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Reconstruction of Prehistoric Fire Regimes in East Africa by Lake Sediment Analysis

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A few years ago, analysis of data from the Total Ozone Mapping Spectrometer (TOMS) instrument aboard Nimbus 7 suggested seasonally enhanced concentrations of tropospheric ozone over the southern tropical Atlantic between South America and southern Africa from August until October (Fishman et al. 1990). For a long time, southern Africa and parts of South America had been considered to be clean air regions because of low industrial emissions. Thus, the causes of these seasonally elevated tropospheric ozone concentrations needed to be investigated. Every year during the dry season, large vegetation fires take place in the savannas, producing significant emissions of trace gases to the atmosphere (Andreae 1991). Simultaneous occurrences of high ozone values and vegetation fires in both continents were observed and a connection between both phenomena was proposed. The SAFARI-92 experiment (Southern African Fire-Atmosphere Research Initiative) confirmed that high tropospheric ozone concentrations are the consequence of seasonal vegetation fires in the tropics (Andreae et al. 1994).

The reconstruction of Quaternary fire regimes will be helpful in clarifying whether high ozone concentrations were also present in the past. Our understanding of the role of vegetation fires in ecosystems has improved over the year, but little is yet known about past fires, especially in the tropics and subtropics. The 1994 NATO Advanced Research Workshop "Sediment Records of Biomass Burning and Global Change" also made clear that there are still many uncertainties (Clark et al. 1996).

Vegetation fires are documented since the Devonian (Francis 1961). In the further development of the earth's history, fire was established as a component of the ecosystems in many regions of the world. The use of fire by hominids has been confirmed for the last 1.5 million years (Brain and Sillen 1988).

Cores of lake sediment deposits contain highly useful stratigraphic sequences. Sedimentary charcoal is a product of vegetation fires indicating former fire occurrences. Details such as the number and the intra-annual timing of fires, however, are generally unknown (Clark and Robinson 1993). For the reconstruction of late-Quaternary fire regimes in East Africa, one lake sediment (F-core) recovered from Lake Mobutu Sese Seko, Uganda, was analysed to determine its content of charcoal particles. Because fire regimes are characterized by a combination of climate features, fuel types, and anthropogenic influences, additional information on environmental conditions during the last 30 000 years was necessary to interpret the changing frequencies of charcoal particles. Therefore, in order to outline the state of knowledge of environmental conditions during the late Quaternary, the second part of this work provides an extensive review and interpretation of the historic and prehistoric climate and vegetation, as well as the anthropogenic effects. Our results suggest a correlation between changes in climate and vegetation in savanna biomes and the fire activities in East Africa.

Technical Description

Collection Site

Between 1960 and 1970 several sediment cores were recovered from East African lakes by D. A. Livingstone (Duke University, Durham, North Carolina, United States). Lake Mobutu Sese Seko (formerly Lake Albert) is located at the West Rift Valley at the border of Uganda and Zaire between 1°03′ to 2°15′N and 30°22′ to 31°24′E. Today, the surface of the lake is 690 m above sea level, and the maximum water depth of 58 m is near the western shore of the lake (Harvey 1976). The tributaries feeding the lake are the Semliki River discharging form the south and the Victoria Nile discharging from the east side of Lake Victoria. The most important outlet is the White Nile at the northern end of the lake.

In 1971, the F-core investigated was taken by T. J. Harvey, under the guidance of D. A. Livingstone, from the northeastern part of the lake at 01°50.1′N and

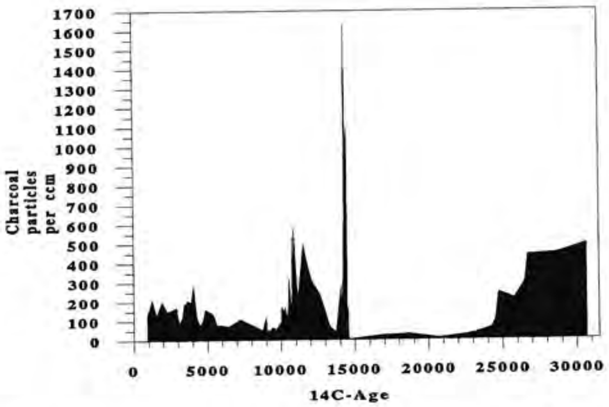

Figure 52.1 Number of charcoal particles per cm^3 within the F-core from Lake Mobutu Sese Seko, Uganda, during the last 30 000 years (from *Weiss*, 1995)

