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Climate of the Past Discussions

Pollen, biomes, forest successions and climate at Lake Barombi Mbo (Cameroon) during the last ca. 33 000 cal yr BP – a numerical approach

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Abstract

The aim of this paper is to provide a more complete and precise interpretation of the 33 000 cal yr BP pollen sequence from Lake Barombi Mbo, southwestern Cameroon (4°39′45.75″ N, 9°23′51.63″ E, 303 m a.s.l.), based on a numerical approach allowing quantitative estimates of vegetation and climate. The biomisation method was applied on fossil pollen assemblages to reconstruct potential biomes and forest successional stages. The modern analogues (MAT) and the artificial neural networks (ANN) techniques were used to reconstruct mean annual rainfall (Pann), mean annual potential evapotranspiration (PETann) and a bioclimatic index α related to the vegetation stature. Our reconstructions testifies of a dense forested environment around Lake Barombi Mbo of mixed evergreen/semi-deciduous type during the most humid phases (highest rainfall and lowest evapotranspiration reconstructed values), but with a more pronounced semi-deciduous facies from ca. 6500 cal yr BP to present day related to increased seasonality. These forests display a mature character until ca. 2800 cal yr BP then become of secondary type during the last millennium probably linked to increased human interferences. Two episodes of fragmentation are evidenced synchronous with the lowest rainfall and highest potential evapotranspiration reconstructed values, the first one centered during the LGM, and the second one from ca. 3000 to ca. 1200 cal yr BP linked mainly to high seasonality. But, as shown by low scores of savanna potential biome and successional stage, open formations never largely extend in the Barombi Mbo basin, and were more probably enclosed inside the forest in form of savanna patches. Concerning the climatic reconstructions at Lake Barombi Mbo, The ANN appears to be the most reliable technique in spite of under-estimated values of Pann all along the sequence mainly due to a lack of modern pollen data from very humid areas in central Africa.

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1 Introduction

Central Africa holds the second world's largest rainforest after the Amazonian basin (Richards, 1981; Puig, 2001) and is and will be subject to modifications related to recent and future global climatic changes (IPCC, 2007). For this reason, predicting the evolution of this important natural forest ecosystem, in terms of distribution, functioning and biodiversity, constitutes a major challenge for scientific community. This challenge results for a large part in a better knowledge of past environments and climate in this African region, which can be reconstructed with the help of paleodata, such as pollen, preserved in sedimentary sequences. Since the end of the last glacial period, tropical central Africa has undergone intense climate changes that disturbed the hydrological system (e.g. Gasse, 2000; Shanahan et al., 2006; Gasse et al., 2008) and influenced the distribution and composition of forest ecosystems (e.g. Maley, 1991; Elenga et al., 2004; Bonnefille, 2007; Lézine, 2007).

Several palynological studies have already been done in the western part of the Congo basin. For instance, in Ghana at Lake Bosumtwi (Maley, 1987, 1991); in Benin at Lake Sélé (Salzmann and Hoelzmann, 2005); in Cameroon at Lakes Mboandong (Richards, 1986), Barombi Mbo (Maley and Brenac, 1998), Ossa (Reynaud and Maley, 1994; Reynaud-Farrera et al., 1996), Bambili (Assi-Kaudjhis et al., 2008), Mbalang (Vincens et al., 2010) and at Nyabessan Swamp (Ngomanda et al., 2009a); in Gabon at Lakes Nguène, Kamalété and Maridor (Ngomanda et al., 2005, 2007, 2009b; Giresse et al., 2009); in Congo at Bilanko and Ngamakala swamps (Elenga et al., 1991, 1994), at Lakes Sinnda (Vincens et al., 1994, 1998), and Kitina (Elenga et al., 1996), and on the Congolese littoral at Coraf and Songolo sites (Elenga et al., 1992, 2001) (Fig. 1). However, most of these works, partly synthetized by Vincens et al. (1999), Elenga et al. (2004) and Lézine (2007), were essentially focused on the Holocene period and/or on the descriptive aspect of landscape interpreted in terms of palaeoclimatic signals, except the work of Ngomanda (2005) which included quantitative reconstructions of vegetation (biomes) and climate (mean annual precipitations) along Holocene

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pollen sequences, or the works of Jolly et al. (1998) and Elenga et al. (2000a) for the 6000 and 18 000 yr BP key periods, respectively. At the same time, numerous quantitative reconstructions, mainly centered on climatic parameters (mean annual rainfall and temperature) along pollen sequences developed in East Africa, for instance by Bonnefille et al. (1990, 1992), Bonnefille and Chalié (2000) on the Burundi Highlands, Vincens et al. (1993) and Chalié (1995) at Lake Tanganyika, or for key periods such as the 6000 yr BP (Peyron et al., 2000, 2006).

The aim of this paper is to present, for the first time in central Africa, quantitative reconstructions of both paleovegetation and paleoclimate along the longest pollen sequence obtained in this region. This sequence was retrieved in the Lake Barombi Mbo, southwestern Cameroon, and the estimated age at its bottom is around 33 000 cal yr BP (Maley and Brenac, 1998). For these reconstructions we used the method of biomisation (Prentice et al., 1992) for palaeovegetation, and the modern analogues (Guiot, 1990) and the artificial neural networks (Peyron et al., 1998) techniques for palaeoclimate.

2 Environmental setting and data sources

2.1 Locality

Lake Barombi Mbo (diameter of ca. 2 km and a present day maximum depth of 110 m; Fig. 2) is a 1 Myr old volcanic and explosive crater lake (Cornen et al., 1992) located at 4°39′45.75′′ N, 9°23′51.63′′ E, and 303 m a.s.l. (above sea level), on a large undulating plain between ca. 250 m and 500 m a.s.l., North of the Cameroon Mount. The catchment, relatively small related to its volcanic origin, lies mostly on the western side of the lake and is drained by a little perennial stream. The level of the lake is stabilized by an outlet cutting the southeastern crater wall (Giresse et al., 1991) (Fig. 2).

Today, Lake Barombi Mbo receives a high total amount of precipitations of about 2350 mm/yr (meteorological station of Kumba; Fig. 2) linked to its proximity to the

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Atlantic ocean and its location in the volcanic dorsal of western Cameroon where upper easterly winds above the monsoon are uplifted so increasing the monsoon activity during summer northern hemisphere (Suchel, 1988). The rainfall distribution has a yearly pattern with only one rainy season from March to November, with maximum from July to October, and one dry season from December to March (Suchel, 1972), mainly controlled by the seasonal North/South migration of the InterTropical Convergence Zone (ITCZ) where the northern trades and the monsoon front converge (Leroux, 1983; Nicholson, 2000). Mean annual Potential EvapoTranspiration (PET) is about 1200 mm/yr (FAO website database, 2008). Under such climatic conditions, the lake is today surrounded by humid lowland evergreen rain forest with patches of semi-deciduous forests (Letouzey, 1968, 1985) rattached to the Guineo-Congolian phytogeographic region (White, 1983).

