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Climate of the Past

Pollen, vegetation change and climate at Lake Barombi Mbo (Cameroon) during the last ca. 33 000 cal yr BP: a numerical approach

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Abstract. This paper presents quantitative reconstructions of vegetation and climate along the pollen sequence of Lake Barombi Mbo, southwestern Cameroon (4°39′45.75″ N, 9°23′51.63″ E, 303 m a.s.l.) during the last 33 000 cal yr BP, improving previous empirical interpretations. The biomisation method was applied to reconstruct potential biomes and forest successional stages. Mean annual precipitation, mean annual potential evapotranspiration and an index of moisture availability were reconstructed using modern analogues and an artificial neural network technique. The results show a dense forested environment around Lake Barombi Mbo of mixed evergreen/semi-deciduous type during the most humid phases (highest precipitation and lowest evapotranspiration), but with a more pronounced semi-deciduous type from ca. 6500 cal yr BP to the present day, related to increased seasonality. This forest displays a mature character until ca. 2800 cal yr BP, then becomes of secondary type during the last millennium, probably due to increased human activity. Two episodes of forest fragmentation are shown, which are synchronous with the lowest reconstructed precipitation and highest potential evapotranspiration values. The first of these occurs during the LGM, and the second one from ca. 3000 to ca. 1200 cal yr BP, mainly linked to high precipitation seasonality. Savanna were, however, never extensive within the Barombi Mbo basin, existing instead inside the forest in form of savanna patches. The climate reconstructions at Lake Barombi Mbo suggest that the artificial neural networks technique would be more reliable in this region, although the annual precipitation values are likely under-estimated through the whole sequence.

1 Introduction

Central Africa holds the world's second largest rainforest after the Amazonian basin (Richards, 1981; Puig, 2001) and is today influenced by recent global climatic changes and will continue to be in the future (IPCC, 2007). A major challenge for the scientific community is to understand how this important natural forest ecosystem will be altered by the predicted climate changes in terms of distribution, functioning and biodiversity. Answering this challenge requires 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 have 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; Vincens et al., 1999; Elenga et al., 2004; Bonnefille, 2007; Lézine, 2007).

Numerous palynological studies have already been carried out in the western part of the Congo basin. For instance, in Ghana at Lake Bosumtwi (Maley, 1987, 1991); in Benin at Lake Sélé (Salzmann et 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, the majority of these studies were focused on the Holocene period and any palaeoclimatic interpretation was quantitative. At the same time, quantitative climate reconstructions have been made from pollen sequences in East Africa (Bonnefille et al., 1990, 1992; Bonnefille and Chalié, 2000 on the Burundi Highlands; Vincens et al., 1993; Chalié, 1995 at Lake Tanganyika).

The aim of this paper is to present, for the first time in central Africa, quantitative reconstructions of both palaeovegetation and palaeoclimate along the longest pollen sequence obtained in this region, previously published by Maley and Brenac (1998). This sequence was retrieved in Lake Barombi Mbo, southwestern Cameroon, and has an estimated basal age around 33 000 cal yr BP. For these reconstructions we have used the biomisation method (Prentice et al., 1992) for palaeovegetation reconstructions (biomes and dynamic forest stages), and both the modern analogues (Guiot, 1990) and the artificial neural networks techniques (Peyron et al., 1998) for palaeoclimate estimates. We have reconstructed the following climate parameters: mean annual precipitation (P_{ann} in mm), potential evapotranspiration ($\mathrm{PET_{ann}}$ in mm), and the bioclimatic parameter α, an index of moisture availability expressed in percentages (Prentice et al., 1992; Peyron et al., 1998). This parameter has been considered by Prentice et al. (1992) and Peyron et al. (1998) as more appropriate for defining the gradient from desert to rainforest than P_{ann}, a threshold value at 65 % discriminating a forest environment ($\alpha > 65\,\%$) from an open system ($\alpha < 65\,\%$) (Peyron, 1998). In contrast to studies in East Africa, the lack of modern samples from mid and high altitudes in west central Africa does not give an adequate range to reconstruct mean annual temperature from the Barombi Mbo pollen sequence.

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 above sea level (m.a.s.l.), on a large undulating plain between ca. 250 m and 500 m.a.s.l., north of the Cameroon Mount. The catchment, relatively small given 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 P_{ann} of about 2350 mm (meteorological station of Kumba; Fig. 2) linked to its proximity to the Atlantic ocean and its location in the volcanic dorsal of western Cameroon, where upper easterly winds above the monsoon are uplifted so increasing the activity during northern hemisphere summer (Suchel, 1988). For this reason, the precipitation distribution has an annual pattern with only one rainy season from March to November, with its maximum from July to October, and one dry season from December to March (Suchel, 1972). This is 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). Modern $\mathrm{PET_{ann}}$ is about 1200 mm (FAO website database, 2009). Due to these climatic conditions, the lake is surrounded today by humid lowland evergreen rainforest with patches of semi-deciduous forests (Letouzey, 1968, 1985) belonging 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 palaeoclimate at Lake Baromnbi Mbo is mainly taken from lowland ecosystems of west equatorial atlantic Africa including Gabon, Cameroon and Congo (Jolly et al., 1996; Elenga et al., 2000; Vincens et al., 2000; Lebamba et al., 2009a). This was 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.

The Modern P_{ann} and $\mathrm{PET_{ann}}$ values were extracted at each pollen site from the FAO website database (2009) and interpolated from the three closest available meteorological stations. No altitudinal correction was made due to the low altitude of all modern pollen data used in this work.

2.2.2 The fossil pollen data

The fossil pollen data (82 spectra and 86 taxa excluding aquatics and ferns) were extracted from the sedimentary sequence BM-6 recovered in the deepest central part of Lake Barombi-Mbo (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 dates obtained by the ORSTOM Geochronological Laboratory, Bondy, France. In this paper, the calibration of these radiocarbon dates into calendar age was made using the CALIB 6.0.1software (Stuiver and Reimer, 1993) and INTCAL09 (Reimer et al., 2009)

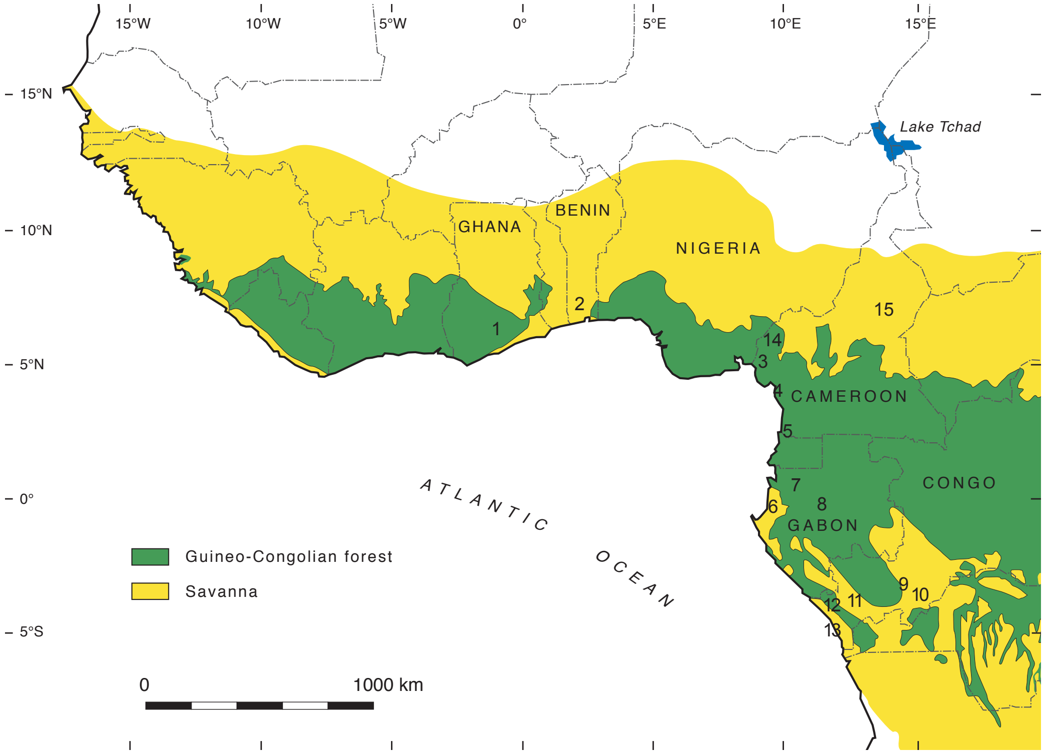

Fig. 1. Location of fossil pollen sites in west and central atlantic Africa 1: Bosumtwi. 2: Sélé. 3: Barombi Mbo/Mboandong. 4: Ossa. 5: Nyabessan. 6: Maridor. 7: Nguène. 8: Kamalété. 9: Bilanko. 10: Ngamakala. 11: Sinnda. 12: Kitina. 13: Coraf/Songolo. 14: Bambili. 15: Mbalang (map adapted from Ngomanda et al., 2009a).