Table 52.1 Depths of charcoal samples within the F-core, Lake Mobutu Sese Seko (Uganda)

Sampling step	Depth of the samples in cm
1	17, 51, 179, 306, 324, 358, 486, 613, 631, 665, 793, 917
2	11, 34, 115, 242, 396, 550, 648, 729, 824, 855, 886
3	10, 14, 21, 25, 30, 42, 83, 210, 351, 441, 518, 590, 635, 640, 644, 652, 656, 661, 697, 761, 808, 840
4	32, 38, 40, 59, 67, 75, 99, 195, 315, 377, 419, 570, 611, 612, 612.5, 632, 642, 646, 650, 654, 659, 816, 848
5	33, 36, 47, 55, 63, 79, 147, 187, 274, 320, 386.5, 425, 430, 436, 463.5, 502, 580, 622, 645, 651, 653, 655, 660, 820, 851.5

31°10.2′E. The core has a length of 917 cm and was recovered with a "Kullenberg Sampler" at ca. 46 m water depth. In 1991 this core was investigated by Sowunmi for pollen. In 1995 we investigated the F-core for charcoal particles. A separate core (G-core) was studied paleolimnologically by Harvey (1976).

Sampling

Samples were taken in five successive steps. During the first step, samples were taken arbitrarily from the core. After treating the samples of the first step in the laboratory, the charcoal particles were counted. The samples for the next steps were chosen at peaks of distinct changes in particle frequencies found in the previous step. This procedure was repeated four times, and a total of 93 samples were taken along the entire length of the core. Finally the results of all five steps were evaluated (figure 52.1). Table 52.1 shows the depths of all samples.

Table 52.2 ^{14}C-data of the sediment core (F-core) from Lake Mobutu Sese Seko (Uganda)

Depth of ^{14}C samples (cm)	^{14}C-age (year BP)	Laboratory no.
35–39	3370 ± 250	Gif-6694
140–150	8750 ± 400	Gif-6695
450–460	10 980 ± 260	Gif-6696
658–673	14 700 ± 260	Beta-9901
902–907	29 900 ± 750	Gif-6698

Age Determination

Five radiometric (^{14}C) data were available to determine sedimentation rates and to allocate charcoal samples accordingly (table 52.2).

Sample Treatment

Sediment samples were heated in a water bath with distilled water, potassium hydroxide (KOH), hydrochloric acid (HCl), and hydrogen fluoride (HF), and centrifuged after each step.

Samples were then sieved through a 125 μm-mesh sieve to remove particles <125 μm. The residue contained quartz, organic pieces, and charcoal particles $\geq$125 μm. The particles were recognized clearly and counted with the help of a binocular.

Results

Charcoal Concentrations

Charcoal counts and age determination of the sediment samples provided a record of charcoal concentration in the sediment column for the last 30 000 years (figure 52.1). Five epochs are distinguished:

1. High charcoal concentrations occur between 30 000 and 26 000 B.P. followed by a subsequent rapid decrease.
2. Between 23 000 and 14 800 B.P. concentrations drop to minimal values.
3. Several oscillations with sometimes very high charcoal abundances occur in the late glacial period from 14 800 to 10 000 B.P.
4. The first half of the Holocene, up to 4000 B.P., is characterized by moderate concentrations.
5. A slight increase occurs over the last 4000 years.

Fire in African Savanna Biomes

The interpretation of the charcoal concentrations is based on the ecological interconnectedness of fire and vegetation in African savannas. Long before hominids were able to control fire for their own use, vegetation fires were a natural component of the savanna ecosystems in southern African and had considerable influence on vegetation dynamics and composition. Fire return intervals in African savannas average one to three years. The fire return interval depends on the amount of precipitation and the duration of the dry season. Areas with relatively high rainfall burn nearly every year, whereas those with moderate to low moisture are influenced by fire at longer intervals (Menaut et al. 1991).

Most of the biomass consumed by savanna fires consists of grasses. Adult trees are rarely affected by fires, because most of the tree species are fire resistant. Only occasionally will the cambium be killed and result in mortality of the whole tree. The younger trees are not yet fire resistant, and most tree seedlings will be destroyed completely during each fire. They require a longer regeneration period than grasses, which regrow within a few weeks after a fire.

