South African peatlands: a review of Late Pleistocene-Holocene developments using radiocarbon dating

S. Elshehawi[1], P. Grundling[2,3], M. Gabriel[4], A.P. Grootjans[1,5] and J. Van der Plicht[6]

[1] Centre for Energy and Environmental Studies, University of Groningen, The Netherlands
[2] Centre for Environmental Management, University of the Free State, Bloemfontein, South Africa
[3] Working for Wetlands, NRM, Department of Environmental Affairs, Pretoria, South Africa
[4] Faculty of Life Science, Humboldt-Universität zu Berlin, Germany
[5] Institute of Water and Wetland Research, Radboud University of Nijmegen, The Netherlands
[6] Centre for Isotope Research, University of Groningen, The Netherlands

SUMMARY

South Africa has a limited number of peatlands and most of them are relatively small compared to those in cooler temperate regions in the northern hemisphere. We gathered 40 basal peat samples representative of South Africa's peatlands to explore their development during the Late Pleistocene and Holocene. Depth profiles of nine of them were also investigated using radiocarbon dating, which yielded information on past environmental changes affecting South African peatlands. The data showed three peaks in the frequency of peatland initiation, which are consistent with available climatic and sea level fluctuation data: one after the Last Glacial Maximum (LGM) and two during the Mid to Late Holocene. Inland peatlands in mountain valleys showed optimal growing conditions during the glacial-interglacial transition, continuing until the Early-Holocene. This is due to the switch to the wet and warm interglacial climate. In contrast, coastal peatlands showed optimal initiation conditions over two phases during the Holocene, which is consistent with sea level rise peaks that led to optimal moist conditions occurring ca. 6,000–3,000 and 1,000 years ago. Sea level rise reduced groundwater drainage, which led to a rise in the primary groundwater table. However, data from some of the coastal peatlands indicate independence from the sea level fluctuation, and that they are rather controlled by climatic conditions and their local hydrogeomorphic setting, e.g. perched groundwater aquifers. Some peatland complexes show a pattern of phased initiation with peat initiation consistent with altitude difference, which could be due to a positive feedback of blocking caused by peat accumulation in lower reaches, reducing groundwater drainage to the sea.

KEY WORDS: accumulation rates, fen, mire, peat, South Africa

INTRODUCTION

Peatlands are important for climate regulation due to their role as carbon sinks (Graham 1991). Acting as archives for palaeoclimatic research, peatlands can allow us to reconstruct past climates extending back to the Late Pleistocene (Lowe & Walker 1984, Kalnina *et al*. 2014). Peatlands form by the accumulation of partly decomposed plant remains (peat), and are defined as having a peat thickness of at least 30 cm and over 30 % dry mass by volume of organic matter (Joosten & Clarke 2002). While most peatlands are located in the temperate zones of the northern hemisphere, some exist in the southern hemisphere (Mitsch & Gossilink 2000, Joosten & Clarke 2002, Yu *et al*. 2010). Peatlands cover less than 0.5 % of the area of South Africa (Marneweck *et al*. 2001, Joosten & Clarke 2002). An overview of the distribution and types of peatlands in South Africa has been given by Grundling *et al.* (1998) and Grundling & Grobler (2005). They found that the coastal plain of Maputaland, which is a part of KwaZulu-Natal province, contains about 60 % of South Africa's peatlands (Figure 1).

Meadows (1988) assessed the beginning (initiation) and subsequent growth of peatlands in South Africa by radiocarbon dating the basal peat of 26 peatlands. The histogram of the peat initiation data spans the Late Pleistocene and Holocene, with increased frequency of initiation during the Holocene. The peatland initiation frequency was related to the glacial-interglacial transition and to the rainfall increase that took place during the Holocene (Meadows 1988, Chase & Meadows 2007). However, this study did not include peatlands from Maputaland, some of which were sampled later (e.g. Grundling *et al*. 1998, Grundling *et al.* 2000, Finch & Hill 2008, Baker *et al.* 2014). Also, the southwestern coast with its year-round rainfall hosts some peatlands, for example, Kromme and Vankervelsvlei (Irving & Meadows 1997, Chase & Meadows 2007). Some studies on South African coastal peatlands have suggested a possible link between sea level and accumulation rates of coastal peatlands in Maputaland (Grundling 2004, Gabriel *et al*. 2017).

In this article, we update and expand on the existing literature on Late Quaternary peat accumulation in South Africa and analyse peatland development from the Late Pleistocene to the Late Holocene. For instance, we update the peatland initiation frequency by incorporating the coastal peatlands from Maputaland and other peatlands which were dated later than 1988. Further, we investigate seven peat profiles to infer the changes in the conditions favouring peat accumulation. Age-depth radiocarbon calibration models enable the assessment of peat-accumulation rates (Blaauw & Christen 2005, 2011). Accumulation rates can be deduced and used to understand climatic changes over the time scale studied (Meadows 1988, Blaauw & Christen 2005, Piotrowska *et al*. 2011). Increasing (or decreasing) peat accumulation rates are functions of climate, vegetation and hydrology (Joosten & Clarke 2002). For example, moist colder conditions are expected to result in higher peat initiation frequency and accumulation rates (Meadows 1988). We aim to identify past spatiotemporal patterns in peat initiation and conditions favourable for peat accumulation in South Africa and how this relates to their current distribution.

Peatlands in South Africa

South Africa is a predominantly semi-arid country. The climate varies from relatively humid on the eastern coast to relatively dry on the western coast. The higher mountains and plateaus, mainly in the central parts, are also relatively humid. Average rainfall ranges from 600 to 1100 mm yr^{-1} (Chase & Meadows 2007). The southwestern part of South Africa has two rainfall zones: a winter rainfall zone (WRZ) and a year-round rainfall zone (YRZ), while the rest of South Africa has a summer rainfall zone (SRZ) (Gasse 2000, Chase & Meadows 2007). Maputaland (in the summer rainfall zone) is the most humid region of South Africa, as the precipitation ranges from 600 mm yr^{-1} in the west to 1100 mm yr^{-1} in the east (A.T. Grundling 2014). South African peatlands are mainly minerotrophic (fens), with