(Table 1). Using this set of calendar ages, a second-order polynomial-age model was made, which shows the entire sequence to cover the last ca. 33 000 calendar years (Fig. 3). Between 0 and ca. 25 000 cal yr BP, the errors on the dates is low, but increase beyond this, 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). According to this estimated time scale, the temporal resolution of the pollen data is about ca. 200–300 yr for the Holocene period and about ca. 500–600 yr in earlier periods.

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. (1998a) to data from the key periods of 0 and 6000 ^{14}C BP. This is based on the Plant Functional Type (PFT) concept (Smith et al., 1997). The principal steps of this method are: (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 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 and a second PFTs-Biomes matrix is built; and (3) the two matrices are then used to estimate the scores of each PFT and of each biome in each pollen spectra, according to its composition. In this paper, and for the first time in Africa, scores of all the reconstructed potential biomes (TRFO: tropical rainforest; TSFO: tropical seasonal forest; SAVA: savanna) are plotted versus time (Fig. 4). For taxa present both in the modern dataset and in the Barombi Mbo pollen sequence, the Taxa-PFTs and PFTs-Biomes matrices defined by Lebamba et al. (2009b) were used, extended to include newly identified taxa in the first matrix with their allocation to PFTs (Table 2).

This method, now currently used for modern or past biome reconstructions all around the world, has been adapted by Lebamba et al. (2009b) to the modern stages of forest dynamics, highlighting the various phases of a structural succession. In this paper, the new PFTs and forest succession stages defined by these authors, and based (1) on the life-form of the plants as in biome reconstructions and (2) on the place they occupy in a forest succession in function of their behavior and growth strategies (e.g. Kahn, 1982; Köhler et al., 2000), are considered. As for biome reconstructions, the new taxa present in the Barombi Mbo sequence have been included in the previous Taxa-PFTs matrix (Table 3) and the scores of all the reconstructed successional stages (TMFO: tropical

Table 1. Radiocarbon ages performed on core BM-6, Lake Barombi Mbo, western Cameroon.

Laboratory code number	Depth(m)	14C age[yr BP]	σ Calibrated age[cal yr BP]	Calibrated age 2-σ-error bounds	Relative area under distribution
OBDY 660	0.25	770±100	768	555/609; 622/914	0.106 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; 8679/8681	1.00; 0.00
OBDY 138	9.90	8690±475	9715	8552/10 878; 10 941/11 079	0.982; 0.018
OBDY 751	10.80	9900± 2500	11 437,5	10 654/12 221; 12 346/12 377	0.985; 0.005
OBDY 61	13.45	13 120±965	15 629	13 208/18 050; 18 353/18 429	0.96; 0.004
OBDY 757	13.75	13 480±240	16 208,5	15 279/15 353; 15 401/17 016	0.013; 0.987
OBDY 811	15.10	15 470 ±100	18 705	18 540/18 870	1.00
OBDY266	16.65	17 080 ± 885	20 506	18 583/22 429	1.00
OBDY 59	18.75	20 420 ±1500	24521	20 900/28 134; 20 908/28 134	0.004; 0.996
OBDY 58	21.05	24 080±3500	27 817,5	20 243/35 392; 35 992/36 142	0.998; 0.002

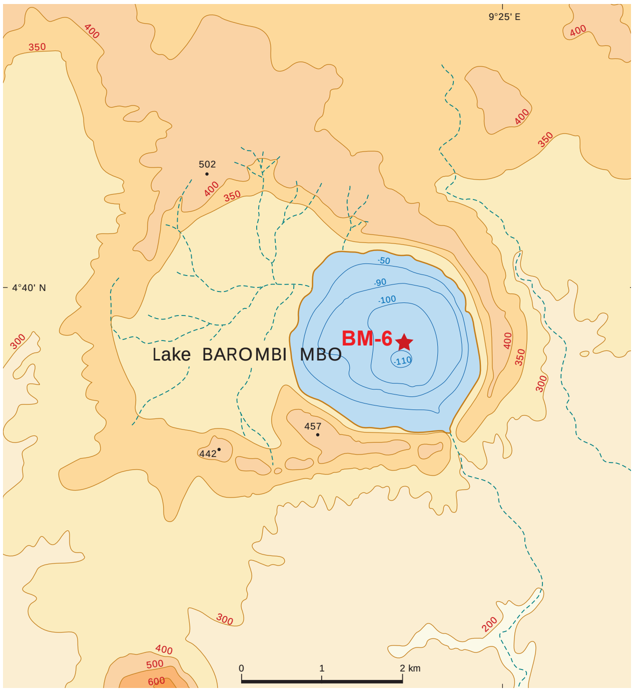

Fig. 2. Lake Barombi Mbo. Location of core BM-6 (after Giresse et al., 1991).

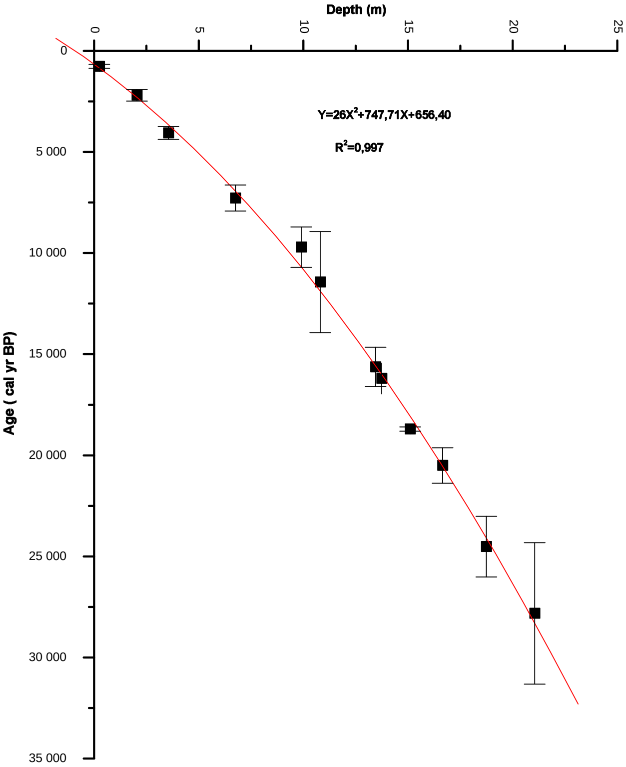

Fig. 3. Depth-age model of core BM-6 of Lake Barombi Mbo, western Cameroon.

mature forest; TSFE: tropical secondary forest; TFRE: tropical forest regrowth; SAVA: savanna) plotted versus time (Fig. 5).

3.2 The Modern Analogues Technique (MAT)

The MAT technique 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. The method has been previously used to estimate P_{ann} and temperature in East Africa (Bonnefille et al., 1990, 1992; Vincens et al., 1993; Chalié, 1995; Bonnefille and Chalié, 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, the use of PFTs allowing to deal with situations where pollen assemblages have only partial modern analogues. For each modern and fossil

Table 2. Allocation of the pollen taxa identified in the Barombi Mbo sequence to the plant functional types (PFTs) used for biome reconstructions.

