Current state, pressures and protection of South African peatlands

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SUMMARY

Temperate regions in the Southern Hemisphere make a small contribution to the global carbon sequestration of peatlands which, in these drier regions, are relatively rare and vulnerable to increasing anthropogenic and climate change pressures. Using South Africa as a case study, we review the availability of spatially explicit information on peatlands and their protection. The South African Peatland Database recorded 635 peatland observations, which reflect a carbon storage capacity of 29,254,495 ± 5,798,831 (total ± standard deviation) tons. Of the total 121,128 ha of peatlands mapped in this study, forested peatlands (11,851 ha, 10 % of all peatlands) were considered vulnerable. Non-forested peatlands (109,277 ha) had higher levels of uncertainty with regard to extent and degree of degradation, and most (74 %) of these had only partial protection. Cumulative anthropogenic pressures have resulted in an increase in the number and temporal frequency of peat fires, with 49 peatland sites having burned in the past five years, compared to 23 in the 24-year period preceding it. The total loss of carbon due to peat fires equates to 280,513 tons to date. The inventory, assessment and management of forested and non-forested peatlands in South Africa, and most probably in other southern-hemisphere temperate regions, requires urgent attention. The information presented demonstrates that forested peatlands have been historically well mapped because of their ease of detection with remote sensing. In contrast, the paucity of information on non-forested palustrine peatlands dictates that more extensive infield validation should be undertaken before their conservation status can be determined.

KEY WORDS: carbon content, CO_2 loss, forested wetland, non-forested wetland, peatland degradation

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INTRODUCTION

A multitude of anthropogenic pressures have resulted in an estimated global loss of > 85 % of the extent of wetlands to date, with the rate of losses globally considered to be higher than for many other ecosystems (IPBES 2019). Recently an unprecedented increase in the areal extent of peatland fires has been observed in locations around the world, from the Arctic (Hines 2019) to California (USA) (Staletovich 2020), Indonesia (Mariska 2020), Poland (Dowell 2020) and Scotland (Wiltshire *et al.* 2019), as well as in South Africa (Daniels 2019). In the previous decade, peat fires in both Russia (2010) and Indonesia (2015) led to a tremendous release of greenhouse gas emissions and a negative effect on the health of citizens and in other sectors (Konovalov *et al.* 2011, Atwood *et al.* 2016, Koplitz *et al.* 2016, Hu *et al.* 2018, Bourgeau-Chavez *et al.* 2020). The Russian peat fires followed an 'unprecedented intensive heat wave' with temperatures exceeding the maximum temperature recorded in 100 years (above 30 °C) in the two months preceding the fire (Konovalov *et al.* 2011). The Indonesian peat fires resulted from a combination of two decades of peatland degradation and transformation with extreme drought arising from climatological phenomena such as the El Niño - Southern Oscillation (ENSO) event in 2015 (Atwood *et al.* 2016). Therefore, urgent intervention is required to understand the risk of peatlands collapsing and to curb the extent and degree of losses, especially to retain their carbon (C) sequestration functionality and avoid negative effects on microclimate and health.

Even though it is estimated that only a small percentage (< 5 %) of wetlands in the Southern Hemisphere are peatlands, and most (90 %) of the peatlands occur in moist temperate or tropical climate zones (Lappalainen 1996, Melton *et al.* 2013), peatlands in the drier temperate regions of the Southern Hemisphere serve as important ecological infrastructures that provide ecosystem services such as C sequestration, water regulation and biodiversity (Mulders *et al.* 2017). Yet, there is a paucity of information on peatlands in the Southern Hemisphere (Goodrich *et al.* 2017), particularly in temperate regions of countries such as South Africa, where the vulnerability and loss of peatlands are critical.

