

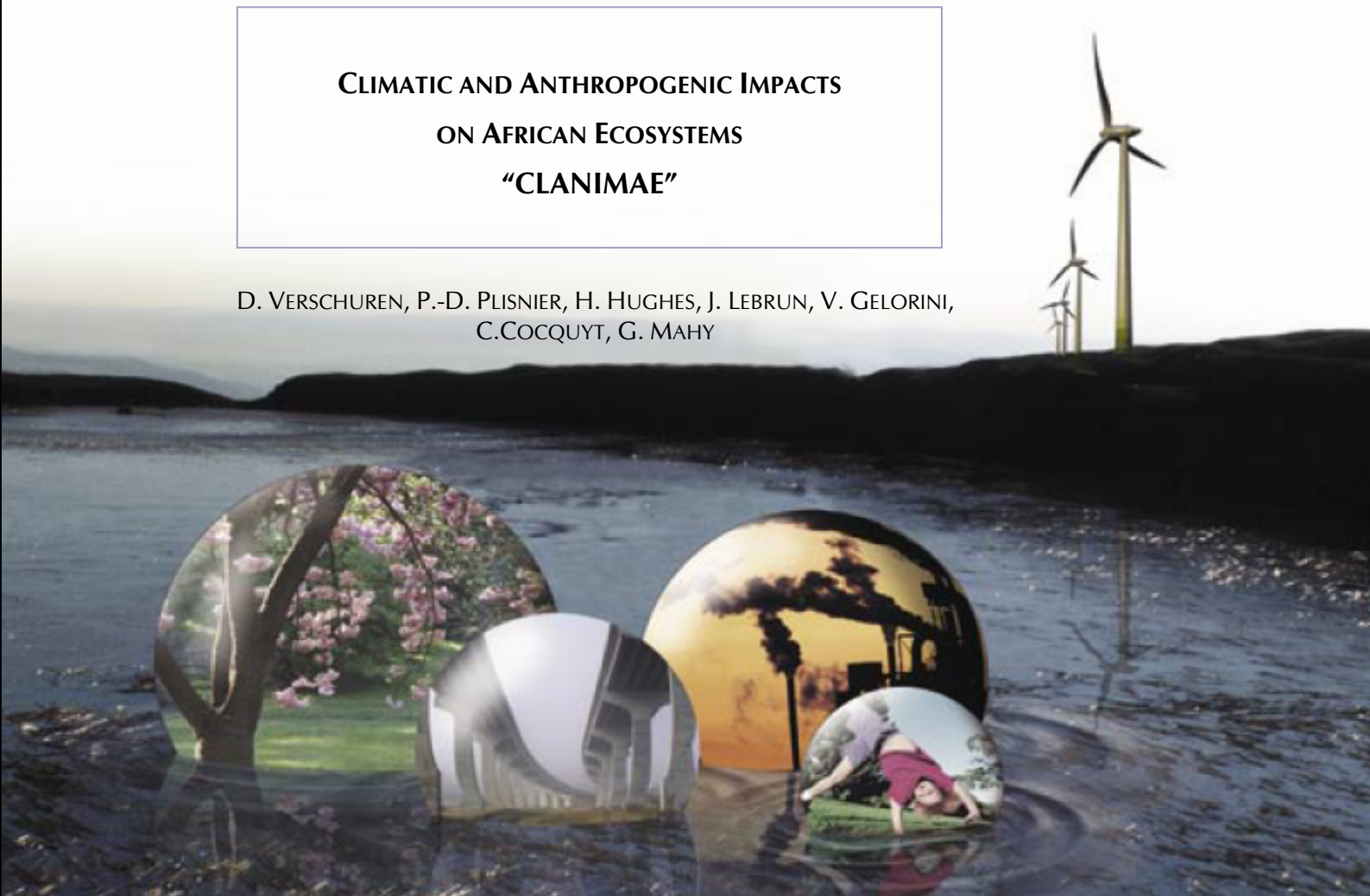
# SSD

SCIENCE FOR A SUSTAINABLE DEVELOPMENT



**CLIMATIC AND ANTHROPOGENIC IMPACTS  
ON AFRICAN ECOSYSTEMS  
"CLANIMAE"**

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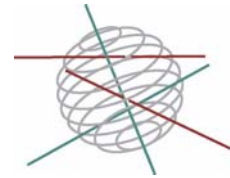
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ATMOSPHERE AND TERRESTRIAL AND MARINE ECOSYSTEMS 

TRANSVERSAL ACTIONS 



***Biodiversity***

FINAL REPORT PHASE 1  
SUMMARY

**CLIMATIC AND ANTHROPOGENIC IMPACTS  
ON AFRICAN ECOSYSTEMS  
“CLANIMAE”**

SD/BD/03A

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## 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-20<sup>th</sup> 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  $\delta^{30}\text{Si}$  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  $^{14}\text{N}^{16}\text{O}$  and  $^{14}\text{N}_2$  with the  $^{30}\text{Si}$  and  $^{28}\text{Si}$  peaks, thus enabling more accurate measurement of both  $\delta^{30}\text{Si}$  and  $\delta^{29}\text{Si}$ . Second, we gathered linked data on DSi concentration, temperature and diatom  $\delta^{30}\text{Si}$  and  $\delta^{18}\text{O}$  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  $\delta^{30}\text{Si}$  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 ‰  $\delta^{30}\text{Si}$  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 18<sup>th</sup>-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 20<sup>th</sup> 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 17<sup>th</sup> 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 20<sup>th</sup> 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.