Taxa	Te1	Te2	Tr1	Tr2	Tr3	TLw	TLd	THw	THd	g
Adenia						**x**				
Afzelia	**x**	**x**	**x**	**x**						
Alchornea	**x**	**x**	**x**							
Allophylus	**x**	**x**	**x**	**x**	**x**	**x**				
Amaranthaceae/Chenopodiaceae undiff.						**x**		**x**	**x**	
Anthonotha-type	**x**	**x**								
Antidesma-type	**x**	**x**	**x**	**x**	**x**					
Antrocaryon-type	**x**	**x**	**x**							
Asteraceae undiff.				**x**	**x**				**x**	
Baphia-type	**x**	**x**	**x**							
Berlinia-type	**x**	**x**	**x**							
Blighia	**x**	**x**	**x**	**x**	**x**					
Brachystegia		**x**	**x**							
Bridelia micrantha-type	**x**	**x**	**x**	**x**	**x**					
Brucea			**x**							
Caesalpiniaceae undiff.	**x**	**x**				**x**				
Canarium-type	**x**	**x**	**x**							
Cassia-type				**x**	**x**				**x**	
Ceiba pentandra		**x**	**x**							
Celastraceae/Hippocrateaceae undiff.	**x**	**x**	**x**	**x**	**x**	**x**	**x**			
Celtis		**x**	**x**							
Chaetacme aristata			**x**							
Cissus quadrangularis-type									**x**	
Cnestis	**x**	**x**	**x**			**x**				
Combretaceae/Melastomataceae undiff.	**x**	**x**	**x**	**x**	**x**	**x**		**x**	**x**	
Connaraceae undiff.	**x**	**x**	**x**			**x**				
Copaifera-type	**x**	**x**								
Crudia-type gabonensis	**x**									
Cryptosepalum	**x**	**x**	**x**							
Cynometra-type	**x**	**x**								
Daniellia	**x**			**x**	**x**					
Detarium	**x**	**x**	**x**	**x**						
Dialium	**x**	**x**	**x**		**x**					
Diospyros	**x**	**x**								
Discoglypremna caloneura	**x**	**x**	**x**							
Distemonanthus benthamianus-type	**x**	**x**	**x**							
Drypetes-type	**x**	**x**	**x**							
Fabaceae undiff.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	
Flacourtiaceae undiff.	**x**	**x**	**x**	**x**	**x**					
Gilletiodendron-type	**x**	**x**								
Gossweilerodendron-type	**x**	**x**	**x**							
Griffonia	**x**	**x**	**x**			**x**				

Table 2. Continued.

Taxa	Te1	Te2	Tr1	Tr2	Tr3	TLw	TLd	THw	THd	g
Guibourtia	**x**									
Hallea-type rubrostipulata	**x**									
Holoptelea grandis			**x**							
Hylodendron gabunense	**x**	**x**	**x**							
Hymenostegia-type pellegrinii	**x**									
Irvingia-type gabonensis	**x**	**x**	**x**							
Julbernardia-type		**x**	**x**							
Klaineanthus gaboniae	**x**									
Lannea-type		**x**	**x**	**x**	**x**					
Leonardoxa	**x**									
Lophira alata-type	**x**									
Macaranga-type	**x**	**x**	**x**							
Mallotus-type oppositifolius	**x**	**x**	**x**							
Margaritaria discoidea	**x**	**x**	**x**							
Mezoneuron-type		**x**	**x**							
Microdesmis	**x**	**x**	**x**							
Milicia-type excelsa	**x**	**x**	**x**							
Moraceae undiff.	**x**	**x**	**x**	**x**	**x**	**x**				
Nauclea-type	**x**	**x**	**x**	**x**	**x**					
Oxystigma -type	**x**									
Phyllanthus-type	**x**	**x**	**x**	**x**	**x**			**x**	**x**	
Piptadeniastrum-type africanum	**x**	**x**	**x**							
Poaceae undiff.										**x**
Pycnanthus angolensis-type	**x**	**x**	**x**							
Rubiaceae undiff.	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	
Sapotaceae undiff.	**x**	**x**	**x**							
Scottelia klaineana-type	**x**	**x**								
Sorindeia-type	**x**	**x**	**x**							
Sterculiaceae undiff.		**x**	**x**	**x**	**x**					
Strombosia	**x**	**x**								
Syzygium-type	**x**	**x**	**x**	**x**	**x**					
Tessmannia	**x**									
Tetracera	**x**	**x**	**x**			**x**				
Tetrorchidium	**x**	**x**	**x**							
Trema-type orientalis	**x**	**x**	**x**	**x**	**x**					
Trichilia-type	**x**	**x**	**x**							
Trichoscypha-type	**x**	**x**	**x**			**x**				
Trilepisium-type madagascariensis			**x**							
Uapaca	**x**	**x**	**x**							
Urticaceae undiff.						**x**		**x**		
Ximenia				**x**	**x**					
Zanthoxylum-type		**x**	**x**			**x**				

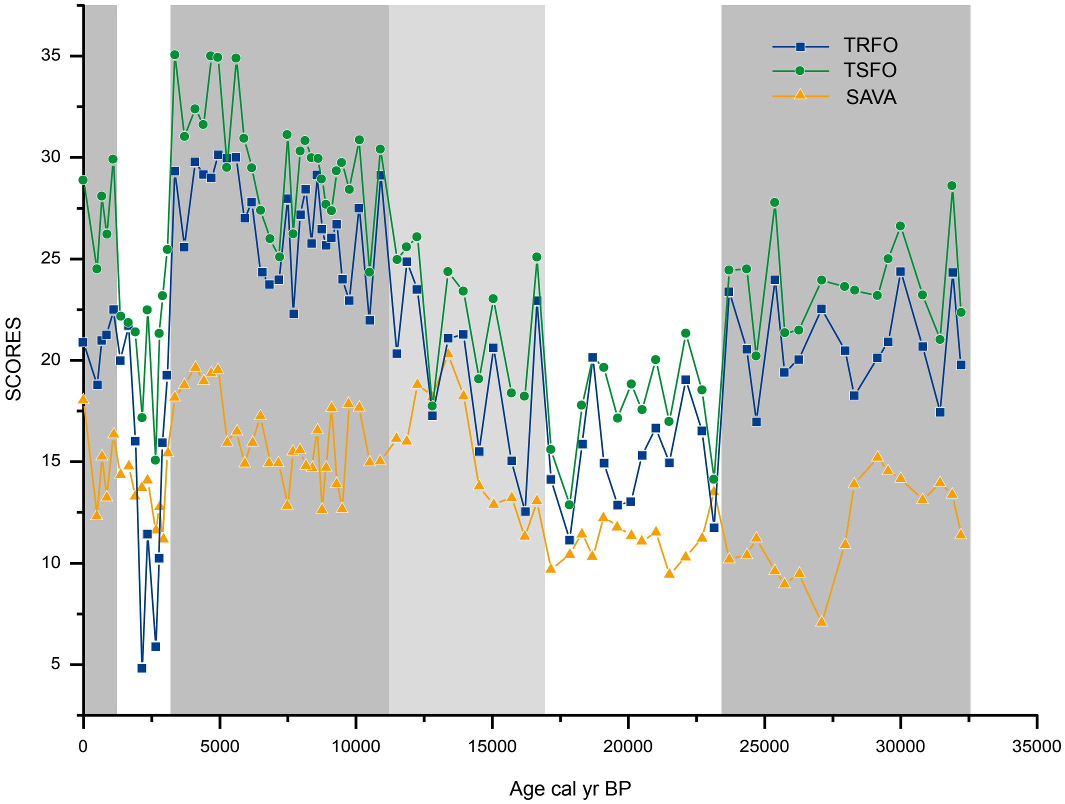

Fig. 4. Reconstructed potential biomes along the Barombi Mbo pollen sequence. TRFO (Tropical Rain FOrest), TSFO (Tropical Seasonal FOrest), SAVA (SAVAnna).

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. 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 MAT 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 also uses PFT scores. PFTs scores derived from modern pollen data are related to climatic parameters by using an artificial neural network to calibrate non linear relationships between PFTs and climatic variables (Guiot et al., 1996). This PFT climate calibration – climate calibration is considered to be more robust than the previous taxon (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 ANN technique are then applied to the fossil PFT scores to infer climatic variables.

In this paper, these two methods (MAT and ANN) were used to reconstruct P_{ann}, $\mathrm{PET}_{\mathrm{ann}}$ and α along the Barombi Mbo sequence.

In order to evaluate the reliability of both methods, climate parameters for each surface sample were estimated using the other modern samples (Peyron et al., 2005). 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 the two 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 4. The results show that the coefficients of correlation obtained for the three climatic parameters are good following the two techniques, though the ANN shows higher R^2.