2.2 Sources of the data

2.2.1 The modern data sets

The modern pollen data set used for the quantitative reconstructions of palaeovegetation and paleoclimate at Lake Baromnbi Mbo is mainly issued from lowland ecosystems of central atlantic Africa including Gabon, Cameroon and Congo (Jolly et al., 1996; Elenga et al., 2000; Vincens et al., 2000 and unpublished data; Ngomanda unpublished data; Lebamba et al., 2009a), complemented with western african pollen data from Mauritania and Senegal (Lézine, 1987), Togo (Lézine and Edorh, 1991), Niger (Caratini et al., 1988) and Ivory Coast (Ybert, 1975) extracted from the African Pollen Database (2008). This matrix includes 354 spectra and 300 taxa.

Mean Annual Precipitations (Pann) and Potential EvapoTranspiration (PETann) were extracted at each pollen site from the FAO website database (2009) and interpolated from the three closest available meteorological stations without altitudinal correction.

2.2.2 The fossil pollen data

The fossil data are extracted from the sedimentary sequence BM-6 recovered in the western part of Lake Barombi-Mbo (Maley and Brenac, 1998) (Fig. 2). The sedimentary geology, geochronology (^{14}C), isotopic geochemistry (δ^{13}C), volcanology and paleomagnetism of this core have been studied in detail (Thouveny and Williamson, 1988; Maley et al., 1990; Giresse et al., 1991, 1994; Cornen et al., 1992). The chronology of the sequence was established from 12 conventional radiocarbon datings performed in the ORSTOM Geochronological Laboratory, Bondy (for more detail see Giresse et al., 1991, 1994; Maley and Brenac, 1998). In this paper, the calibration of radiocarbon date into calendar age was made using the CALIB 5.0.1 software (Stuiver and Reimer, 1993) and incal04 data (Reimer et al., 2004) (Table 1). Using this set of calendar ages, a second-order polynomial-age model was established along the whole sequence showing that the sedimentary sequence covers ca. 33 000 calendar years (Fig. 3). Between 0 and ca. 25 000 cal yr BP, age confidence interval seems to be good, but beyond it presents some uncertainty according to an error margin of about 7000 years, which has been previously related to perturbed sediments by volcanic activity in the last two meters of the core (Giresse et al., 1991, 1994; Maley and Brenac, 1998).

3 Methods

3.1 The biomisation method

The biomisation method was described by Prentice et al. (1992, 1996) and applied for the first time in Africa by Jolly et al. (1998). It is based on the Plant Functional Type (PFT) concept (Smith et al., 1997). The principal steps of this method are as follows: (1) each pollen taxon is assigned to one or several PFTs, which are groups of plants having the same ecological requirements, especially the same physiological

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characteristics stature, leaf-form and climatic thresholds. A first Taxa-PFTs matrix is thus obtained; (2) the PFTs are associated to one or several biomes. A second PFTs-Biomes matrix is built, and (3) the two matrices are then used to estimate the affinities of the scores of each PFT and of each biome in each pollen spectra. The pollen spectrum is assigned to the biome to which it has the highest affinity. In this paper, Taxa-PFTs and PFTs-Biomes matrices used are those defined by Lebamba et al. (2009b).

This method, now currently used for modern or past biome reconstructions all around the world, has been used and adapted by Lebamba et al. (2009b) for reconstructing the modern stages of forest dynamics, highlighting the various phases of an ecological succession. In this paper, the same news PFTs and forest succession stages defined by these authors are considered.

3.2 The Modern Analogues Technique (MAT)

This method was developed by Overpeck et al. (1985) and extended by Guiot (1990) to reconstruct climate parameters from fossil assemblages along sedimentary sequences or for key periods. Several applications of this method were performed to estimate mean annual rainfall and temperature in East Africa (Bonnefille et al., 1990, 1992; Vincens et al., 1993; Chalié, 1995; Bonnefille and Chalié, 2000; Peyron et al., 2000). Here, we used the approach of Davis et al. (2003) in which the values of the taxa percentages are replaced by values of the PFTs scores. For each modern and fossil spectrum, a score is calculated for each PFT, given as the sum of the square root of the percentage of the taxa belonging to the PFT. Basically, a chord distance is calculated to measure the dissimilarity between each fossil spectrum and all of the modern ones. The modern spectra associated with the smallest distance are taken as the "best modern analogues" for each fossil pollen spectrum. The climatic parameters associated with these best analogues are averaged with a weighting inverse to the distance between the fossil and the modern spectra. This weighted average provides the climatic estimate attributed to each fossil pollen spectrum (Peyron et al., 2000). The modern analogues technique provides error bars defined by the climate variability among the modern best analogues (Guiot, 1990). In this paper, this climate variability is based on the first five best analogues.

3.3 The Artificial Neural Networks technique (ANN)

The main steps of this method were largely described by Peyron et al. (1998, 2000). This method is also essentially based on the concept of plant functional types (PFT) where pollen counts are transferred into PFT scores. PFTs scores derived from modern pollen data are calibrated in terms of climatic parameters. It uses an artificial neural network technique enable to calibrate non linear relationships between PFTs and climatic variables (Guiot et al., 1996). This PFT-climate calibration is considered to be more robust than the previous taxon-climate calibration (Huntley and Prentice, 1988; Guiot et al., 1993) because groups of taxa have a better-defined response to climatic changes than individual taxa (Prentice et al., 1992). The coefficients obtained with the neural network are then applied to the fossil PFT scores to infer climatic variables.

In this paper, these two last methods (MAT and ANN) were used to reconstruct mean annual precipitation (Pann), mean annual potential evapotranspiration (PETann) and a bioclimatic index α along the Barombi Mbo sequence. The index α (ratio of actual evapotranspiration versus equilibrium evapotranspiration) was calculated following Prentice et al. (1992) method. This ratio shows a good correlation between available moisture and distribution of vegetation physiognomy, a threshold value at 65 discriminating a forested environment ($\alpha > 65$) from an open system ($\alpha < 65$) (Peyron, 1998). Contrary to previous work undertaken in East Africa, the lack of available modern pollen data from mid- and high altitudes in Central Africa has not allowed us to reconstruct mean annual temperature at Barombi Mbo.

Such as in Peyron et al. (2005), to evaluate the reliability of both methods, climate parameters for each surface sample were estimated using the other modern samples. The difference between present day climate data at the pollen sites and the estimated climate at each site is an indicator of the reliability of each of these climatic reconstruction methods. The coefficients of correlations (R^2) between the observed and estimated parameters and the root mean squared error (RMSE) are given in Table 2. The results show that the coefficients of correlation obtained for the three climatic parameters are good following the two techniques, though the neural network shows higher R^2.