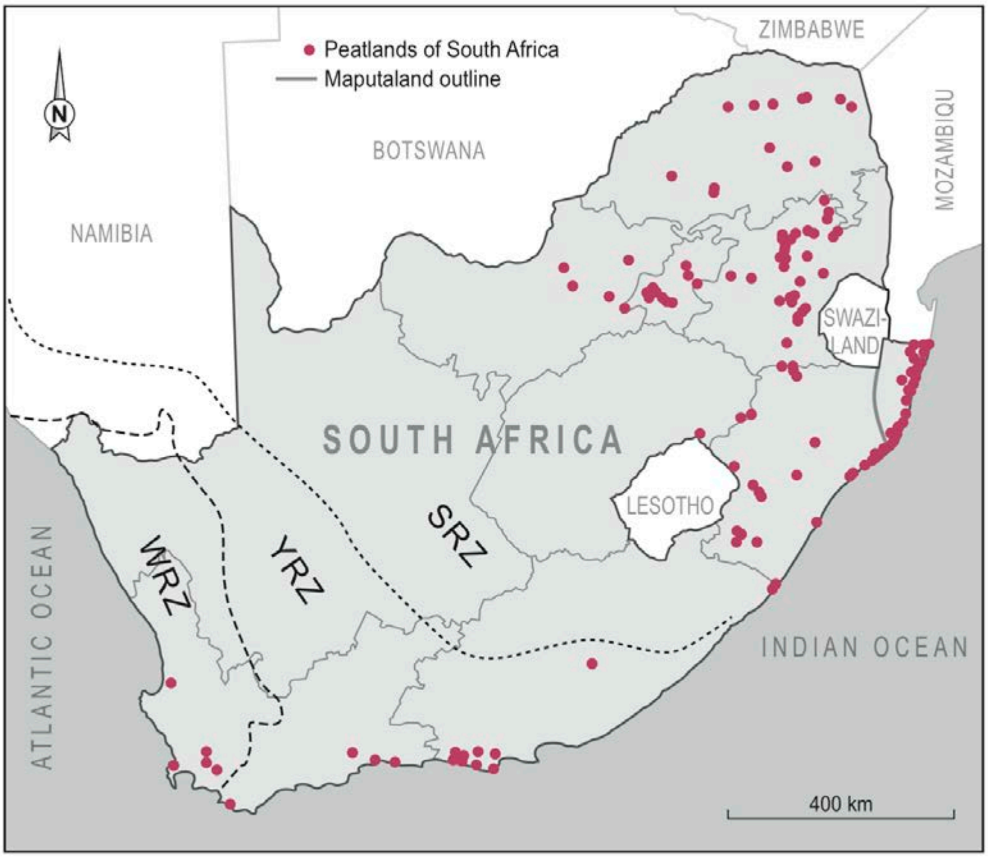

Figure 1. Peatland distribution in South Africa, SRZ: summer rainfall zone; YRZ: year-round rainfall zone; WRZ: winter rainfall zone (adapted from Grundling *et al.* 2017).

primary dependence on groundwater supply (Grundling & Grobler 2005). The negative balance between rainfall and total evaporation makes it likely that peatlands in South Africa originate from continuous groundwater flow (e.g. Grundling *et al.* 2015). Nevertheless, the present distribution of peatlands in South Africa reflects the rainfall distribution of the country (e.g. P. Grundling 2014).

Mfabeni mire, a coastal mire in Maputaland, is the oldest known mire in South Africa, dating back to more than 43,000 years ago (Finch & Hill 2008, Baker *et al*. 2014, P. Grundling 2014). Generally in Maputaland, accumulation rates derived from radiocarbon dating of peat layers are about 1–2 mm yr^{-1} (e.g. Thamm *et al*. 1996, Baker *et al*. 2014). Further, Wonderkrater is in the interior and dates back to about 35,000 years ago (Scott *et al*. 2003, McCarthy *et al*. 2010). In Wonderkrater, increased accumulation took place about 7,500 years ago (Meadows 1988), with accumulation rates increasing from ca. 0.06–0.1 mm yr^{-1} during the Late Pleistocene to 0.2–0.38 mm yr^{-1} during the Holocene (McCarthy *et al*. 2010).

METHODS

Sampling and laboratory analysis

Peat cores were taken from seven study areas during this investigation. The study areas cover two of the rainfall zones: the summer and the year-round rainfall zones. They are distributed over different landscape types including coastal and inland areas (Figure 2). The cores were taken from the central parts of the peatlands, which also have the deepest peat accumulation at each area. Core sites were chosen after a quick investigation of the peat depths, using a Russian corer, in longitudinal transects through the study areas. Table 1 lists the site names, locality, current land use, landscape and vegetation, and closest town. Age-depth models of peat profiles were produced for seven study areas in this investigation, supplemented with two areas that were studied by Baker *et al*. (2014) and Scott *et al*. (2003), and calibrated using "BACON" (Blaauw & Christen 2011).

The peat sampling was conducted using a Russian D-corer with 50-cm sections (De Vleeschouwer *et al*.