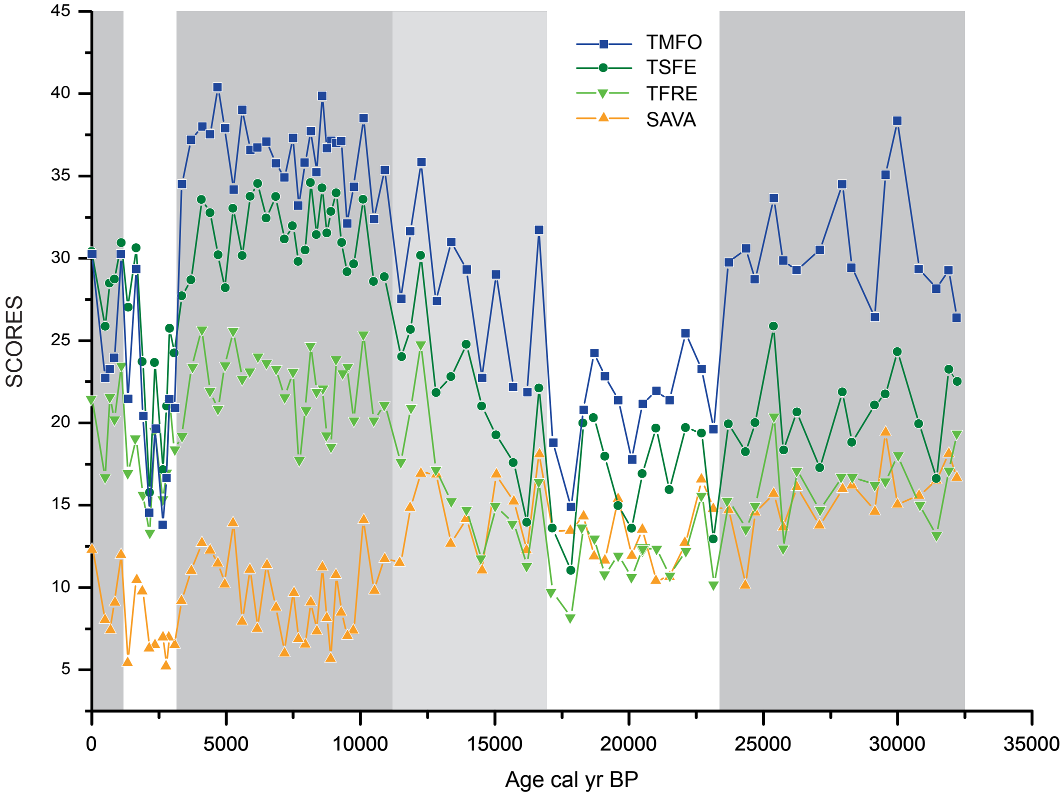

Fig. 5. Reconstructed successional stages along the Barombi Mbo pollen sequence. TMFO (Tropical Mature FOrest), TSFE (Tropical Secondary ForEst), SAVA (SAVAnna), TFRE (Tropical Forest REgrowth).

4 Quantitative environmental reconstructions at Lake Barombi Mbo

Our vegetation reconstructions (biomes and forest dynamic stages) are illustrated in Figs. 4 and 5, with mean (and also minima and maxima) score values for each defined period given in Table 5. Figure 6 shows reconstructed P_{ann}, PET_{ann} and index α on curves restricted within the errors bars, with mean (and also minima and maxima) values given in Table 6.

Between ca. 33 000 and ca. 23 400 cal yr BP, high reconstructed TSFO and TRFO biomes scores (Fig. 4), and a mean index α value of ca. 76 % (Fig. 6) indicate that a forest of mixed type was surrounding the lake. The mature facies of this forest is indicated by high scores of TMFO potential successional stage compared to TSFE ones (Fig. 5). This vegetation reconstruction is 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 the poorly dispersed Caesalpiniaceae (average of 7.2 with maximum of 10.5) would indicate a forest type largely dominated by this family under very wet climatic conditions. However, our reconstruction show a mean P_{ann} of only ca. 1300 mm and ca. 1000 mm using MAT and ANN techniques, respectively, associated with high mean PET_{ann} values of about 1500 mm in both methods (Fig. 6; Table 6).

From ca. 23 400 until ca. 17 000 cal yr BP, a period containing the Last Glacial Maximum (LGM, 23 000 to 19 000 cal yr BP; Yokoyama et al., 2000), there is a substantial reorganization of the floristic composition and structure of the vegetation surrounding the lake. The scores of TRFO and TSFO potential biomes abruptly fall, coming close to the scores of the savanna (SAVA) potential biome (Fig. 4). 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 (Fig. 5). This indicates that the environment of the lake becomes more open, with development of disturbed forest and of savanna, probably in the form of a forest-savanna mosaic. Low mean α values (68 %) derived from ANN technique are consistent with this opening of the vegetation, although no change is observed when using the MAT technique (mean α of 76 %) (Fig. 6). Previous empirical interpretations of pollen data (Pollen-zone IIA, Maley and Brenac, 1998) indicate such a fragmentation of the forest marked by a general decrease in tree pollen, local peaks of pioneer taxa such as *Trema*, *Alchornea*, *Musanga/Myrianthus* and a large increase in Poaceae. Inside this time interval, Elenga et

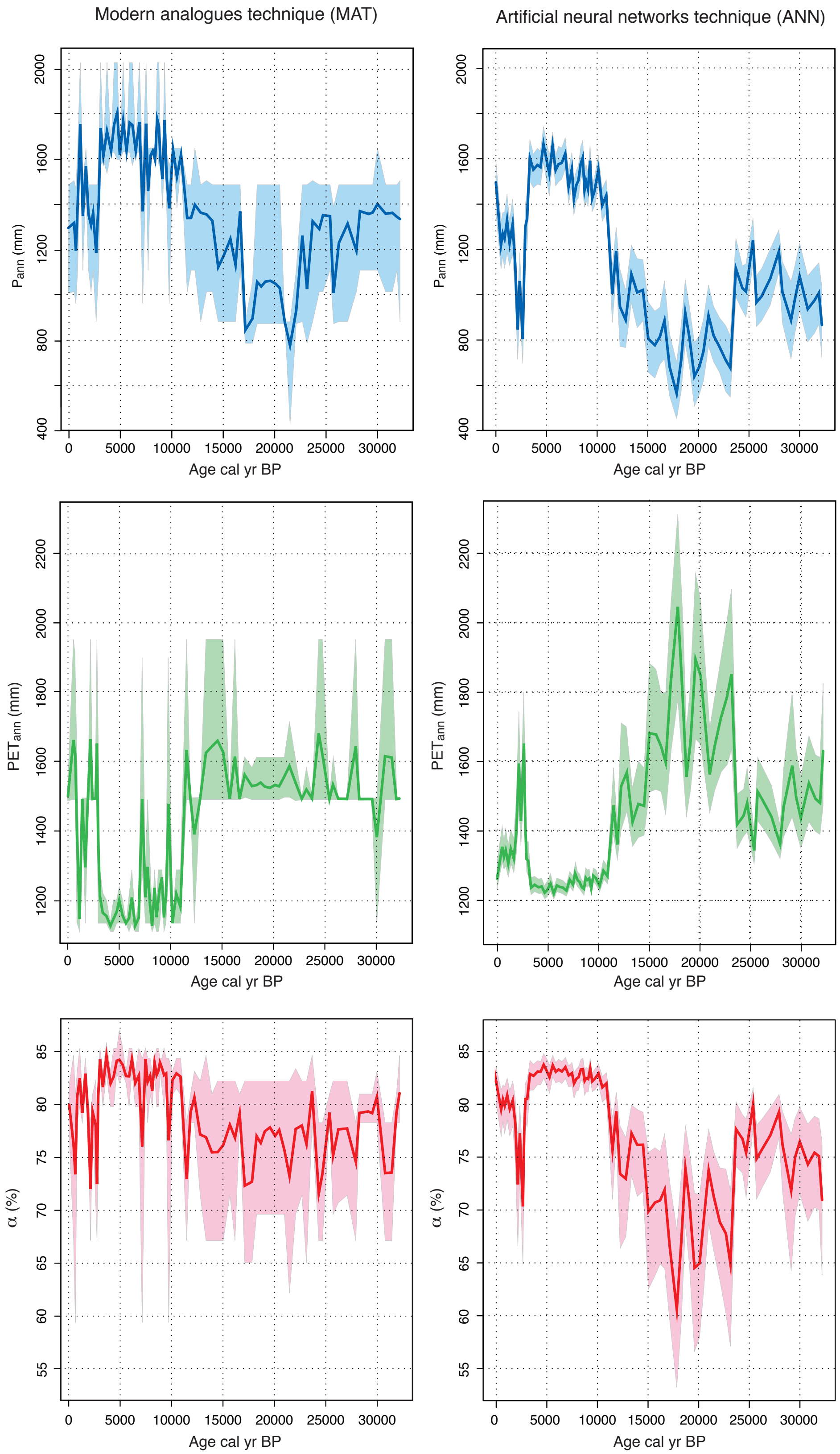

Fig. 6. Reconstructed climatic parameters (P_{ann}, PET_{ann} and index α) along the Barombi Mbo pollen sequence.