Interpretation by Comparison with Other Paleoenvironmental Information

Apart from astronomical forcing, changes in the atmospheric content of CO_2 and other greenhouse gases played an important climatic role during the Quaternary (Barnola et al. 1987). The climate changes of glacial/interglacial cycles altered vegetation composition, which in turn, influenced past fire regimes. The coldest epochs in Africa were at 420 000 B.P. and 16 000 B.P. The warmest period was during the last interglacial, approximately 125 000 years ago, when temperatures were slightly higher than they are today (Prell et al. 1979; Jouzel et al. 1987). In the tropics the temperatures were ca. 2°C higher between 140 000 and 116 000 B.P. than in the Holocene (Delmas 1992). Temperature fluctuations as manifested in the Vostock temperature record (Jouzel et al. 1987), as well as CO_2 and CH_4 concentrations (Barnola et al. 1987; Chappellaz et al. 1990), and the $\delta^{18}O$-values of the European Greenland Ice-Core Project (GRIP) (Dansgaard et al. 1993), correspond to each other and show significant agreements with other environmental oscillations (Delmas 1992). The $\delta^{18}O$-values of GRIP (Dansgaard et al. 1993) correlate very well with the results of the $^{18}O/^{16}O$ ratio of an equatorial Pacific sediment core from Shakleton and Opdyke (1973). All parameters mentioned reflect distinct temperature changes during the last glacial/interglacial transition at ca. 15 000 B.P.

In eastern Africa a cooler climate also prevailed during the last glacial maximum. The temperatures in the lowland tropics were reduced between 2°C to 11°C (Hamilton 1972; van der Hammen, 1974; Flenley, 1979b), and the former glaciation of Mt. Kilimanjaro and Mt. Kenya can be reconstructed by the traces of firnlines, that is, the limits of net accumulation and net ablation of the former glaciers. Even today there remain small ice caps on these mountains (Hamilton 1982).

The altitudinal shifting of the ice caps of tropical mountains during the glacial/interglacial periods led to repeated vegetation changes. Several lines of evidence show that these changes took place also in the lowland tropics (Flenley, 1979a). Livingstone (1971; 1975; 1982), Coetzee (1967), Agwu and Beug (1984), Maley (1991), Schulz and Pomel (1992), and Neumann and Ballouche (1992) reconstructed the ancient vegetation of equatorial and southern Africa mostly by pollen analysis. Expansion and shrinking of savanna and forest areas accompanied temperature and moisture changes between the glacial and interglacial periods. As a result, different fire activities established themselves over time.

The earliest natural vegetation fires are documented around 350×10^6 years ago (Francis 1961; Clark and Robinson 1993). They became an important part of the ecosystem development in many regions of the world. Savannas—defined as a vegetation type with more or less continuous grass layer and with various components of trees and bushes—have existed since the Eocene, as evidenced by the first occurrence of pollen of tropical *Poaceae* during this epoch (van der Hammen 1983). Also, fire scars on stems of savanna tree species show that savanna fires have occurred for at least 10×10^6 years (Dechamps and Maes 1990).

Pollen analysis from southwestern Uganda suggests that it was cool and dry from 38 000 to 32 000 B.P., slightly warmer and more moist between 32 000 and ca. 21 000 B.P., and very dry and cold during the last glacial maximum (Taylor 1988). A sharp decline in temperature began at 28 000 B.P. attaining the lowest temperatures between 20 000 and 12 000 B.P. (Hamilton 1982; van der Hammer 1983; Hamilton and Taylor 1991).