The effects of climate change on aquatic ecosystems of the southern African continent are expected to exacerbate the negative effects of existing anthropogenic pressures such as water abstraction, habitat fragmentation and pollution (Dallas & Rivers-Moore 2014, Van Deventer *et al.* 2019). Various observations to date and predictions for the year 2050 show increased temperature and evapotranspiration along with intensification of drought, hot days and heatwaves (Dallas & Rivers-Moore 2014, Niang *et al.* 2014, Engelbrecht *et al.* 2015, Davis-Reddy & Vincent 2017, Kruger & Nxumalo 2017). With rainfall already being highly variable in southern Africa (Schulze & Lynch 2007), water availability will become more uncertain in future so the demand for water is likely to increase, resulting in excessive over-abstraction of water from surface and groundwater resources and consequent lowering of the water table. Should this occur, peatlands in the temperate regions of the Southern Hemisphere may be at a higher risk of collapse, especially in South Africa where peatlands are dependent upon groundwater (Grundling *et al*. 2017).

This article reviews the status and trends of pressures on peatlands in the temperate regions of southern Africa, considering the available knowledge and data for South African peatlands. The review is supported by investigating (i) the availability and completeness of inventories that represent the geographical distribution and diversity of peatlands in the country; (ii) the status of the ecological condition of peatlands and their rates of decline; (iii) the protection of peatlands; and (iv) whether management interventions are currently in place.

THE DISTRIBUTION OF PEATLANDS IN SOUTH AFRICA

Definition and criteria for peatlands

In South Africa the Joosten & Clarke (2002) definition of peatlands is used. A peatland is considered to be a type of wetland or, specifically, '*an area with or without vegetation with a naturally accumulated peat layer at the surface*', where peat is '*sedentarily accumulated material consisting of at least 30 % (dry mass) of dead organic material*'.

The inventory of the peatlands in South Africa was initially compiled as an Excel point database of infield samples collected from a variety of sources, with associated peat ecoregions indicating their potential distribution in the country modelled using environmental variables, by Grundling *et al.* (2017). For some of these points, the areal extents of the peatlands had been mapped. Subsequent to compilation of the point database, the data on areal extents were collated as the basis of this review and assessment. In the following subsections, the datasets are described in more detail.

Early mapping of peatlands in the National Peatlands Database of South Africa

The current (2016) version of the South African Peatland Database was compiled from various infield soil sample records (Smuts 1992, Grundling *et al.* 1998, 2000; Marneweck *et al.* 2001, Grundling & Grobler 2005), with a total of 635 verified peat sample points meeting the criteria for peat (Grundling *et al.* 2017). In general, the verified points contained in the database show a geographical distribution mostly in the well-watered eastern and southern regions of South Africa, with a high mean annual recharge of primary aquifers (Figure 1). The database allows various attributes of the verified peatlands to be recorded including the bulk density, thickness, volume and quality of peat across the peatlands. Peat distribution and extent were based on limited sampling, and wetland area was used as the *de facto* peatland extent. The more detailed observations in the database (Figure 1) are available for selected parts of karst landscapes (North West Province, Gauteng Province), the moister Highveld and escarpment (Mpumalanga Province, Free State Province), Maputaland Coastal Plain (MCP; KwaZulu-Natal (KZN) Province) and parts of the Cape Fold mountains (Eastern Cape Province, Western Cape Province).

Modelling the diversity of peat ecoregions

The potential distribution of peatlands across the country and their diversity were modelled using a variety of environmental variables, initially by Marneweck *et al.* (2001) and subsequently with improvements by Grundling *et al.* (2017). The latter included areas with Mean Annual Precipitation (MAP) ≥ 500 mm (Malherbe *et al*. 2016), dolomitic areas (CGS 2014), areas with slope ≤ 12 % (Weepener *et al.* 2011), ≥ 5 mm mean annual groundwater recharge and a groundwater discharge of ≥ 10 mm of the river base flow and where water levels were ≤ 20 m deep (Vegter 1995) and coincided with thermal or cold springs from the former South African Department of Water Affairs and Forestry (DWAF 2014) (Figure 1; Marneweck *et al.* 2001,