Table 3. Allocation of the pollen taxa identified in the Barombi Mbo sequence to the plant functional types (PFTs) used in dynamic reconstructions.

Taxa	Tma	Lma	Hma	Tosf	Tysf	Lsf	Hsf	Tpi	Lpi	Hpi	Tr3	Lr3	Hr3	g
Adenia						x			x			x		
Afzelia	x			x	x						x			
Alchornea	x			x	x			x						
Allophylus	x	x		x	x	x		x			x			
Amaranthaceae/Chenopodiaceae undiff.		x	x			x	x		x	x			x	
Anthocleista					x			x			x			
Anthonotha-type	x													
Antidesma-type	x			x	x			x			x			
Antrocaryon-type	x			x										
Asteraceae undiff.											x		x	
Baphia-type	x			x	x			x						
Berlinia-type	x													
Blighia	x										x			
Brachystegia	x													
Bridelia micrantha-type	x			x	x			x			x			
Brucea	x			x	x									
Caesalpiniaceae undiff.	x	x		x	x			x		x	x			
Canarium-type	x			x										
Cassia-type								x		x			x	
Ceiba pentandra	x			x										
Celastraceae/Hippocrateaceae undiff.	x	x		x	x	x		x	x		x	x		
Celtis	x			x	x									
Chaetacme aristata	x			x	x			x						
Cissus quadrangularis-type										x			x	
Cnestis	x	x			x	x			x					
Combretaceae/Melastomataceae.undiff.	x	x	x	x	x	x	x	x	x	x	x		x	
Connaraceae undiff.	x	x	x											
Copaifera-type	x													
Crudia-type gabonensis	x													
Cryptosepalum	x													
Cynometra-type	x													
Daniellia	x			x	x						x			
Detarium	x										x			
Dialium	x										x			
Diospyros	x													
Discoglypremna caloneura	x			x										
Disthemonanthus benthamianus-type	x			x										
Drypetes	x													
Elaeis guineensis				x	x			x						
Fabaceae undiff.	x	x		x	x	x	x	x	x	x	x	x	x	
Flacourtiaceae undiff.	x			x	x			x			x			
Gilletiodendron-type	x													

Table 3. Continued.

Taxa	Tma	Lma	Hma	Tosf	Tysf	Lsf	Hsf	Tpi	Lpi	Hpi	Tr3	Lr3	Hr3	g
Gossweilerodendron-type	x													
Griffonia	x													
Guibourtia	x													
Hallea-type rubrostipulata	x													
Holoptelea grandis	x			x										
Hylodendron gabunense	x			x										
Hymenostegia-type pellegrinii	x													
Irvingia-type gabonensis	x			x										
Julbernardia-type	x													
Klaineanthus gaboniae	x													
Laccosperma									x					
Lannea -type	x			x	x			x			x			
Leonardoxa	x													
Lophira alata-type	x			x	x			x						
Macaranga-type	x			x	x			x						
Mallotus-type oppositifolius	x			x	x			x						
Margaritaria discoidea	x			x	x			x						
Mezoneuron-type	x													
Microdesmis	x			x	x			x						
Milicia-type excelsa	x			x										
Moraceae undiff.	x	x		x	x			x			x			
Musanga					x			x						
Nauclea-type	x			x	x			x			x			
Oxystigma-type	x													
Phyllanthus-type	x		x	x	x		x	x		x	x		x	
Piptadeniastrum-type africanum	x			x										
Poaceae undiff.														x
Pycnanthus angolensis-type	x			x										
Rubiaceae undiff.	x	x	x	x	x	x	x	x	x	x	x	x	x	
Sapotaceae undiff.	x													
Scottelia klaineana-type	x			x										
Sorindeia-type	x													
Sterculiaceae undiff.	x			x	x			x			x			
Strombosia	x													
Syzygium-type	x			x	x			x			x			
Tessmannia	x													
Tetracera	x	x		x	x	x		x	x					
Tetrorchidium	x			x	x			x						
Trema-type orientalis	x			x	x			x			x			
Trichilia-type	x			x										
Trichoscypha-type	x	x												
Trilepisium-type madagascariensis														
Uapaca	x			x										
Urticaceae undiff.		x	x			x	x		x	x				
Ximenia	x							x						
Zanthoxylum-type	x	x		x	x	x		x						

Table 4. Correlation coefficients between observed and reconstructed values of climate parameters reconstructed from modern pollen samples.

Climate Parameters	MAT		ANN	
	Correlation coefficient	RMSE	Correlation coefficient	RMSE
P_{ann} (mm)	0,65	360,6	0,7	387,9
PET_{ann}(mm)	0,71	259,4	0,77	233,1
α	0,65	8,4	0,67	8,2

Table 5. Mean and minima and maxima (between brackets) values of scores of reconstructed potential biomes and successional stages in the Barombi Mbo pollen sequence.

PERIOD (cal yr BP)	BIOMES (scores)			STAGES (scores)			
	TRFO	TSFO	SAVA	TMFO	TSFE	TFRE	SAVA
0–1200	21 (18 to 22)	27 (24 to 30)	15 (12 to 18)	26 (23 to 30)	29 (26 to 31)	21 (17 to 23)	10 (7 to 13)
1200–3000	14 (5 to 22)	21 (15 to 25)	13 (11 to 15)	19 (14 to 29)	23 (15 to 31)	17 (13 to 21)	7 (6 to 10)
3000–11 500	27 (22 to 30)	30 (24 to 35)	16 (13 to 20)	36 (32 to 40)	31 (28 to 34)	22 (18 to 26)	10 (6 to 14)
11 500–17 000	19 (13 to 25)	22 (18 to 26)	16 (12 to 20)	28 (22 to 36)	22 (14 to 30)	16 (11 to 24)	15 (11 to 18)
17 000–23 400	15 (11 to 20)	18 (13 to 21)	11 (9 to 14)	21 (15 to 25)	17 (11to 20)	12 (8 to 16)	13 (10 to 17)
23 400–33 000	21 (17 to 24)	24 (20 to 29)	12 (7 to 15)	30 (26 to 38)	21 (17 to 26)	16 (12 to 20)	15 (10 to 19)

al. (2000) reconstructed for the 18 000 ^{14}C yr BP key period a TSFO potential biome, whereas Maley and Brenac (1998) noted the importance of the Caesalpiniaceae before and after this episode, during which their percentage values were higher than present day. Taken together, this could indicate that during the LGM, evergreen forest patches, interpreted as refugia, remained in this inland region (Maley, 1991, 1996). During this episode, previously interpreted by Maley and Brenac (1998) as dry, our reconstructions of P_{ann} using MAT and ANN techniques show a decrease of 300 mm from the preceding period, with reconstructed minima of ca. 770 mm and ca. 600 mm, respectively (Fig. 6). Mean PET_{ann} increases by about 300 mm with the ANN method, while no change is observed using the MAT method (Fig. 6). These drier conditions would have caused an important deficit in soil moisture and the loss of forest tree taxa unable to support such a hydrological stress. This is supported by the lower values of α, close to the threshold value discriminating a forested environment from an open system (ANN). These dry conditions also caused the level of Lake Barombi Mbo to drop, shown by the expansion of Cyperaceae dominated swamps on the western drained deltaic zone offshore from the main modern inlet (Fig. 2) (Maley and Brenac, 1998).