4 Results

4.1 Potential biome and successional stage reconstructions

These reconstructions are illustrated on Figs. 4 and 5. They show large and synchronous oscillations along the pollen sequence indicating that during the last ca. 33 000 cal yr BP the vegetation environment surrounding the Lake Barombi Mbo was subject to important modifications that have affected its floristic composition as well as its structure. The main identified episodes are:

– ca. 33 000 to ca. 23 400 cal yr BP

During this period, TSFO (Tropical Seasonal Forest) and TRFO (Tropical Rain Forest) potential biomes display relatively high scores, with values of 20 to 28 and 17 to 24, respectively. The scores of the savanna biome (SAVA) stay low, between 7 and 15, with the highest values from ca. 33 000 to ca. 28 000 cal yr BP. Among the potential succession stages, TMFO (Tropical Mature Forest) stage displays the highest scores with values between 26 and 38. The scores of the Tropical Secondary Forest (TSFE) stage show intermediate values between 16 and 26, whereas the Tropical Forest Regrowth (TFRE) and Savanna (SAVA) stages display similar relatively low values from 10 to 20.

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– ca. 23 400 to ca. 17 000 cal yr BP

This episode registers a significant decrease of the scores of TSFO and TRFO potential biomes compared with the previous episode, with values between 13 and 21, and between 11 and 20, respectively. Scores of SAVA potential biome fluctuate between 10 and 13, and are very close to those of TRFO and TSFO biomes when they display their lowest values. At the same time, the scores of TMFO and TSFE potential stages largely decrease with values between 14 and 25, and 11 and 20, respectively, whereas score values of TFRE and SAVA stages stay relatively stable and similar varying from 8 to 16.

– ca. 17 000 to ca. 11 500 cal yr BP

An irregular and parallel increase in the scores of TSFO and TRFO potential biomes is observed, attaining at the end of this episode similar values than between ca. 33 000 and ca. 23 400 cal yr BP. Scores of the SAVA biome increase more regularly until ca. 13 400 cal yr BP when they reach a maximum value of 20, then they decrease. Potential successional stages TMFO and TSFE also increase their scores. The scores of TMFO stage reach similar values than before ca. 23 400 cal yr BP. The difference between score values of TSFE and SAVA stages regularly increases along this episode and TSFE and TFRE present for the first time high values of about 30 and 25, respectively.

– ca. 11 500 to ca. 3000 cal yr BP

The scores of TSFO and TRFO potential biomes reach their maximum values during this period, values of 25 to 35 and 22 to 30, respectively. The SAVA biome scores are from 13 to 19 with a large lag with TSFO and TRFO score values as before ca. 23 400 cal yr BP. Similar features are observed concerning the scores of the potential successional stages. TMFO and TSFE reach also their maximum values of the

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sequence, between 32 and 40, and between 28 and 34, respectively. Score values of SAVA stage largely decrease until 6 while those of TFRE increase until 25.

– ca. 3000 to ca. 1200 cal yr BP

An abrupt change is observed both in the floristic composition and the structure of the vegetation at ca. 3000 cal yr BP. The scores of TRFO biome reach their minima with values, about 5 and 6, at ca. 2650 and ca. 2150 cal yr BP, respectively. TSFO biome scores also greatly decrease with values close to those of the SAVA biome. At the same time, potential TMFO, TSFE and TFRE stage scores also abruptly decrease, reaching similar values, less than 17.

– ca. 1200 to present day cal yr BP

At the beginning of this period, a new abrupt change is observed. The scores of TRFO and TSFO potential biomes increase significantly, then stabilise around similar values than those before ca. 28 000 cal yr BP. Scores of potential stages TMFO, TSFE and TFRE also increase, but the values of TMFO and TSFE stages never reach the values registered between ca. 11 500 and ca. 3000 cal yr BP.

4.2 Quantitative climatic reconstructions

Quantitative reconstructions of Pann, PETann parameters and of the bioclimatic index α following the modern analogues (MAT) and the artificial neural networks (ANN) techniques are illustrated on curves restricted within the errors bars in Fig. 6.

– ca. 33 000 to ca. 23 400 cal yr BP

During this episode, Pann, PETann and the index α are reconstructed by the two methods with close mean values of about 1310 mm (MAT) and 1023 mm (ANN) for

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Pann, 1530 mm (MAT) and 1476 mm (ANN) for PETann and mean humidity values of 77 (MAT) and 76 (ANN) for the index α.

– ca. 23 400 to ca. 17 000 cal yr BP

Ca. 23 400 cal yr BP, and abrupt change is registered in Pann, PETann and the index α using the ANN method. Pann and this index largely decrease towards mean values of 743 mm and 68, respectively. At the same time, PETann estimates greatly increase reaching mean values of about 1764 mm. The MAT method displays a less important decrease of Pann with mean values of 991 mm, and above all, no real changes in the values of PETann and index α compared to the previous episode.

– ca. 17 000 to ca. 11 500 cal yr BP

The two methods show irregular increased values of Pann and index α whereas PETann values decrease, but these trends are better marked using the ANN method.

– ca. 11 500 to ca. 3000 cal yr BP

This episode registers the highest values of Pann and index α and the lowest values of PETann of the pollen sequence, whatever the method used. Pann reach mean values of 1644 mm and 1536 mm, PETann values of 1204 mm and 1248 mm and index α values of 82 and 83 using MAT and ANN, respectively.

– ca. 3000 to ca. 1200 cal yr BP

This episode registers a sharp decrease of Pann and index α estimates towards mean values of 1400 mm (MAT) and 1121 mm (ANN), and of 79 and 77 (MAT and ANN), respectively. PETann values reach about 1400 mm whatever the method.

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– ca. 1200 to present day cal yr BP

Using the ANN method, values of Pann and index α regularly increase whereas PETann values regularly decrease until present day. MAT method displays the same trends until ca. 680 cal yr BP, then a sharp inversion in all the parameters is registered until present day.

5 Discussion

The reconstructions of potential biomes (Fig. 4), successional stages (Fig. 5), and climatic parameters (Fig. 6) show large and synchronous oscillations along the Lake Barombi Mbo pollen sequence.

Between ca. 33 000 and ca. 23 400 cal yr BP, high reconstructed TSFO and TRFO biomes scores, and a mean index α value of ca. 76 indicate that a forest of mixed type was surrounding the lake. A clear mature facies of this forest is indicated by high values of TMFO potential successional stage. This vegetation reconstruction appears rather coherent with pollen data (pollen-zone I; Maley and Brenac, 1998) that show an association of evergreen forest elements such as Caesalpiniaceae, Sapotaceae and *Strombosia* and of semi-deciduous forest ones such as *Antiaris*, *Celtis* and *Milicia*, with scarce pioneer species. However, the relatively high percentages of Caesalpiniaceae according to their low pollen dispersion (average of 7.2 with maximum at 10.5) would point to a forest type largely dominated by this family under very wet climatic conditions when our quantitative reconstruction of Pann are only about 900–1300 mm/yr and 1000–1400 mm using ANN and MAT techniques, respectively associated with high PETann values of about 1500 mm/yr whatever the method used.