Between 29 000 and 25 000 B.P. the pollen spectra indicate moist and dry forest species Sowunmi (1991). High- and medium-altitude forests shifted down the slopes during glacial periods. The high percentage of pollen from lowland savannas, thicket and bushland speaks for a well-developed dry savanna and rather poor forest cover. The high percentage of aquatic and swamp pollen indicates well-established swamp vegetation at the shore of the lake (Sowunmi 1991). Between 30 000 and 25 000 B.P., the high number of charcoal particles may reflect more frequent vegetation fires due to extended grasslands. The lake level of Mobutu Sese Seko was as high as it is today. There was a slow reduction of the lake level from 25 000 to 18 000 B.P. causing it to fall below the outlet, and the lake became closed due to decreasing rainfall (Harvey 1976). Between ca. 25 000 to 22 000 B.P., *Poaceae* and charcoal decreased dramatically (Sowunmi 1991). There was also a reduction in the variety and amount of pollen from aquatic and swamp vegetation and other plant species between ca. 22 000 to 15 000 B. P. The most striking changes were in the pollen quantity of *Poaceae* and *Cyperaceae*, which declined continuously until 14 700 B.P. (Sowunmi 1991). The seasonal shift of the Intertropical Convergence Zone (ITCZ) was less distinct at 18 000 B.P. The subtropical high-pressure areas were diminished so that colder sea water could enter the equatorial zones. This led to reduced oceanic evaporation and, consequently, lowered precipitation (Nicholson and Flohn 1980; Shaw 1985). Decreased alkalinity from 18 000 to 14 000 B.P. suggests the level of Mobutu Sese Seko rose again (Harvey 1976). This is in contradiction to the reduced vegetation in the catchment of the lake, which is reflected by the grass pollen distribution in the F-core (Sowunmi 1991), and by the lowest values of charcoal particles between ca. 22 000 and 14 000 B.P. The period of open lake conditions during the glacial maximum is questionable because, in general, lake levels in equatorial Africa dropped until 15 000 B.P., and in East Africa until 13 000 B.P. (Kendall 1968; Street and Grove 1979; Street-Perrott et al. 1989). Stager et al. (1986) have not found evidence for an intensive humid phase during the last glacial maximum.

The period between 14 000 and 10 000 B.P. is characterized by several climatic and vegetational changes. At ca. 14 800 B.P., the climate shifted, and a highly-diversified vegetation developed where *Poaceae* were favored compared to other plant families (Weiss 1995). This is indicated by the strong peak of *Poaceae* pollen that occurred at 14 800 to ca. 14 000 B.P. Charcoal particle distribution shows a simultaneous strong peak. In the following millennia, the number of charcoal particles shifted several times from higher to lower levels. This corresponds with two more pollen analyses that show a similar fluctuating distribution of *Poaceae* pollen in the late glacial period, based on the P-2-core from Lake Victoria (Kendall 1968) and the 3PC-core from the southern part of Lake Mobutu Sese Seko (Ssemmanda and Vincens 1993). *Poaceae* pollen in the F-core decreased continuously through the end of the Pleistocene.

The late glacial period from 12 000 to 10 000 B.P., slowly turned warmer (Livingstone 1967; van der Hammen 1983), interspersed by many cooler periods and a short glacial epoch from ca. 11 500 to 10 500 B.P. (Hamilton 1982; Mahaney 1987; Delmas 1992). The lake levels in Africa rose during this time (*COHMAP* 1988; Street-Perrott et al. 1989). The level of Lake Mobutu Sese Seko was low between 14 000 and 12 500 B.P. From 12 500 to 5000 B.P., the lake level was similar to its level 28 000 years ago due to higher inflow (Harvey 1976).

Without taking into account the breif fluctuations of the vegetational composition in late glacial time, the general tendency is for *Poaceae* pollen to decrease. To the same degree that *Poaceae* declined, the woody vegetation expanded (Kendall 1968; Sowunmi 1991; Ssemmanda and Vincens 1993).

Precipitation increased and average temperatures rose at the beginning of the Holocene (Hamilton 1982; Taylor 1988) resulting in the expansion of forest cover in East Africa (Kendall 1968; Sowunmi 1991). Between 10 000 and 8000 B.P. the seasonality became more prominent and the ITCZ migrated further from the equator during summer and winter. Rainfalls increased due to increasing oceanic evaporation (Nicholson and Flohn 1980; Shaw 1985). The warmest and wettest episode was between 8000 and 7000 B.P. (Kutzbach and Street-Perrott 1985). Below the closed canopy of tropical forests, little or no continuous layer of grasses and herbs exist. Tropical evergreen rain forests are rarely combustible, because of the lack of surface fuels and the moist microclimate. Tropical semideciduous lowland rainforests and tropical deciduous moist forests also burn less frequently than do savannas, depending on crown coverage and the seasonality of the climate. These climatic influences critically shaped the vegetational conditions until 4000 B.P. and may have caused reduced fire activity and fewer charcoal particles.

Since 5000 B.P. a reduction in precipitation occurred (Harvey 1976) without decreasing temperatures (Hamilton 1982). The level of Lake Mobutu Sese Seko dropped at ca. 5000 B.P. to its modern state (Harvey 1976). Increased grassy and decreased woody vegetation, prevailed in East Africa in the last 2000 to 3000 years (Kendall 1968; Livingstone 1975, Hamilton et al. 1989). The drier climate in the last millennia may have led to higher fire activity, which is reflected by the slight increase in the number of charcoal particles. Increased use of fire by more settled human populations may also have caused a higher occurence of fires.