After ca. 17 000 cal yr BP and until ca. 11 500 cal yr BP, the irregular, but parallel increase in scores of TRFO and TSFO potential biomes indicates progressive reforestation of the Lake Barombi Mbo area. SAVA potential biome scores remain high however, indicating the continued presence of patches of open formations in the vicinity of the lake until ca. 13 500 cal yr BP (Fig. 4). The scores of TMFO and TSFE potential successional stages also increase, but TSFE stage values are more similar to the TMFO stage values than during the forest episode recorded between ca. 33 000 and ca. 23 400 cal yr BP (Fig. 5). This could indicate a more perturbed and unstable forest environment, supported by a lower and fluctuating mean value of α (ca. 74 % with ANN technique; Fig. 6). This period corresponds to pollen-zone IIb (Maley and Brenac, 1998) when Poaceae regularly decrease, while tree taxa such as the Caesalpiniaceae and Sapotaceae develop. This is followed at ca. 14 000 cal yr BP by evergreen forest taxa including *Trichoscypha*, *Strombosia*, *Lophira* (a light demanding pioneer tree in its young phase of ecological behavior) and semi-deciduous forest taxa associated with increase of the forest pioneer *Macaranga*, including *Nauclea*, *Uapaca* and *Antiaris*. This combination of taxa has been interpreted as an episode of forest recolonisation of open and disturbed formations around Lake Barombi Mbo, also supported by decreased δ^{13}C values (Giresse et al., 1994), and related to increased precipitation. In our reconstructions, mean P_{ann} estimates follow a similar trend to the forest biome scores, increasing from 800 mm ca. 16 500 cal yr BP to 1100 mm ca. 11 500 cal yr BP (ANN), and from 800 to 1350 mm (MAT), whereas PET_{ann} values show opposing trends indicating a return to more humid conditions after the LGM (Fig. 6). During this period, a decrease in P_{ann} of about 100–200 mm is shown in the ANN reconstructions, but not

Table 6. Mean and minima and maxima range (between brackets) values of the 878 reconstructed climatic parameters in the Barombi Mbo pollen sequence.

PERIOD (cal yr BP)	Climatic parameters					
	P_{ann} (MAT) mm	P_{ann} (ANN) mm	PET_{ann} (MAT) mm	PET_{ann} (ANN) mm	α (MAT) %	α (ANN) %
0–1200	1392 (1194 to 1399)	1311 (1219 to 1493)	1462 (1148 to 1660)	1319 (1263 to 1354)	78 (73 to 82)	81 (78 to 82)
1200–3000	1400 (1184 to 1739)	1121 (804 to 1335)	1463 (1213 to 1492)	1422 (1314 to1594)	79 (72 to 84)	77 (70 to 80)
3000–11 500	1644 (1512 to 1807)	1536 (1394 to 1664)	1204 (1128 to 1491)	1248 (1219 to 1285)	82 (76 to 85)	83 (82 to 84)
11 500–17 000	1288 (1121 to 1398)	949 (777 to 1192)	1559 (1390 to 1642)	1537 (1361 to 1681)	77 (73 to 81)	74 (70 to 79)
17 000–23 400	991 (774 to 1261)	743 (564 to 920)	1535 (1492 to 1586)	1764 (1556 to 2046)	76 (72 to 78)	68 (61 to 74)
23 400–33 000	1310 (1006 to 1401)	1023 (866 to 1240)	1532 (1382 to 1679)	1476 (1343 to 1630)	77 (72 to 81)	76 (71 to 80)

in the MAT reconstructions. This occurs ca. 12 500 cal yr BP, synchronous with the Younger Dryas episode of Northern Hemisphere (12 800–11 600 cal yr BP; Bard and Kromer, 1995) (Fig. 6). During this short dry episode, the biome scores of TRFO, TSFO and SAVA become similar, indicating a slight opening of the vegetation and is accompanied with the end of an abrupt lake lowering (Maley and Brenac, 1998).

The period between ca. 11 500 and ca. 3000 cal yr BP is the mostly densely forested of the whole sequence. TRFO and TSFO potential biomes reach their highest values (Fig. 4) as do the TMFO and TSFE potential successional stages (Fig. 5). The high TSFO scores, together with an α index of 82–84 % (ANN) or of 76–85 % (MAT), indicate the existence around the lake of a mixed evergreen/semi-deciduous forest and not of a pure stand evergreen forest (Fig. 6). This is consistent with pollen data (Pollen-zone III, Maley and Brenac, 1998) indicating the presence and abundance of elements from these two forest facies, and previous reconstructions of TSFO potential biome at the 6000 ^{14}C yr BP key period (Jolly et al., 1998a). The constant presence of forest pioneers during this period in the pollen diagram and relatively high values of TFRE successional stage (Fig. 5) may result from local and natural openings of the canopy during this period of maximum development. Reconstructed mean P_{ann} values are about 1650 mm (MAT) and 1550 mm (ANN), and correspond to the highest values obtained along the whole sequence. For the first time, P_{ann} values are higher than PET_{ann} values, which are of about 1200 mm and 1250 mm, respectively (Fig. 6). This period represents the most humid episode in the sequence.

From ca. 6500 to ca. 3000 cal yr BP, the differences between TRFO and TSFO biome scores increase (Fig. 4), indicating a change in the composition of the local forest toward a more pronounced semi-deciduous facies than before. As the reconstructed P_{ann} change little from the preceding period, these differences may be caused by increased seasonality, but the mature character of the forest remains well established (Fig. 5).

An abrupt change in the vegetation of Lake Barombi Mbo is registered at ca. 3000 cal yr BP, shown by a rapid and marked decrease of scores of forest biomes, TRFO and TSFO, and of forest successional stages, mainly TMFO and TSFE (Figs. 4 and 5). Between ca. 3000 and ca. 1200 cal yr BP, TRFO scores are at their lowest for the whole sequence, and TSFO and SAVA scores decline. TMFO, TSFE and TFRE have similar values. This shows a new perturbation and fragmentation of the forest in this area. The shorter duration of this period reduced the impact of this perturbation, compared to the LGM. Openings in the environment were smaller, and α values were reduced slightly to between 72 and 84 % (MAT) or between 70 and 80 % (ANN). In the pollen diagram (pollen-zone IVa; Maley and Brenac, 1998), Poaceae and pioneer taxa, mainly *Alchornea*, increase whereas typical forest taxa, mainly evergreen taxa, are less abundant and diversified (Fig. 4). Reconstructed P_{ann} estimates drop to values of about 1400 mm (MAT) and of about 1100 mm (ANN), with minima of 1200 mm and 800 mm, respectively. PET_{ann} increases to a mean of 1400 mm, with maxima of ca. 1650 mm or 1500 mm (Fig. 6; Table 6). Taken together, this shows that low P_{ann} together with increased seasonality and high PET_{ann} would have reduced the capacity of forest species to regenerate, opening the way for the spread of pioneers (Fig. 5).

Following this dry episode, α increases to 78 % (MAT) and 81 % (ANN) and the forest around Lake Barombi Mbo regenerates from ca. 1200 cal yr BP until the present day (Fig. 6). As during the period between ca. 6500 and ca. 3000 cal yr BP, the differences between scores values of TRFO and TSFO potential biomes indicate that the dominant facies of this forest is of a semi-deciduous type (Fig. 4). The higher scores of TSFE potential stage than of TMFO stage indicate a more pronounced secondary and disturbed character (Fig. 5). In the pollen diagram (Pollen-zone IVb, Maley and Brenac, 1998), dominant taxa are from semi-deciduous forest or forest pioneers. During the last millennium, mean P_{ann} estimates are about 1400 mm (MAT) and about 1300 mm (ANN), and mean PET_{ann} estimates are 1450 mm and 1300 mm, respectively, with higher variations in the MAT reconstructions (Fig. 6). In both techniques, present day P_{ann} estimated at the top of the core are lower than measured values at the nearby meteorological station of Kumba (2350 mm). In contrast, mean PET_{ann}

is well reconstructed by ANN technique when compared to the present day value (ca. 1200 mm) (Fig. 6).

5 Discussion

The discussion will focus on the major points and questions arising from our vegetation and climate quantitative reconstructions at Lake Barombi Mbo during the last 33 000 cal yr BP, complemented by a comparison with quantitative results previously obtained at this site and in other African regions.