The following episode, from ca. 23 400 until ca. 17 000 cal yr BP, intervening during the Last Glacial Maximum (LGM, 23 000 to 19 000 cal yr BP; Yokoyama et al., 2000), is characterized by a great change in the floristic composition and the structure of the vegetation surrounding the lake. The scores of TRFO and TSFO potential biomes

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abruptly fall, approaching the scores of the savanna (SAVA) potential biome. The same feature is observed in the reconstructions of the potential successional stages, where TMFO scores drop and display closer values to TSFE, TFRE and SAVA scores than before. This testifies of an opening of the environment of the lake, with development of degraded forest and of savanna, probably in the form of a forest-savanna mosaic. Low mean bioclimatic index α values (68) derived from ANN technique confirms such opening of the vegetation while no change is observed when using the MAT technique (mean α of 76). Previous empirical interpretations of pollen data (Pollen-zone IIA; Maley and Brenac, 1998) and of isotopic results (Giresse et al., 1994) indicate such a fragmentation of the forest, marked by a general decrease in tree pollen with local peaks of pioneer taxa such as *Trema*, *Alchornea*, *Musanga/Myrianthus*, associated to a large increase in Poaceae, and several episodes of bulk organic matter $C^{13}C$ and C/N ratio (> 20) increase, respectively. For the same time interval, Elenga et al. (2000) reconstructed on this site a tropical seasonal forest, whereas Maley and Brenac (1998) point that the importance of the Caesalpiniaceae before and after this episode, during which their percentage values were a few larger than present day, could indicate that during the LGM evergreen forest patches, interpreted as refugia, remained in this inland region (Maley, 1991, 1996) and not only along the shore of the Bay of Biafra, as proposed by Anhuf et al. (2006) in their reconstruction. During this episode, interpreted by Maley and Brenac (1998) as dry, our reconstructions of Pann using ANN and MAT methods exhibit an important decrease in annual rainfall of 300 mm/yr relative to the previous episode, with reconstructed minima of 600 mm and of 770 mm, respectively. Potential evapotranspiration increases of about 300 mm/yr with the ANN method, while no change is observed using the MAT method. Such new climatic conditions can have caused important deficit in soil moisture and a deterioration of the forest by reduction and/or disappearance of some forest tree taxa unable to support such a hydrological stress. They had also as consequence a lowering of the level of Lake Barombi Mbo as evidenced by the expansion of swamps dominated by Cyperaceae on the western drained deltaic zone offshore the main modern inlet (Fig. 2) (Maley and Brenac, 1998).

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For the Barombi Mbo area, the quantitative reconstructions of mean annual rainfall during the LGM yield a mean decreased precipitation of 68% relative to modern measured value at Kumba station. Previous reconstructions, essentially performed in East Africa using the modern analogues technique (MAT), have estimated a ca. 32% precipitation decrease relative to the present, with a maximum of 42%, on the equatorial highlands of central East Africa (Bonnefille et al., 1990; Bonnefille and Chalié, 2000) and a ca. 25% precipitation decrease in the southern Tanganyika basin (Vincens et al., 1993; Chalié, 1995; Bonnefille and Chalié, 2000). On this latest site, a water and energy balance model has simulated a mean decreased precipitation of 25% during the LGM (Bergonzini et al., 1997) but, according to Tyson et al. (1997), this value must be considered as a minima estimate, decrease in precipitation been substantially amplified when including empirical changes in atmospheric transmission coefficient, whereas large changes in cloud cover and air humidity not modify these trends. In central Africa, Peyron (1998) estimated a ca. 400 mm/yr precipitation decrease using the PFTs method and a ca. 200 mm/yr decrease value using inverse vegetation modelling (Guiot et al., 2000) under CO_2 concentrations of 340 ppmv and 200 ppmv. Compared to these results, our values of decreased precipitation estimates for the LGM seem to be over-estimated with the two methods, MAT and ANN.

After ca. 17 000 cal yr BP until ca. 11 500 cal yr BP, the irregular and parallel increase in scores of TRFO and TSFO potential biomes evidences a new progressive reforestation of the Lake Barombi Mbo area. But the relative high and close scores of the SAVA potential biome still indicate the presence of patches of open formations in the vicinity of the lake until ca. 13 500 cal yr BP. The scores of TMFO and TSFE potential successional stages also increase, but TSFE stage displays closer values with TMFO stage than during the forest episode recorded between ca. 33 000 and ca. 23 400 cal yr BP. This could indicate a more perturbed and unstable forest environment, confirmed by a lower mean value of the index α of 74 (ANN technique). This episode corresponds to the pollen-zone IIb (Maley and Brenac, 1998) when Poaceae regularly decrease whereas tree taxa develop such as the Caesalpiniaceae and Sapotaceae followed

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ca. 14 000 cal yr BP by *Trichoscypha*, *Strombosia*, *Lophira* (a light demanding pioneer tree in its young phase of ecological behaviour) among evergreen forest taxa, *Nauclea*, *Uapaca* and *Antiaris* as semi-deciduous forest taxa and the forest pioneer *Macaranga*. These pollen data have been interpreted as an episode of forest recolonisation of previous open formations around Lake Barombi Mbo, also testified by decreased $\delta^{13}C$ values (Giresse et al., 1994), and indicating increased rainfall. In our reconstructions, Pann estimates follow the same trend than the forest biome scores, increasing from 800 mm/yr ca. 16,500 cal yr BP to 1100 mm/yr ca. 11 500 cal yr BP using ANN technique, and from 800 to 1350 mm/yr using MAT technique, whereas PETann values display inverse trends evidencing a progressive return to more humid conditions after the LGM. During this period, a slight decrease in annual rainfall of about 100–200 mm/yr using ANN technique, but not clearly recorded with the MAT technique, is registered around ca. 12 500 cal yr BP, i.e. synchronous with the Younger Dryas episode of Northern Hemisphere (12 800–11 600 cal yr BP; Bard and Kromer, 1995). This short dry episode corresponds in our biome reconstructions to similar score values of TRFO, TSFO and SAVA indicating a slight opening of the vegetation and is synchronous with the end of an abrupt lake lowering (Maley and Brenac, 1998).

The following period dated between ca. 11 500 and ca. 3000 cal yr BP corresponds to the most densely forested episode of the pollen sequence of Lake Barombi Mbo. Scores of TRFO and TSFO potential biomes reach their highest values such as the scores of TMFO and TSFE potential successional stages. However, the high values of TSFO scores associated with an α index not more than 82–84 using the ANN technique or of 76–85 using the MAT technique indicate the existence around the lake of a mixed evergreen/semi-deciduous forest and not of a pure stand evergreen forest. Such a reconstruction is coherent with a TSFO potential biome reconstructed by Jolly et al. (1998) at 6000 yr BP and also with pollen data (Pollen-zone III; Maley and Brenac, 1998) indicating the presence and abundance of elements from these two forest facies. The constant presence of forest pioneers in the diagram and of relatively high values of TFRE successional stage at this time of maximum development of the forest could be explained by local and natural openings of the canopy. Reconstructed Pann values are about 1550 mm/yr using the ANN technique and 1650 mm/yr using the MAT technique, and represent the highest values obtained along the whole sequence. For the first time, Pann values are higher than PETann values which are of about 1250 mm/yr and 1200 mm/yr, respectively. This period represents the most humid episode registered in the sequence.