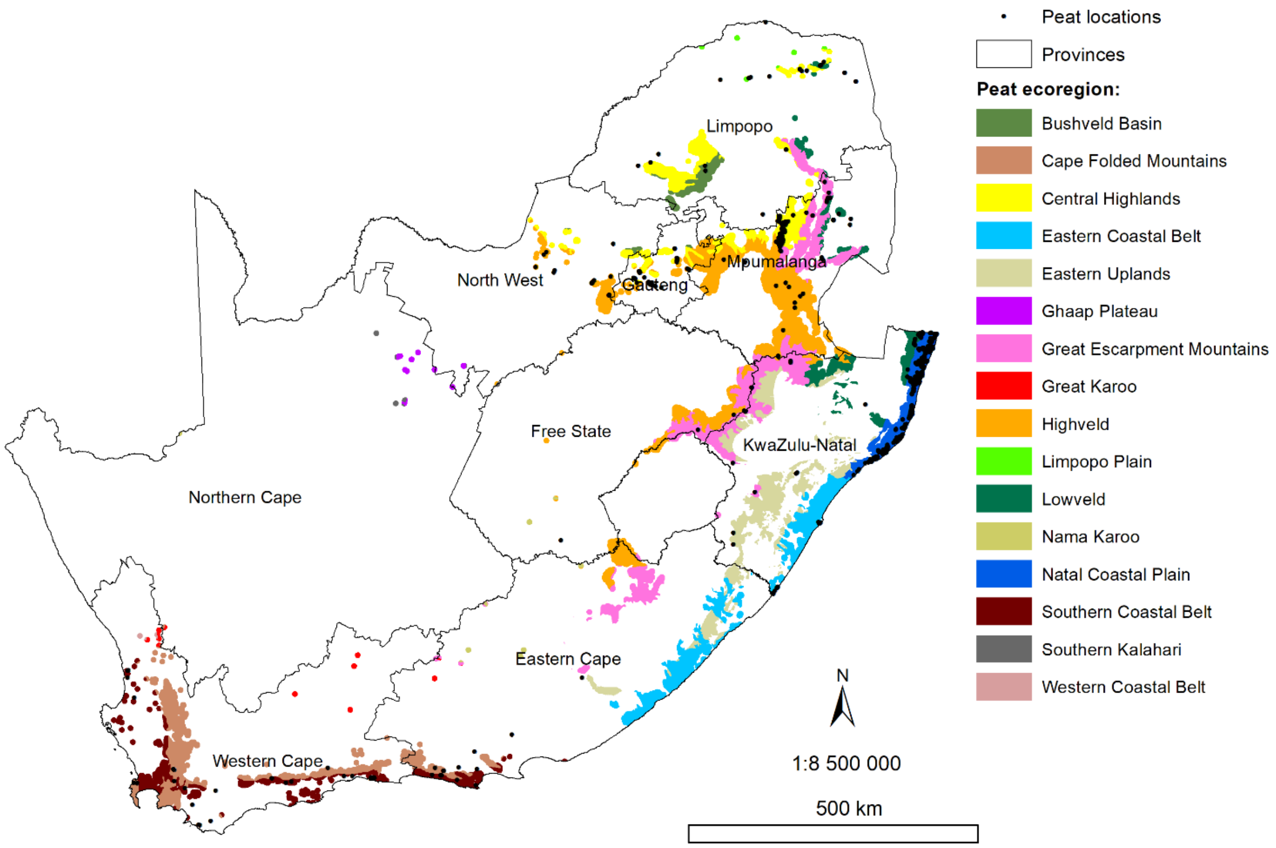

Figure 1. The distribution of 635 confirmed peat locations from the South African National Peatlands Database, used to inform modelling of the extent of peat ecoregions (Grundling *et al.* 2017).

Grundling *et al.* 2017). The latest model of the South African peat ecoregions resulted in 16 regions, covering a total area of 14,329,577 ha or 12 % of South Africa (Figure 1, Table 1; Grundling *et al.* 2017).

The range of C stock in the peatlands across their peat ecoregions was calculated as part of an economic valuation of peatland ecosystem services (Grundling *et al.* 2017, Mulders *et al.* 2017). Statistics (minimum, mean and maximum) were derived from available information on peat thickness, C content and bulk density (Table 1). Bulk densities were estimated using values derived by Grundling *et al.* (2015), who determined an exponential trend line for increasing percentage of Soil Organic Matter against bulk density (Table 1).