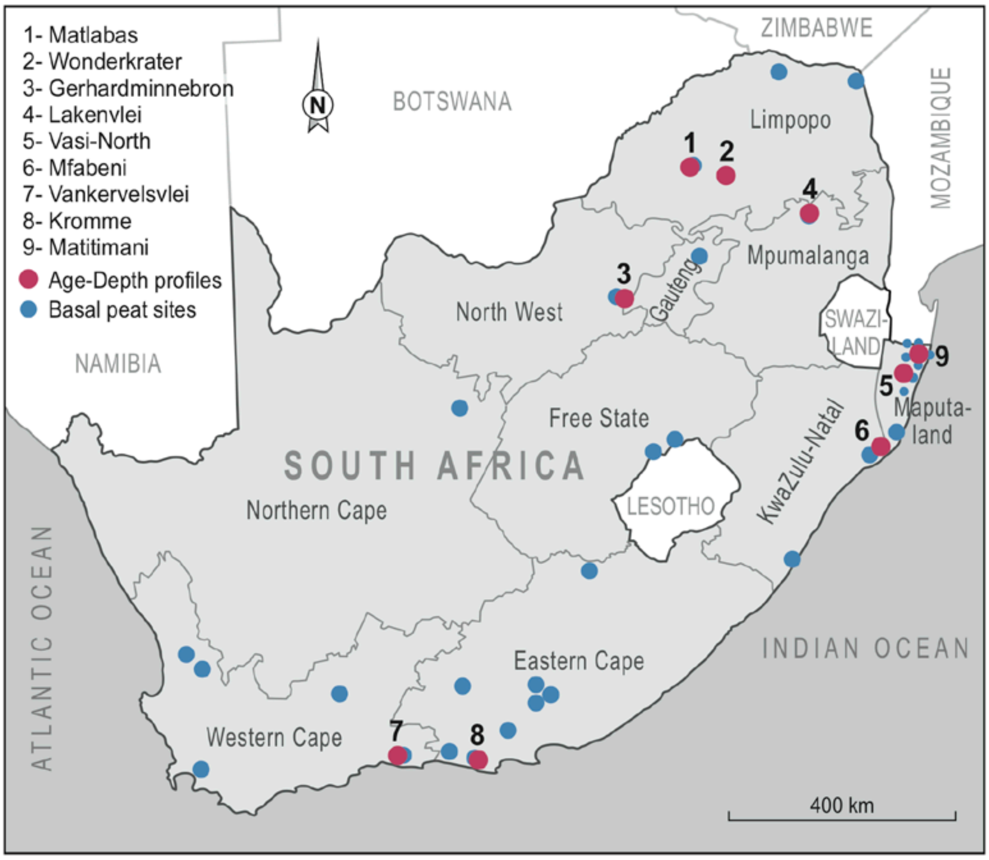

Figure 2. Red dots: Study areas where age-depth models have been constructed for the peat profiles (numbered, red dots). Seven of these areas were studied as part of this research, and two (Mfabeni and Wonderkrater) were taken from previous studies. These last two were updated with the SHCAL13 curve. Blue dots: study areas where basal peat samples were analysed.

(2010). Samples for radiocarbon dating were taken as one-centimetre sections from the cores. All samples were sealed in plastic bags and sent to the Centre for Isotope Research (CIO) laboratory at the University of Groningen, the Netherlands. The samples were chemically treated using the standard AAA (Alkali-Acid-Alkali) method (Piotrowska *et al*. 2011). Then the purified datable fraction was combusted into CO_2 gas using an Elemental Analyser coupled to an Isotope Ratio Mass Spectrometer (IRMS) (IsoCube/IsoPrime). IRMS measures the stable $^{13}C/^{12}C$ isotope ratio.

For radiocarbon analysis, a part of the CO_2 was routed to a cryogenic trap to collect the samples for further processing. The CO_2 was transformed into graphite powder by the reaction $CO_2 + 2H_2 \rightarrow 2H_2O + C$ at a temperature of 600 °C using Fe powder as a catalyst (Aerts *et al*. 2001). Next, the graphite was pressed into target holders for the ion source of the Accelerator Mass Spectrometer (AMS). The Groningen AMS system is based on a 2.5 MV tandetron accelerator (Van der Plicht *et al*. 2000). It measures the $^{14}C/^{12}C$ ratios of the graphite. From these numbers, the conventional radiocarbon age was determined.

Basal peat histogram

To update the histogram of Meadows (1988), we combined the 15 basal dates from that publication with 13 basal dates from Maputaland (Figure 2; Grundling *et al*. 1998, Grundling *et al*. 2000, Gabriel *et al*. 2017), 2 from Kruger National Park (Gillson & Duffin 2007), 1 from Wonderkrater (Scott *et al*. 2003) and 9 from this study. Table 2 lists the 40 basal radiocarbon dates of all these peatlands.

The basal radiocarbon dates were calibrated using the "OxCal" software, which uses a Bayesian statistical framework for age modelling (Bronk Ramsey 2009). The calibration was carried out with the southern hemisphere calibration curve, namely SHCAL13 for zone 1–2 (Hogg *et al*. 2013). Some samples were affected by the post-bomb period (after 1960) and were reported in percent modern carbon (pMC) instead of BP. These were dated using the bomb-matching calibration curve for the southern hemisphere (Hua *et al*. 2013).

Table 1. Description of the study areas where peat cores were taken. SRZ: summer rainfall zone; YRZ: year-round rainfall zone.

No.	Site	(coastal / interior)	Land use	Landscape / vegetation	Closest town	Rainfall zone
1	Vasi-North	Coastal	Conservation/ tourism	Interdune valley / reeds sedge	Emanguzi	SRZ
2	Vankervelsvlei	Coastal	Forestry	Interdune valley / *Sphagnum*	Sedgefield	YRZ
3	Kromme	Coastal	Agriculture/ water supply	Palmiet	Kareedouw	YRZ
4	Lakenvlei	Highveld (interior)	Tourism	Headwater and valleybottom / reed and sedge	Dullstroom	SRZ
5	Matlabas	Mountain (interior)	Tourism	High altitude and steep slopes / grass and reeds	Thabazimbi (in Marakele National Park)	SRZ
6	Gerhardminnebron	Interior	Agriculture/ mining	Karst / reeds sedge	Potchefstroom	SRZ
7	Matitimani	Coastal	Conservation/ tourism	Valley bottom / swamp forest	Pretoria	SRZ

Table 2. The 40 basal peat samples for radiocarbon dating of peatland initiation. Calibrated ranges were calculated using the OxCal program's SHCal13 curve for zone 1–2. We used 1-sigma with statistical accuracy of 68.2 %. **: Lab. no. was not found in the source study. The altitude data are estimated relative to mean sea level (m a.m.s.l.).