From ca. 6500 to ca. 3000 cal yr BP, differences between score values of TRFO and TSFO potential biomes and between score values of TMFO and TSFE potential successional stages increase, indicating a change in the composition of the local forest toward a more pronounced semi-deciduous facies than before. According that Pann reconstructed values are similar or close than those reconstructed between ca. 11 500 and ca. 6500 cal yr BP, such differences are probably linked to a new intervened climatic parameter that is increased rainfall seasonality, but the mature character of the forest is still well established.

An abrupt change in the vegetation environment of Lake Barombi Mbo is registered between ca. 3000 and ca. 1200 cal yr BP as shown by an abrupt and important decrease of scores of forest biomes (TRFO and TSFO) and forest successional stages (mainly TMFO and TSFE). TRFO potential biome displays its lowest score values of the pollen sequence whereas TSFO and SAVA potential biome values are very close. At the same time, scores of TMFO, TSFE and TFRE potential stages display similar values. This evidences a new perturbation and fragmentation of the forest in this area. But this perturbation was not as intense as during the LGM probably linked to its shorter duration which thereby has not created larger open environments as shown by lower values of the scores of the reconstructed SAVA successional stage and also by higher values of the index α between 70 and 80 or 72 and 84 using ANN or MAT techniques, respectively. In the pollen diagram (pollen-zone IVa; Maley and Brenac, 1998), Poaceae and pioneer taxa, mainly *Alchornea*, display high frequencies whereas typical forest taxa are less abundant. During this episode, reconstructed mean annual rainfalls drop to minima values of about 800 mm/yr using ANN technique or 1200 mm/yr using

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MAT technique, with mean values of 1100 mm/yr or 1400 mm/yr, respectively. Potential evapotranspiration increases until 1650 or 1500 mm/yr maximum, with a close mean value of 1400 mm/yr using the two techniques. All these data would evidence a decreased mean annual rainfall associated with increased rainfall seasonality as shown by the lowest values of TRFO potential biome scores registered in the sequence.

This dry episode, centered around 2600 cal yr BP, is probably the better documented period in central atlantic Africa by pollen data. Empirical interpretations have shown that during this episode the structure and the floristic composition of the Guineo-Congolian forest massif was locally largely modified (Vincens et al., 1999), creating favorable conditions for farming and for expansion and migration of Bantu speaking populations (Schwartz, 1992; Ngomanda et al., 2009a). The pollen sequences located today in forest environment such as Lake Ossa (Reynaud-Farrera et al., 1996; Giresse et al., 2005) and Nyabessan swamp (Ngomanda et al., 2009a) in southern Cameroon, Lake Nguène from Gabon (Ngomanda et al., 2007) and Lake Kitina from Congo (Elenga et al., 1996), show, such as at Lake Barombi Mbo, a reduction of typical humid forest elements on behalf of heliophilous species of secondary forest, or a fragmentation of the forest including patches of savanna according to the sites. In areas today occupied by savanna, former forest completely disappeared such as at Lake Sinnda in Congo (Vincens et al., 1994, 1998) or at Lake Mbalang in Cameroon (Vincens et al., 2010). As suggested by Ngomanda et al. (2009a) at Nyabessan swamp, low rainfall with high seasonality and intense evapotranspiration, would have reduced the capacity of forest species to regenerate, opening temporally the way for the spread of pioneers or grasses. At the same time, a drop in lake-level is inferred from pollen data at Lake Nguène (Ngomanda et al., 2007) and at Nyabessan swamp (Ngomanda et al., 2009a) and from diatoms at Lake Ossa (Nguetsop et al., 2004).

Following this dry episode, forest around Lake Barombi Mbo regenerates from ca. 1200 cal yr BP until present day as shown by a high α index of 81 (ANN) and 78 (MAT). As between ca. 6500 and ca. 3000 cal yr BP, the difference between scores values of TRFO and TSFO potential biomes indicates that the dominant facies of this forest is of a semi-deciduous type but with a more pronounced secondary character as shown by highest scores of TSFE potential stage than of TMFO stage and by closer scores of TFRE stage. In the pollen diagram (Pollen-zone IVb; Maley and Brenac, 1998), dominant taxa are from semi-deciduous forest or forest pioneers. During this last millennium, mean annual rainfall estimates are about 1300 mm/yr using the ANN technique and about 1400 mm/yr using the MAT one, and mean PETann estimates are of 1300 mm/yr and 1450 mm/yr, respectively, with high fluctuations using the MAT technique. In the two techniques, present day mean annual rainfall estimates never reach measured values at the meteorological station of Kumba (2350 mm/yr). On the contrary, mean annual potential evapotranspiration is well reconstructed using ANN technique compared to the present day measured value in this area (ca. 1200 mm/yr).

6 Conclusions

The numerical approach used to reconstruct vegetation and climate at Lake Barombi Mbo during the last ca. 33 000 cal yr BP largely complements the previous empirical interpretations proposed by Maley and Brenac (1998) on this site. Our reconstructions of the vegetation, using the biomisation method and the values of the bioclimatic index α always less than 95 (Prentice et al., 1996), testifies of the presence of a dense forested environment around the lake of mixed evergreen/semi-deciduous type during the most humid phases, but with a more pronounced semi-deciduous facies from ca. 6500 cal yr BP to present day in relation with an increased seasonality. These forests display a mature character until ca. 3000 cal yr BP then, during the last millennium, become clearly of secondary type which could be partly related to increased human interferences. Two episodes of fragmentation of these forests are evidenced when the lowest rainfall and highest potential evapotranspiration values are registered in the sequence. The first one, between ca. 23 400 and ca. 17 000 cal yr BP, is synchronous with the LGM in the high latitudes of Northern Hemisphere, with a maximum of forest opening intervening during the first Heinrich Event (HS1) in northern Atlantic (Hessler

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et al., 2010). The second one occurred between ca. 3000 and ca. 1200 cal yr BP and as the first episode was interpreted in terms of decreased monsoon activity linked to low sea surface temperature of the Atlantic Ocean (Kucera et al., 2005; Weldeab et al., 2005, 2007). But, as shown by low scores of savanna potential biome and savanna successional stage, open formations never largely extend in the Barombi Mbo basin, but were more probably enclosed inside the forest in the form of savanna patches

Concerning the methodology, the results obtained with the two techniques (MAT and ANN) seem to indicate, that the most appropriate and reliable technique to reconstruct past climate at Lake Barombi Mbo is the ANN one. Indeed, using this technique (i) the fluctuations of the reconstructed climatic parameters follow the main changes registered in the vegetation using the biomisation method. Values of Pann and α index fluctuate synchronously with scores of TRFO and TDFO potential biomes, and with scores of TMFO potential successional stage when PETann estimates displaying normal inverse trends. On the contrary, when using the MAT, no real change is observed in PETann values and in the index α, between ca. 13 000 and ca. 33 000 cal yr BP; (ii) ANN reconstructions are better consistent with that is known concerning palaeoclimate fluctuations in tropical Africa during the last 33 000 cal yr BP; and (iii) the confidence intervals provided by the ANN technique are generally not as important as those provided by the MAT technique. This feature is probably linked to the method used for the estimation of the error bars.