The inventory and analysis of peatland data in the context of modelling peatland ecoregions revealed significant differences in sample density among ecoregions, which in turn may affect the significance of calculations and interpretations. The Highveld peat ecoregion has the largest areal extent (nearly three million ha) but shows one of the lowest sampling densities compared to the other regions (Table 1). In fact, the seven peat ecoregions with the largest extent of more than one million ha (Highveld, Great Escarpment Mountains, Eastern Uplands, Cape Fold Mountains, Eastern Coastal Belt, Central Highlands and Southern Coastal Belt) all have low sampling densities of less than seven points per 100,000 ha. In contrast, the Natal Coastal Plain peat ecoregion hosts the highest density of samples (49 per 100,000 ha) and the highest number of verified peat sample points (54 %). The database contains no verified sample points for peatlands in four peat ecoregions (Ghaap Plateau, Great Karoo, Nama Karoo, Southern Kalahari) which are located primarily in arid regions and account for about 2 % of the areal extent of modelled peat ecoregions across South Africa (Table 1). Therefore, further sampling is required to address the gaps and imbalance in sampling density of peatlands across the 16 peat ecoregions - a costly exercise owing to the need for extensive infield validation, as wetlands generally occupy less than 3 % of the South African landscape.

Integration of available data for mapping the areal extent of South African peatlands

Various studies have mapped the areal extent of peatlands in South Africa at local, regional and country-wide scales (Table A1 in the Appendix). The

Table 1. Summary statistics per peat ecoregion, derived from 635 South African peatland samples (adapted from Grundling *et al.* 2017). N = number of samples; % = % of sampled points; D = density (points $ha^{-1} \times 10^5$); min. = minimum; max. = maximum. Asterisks (*) indicate peat ecoregions with no verified peat sample points.

Ecoregion	Ecoregion area (ha)	N	%	D	Peatland area (ha)	Peat thickness (m)			Volume of peat (m^3)			Bulk density ($t\ m^{-3}$)			% carbon			Mass of dry peat (t)		
						min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.	min.	mean	max.
Bushveld Basin	286,711.2	2	0.3	0.7	2.7	0.40	0.40	0.40	10,800	10,800	10,800	0.09	0.14	0.39	10	34	45	972	4,212	1,512
Cape Fold Mountains	1,496,484.7	14	2.2	0.9	464.4	0.15	0.20	0.20	2,317,100	6,715,600	12,503,100	0.10	0.20	0.39	10	26	41	231,710	4,876,209	1,343,120
Central Highlands	1,401,339.8	93	14.6	6.6	2,564.3	0.50	1.10	4.50	12,942,185	27,933,993	114,581,561	0.13	0.23	0.39	10	22	36	1,682,484	44,686,809	6,424,818
Eastern Coastal Belt	1,451,196.8	12	1.9	0.8	67.8	0.40	2.60	4.00	271,200	1,742,460	2,712,000	0.05	0.11	0.25	20	40	60	13,560	678,000	191,671
Eastern Uplands	1,637,455.3	6	0.9	0.4	1,405.0	0.60	1.30	1.90	8,431,198	17,557,198	26,683,198	0.11	0.20	0.39	10	25	40	927,432	10,406,447	3,511,440
Ghaap Plateau*	70,638.3	0	0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Great Escarpment Mountains	2,387,853.8	34	5.4	1.4	990.9	0.01	0.70	2.00	7,256,987	12,212,438	19,169,128	0.15	0.27	0.39	10	14	32	10,885,485	7,475,960	3,297,358
Great Karoo*	71,988.1	0	0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Highveld	2,950,277.4	71	11.2	2.4	2,864.0	0.40	3.60	5.80	25,256,053	88,843,580	162,430,759	0.10	0.19	0.28	18	27	41	2,525,605	45,480,613	16,880,280
Limpopo Plain	35,687.3	2	0.3	5.6	11.0	1.40	1.90	2.40	154,000	212,300	264,000	0.25	0.31	0.39	10	15	20	38,500	102,960	65,813
Lowveld	698,389.4	30	4.7	4.3	1,061.5	0.30	1.40	3.50	3,196,687	18,872,166	37,089,615	0.25	0.32	0.39	10	14	20	799,172	14,464,950	6,039,093
Nama Karoo*	53,389.0	0	0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Natal Coastal Plain	703,391.1	344	54.2	48.9	20,230.0	2.00	2.00	10.80	404,600,000	410,669,000	2,023,000,000	0.06	0.15	0.36	12	32	52	24,276,000	728,280,000	61,600,350
Southern Coastal Belt	1,037,980.2	25	3.9	2.4	1,054.4	0.60	1.80	10.20	9,575,838	20,879,538	97,799,838	0.08	0.13	0.21	24	35	48	766,067	20,537,966	2,714,340
Southern Kalahari*	32,082.0	0	0.0	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Western Coastal Belt	14,712.6	2	0.3	13.6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Total [Average] (Range)	14,329,577.0	635	100	[4.4]	30,716.1	[0.60]	[1.60]	[4.20]	474,012,048 (10,800)	605,649,073 (55,059,007)	2,496,243,999 (2,023,000,000)	(0.05)	(0.2)	(0.39)	(10)	(26)	(60)	32,350,050 (972)	876,994,125 (9,279,072)	102,069,795 (728,280,000)