No.	Lab. no.	Name	Altitude (m a.m.s.l.)	Radiocarbon (BP)	Error (%)	Maximum (calBP)	Minimum (calBP)	Reference
1	Pta-7150	Mfabeni	5	45100	4900		>	Grundling *et al*. 1998
2	Pta-7555	Mhlanga	15	35600	1300	42770	37435	Grundling *et al*. 2000
3	Pta-2050	Wonderkrater	1100	34400	1900	41991	33570	Scott *et al*. 2003
4	Pta-4523	Driehoek	900	14600	290	18455	16975	Meadows 1988
5	GrN-4011	Aliwal North	1550	12600	110	15210	14255	Meadows 1988
6	Pta-3845	Cornelia, Clarens	1900	12600	100	15195	14280	Meadows 1988
7	Pta-4207	Dunedin	1400	12500	160	15190	14070	Meadows 1988
8	Pta-4318	Salisbury	1400	11800	120	13835	13310	Meadows 1988
9	63604	Gerhardminnebron	1400	11680	60	13560	13455	This article
10	GrN-4586	Cape Hangklip	100	11140	65	13090	12790	Meadows 1988
11	Pta-3682	Craigrossie, Clarens	1900	10600	100	12705	12080	Meadows 1988
12	63458	Matlabas	1800	9755	50	11220	11095	This article
13	Pta-7572	Trafalgar Mpenjati	10	9730	100	11255	10725	Grundling *et al*. 2000
14	Pta-4522	Sneeuberg	1000	9460	70	9540	9265	Meadows 1988
15	63598	Lakenvlei	1850	8295	45	9415	9255	This article
16	63247	Vasi-North	50	7760	45	8545	8435	This article
17	63612	Vankervelsvlei	30	7640	40	7670	7610	This article
18	Pta-7566	Trafalgar: Lot 187	15	5870	70	6795	6445	Grundling *et al*. 2000
19	Pta-1388	Scot	700	5070	60	5910	5625	Meadows 1988
20	13333	Matitimani	10	5465	25	6305	6175	This article
21	Pta-5256	Nhlangu	20	4840	100	5740	5310	Grundling *et al*. 1998
22	Pta-7083	KuKalwe	5	4640	60	5570	5045	Grundling *et al*. 1998
23	Pta-4335	Ellerslie	1400	4200	60	4840	4525	Meadows 1988
24	Pta-7074	Muzi	40	4200	50	4835	4530	Grundling *et al*. 1998
25	Pta-6370	KwaMboma	25	4120	60	4820	4425	Grundling *et al*. 1998
26	UW-169	Loerie	300	4010	70	4790	4155	Meadows 1988
27	Pta-3868	Deelpan	1200	3890	90	4515	3985	Meadows 1988
28	63238	Vasi Pan	55	3660	35	3980	3870	This article
29	Pta-4342	Compassberg	1300	3590	70	4075	3640	Meadows 1988
30	63678	Kromme	460	3415	35	3700	3610	This article
31	**	Malahlapanga	400	4940	100	5840	5480	Gillson & Duffin 2007
32	Pta-2683	Norga	200	2980	80	3340	2870	Meadows 1988
33	Pta-7087	Velindlovu	20	2820	45	2995	2770	Grundling *et al*. 1998
34	63616	Colbyn	1330	2360	30	2380	2340	This article
35	Pta-6752	Majiji	70	2140	70	2310	1925	Grundling *et al*. 1998
36	**	Mfayeni	350	1365	35	1295	1185	Gillson & Duffin 2007
37	Pta-5253	Mgobezeleni	10	1100	40	1065	905	Grundling *et al*. 1998
38	12588	KwaMazambane	20	997	80	922	860	Gabriel *et al*. 2017
39	Pta-6363	Mseleni	15	770	50	740	560	Grundling *et al*. 1998
40	Pta-4531	Nuweveldberg	1800	760	50	735	560	Meadows 1988

RESULTS

Frequency of peatland initiation

Peatland initiation frequency of the 40 South African peatlands over a period of 50,000 years was plotted in Figure 3. It shows four peaks, at 15,000, 10,000, 6,000 (up to 3,000) and 1,000 calBP. Less than 10 % of the radiocarbon dated peatlands were initiated in the period ca. 50,000–21,000 calBP, 30 % during 21,000–11,000 calBP and 17 % in the period ca. 11,000–6,000 calBP. The majority of the peatlands (> 40 %) were initiated after ca. 6,000 calBP, and 75 % of these were coastal peatlands. The peak for interior mountain peatlands occurred during the time interval of 21,000–11,000 calBP. The largest number of total peatland initiations occurred during the period after 6,000 calBP.

Time-space series

Time-space series were constructed to show the spatial distribution of peatland basal dates in South Africa. The series consists of four time-space maps showing the basal radiocarbon dates of 40 peatlands within the following time intervals (calBP): 50,000–21,000, 21,000–11,000, 9,000–6,000, 6,000–recent (Figure 4).

Age-depth models

Figure 5 shows the peat accumulation rates of nine peatlands, each having different scales and segments with different slopes, which show the change in accumulation rates. The age-depth model for Mfabeni had seven segments with a period of high accumulation (almost-vertical line) after 20,000 calBP until 10,000 calBP. The slope of the curve for Wonderkrater was almost constant except for the last few thousand years when the slope became slightly more horizontal (peat accumulation slowed down). The Gerhardminnebron peatland commenced during the Late Pleistocene and showed a steady rate of accumulation. Vasi-North and Lakenvlei both commenced around 8,000 calBP, but Lakenvlei had a more horizontal segment (lower rate of peat accumulation) with accelerated accumulation around 4,000 calBP. Vankervelsvlei, Matlabas and Matitimani were initiated around 7,000–6,000 calBP. Vankervelsvlei had steady rates of peat accumulation while Matlabas and Matitimani went through different phases, but they all had slower rates between 5,000 and 3,000 calBP. Kromme was the last peatland to be initiated and had the highest accumulation rate of the nine sites, especially during the first 1,000 years of development.