Nevertheless, and using the ANN technique, the reconstructed value of modern mean annual rainfall of only 1500 mm/yr is less of ca. 800 mm than the modern reference of ca. 2300 mm/yr measured at the Kumba meteorological station. The best hypothesis to explain such a discrepancy is that the modern pollen data set used in the Pann reconstructions contains too less samples from areas characterized by very high rainfall (above 1600 mm/yr only 18% of the samples, and above 2000 mm/yr only 10 samples). There is an evident lack of present day pollen samples from the West Cameroon forest area, which is characterized by a very humid climate (Pann $\geq$2500 mm and a continuous rainy season going from March to November, i.e. without

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a "summer little dry season" which intervenes usually in July and August, contrary to southern Cameroon and Gabon forest areas). Such a bias in the pollen data set may have induced an underestimation of the reconstructed annual rainfall for present day but also all along the pollen sequence explaining particularly the great difference between estimated rainfall decrease relative to present at Barombi Mbo and in central eastern Africa during the LGM. On the contrary, mean annual Potential EvapoTranspiration (PETann) is rather well reconstructed using ANN technique (1300 mm/yr) compared to the present day measured value for the Kumba station (ca. 1200 mm/yr). It is clear that in the future, the Pann reconstructions must be improved by adding modern pollen data from the most humid central African lowland evergreen forests such as the Biafrean and the littoral Atlantic forests. But, it is unlikely that the pattern of variations of mean annual rainfall presented here will be strongly modified. Finally, for future reliable reconstructions of other climatic parameters such as mean annual temperatures our data set must be completed with samples from mid- and high altitudes in Central Africa.

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Pollen, biomes, forest successions and climate at Lake Barombi Mbo

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Table 1. Radiocarbon chronology of core B, Lake Barombi Mbo, western Cameroon.

Laboratory code number	Depth (m)	14 C age [yr BP]	Calibrated age [cal yr BP]	Calibrated age 2-σ-error bounds	Relative area under distribution
OBDY 660	0.25	770 ± 100	768	555/609	0.106
				622/914	0.894
OBDY 146	2.05	2200 ± 285	2196	1535/2857	1.00
OBDY 96	3.55	3690 ± 315	4062	3257/4867	1.00
OBDY 263	6.75	6520 ± 645	7278,5	5910/8647	1.00
				8679/8681	0.00
OBDY 138	9.90	8690 ± 475	9715	8552/10 878	0.982
				10 941/11 079	0.018
OBDY 751	10.80	9900 ± 2500	11437,5	10 654/12 221	0.985
				12 346/12 377	0.005
OBDY 61	13.45	13 120 ± 965	15 629	13 208/18 050	0.96
				18 353/18 429	0.004
OBDY 757	13.75	13480 ± 240	16 208,5	15 279/15 353	0.013
				15 401/17 016	0.987
OBDY 811	15.10	15 470 ± 100	18705	18 540/18 870	1.00
OBDY 266	16.65	17 080 ± 885	20506	18 583/22 429	1.00
OBDY 59	18.75	20 420 ± 1500	24521	20 900/28 134	0.004
				20 908/28 134	0.996
OBDY 58	21.05	24080 ± 3500	27 817,5	20 243/35 392	0.998
				35 992/36 142	0.002

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Table 2. Correlation coefficients between observed and reconstructed values of climate parameters obtained from application of both MAT and PFT approaches to the modern samples.

Climate Parameters	MAT		ANN	
	Correlation coefficient	RMSE	Correlation coefficient	RMSE
Pann (mm)	0.65	360.6	0.7	387.9
PETann (mm)	0.71	259.4	0.77	233.1
α	0.65	8.4	0.67	8.2

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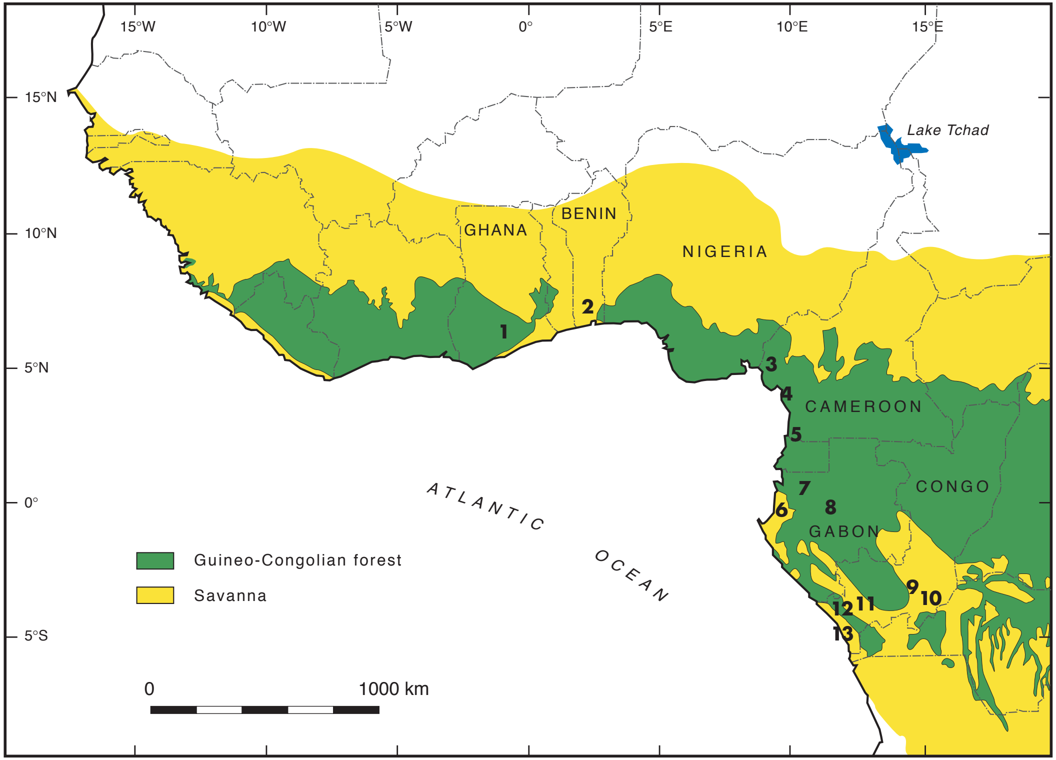

Fig. 1. Location of fossil pollen sites in west and central atlantic Africa (1: Bosumtwi, 2: Sélé, 3: Barombi Mbo/Mboandong, 4: Ossa, 5: Nyabessan, 6: Maridor, 7: Nguène, 8: Kamalété, 9: Bilanko, 10: Ngamakala, 11: Sinnda, 12: Kitina, 13: Coraf/Songolo) (map adapted from Ngomanda et al., 2009a).