data collected include infield samples (Grundling *et al.* 1998, 2000; Venter 2003, Sliva 2004, Grobler 2009) and a collation of sample points grouped under the class ‘swamp forest’ on the basis of floristic composition or ‘peat’ based substrate, in a countrywide point dataset (Sieben *et al.* 2014). In some instances the areal extent of peatlands had been mapped subsequent to infield sampling of both peat and vegetation, as for a number of palmiet wetlands by Rebelo *et al.* (2017). More extensive representation of peatlands was available from desktop mapping using vegetation types with inferred association, for which polygons were mapped at a country-wide scale (Mucina & Rutherford 2006, Dayaram *et al.* 2019) and for KZN (Scott-Shaw & Escott 2011), as proxies for peatlands (see Van Deventer *et al.* (2021) for the list of key indicator tree species). The desktop studies showed contradictions in the areal extent of swamp and coastal forests, both between studies and when compared to the sample point data. Several omission errors were also noted during a review of grey literature and from field observations.

Polygon datasets were integrated through a union process in ArcGIS 10.6 (ESRI 1999–2017) and supplemented with polygons from version 5 of the National Wetland Map (NWM5; Van Deventer *et al.* 2020) which coincided with point data; while the remaining sampling points from the National Peatland Database, not represented in NWM5, were digitised from Google Earth Pro (Google LLC 2020) and incorporated into a single new data layer. Where information on the extent of plant species was available, polygons associated with *Barringtonia racemosa* were removed because these have insignificant peat substrates (Grundling *et al.* 2000). Polygons were then unioned and classified according to the two Ramsar Convention peatland categories relevant to South Africa, namely ‘Xp – Forested peatlands; peat swamp forests’ and ‘U – Non-forested peatlands; includes shrub or open bogs, swamps, fens’ (Ramsar Convention Secretariat 2016). A three-class confidence rating was also assigned to the polygons to distinguish whether the areal extent was mapped with high confidence (infield sampling and subsequent mapping of polygon) or medium confidence (desktop mapping by experts but no infield visits). Generally, polygons from NWM5 were assigned a low confidence rating because the true extent of peat was not confirmed. Additional polygons mapped for this study were assigned high confidence if the authors were familiar with the site, and low confidence if not.

The results show that 121,128 ha of peatland are currently present in the country (Table 2), constituting 0.1 % of the land mass of South Africa (121,973,563.7 ha) and < 0.00003 % of the world’s global peatland area of 423 million ha (Xu *et al.* 2018). This figure is almost four times the 30,716 ha reported by Grundling *et al.* (2017) as the inferred peatland area derived from the wetland area at confirmed peat sample points. The majority (90 %) of the peatlands are non-forested, while only 10 % are coastal swamp or floodplain forests stretching across the KZN and Eastern Cape provinces. It is interesting to note that the areal extent (11,851 ha) of forested wetlands, which have predominantly peat substrates (high confidence; Grundling *et al.* 2000), is 27 % more than the 8,554 ha reported for coastal swamp forest by Jewitt (2018), the most comprehensive study to date [value excludes *B. racemosa*].