5.1 Vegetation reconstructions

At Lake Barombi Mbo and for the first time in Africa, the biomisation technique has been applied to reconstruct (1) vegetation along a continuous pollen sequence and (2) the relative dominance of different vegetation classes, by using scores of all biomes (and in this paper also of all successional stages) plotted versus time. Previously, all applications of this technique were focused on key periods (0, 6000 and 18 000 ^{14}C yr BP, i.e. 0, 6800 and 21 000 cal yr BP for a better comparison with our data) and only the most dominant biome was considered in the reconstructions (Jolly et al., 1998a, b; Elenga et al., 2000; Peyron et al., 2000; Vincens et al., 2006; Hely et al., 2009; Lebamba et al., 2009b; Lézine et al., 2009). In South America, Marchant et al. (2006), using a similar methodology to this paper, have shown that considering only the biome with the highest score value to reconstruct vegetation resulted in a large amount of lost information. Our data support such conclusion and also show that biased or erroneous reconstructions may be obtained. This can be clearly shown by comparing our results with those obtained by Jolly et al. (1998a) and Elenga et al. (2000) on the Barombi Mbo site at 0, 6800 and 21 000 cal yr BP, periods known to be climatically and hydrologically very different (e.g. Gasse, 2000). These authors have reconstructed the same vegetation type for these three periods, i.e. a tropical seasonal forest (TSFO dominant biome). While the TSFO biome has the highest score values in our reconstructions for these key periods (Fig. 4), the scores displayed by the other biomes can be used to make more complete and precise vegetation reconstructions. At ca. 6800 cal yr BP, during the African Humid Period (AHP, de Menocal et al., 2000), TSFO and TRFO score values are closer than at 0 and ca. 21 000 cal yr BP, and the difference between TSFO and SAVA score values is greatest. This would indicate that during this period, the forest surrounding Lake Barombi Mbo displayed a more mixed rain (evergreen)/seasonal (semi-deciduous) character with less open formations than during the two other periods. At ca. 21 000 cal yr BP, during a period of lower α values (Fig. 6), the reduced difference between TSFO and SAVA biome scores indicate a more disturbed and open forest. The low scores of all the reconstructed biomes would suggest a poor floristic diversity. For the modern periods, the vegetation appears to have a more pronounced seasonal (semi-deciduous) character, as shown by a higher difference between TSFO and TRFO score values than at ca. 6800 and ca. 21 000 cal yr BP.

These results show that taking a combination of all reconstructed biome score values into account makes possible to better differentiate forest types occurring around Lake Barombi Mbo at 0, ca. 6800 and ca. 21 000 cal yr BP, and gives better agreement with pollen data and climate. Further, if only the dominant biome had been considered throughout the sequence, this record would show no response to environmental change (TSFO biome always dominant), supporting the results from South American sequences by Marchant et al. (2006).

5.2 Climate reconstructions

Our quantitative climate reconstructions, while following the general climate trends of previous studies in Africa, raise some questions which we discuss here. This discussion will focus on (1) a comparison of the results and their reliability according to the techniques used, and (2) the P_{ann} estimates as (a) it is the climatic parameter whose quantitative reconstruction appears as the most uncertain and (b) a comparison can be made with previous quantitative estimates and model-simulations available at 0, 6800 and 21 000 cal yr BP for Lake Barombi Mbo (Jolly et al., 1998b; Peyron, 1998; Peyron et al., 2006; Wu et al., 2007) and for fossil pollen sequences in other parts of Africa (e.g. Bonnefille and Chalié, 2000).

5.2.1 Comparison of MAT- and ANN-inferred climate reconstructions

The comparison of the results obtained using the two techniques shows both similarities and differences along the Barombi Mbo pollen sequence.

Similar trends are shown in P_{ann} estimates with both techniques during the last 33 000 cal yr BP, and follow the main vegetation changes obtained using the biomisation method. However, with the MAT technique, reconstructed P_{ann} values are always higher than using the ANN technique. These differences are often greater than 200 mm, with the greatest and over 400 mm at ca. 2500 cal yr BP and before 27 000 cal yr BP. Under-estimation of P_{ann} values by ANN technique was already reported by Peyron et al. (2006) for 0 and 6800 cal yr BP, leading these authors to suggest that the MAT technique is more reliable to reconstruct this parameter than ANN. However, the confidence intervals provided by the MAT technique are generally higher than those provided by the ANN one (Fig. 6). This may be due to the method used for the estimation of the error bars, but is more probably due to the lack of good analogues for the MAT technique, which despite the use of PFTs scores instead of pollen percentages, is a method that helps where pollen assemblages have only partial modern analogues (Peyron et al., 1998).

ANN-inferred estimates of $\mathrm{PET}_{\mathrm{ann}}$ show opposing trends to P_{ann} reconstructions and to hydrological data available at such altitude in tropical west and central Africa (e.g. Gasse, 2000), as does the related index α whose values correspond well with vegetation reconstructions. In contrast, no clear change is observed in either parameter when using the MAT technique between ca. 13 000 and ca. 33 000 cal yr BP. Comparisons with quantitative reconstructions of this climatic parameter, either locally or with other regions of Africa, suggest that this climate parameter is better reconstructed using the ANN technique than the MAT one. This hypothesis is supported by the greater similarity between the modern reference and the 0 yr BP ANN-inferred $\mathrm{PET}_{\mathrm{ann}}$ value than the 0 yr BP MAT-inferred value (FAO website database, 2009).

5.2.2 P_{ann} reconstructions

Present day P_{ann} reconstructions

Our results clearly show a discrepancy between our modern P_{ann} estimates using both the MAT (ca. 1300 mm) and the ANN (ca. 1490 mm) techniques and the value (2350 mm) measured today at the nearest meteorological station of Kumba. One explanation for this discrepancy is that the modern pollen data set used in our work contains too few samples from areas with very high precipitation (only 18 % of the samples are above 1600 mm yr^{-1}, and only 3 % are above 2000 mm yr^{-1}). There is a notable lack of present day pollen samples from the West Cameroon lowland forest, which is characterized by a very humid climate ($P_{\mathrm{ann}} \geq 2500$ mm and a continuous rainy season going from March to November, i.e. without a “summer little dry season”, usually in July and August). This hypothesis could be supported by the work of Peyron et al. (2006, Fig. 3a). These authors have shown that in West Africa the ANN technique under-estimates modern P_{ann} values above 2000 mm (with differences of ca. −700 mm), and that neither technique is capable of reproducing modern P_{ann} around 3000 mm (with differences of ca. −800 mm using MAT and ca. −1100 mm using ANN). This under-estimation of modern P_{ann} in very humid areas has been mainly linked to the quality of modern analogues (shown by an increase in chord distance) as well as the presence of numerous “no-analogue” situations. As the top of a lacustrine core may not record present day sedimentation due to possible perturbation of surface sediments during coring, we have applied the MAT and ANN techniques to a modern lacustrine mud from the Lake Barombi Mbo and analyzed for pollen content by Reynaud (1991). P_{ann} reconstructions of this sample give estimates of ca. 1520 mm and of ca. 1480 mm, respectively, remaining lower (with anomaly values of about ca. −830 and ca. −870 mm) than modern values, and so confirming our reconstructions at the top of the pollen sequence.

Other hypotheses may explain such modern P_{ann} discrepancy. The first one, observed in many tropical humid forest regions, is that many characteristic plants that occur in the wettest forests of Cameroon are entomophilous and/or have low pollen dispersion leading to an absence or very low representation of their pollen grains in sediments. Such a feature has been previously shown in modern pollen rain from West Cameroon by Reynaud-Farrera (1995). The second hypothesis is that the pollen taxonomy is limited due to morphological affinities. In this paper, the nomenclature of the taxa identified by Maley and Brenac (1998) has been homogenized according to Vincens et al. (2007) and the APD (2008) nomenclature to allow comparison with our pollen taxa present in our modern pollen database, an essential work to make reliable modern and past quantitative reconstructions of both vegetation and climate. In this way, many taxa have been considered as “type”, and may be present today in diverse west central African forest environment from the most humid to semi-deciduous forest as shown in Table 2. Finally, the last hypothesis that can be involved would be that recent vegetation around Lake Barombi Bo has been sufficiently perturbed (naturally or by human activities) to make the pollen assemblages at the top of the sequence and in the modern sediment unrepresentative of its natural status, as suggested for some sites from Burundi by Bonnefille and Chalié (2000). However, we suggest that it is more likely a combination of these factors for this peculiar key period; both the lack of modern data from very wet areas and the occurrence of local perturbed vegetation have resulted in under-estimation of P_{ann}.

However, if our modern dataset is biased by (1) the lack of data from the wettest areas of western Cameroon, although it is the most complete currently available; (2) an absence or scarce representation in the pollen rain of characteristic elements of very wet forest; and (3) inadequate identification of pollen taxa, this bias could have also induced an under-estimation of reconstructed P_{ann} throughout the pollen sequence, particularly during humid periods such as the early and mid-Holocene.

P_{ann} reconstructions at 6800 cal yr BP

This period falls within the most recent humid period in Africa (“African Humid Period”, or “AHP”, DeMenocal et al., 2000), when our MAT and ANN reconstructions display the highest mean P_{ann} estimates of the whole sequence (Table 6). These are only slightly higher than present day reconstructed ones, but remain lower than modern values at the Kumba station. More precisely, at ca. 6800 cal yr BP, the mean P_{ann} estimates are ca. 1770 mm (MAT) and ca. 1600 mm (ANN), with anomaly values of ca. −580 mm and ca. −750 mm relative to Kumba measurement, respectively.