At the transition from Pliocene to Pleistocene, savanna areas expanded due mainly to a drier climate and to a lesser degree, human influences (Kershaw et al. 1996). At ca. 1.5×10^6 B.P. hominids left their forest habitat and settled in the open savanna landscapes (Clark 1970; 1976). As the populations of hominids grew, they rapidly reduced the number of megaherbivores in their African savanna habitats. Hominids, therefore, had to shift their hunting activities to the smaller, but quicker ungulates of the savannas (Schüle 1990a). The earliest evidence of fire use by hominids is from the Swartkrans Cave in South Africa, 1.5×10^6 B.P. It is not known whether hominids were able to produce fire or were only tending fire (Brain and Sillen 1988). However, it is assumed that hominids used fire as a hunting tool. At about 30 000 B.P., nearly every biome was occupied by *Homo sapiens sapiens* (Clark 1970). In the early Holocene, intense settlement took place in Ethiopia and in the southern part of the Sahara where the first agricultural systems were established (Hamilton 1982; Sutton 1974). Before ca. 5000 B.P., when the climate became drier, farmers of the southern Sahara moved to equatorial Africa, where moister conditions made agriculture easier (Clark 1976; Neumann 1989). Pollen of secondary tree species in the southwest of Uganda, which in former times was limited to occasional natural disturbances, appeared more frequently (Hamilton et al. 1989). The forests became more open as more agricultural and pastural land was needed. The repeated peaks of *Poaceae* found by Hamilton et al. (1989) are interpreted by the authors to be caused by secondary grasslands. In the lower elevation around Lake Mobutu Sese Seko and Lake Victoria, the vegetation is dominated by lowland savanna formations and evergreen and semievergreen thicket and bushland. More than 80% of the modern flora in this area has been altered by anthropogenic influences (Sowunmi 1991). The mountain ranges of nearly all elevations in East Africa were burned periodically over a long time for pasture management (Flenley 1979b). Hunters and gatherers in Central Africa became agriculturalists in the second half of the Holocene and used fire as an efficient tool for agriculture, hunting, and many other purposes, and they still do today (Flenley 1979b; Hamilton 1982; Hamilton et al. 1986; 1989; Schüle 1990b).

Ultimately, it cannot be shown whether climate change or human activities has had more pronounced effects on East Africa's vegetation. Palynologists believe mainly that anthropogenic influences had a dominating influence on the ecological development during the last millenia (Sowunmi 1991; Schulz and Pomel 1992; Pyne 1993; Kershaw et al. 1996).

Conclusions

The changes in charcoal frequencies during the last 30 000 years found in the F-core are the result of changing environmental conditions. The comparison of charcoal particles distribution with data from the paleoecological literature shows ecological coherences between the recurrence of vegetation fires and the corresponding climatic and vegetational conditions. The interpretation is based primarily on the antagonism between grass and woody vegetation and the alternating extension of grasslands and forests in the African savanna biome. Varying abundances of charcoal particles do not allow any quantitative conclusions; however, a rough approximation of former fire regimes in East Africa is possible by interpreting the charcoal particle depositional history.

During the last glacial maximum when temperatures were low and precipitation reduced, the vegetation cover was sparse and fewer charcoal particles were found in the core. This may be because vegetation fires did not spread over large areas due to the lack of fuels. Periods with moderate temperatures and rainfall allowed the development of large, extended savannas and marginal forest cover. At these times, the highest number of charcoal particles appeared, possibly reflecting higher frequencies of vegetation fires. The climatic conditions with high temperatures and precipitation that existed in the early Holocene led to the shift of the tree line to higher altitudes and to a reduction of the grass cover under closed canopies. Moderate numbers of charcoal particles reflect fewer vegetation fires.

The charcoal concentrations in the F-core show that the number of charcoal particles entering Lake Mobutu Sese Seko fluctuated considerably between 30 000 and 900 B.P. Thus, the level of fire activities was temporarily higher, but also lower when compared with the level at the beginning of the last millennium. We propose that the concentrations of tropospheric ozone from vegetation fires during the last 30 000 years may have fluctuated accordingly. More research is needed to verify the results of this case study.

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