The Natal Coastal Plain peat ecoregion hosts the largest portion (59 %) of South Africa’s areal extent of peatlands, followed by the Highveld peat ecoregion at 10 % (Table 2), while none were recorded in the Ghaap Plateau, Great Karoo and Nama Karoo peat ecoregions. In terms of confidence, the occurrence of the majority of the peatlands remains at low confidence (84.5 %), with only 9.6 % mapped at medium and 5.8 % at high confidence. It is likely that the low confidence extent contains commission errors on the edges of the polygons, while omission errors may remain across all peat ecoregions. Therefore, further work is essential to address the gaps in the true areal extent of peatlands, particularly the non-forested ones that are more challenging to map across the country, as well as to obtain information on peat thickness and C content.

ACCUMULATION RATES AND TOTAL CARBON SEQUESTERED

The sample points show that the average total carbon stock of the 16 peatland ecoregions of South Africa is 29,254,495 ± 5,798,831 (total ± standard deviation) metric tons (t) (Table 3; Grundling *et al.* 2017). The estimated total carbon stock in peat varies across the peat ecoregions, with Bushveld Basin recording the lowest (93 t) and Natal Coastal Plain the highest (375 Mt) stock (Table 3). The variation can be attributed to different climatic conditions, landscape settings, vegetation and depositional processes.

The Eastern and Western Cape provinces (associated with the Southern Coastal Belt peat ecoregion) host wetlands dominated by the palmiet *Prionium serratum* which is endemic and range restricted, occurring primarily in the Cape Fold mountains with outliers in the southern part of KZN

Table 2. Distribution of the geographical extent of peatlands across 16 peat ecoregions (see Figure 1). Asterisks (*) indicate peat ecoregions within which no peat polygons were mapped. Units: ha.

Peatland ecoregion	Ramsar wetland types		Grand total	% of total peatland extent	% of peat ecoregion	Confidence of representing peat areal extent (%)		
	U. Non-forested peatlands	Xp. Forested peatlands				High	Med	Low
Bushveld Basin	3.8	–	3.8	< 0.1	0.0	–	–	100.0
Cape Fold Mountains	2,478.7	–	2,478.7	2.0	0.2	11.2	–	88.8
Central Highlands	5,328.8	–	5,328.8	4.4	0.4	0.2	–	99.8
Eastern Coastal Belt	5,112.4	360.2	5,472.6	4.5	0.4	63.4	6.6	30.0
Eastern Uplands	10,034.5	36.5	10,071.0	8.3	0.6	–	0.4	99.6
Ghaap Plateau*	–	–	–	–	–	–	–	–
Great Escarpment Mountains	1,069.8	–	1,069.8	0.9	0.0	–	–	100.0
Great Karoo*	–	–	–	–	–	–	–	–
Highveld	12,522.5	–	12,522.5	10.3	0.4	5.0	–	95.0
Limpopo Plain	0.1	–	0.1	< 0.1	0.0	–	–	100.0
Lowveld	84.1	–	84.1	0.07	0.0	–	–	100.0
Nama Karoo*	–	–	–	–	–	–	–	–
Natal Coastal Plain	60,061.2	11,454.5	71,515.7	59.0	10.2	2.6	5.7	81.7
Southern Coastal Belt	11,996.3	–	11,996.3	9.9	1.2	5.9	–	94.1
Southern Kalahari*	–	–	–	–	–	–	–	–
Western Coastal Belt	584.7	–	584.7	0.5	4.0	25.6	–	74.4
Total	109,276.9	11,851.2	121,128.1	100.0	17.3	5.9	9.6	84.5

Table 3. Carbon stock range and carbon accumulation rate of peat per peatland ecoregion in South Africa (adapted from Grundling *et al.* 2017); min. = minimum, max. = maximum.