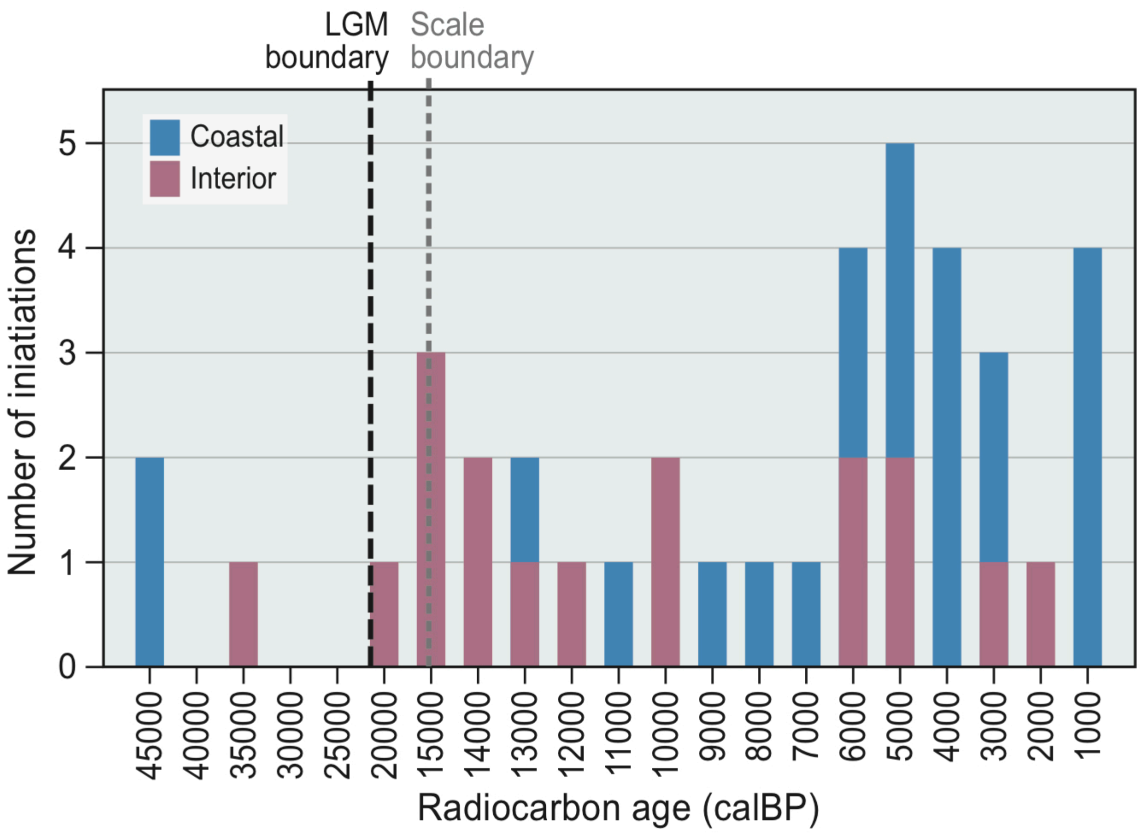

Figure 3. Histogram of interior (n = 17) and coastal (n = 23) peatland initiation based on 40 basal radiocarbon dates in South Africa over a period of ca. 45,000 calBP years. LGM = Last Glacial Maximum.

DISCUSSION

50,000–11,000 calBP

During the Late Pleistocene, the cold and dry conditions of the glacial period were not favorable for peat formation on a global scale (Bell & Walker 1992, Yu *et al*. 2010). However, some areas in the southern hemisphere developed peatlands in marginal conditions. Tropical peatlands in Southeast Asia, for instance, were initiated earlier during this period than ones in the northern hemisphere (Yu *et al*. 2010). We also found that in South Africa, around twelve peatlands initiated their development during the Late Pleistocene and that this period had two distinct periods of peatland initiation. The first period, prior to the LGM, included the smallest portion of peatland initiation. It included the initiation of only three peatlands: Mfabeni and