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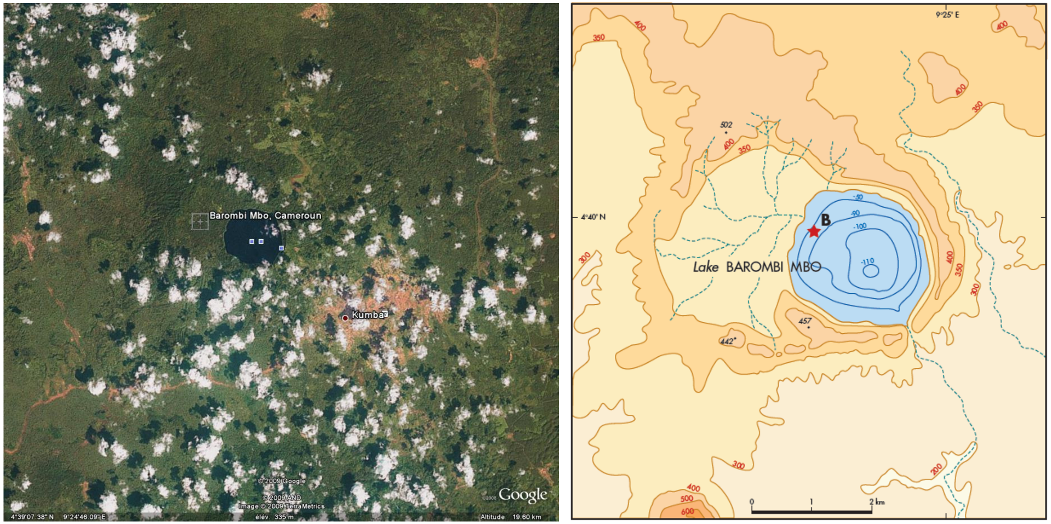

Fig. 2. Lake Barombi Mbo. Location of core B (after Giresse et al., 1991).

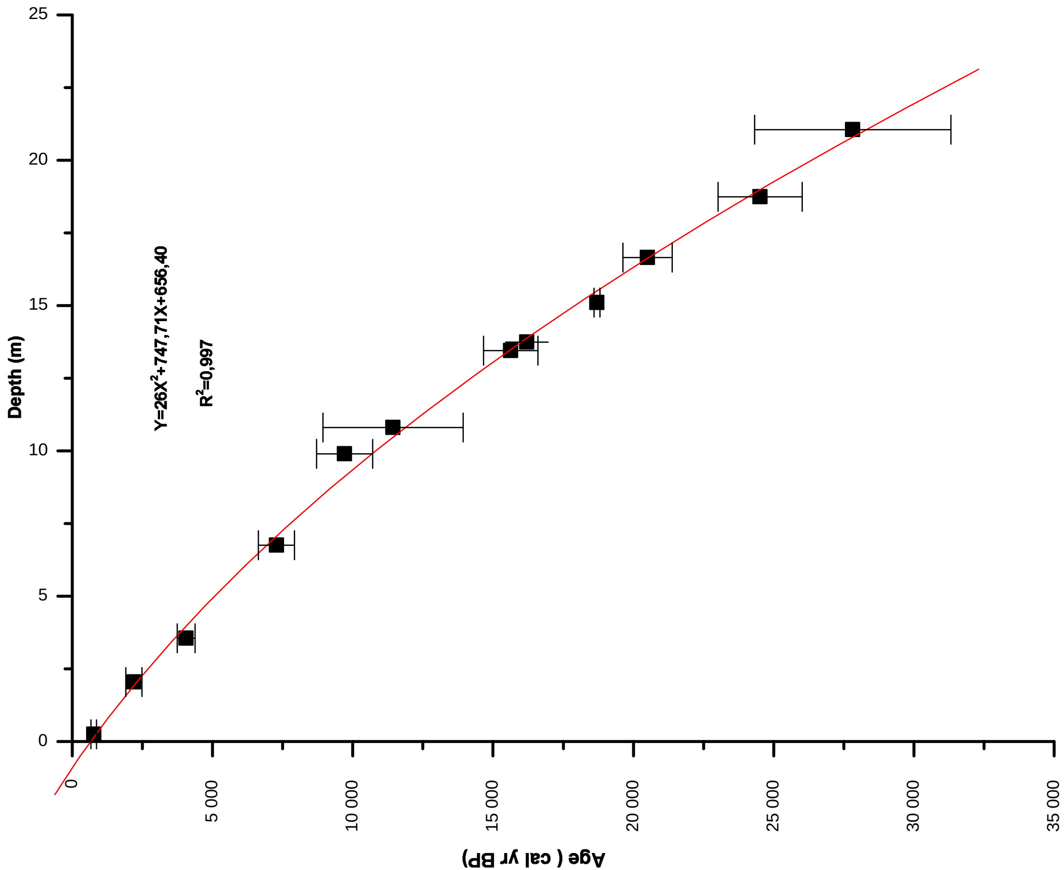

Fig. 3. Depth-age model of the core B of Lake Barombi Mbo, western Cameroon.