Ecoregion	Carbon stocks in peat (t)			Carbon accumulation in peat (t yr^{-1})		
	min.	mean	max.	min.	mean	max.
Bushveld Basin	97	514	1,895	< 0.1	0.6	2.4
Cape Fold Mountains	23,171	349,211	1,999,246	23.7	117.8	370.3
Central Highlands	168,248	1,413,460	16,087,251	162.7	655.1	1,795.5
Eastern Coastal Belt	2,712	76,668	406,800	6.1	29.0	102.8
Eastern Uplands	92,743	877,860	4,162,579	75.2	357.9	1,092.5
Ghaap Plateau	–	–	–	–	–	–
Great Escarpment Mountains	108,855	461,630	2,392,307	87.1	250.4	576.9
Great Karoo	–	–	–	–	–	–
Highveld	454,609	4,557,675	18,647,051	263.6	722.9	1,617.9
Limpopo Plain	3,850	9,871	20,592	1.4	2.6	4.3
Lowveld	79,917	845,473	2,892,990	134.2	249.6	412.7
Nama Karoo	–	-	-	–	–	–
Natal Coastal Plain	2,913,120	19,712,112	378,705,600	1,545.2	9,756.7	37,542.1
Southern Coastal Belt	183,856	950,019	9,858,223	191.4	488.7	1,076.8
Southern Kalahari	–	–	–	–	–	–
Western Coastal Belt	–	–	–	–	–	–
Total and standard deviation	4,031,179 ±854,701	29,254,495 ±5,798,831	435,174,535 ±112,668,155			

Province (Boucher & Withers 2004, Sieben 2012, Rebelo *et al.* 2017). Measurements have shown the thickness range of peat layers accumulated in these palmiet valley-bottom wetlands to be 0.5–10 m (Rebelo *et al.* 2017). Annual carbon accumulation rates of the palmiet systems range from 21 to 41 g m^{-2} and the amount of C sequestered by the major peatlands is 17,404–583,789 t (Rebelo *et al.* 2019).

The MCP on the north-eastern seaboard of the Natal Coastal Plain peat ecoregion (in KZN Province) is considered to be a unique hotspot with a high density of peatlands (Smuts 1992, Thamm *et al.* 1996, Grundling *et al.* 1998, Ellery *et al.* 2012). Approximately 54 % of the country's known peatland samples (Table 1) were collected and 59 % of the peatland polygons were mapped in this region alone (Table 2). The MCP also hosts the Mkuze Floodplain peatland (Figure 2), which is the largest peatland in South Africa and lies mostly within the iSimangaliso Wetland Park. This peatland contains some 4,279,400 tons of C (Grundling *et al.* 2000), or about 60 % of the C pool in the iSimangaliso Wetland Park's peatlands and 25 % of the C deposited in South Africa's peatlands. This wetland extends to more than 8,800 ha, of which 7,265 ha (83 %) is peatland with a peat thickness of up to 5.8 m storing 589 t ha^{-1} of C. For comparison, the C store of the Mfabeni peatland (1,250 ha) is 1,768 t ha^{-1} with a peat thickness of up to 10.8 m (Grundling *et al.* 1998).

Comparable to C stock, the total C accumulation rates per region also vary across the peat ecoregions, from the Bushveld Basin peat ecoregion recording the lowest C accumulation rates (0.1 t yr^{-1}) to the Natal Coastal Plain peat ecoregion having the highest accumulation rate of 37,542 t yr^{-1} (Table 3). In terms of peat accumulation rates, these vary from < 0.3 mm yr^{-1} for Late Pleistocene aged peatlands to ~ 1 mm yr^{-1} for Holocene-aged peatlands (Grundling *et al.* 2017, Elshehawi *et al.* 2019b); with exceptions such as the inland Matlabas mire in the Marakele National Park, where peat accumulation is estimated at 4 mm yr^{-1} owing to a high load of clastic sediment being deposited into the accumulated peat (Elshehawi *et al.* 2019b). Further infield verification could contribute to better representation of C stock and accumulation rates across the peat ecoregions, particularly for those in the temperate regions of southern Africa.