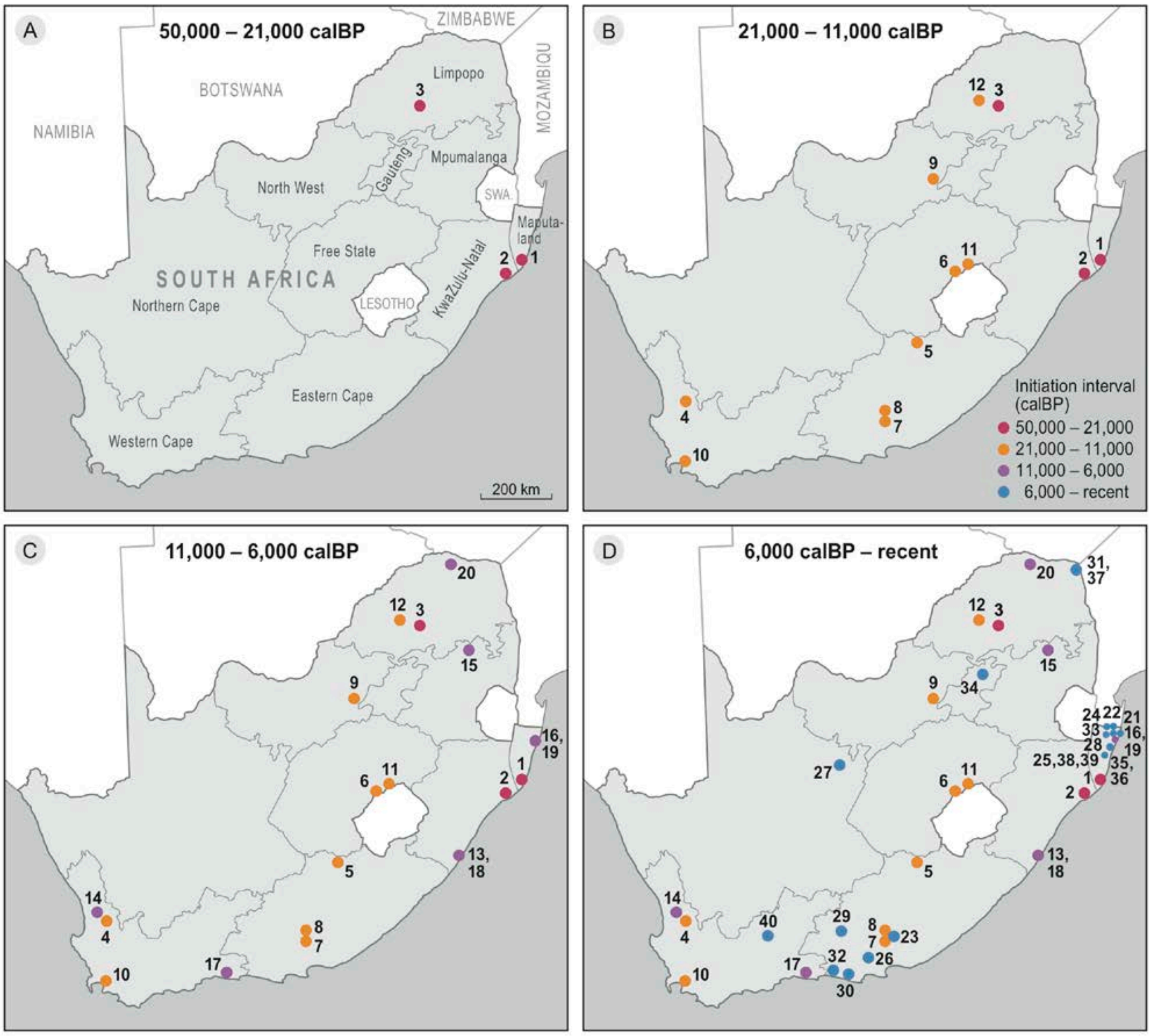

Figure 4. Time-series maps of peatland initiation based on radiocarbon dating in South Africa. Basal radiocarbon dates (calBP) are given in four time intervals: 50,000–21,000, 21,000–11,000, 11,000–6,000, 6,000–recent; for 40 peatlands: 1 = Mfabeni, 2 = Mhlanga, 3 = Wonderkrater, 4 = Driehoek, 5 = Aliwal North, 6 = Cornelia, Clarens, 7 = D unedin, 8 = Salisbury, 9 = Gerhardminnebron, 10 = Cape Hangklip, 11 = Craigrossie, Clarens, 12 = Matlabas, 13 = Trafalgar Mpenjati, 14 = Sneeuberg, 15 = Lakenvlei, 16 = Vasi-North 17 = Vankervelsvlei, 18 = Trafalgar: Lot 187, 19 = Matitimani, 20 = Scot, 21 = Nhlangu, 22 = KuKalwe, 23 = Ellerslie, 24 = Muzi, 25 = KwaMboma, 26 = Loerie, 27 = Deelpan, 28 = Vasi Pan, 29 = Compassberg, 30 = Kromme, 31 = Malahlapanga, 32 = Norga, 33 = Velindlovu, 34 = Colbyn, 35 = Majiji, 36 = Mgobezeleni, 37 = KwaMazambane, 38 = Mfayeni, 39 = Mseleni, 40 = Nuweveldberg.

Mhlanga (both in the south of the coastal plain of Maputaland) and Wonderkrater, which is an interior mountain spring peatland, of which Mfabeni is the oldest one. The second period, which occurred post LGM during the glacial-interglacial transition, included the initiation of nine peatlands, seven of which are interior peatlands. The glacial-interglacial transition peak for the South African interior peatland initiation is similar to the pattern of montane peatlands in Southeast Asia, whose initiation peaked around 17,000–13,000 years ago (Page *et al*. 2004, Yu *et al*. 2010).

The accumulation rates during the glacial–interglacial transition period, around 21,000–11,000 years ago, were generally lower than during both the earlier glacial and the later interglacial periods. For instance, both the Mfabeni and Wonderkrater peatlands showed higher accumulation rates prior to LGM, after which the rates decreased by ~50 %. The lower accumulation rates in this period could infer

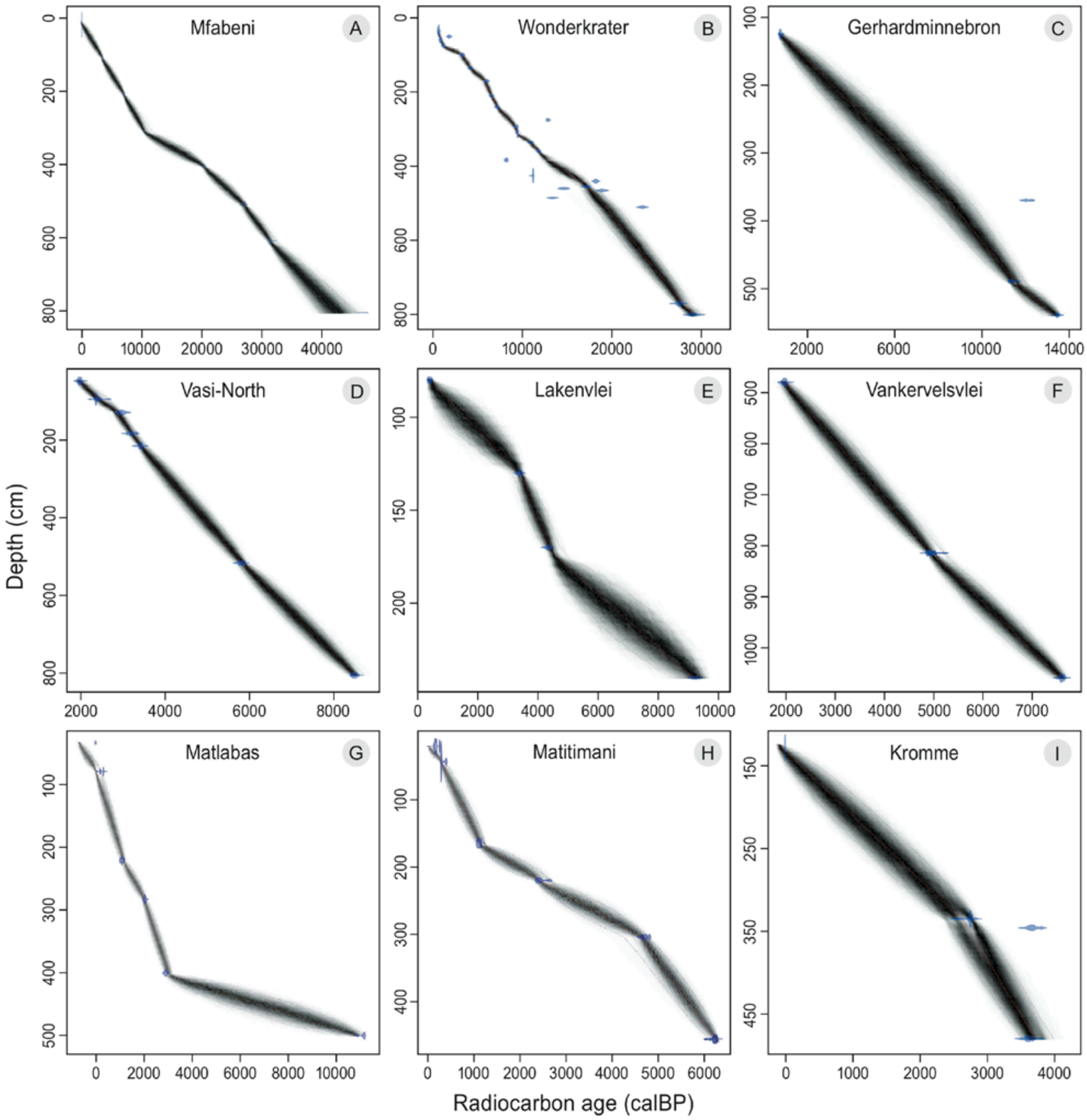

Figure 5. Age-depth models for nine peatlands in South Africa. The blue ranges represent the calibrated sample age ranges while the black shadows represent the calibrated range of each point interpolated between the sampled ages (calBP cm^{-1}). calBP = radiocarbon calibrated calendar age. A: adapted from Baker *et al*. (2014); B: adapted from Scott *et al*. (2003); C–I: data collected during this study.