For a reliable comparison, we have considered the same pollen levels in the Barombi Mbo sequence than the ones used by Jolly et al. (1998a, 1998b), and then by Peyron et al. (2006) for biome scores and climate quantitative estimates. At 6800 cal yr BP, the P_{ann} reconstructions proposed by Peyron et al. (2006) indicate P_{ann} anomalies of 0 to <-90 mm and of 0 to <-204 mm using MAT and ANN techniques, respectively. These authors have considered a modern reference value of 2000 mm (Peyron, personal communication, 2011), lower than the value measured at the Kumba station and considered in this paper as modern reference. These authors have concluded that at Barombi Mbo, mid-Holocene reconstructed hydrological conditions depicted the occurrence of similar to or drier conditions than today. In the same way, all model-data comparisons have simulated P_{ann} values equal or lower than today by 0 to 300 mm (Jolly et al., 1998b; Peyron et al., 2006) or slightly higher (Wu et al., 2007). Peyron et al. (2006) have considered, according the data obtained in west equatorial Africa, that the amplitude of rainfall change at 6800 cal yr BP was almost negligible and in good agreement with previous P_{ann} estimates inferred from several pollen sequence in east equatorial Africa (Bonnefille and Chalié, 2000). At the same time, lake status reconstructions show no change in lake-level (Jolly et al., 1998b). However, the occurrence of an outlet close to the modern level could have stabilized its level during humid periods (Fig. 2).

Although our P_{ann} estimates are slightly lower than in previous works, if these are considered as anomalies from the present day reconstructions, this period is more humid than the present using both methods.

P_{ann} reconstructions at 21 000 cal yr BP

This key period falls with the LGM, an episode climatically considered in tropical Africa as the driest one of the last 30 000 cal yr BP and marked by opening of wooded vegetation and low lake-levels and complete drying up of some lakes (Gasse, 2000; Gasse et al., 2008). Our results at Barombi Mbo are in agreement and clearly show that in both MAT and ANN techniques, the lowest mean P_{ann} estimates along the whole sequence are recorded during this episode (Table 6). More precisely, at ca. 21 000 cal yr BP, the P_{ann} reconstructed values are ca. 874 mm (MAT) and ca. 908 mm (ANN), representing anomalies of ca. -1470 mm and of ca. -1440 mm compared to modern values at the Kumba station. In West equatorial Africa, Peyron (1998) estimates anomalies of ca. -400 mm using the ANN technique, and of ca. -150 mm using an inverse vegetation modelling under both modern CO_2 concentration of 340 ppmv and LGM concentration of 200 ppmv, suggesting that low CO_2 concentration does not seem to affect the LGM vegetation in West African lowlands. These anomaly values appear largely lower than our values, even as for the 6800 cal yr BP, this author used as modern reference a value of only 2000 mm. Model reconstructions made by Wu et al. (2007) show also a lower P_{ann} decrease of ca. 300 mm, using probably the same modern reference than in Peyron (1998) and Peyron et al. (2006).

In East Africa, P_{ann} reconstructions performed using the MAT technique have estimated a mean anomaly during the LGM of ca. -450 mm relative to present with a maximum of ca. -700 mm on the equatorial highlands of central east Africa, and a mean anomaly of ca. -224 mm in the southern Tanganyika basin (Bonnefille and Chalié, 2000). At this last site, a water and energy balance model has simulated a similar decrease in P_{ann} of ca. 275 mm during the LGM (Bergonzini et al., 1997) but, according to Tyson et al. (1997), this value must be considered as a minimal estimate, as decreases in P_{ann} may be substantially amplified when including empirical changes in atmospheric transmission coefficient, whereas large changes in cloud cover and air humidity not modify these trends. For this period, our reconstructions of the decrease in P_{ann} are clearly over-estimated when compared to results obtained in West equatorial Africa and in East Africa.

In addition to results obtained for the 0, 6800 and 21 000 cal yr BP periods, the quantitative reconstructions from the Barombi Mbo sequence show interesting changes in other periods, notably before and after the LGM and around 2500 cal yr BP.

During the period between ca. 33 000 and ca. 23 400 cal yr BP, our mean P_{ann} estimates are only about 1300 mm (MAT) and 1000 mm (ANN), close to values obtained during the deglaciation between ca. 17 000 and ca. 11 500 cal yr BP and lower than those proposed during the AHP. PET_{ann} estimates display also similar values than during the deglaciation but they are higher than during the AHP (Fig. 6 and Table 6). According to the relatively high percentages of Caesalpiniaceae in the pollen diagram and to their low pollen dispersion, Maley and Brenac (1998) have interpreted the environment of Barombi Mbo as a forest type largely dominated by this family under very wet climatic conditions, whereas our biome reconstructions indicated a mixed rainforest/seasonal forest (Fig. 4 and Table 5). This discrepancy for this period between empirical interpretation and our quantitative vegetation and climate reconstructions can be easily explained by the lack in our database of present day pollen samples from the very humid West Cameroon lowland forest rich in Caesalpiniaceae.

The episode centered around 2500 cal yr BP is probably the best documented period in West equatorial Africa as it is recorded at all pollen sites (Fig. 1). This episode is characterized by a reduction of typical humid forest elements, with increases in heliophilous species of secondary forest, or by a fragmentation of the forest, or even by its complete disappearance (e.g. Vincens et al., 1999; Maley, 2002). Such structural and floristic changes in the African forest massif have been linked to decreased P_{ann} associated with higher seasonality and of increased PET_{ann} when compared to the AHP period (e.g. Ngomanda et al., 2009a; Vincens et al., 2010). Our P_{ann} and PET_{ann} reconstructions are in agreement with such climate interpretation. P_{ann} estimates show minimal values of ca. 1200 mm (MAT) and ca. 800 mm (ANN) at ca. 2650 cal yr BP, when $\mathrm{PET}_{\mathrm{ann}}$ estimates are ca. 1650 mm and ca. 1500 mm (Fig. 6). When compared to reconstructions during the LGM, P_{ann} estimates are always higher between 3000 and 1200 cal yr BP using both techniques, and $\mathrm{PET}_{\mathrm{ann}}$ estimates are either lower (ANN) or similar (MAT). This could indicate that this dry episode was not as intense as the LGM, but as it mainly affected rainforest species shown by the lowest TRFO biome scores of the sequence, this suggests that another climatic parameter intervened. This is most likely a change in the rainfall seasonality, i.e. a longer dry season, as early as ca. 6500 cal yr BP, shown in our biome reconstructions. This change was previously suggested by Ngomanda et al. (2009a) in southern Cameroon and northward by Vincens et al. (2010).

6 Conclusions

This work focused on quantitative reconstructions of palaeovegetation and palaeoclimate at Barombi Mbo during the last ca. 33 000 cal yr BP, a lake located in one of the most humid area of West Africa. The aim was to improve previous empirical and quantitative interpretations, and the results show the difficulty to obtain good reconstructions according the techniques used. The reconstructions of palaeovegetation using the biomisation method and taking a combination of all biome (or stages) score values into account instead of the most dominant one, are better and more precise than previously proposed on this site. In contrast, palaeoclimate reconstructions are more uncertain and questionable. If our P_{ann} estimates (using both ANN and MAT) follow the general climate trends of previous studies in central and west Africa and are in agreement with vegetation changes, the reconstructed values are always lower than previous estimates at 6800 and 21 000 cal yr BP key periods, as at 0 yr BP when compared to modern reference at the nearby Kumba station. Such differences have been related to bias due to (1) the lack of data from the wettest areas of western Cameroon; (2) the scarce representation or the absence in the pollen rain of characteristic elements of very wet forest; (3) the nomenclature of the pollen taxa, many of them being considered as "type" and so may be present in divers forested environments; and (4) for the present day, to disturbed vegetation around the lake. Our $\mathrm{PET}_{\mathrm{ann}}$ reconstructions using the ANN technique, and related α index values, seem to be the most reliable according that present day estimate and modern value are similar, and that the main changes follow the general $\mathrm{PET}_{\mathrm{ann}}$ trends observed in central and west Africa, as α values follow the vegetation changes at Barombi Mbo during the last 33 000 cal yr BP. This could indicate that in lowland humid forest environment, the ANN technique would be more reliable than the MAT technique.

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