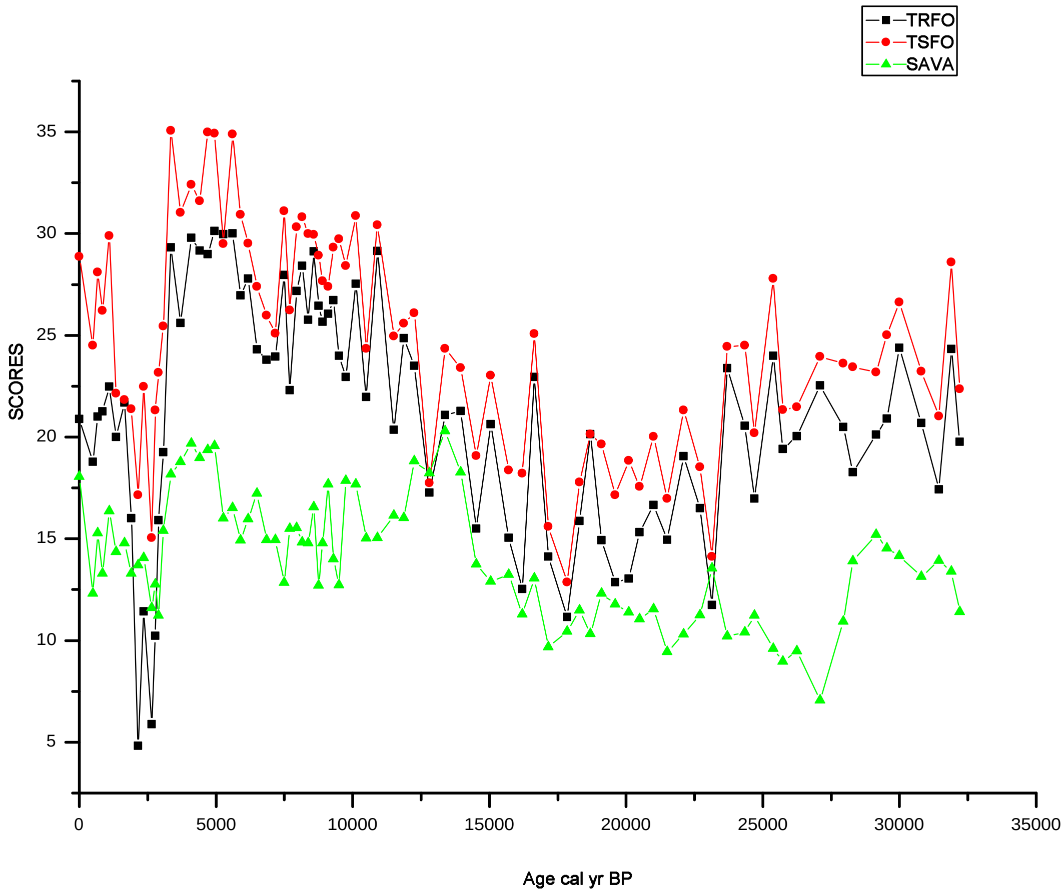

Fig. 4. Reconstructed potential biomes along the Barombi Mbo pollen sequence. TRFO (Tropical Rain FOrest), TSFO (Tropical Seasonal FOrest), SAVA (SAVAnna).

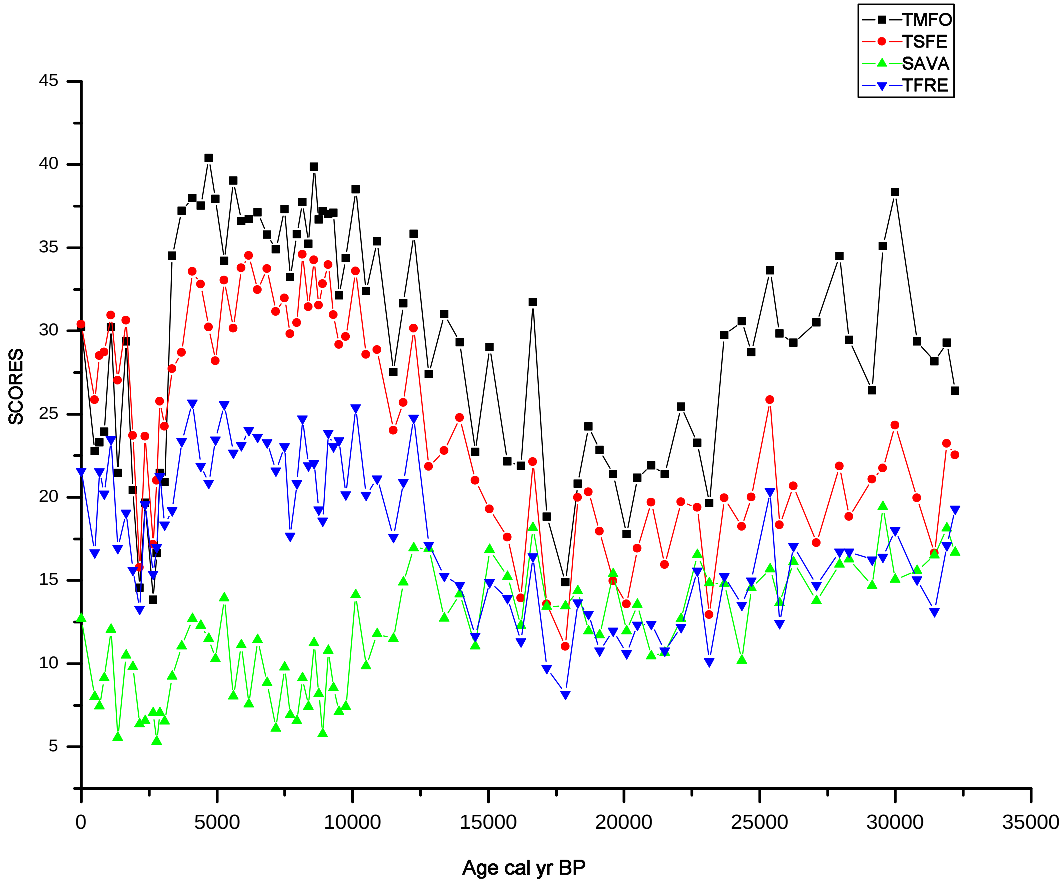

Fig. 5. Reconstructed successional stages along the Barombi Mbo pollen sequence. TMFO (Tropical Mature FOrest), TSFE (Tropical Secondary ForEst), SAVA (SAVAnna), TFRE (Tropical Forest REgrowth).

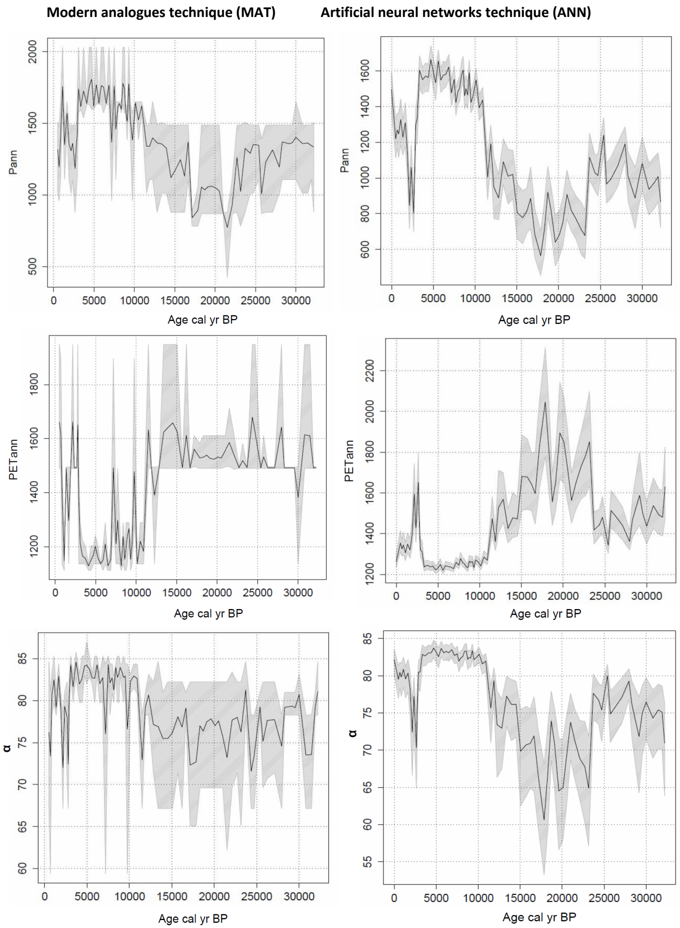

Fig. 6. Reconstructed climatic parameters (Pann, PETann and index α) along the Barombi Mbo pollen sequence.

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