that the transition period was warmer, yet with dry conditions not favouring peat accumulation. However, it is noted that in Mfabeni, the accumulation rates appeared to mirror fluctuations in sea level (Ramsay 1995, Ramsay & Cooper 2002, Grundling 2004, Grundling *et al*. 2013). The accumulation rates at Gerhardminnebron and Matlabas during the Late Pleistocene were also low, indicating that despite the initiation of peatlands in the glacial-interglacial period, the conditions were not optimal until the Holocene.

Holocene

Early Holocene (11,000–6,000 calBP)

Peatland initiation frequency during the Early Holocene was relatively low after LGM. Except for two interior peatlands that initiated, developing during the period 10,000–9,000 calBP, almost all the peatlands that developed during the Early Holocene were situated along the coast. This was due to post glacial climatic changes in Southern Africa, which resulted in a dry and warm climate (Truc *et al.* 2013) with an accompanying rise in sea level starting around 9,000 calBP (Ramsay 1995, Gasse 2000, Ramsay & Cooper 2002, Grundling 2004). Only from 6,000 calBP onwards did the number of peatland initiations increase. In the inland regions, this delay may have been caused by the successive replenishment of groundwater. In the coastal regions, however, rise of the sea level to present levels for the first time around 7,000–6,000 calBP might have been the primary driver of higher water tables (Ramsay & Cooper 2002, Grundling 2004, Gabriel *et al.* 2017). Other studies linked a rise in sea level to an increase in peatland initiation frequency during the Holocene (Yu *et al.* 2010, Dekker *et al.* 2015). However, some peatlands seem not to be related to sea level rise, but to be a reflection of local hydrogeomorphic conditions. For instance, Vasi-North (altitude 45–55 m a.m.s.l.) initiated shortly after 9,000 calBP, in contrast to Matitimani peatland (altitude only 10 m a.m.s.l) which initiated peat accumulation ca. 7,000 calBP (Grundling *et al.* 2013, Gabriel *et al.* 2017). Furthermore, within the Vasi peatland complex, Vasi Pan, which is in the same peatland complex as Vasi-North but at the higher altitude of 64 m a.m.s.l, initiated its peat accumulation ca. 4,000 calBP following infilling of the lower area first. The dependency of peat accumulation on altitude within the Vasi peatland complex (Vasi-North and Vasi Pan), and independently from the primary aquifer in Maputaland, indicates the possible existence of a perched aquifer system that allowed peat initiation independently of sea level fluctuations (Elshehawi *et al*. unpublished data). The perched aquifers might have formed due to formation of iron-rich impervious layers (Botha & Porat 2007, Porat & Botha 2008).

Accumulation rates in the older peatlands, such as Mfabeni, Wonderkrater and Gerhardminnebron, showed increased accumulation rates during the Early Holocene, up to 0.34 and 0.35 mm yr^{-1}, respectively. Matlabas in the Waterberg Mountains kept the same accumulation rate, but this was partly due to the presence of intercalating mineral sediments, which indicate high energy flows eroding the peat. The younger peatlands (e.g. Vasi-North and Lakenvlei) had accumulation rates of 1 and 0.25 mm yr^{-1}, respectively, during this period. Vasi-North started as an open lake with gyttja deposits, which constitutes about 4 m of the total organic layer in this peatland. These different accumulation rates are not only a function of climatic conditions, but also their localised geomorphic conditions and initiation and development process. For instance, Matlabas initiation took place via paludification directly over the mineral soil, due to seasonal inputs of flood water, which came in the form of high energy water flows during the wet seasons. The deposition of clay by these flows reduced the permeability and allowed initiation of peat accumulation. These energy flows were not stable over time which possibly led to loss of peat accumulations from early stages until the mire stabilised. Matlabas and Lakenvlei have similarly slow early accumulation rates, due to their being headwater peatlands with fluctuating energy flows. This is in contrast to peatlands initiating via terrestrialisation in low energy environments.

Mid to Late Holocene (6,000 calBP–recent)

Peatland initiation reached a maximum during the Mid Holocene with a total of 15 peatlands initiating during this period. Two thirds of them were coastal peatlands, mainly in Maputaland and in the year-round rainfall zone, and the other one third were interior mountain peatlands. The northern part of Maputaland had the largest share of the peatland initiations. Later in the Holocene around 2,000 calBP, peatland initiation decreased before increasing again in the last millennium. Ramsay (1995) reported a steady rise in the sea level along the eastern coast of South Africa during the Holocene (Ramsay 1995). Gabriel *et al*. (2017), studying macrofossils in the Matitimani peatland, also referred to sea level rise as a main driver for the initiation of coastal peatlands in Maputaland. Emphasising the connection between peatland formation and sea level, they attributed a decline in seeds of aquatic plant species, which indicates drier hydrological conditions, to a drop in sea level from the Holocene high stand. It is likely that sea level rise also played this role in South African peatlands, especially the coastal ones. Peatlands of the Everglades in Florida showed a similar response to a rise in sea level, which reduced the drainage of the groundwater basin (i.e. loss of water to the sea) prompting peatland initiation (Dekker *et al.* 2015). This rise in initiation is similar in timing (during the Mid to Late Holocene) to that observed by Dommain *et al*. (2011) in some of the Indonesian inland peatland areas. However, the Indonesian coastal peatlands followed a different pattern, in which sea level fall allowed peat accumulation on the newly emergent land (Dommain *et al.* 2011).

