; this would expand our regional coverage of historical land use further into northern Kenya.

Task 3.2: Phytolyth analysis of human impact on vegetation

This task will continue to be conducted by collaborator Dr. J. Lejju (Mbarara University of Technology, Uganda) on the same lake-sediment records which are subjected to analysis of pollen and diverse aquatic proxy indicators. The listed man-months invested by partners C and 4 are required for data quality control and joint interpretation.

7.4 Work Package 4: Reconstruction of past water-quality changes

Tasks 4.1-4.2-4.3: Fossil diatom, aquatic-macrophyte and fungal spore (NPP) analyses in relation to human impact

This task is contiguous with task 2.1 for analyses of fossil diatom and aquatic-macrophyte assemblages, except that it focuses on the impact of (relatively recent) human impact on water transparency and quality, including its biodiversity effects. Analyses will be performed with greater time resolution where desired, and on a greater number of lakes to differentiate between site-specific and general effects.

For fossil fungal spore (NPP) analysis, this task will translate during phase 1 acquired knowledge on the environmental factors (both natural and anthropogenic) influencing NPP distribution into reconstructions of historical land use. In combination with the information derived from fossil pollen and phytolith analyses, these will allow construction of a solid framework of the environmental history of individual lake basins (due to natural and anthropogenic causes) within which the documented historical changes in water quality can be evaluated.

7.5 Work Package 5: Data integration and valorization

Task 5.1: Geographical patterns of past climate and human impact

The relationship between each individual climate-proxy indicator and climate is typically complex, hence reliability of reconstructed climate and environmental history is improved by integrating data from different climate proxies (the multi-proxy indicator approach: Battarbee 2000). The diverse specialist expertise among CLANIMAE partners produces adequate redundancy in climate-proxy information from each sediment record, ensuring reliability and internal consistency of the resulting reconstructions for each study site. Comparative analysis of local reconstructions across the study region (including published and unpublished information from sites not studied by CLANIMAE) is an iterative process in which site-specific time series and the linked age models are progressively integrated to allow evaluation of the patterns, synchrony, and geographical coherence of past climate variation. Estimates for the peak amplitude of rainfall and drought events during recent millennia will be obtained by comparing the relative magnitude of reconstructed long-term hydrological changes with those which have resulted from historical rainfall variation. The second phase of this task is the integration of local vegetation and water-quality reconstructions at each study site with the regional reconstruction of past climate change to trace the evolution of human impact on the terrestrial and aquatic ecosystems of equatorial East Africa through space and time. From this, patterns in the timing and relative magnitude of pre-colonial (indigenous) impact can be related to regional patterns in water-resource availability and environmental stability. Project scientists from partners C, 2 and 4 are involved in this task, with substantial input from the principal investigator.

Task 5.2: Project workshops, valorization, publication

We initially planned project workshops at the end of year 3 and the end of the project in year 4, but now anticipate that the higher frequency of meetings during phase 1 (~once every 4 months) will be continued during phase 2. Final project deliverables include all project data and meta-data, plus their interpretation and the discussion of their implications in the context of fundamental or more applied research questions. We will submit the 4-dimensional CLANIMAE paleoclimate and paleoecological dataset (sites x time slices x proxy indicators x climate signal) to the public database at the World Data Center for Paleoclimatology (NOAA/NCDC, Boulder, USA; www.ncdc.noaa.gov/paleo). The completed project dataset on the timing and magnitude of historical land use in East Africa will be communicated to the IGBP-PAGES working group on 'Human Impacts on Terrestrial Ecosystems' (www.liv.ac.uk/geography/hite). This transfer will initially be subject to restrictions on pre-publication data mining by people and organisations unrelated to this project, as appropriate to avoid premature public presentation or pre-emptive publication. From the start of phase 2 all four funded project scientists will dedicate significant time to publication of project results.

The timing of writing and submission of research publications will be stacked, depending on the end dates of the project scientists' contracts (partners 2 and 3), PhD studentships (partner C) and complexity of the contributing datasets.

Task 5.3. Follow-up committee meetings

Given the complexity of this research field and its intricate links with cultural identity and socio-economic policy, dissemination of project results to target groups will need to be carefully planned, and allow for pre-dissemination comment (or critique) by the respective stakeholders represented in the follow-up committee. Given the multinational character of the CLANIMAE follow-up committee, we will organise the final follow-up committee meeting at the end of phase 2 as an open forum where diverse user communities will be invited to provide feedback on what, from socio-economic and conservation points of view, are the most significant aspects of project results. We will seek additional networking funds from START (SysTem for Analysis, Research and Training on global change), so that this user-committee meeting can be repeated in Uganda and Kenya. In Uganda the meeting would be hosted by NaFIRRI in Jinja, the NARO subsidiary responsible for lake fisheries and water quality. In Kenya, knowledge transfer of CLANIMAE project results can be best accomplished through the Pan-African START secretariat (PACOM) in Nairobi, which is comprised of scientists and policy-makers actively engaged in addressing issues related to global change and sustainable development. A most effective strategy for wide dissemination of CLANIMAE project results would be to provide START-PACOM officials with new research data to be featured in the United Nations Environmental Programme (UNEP) publications 'Africa Environment Outlook' and 'Global Environment Outlook'.