Besides the sea level rise, a period of high precipitation 6,800–3,600 calBP was indicated in a pollen record from Lake Eteza in southern Maputaland, which also coincided with the period of coastal peatland initiations. The higher rainfall in the coastal area of KwaZulu-Natal was caused by a strengthened southward shift of the warm Aghulas Current (Neumann *et al*. 2010). The increase in rainfall attributed to the Aghulas Current might have contributed to the peatland initiation and development, especially in the perched groundwater systems, e.g. Vasi-North. Also, the development of peatlands could create a blocking effect in the lower areas, owing to the lower permeability of peat, which could lower the drainage from the groundwater system in the upper areas, e.g. KwaMazambane and Vasi Pan (Gabriel *et al.* 2017). Dekker *et al.* 2015 attributed peatland development to a combined increase in rainfall, sea level rise and local hydrogeomorphic settings, e.g. the perched groundwater aquifers or the blocking effects (Dekker *et al.* 2015). The Mid Holocene phases could be attributed to sea level rise and combinations of the three effects. In order to verify the amplitude of these effects in each area, detailed scale studies that assess the relation of the peatland hydrology to the landscape’s primary aquifers might be needed.

Further, the accumulation rates of peat in Maputaland were estimated to be 1–2 mm yr^{-1}, deduced from pollen dating (Thamm *et al.* 1996). We found that accumulation rates during the Late Holocene were among the highest reported in South Africa. In Maputaland, the Mfabeni peatland had an accumulation rate of 0.3 mm yr^{-1} (Baker *et al*. 2014), while Vasi-North shifted from gyttja (open lake deposits) to peat or gyttja-peat accumulations (Elshehawi *et al.* unpublished data) with an average accumulation rate of 1.5 mm yr^{-1}. Vasi-North and Vasi Pan recorded the highest accumulation rates in our study, yet both have radiocarbon ages of >2,000 calBP in the topsoil, due to a disturbance which led to peat erosion. Interior peatlands also had increased accumulation rates during this period when compared with the Early-Holocene. Wonderkrater had an accumulation rate of 0.22 to 0.38 mm yr^{-1} (McCarthy *et al*. 2010), while accumulation rates for Matlabas and Lakenvlei increased to almost 1 and 0.5 mm yr^{-1}, respectively. However, Lakenvlei shifted to a lower accumulation rate during the Late Holocene. Vankervelsvlei and Kromme in the year-round rainfall zone showed an accumulation rate of 1 mm yr^{-1} close to these observed in Maputaland. Kromme had a slower rate afterwards (~2.5K calBP) of almost 0.8 mm yr^{-1}. We note that Vankervelsvlei was dated at 2000 calBP at a depth of 5 m, which indicates it had a high accumulation rate of 2.5 mm yr^{-1} during the Late Holocene. On average, the accumulation rates seemed to be higher in the Mid to Late Holocene, which possibly is related to the wetter climatic conditions, which is one of the drivers favouring peat accumulation.

CONCLUSIONS

Peatland initiation patterns in South Africa are consistent with the evidence for climate and sea-level fluctuations, which appear to have played a primary role in peatland initiation and development, with a possible secondary role for local hydrogeomorphic settings, over the Late Pleistocene to Holocene. There were three periods of optimal conditions for peatland initiation, one of which was right after the LGM and the other two were during the Mid to Late Holocene. The formation of interior peatlands dominated the optimal period after LGM (ca. 18,000 to 15,000 calBP) owing to climatic shifts to warm and wet conditions during the glacial-interglacial transition. The coastal peatlands had maximum humid conditions in two periods from ca. 6000 to 3000 calBP and during the last millennium owing primarily to sea level rise and possibly to a mixture of the increased rainfall in the Mid Holocene and the effect of the local hydrogeomorphic settings. Average accumulation rates ranged from 0.07 to 2.19 mm yr^{-1}, with the coastal peatlands having higher average accumulation rates than the interior ones. The average accumulation rates were higher during the Mid to Late Holocene for all of the peatlands in this study.

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Author for correspondence:
Samer Elshehawi, Centre for Energy and Environmental Studies, University of Groningen, Nijenborgh 6, 9747 AG, Groningen, the Netherlands. E-mail: s.e.a.a.elshehawi@rug.nl

Appendix

Table A1. Calculated accumulation rates of peatlands with ^{14}C dating of their profiles.

Name	Segment	^{14}C dating (calBP)		Time difference (yr)	Depth (cm)		Accumulation rate (mm yr^{-1})
		from	to		from	to	
Mfabeni	1	43000	33000	10000	800	620	0.18
	2	33000	27000	6000	620	530	0.15
	3	27000	20000	7000	530	405	0.18
	4	20000	10000	10000	405	340	0.07
	5	10000	0	10000	340	0	0.34
Wonderkrater	1	35600	17000	18600	800	440	0.19
	2	17000	9000	8000	440	350	0.11
	3	9000	7000	2000	350	280	0.35
	4	7000	6000	1000	280	160	1.20
	5	6000	3750	2250	160	100	0.27
	6	3750	1500	2250	100	80	0.09
	7	1500	0	1500	80	0	0.53
Gerhardminnebron	1	13500	11400	2100	540	500	0.19
	2	11400	880	10520	500	120	0.36
Vasi-North	1	8490	5830	2660	805	516	1.09
	2	5830	3410	2420	516	214	1.25
	3	3410	3200	210	214	182	1.52
	4	3200	2890	310	182	128	1.74
	5	2890	2735	155	128	94	2.19
	6	2735	1965	770	94	47	0.61
Lakenvlei	1	9300	4100	5200	240	180	0.12
	2	4100	3500	600	180	130	0.83
	3	3500	350	3150	130	30	0.32
Vankervelsvlei	1	7640	4800	2840	1060	800	0.92
	2	4800	1800	3000	800	490	1.03
Matlabas	1	11160	2800	8360	500	400	0.12
	2	2800	1900	900	400	285	1.28
	3	1900	1400	500	285	230	1.10
	4	1400	-50	1450	230	35	1.34
Matitimani	1	6100	4800	1300	450	300	1.15
	2	4800	1000	3800	300	170	0.34
	3	1000	300	700	170	40	1.86
	4	300	0	300	40	10	1.00
Kromme	1	3500	2500	1000	450	340	1.10
	2	2500	0	2500	350	130	0.88