Considering that the C stocks and accumulation rates of peatlands across the different ecoregions are mostly estimated on the basis of extrapolated data, it is essential that additional research be conducted. This will enable more accurate determination of the

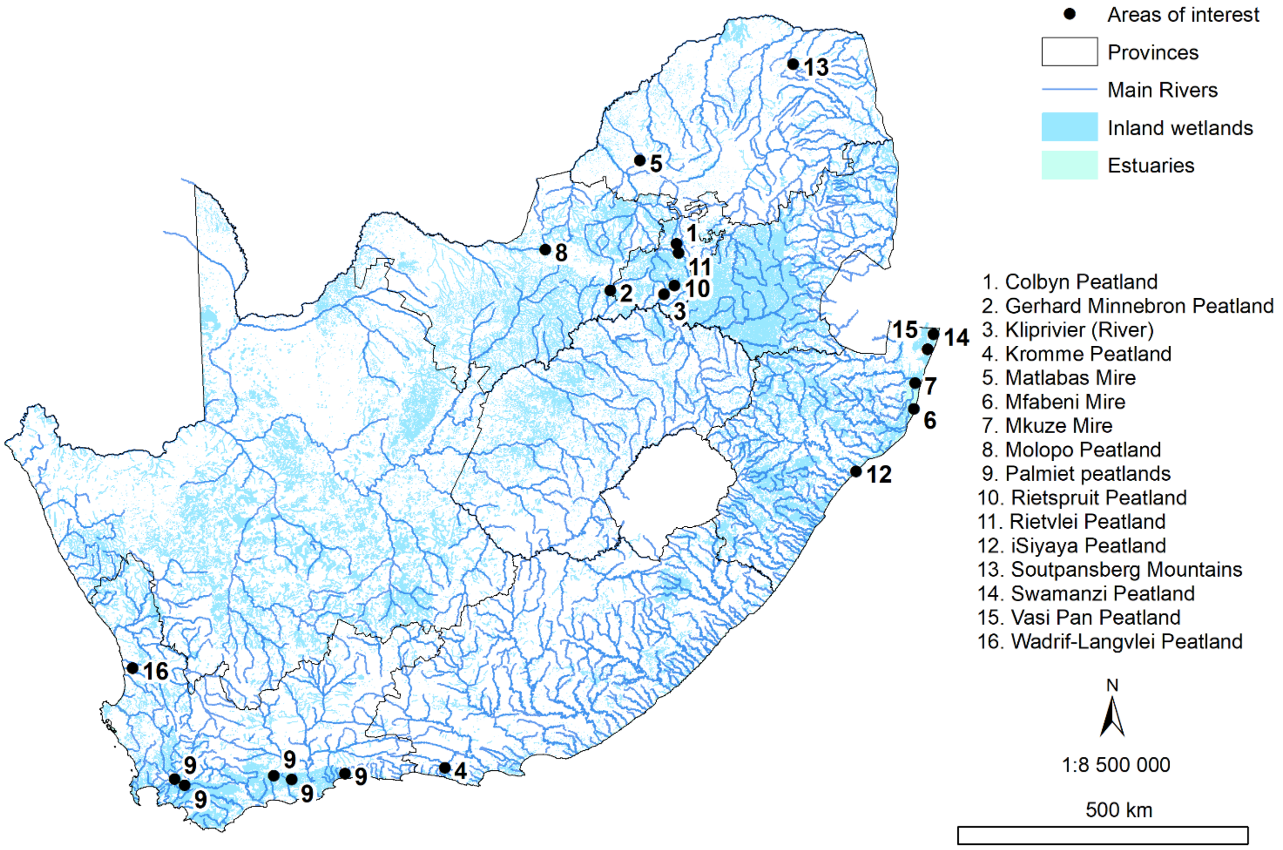

Figure 2. Areas of interest related to the peatlands of South Africa.

C stock values and C sequestration capabilities of different peatlands. A more accurate understanding of the provision of ecosystem services such as climate change mitigation, and how this is affected by current pressures on South Africa's peatlands, will support the development of effective conservation management strategies.

CURRENT PRESSURES ON PEATLANDS

Several pressures negatively affect peatlands, including modifications to the natural hydrological or flow regime, water pollution, peatland and catchment habitat transformation (including clearing of vegetation and fragmentation), peat extraction, accelerated and unnatural erosion and burrowing small mammals damaging the peat substrate (Dudgeon *et al.* 2006, Du Preez & Brown 2011, Grundling *et al.* 2014, Grundling *et al.* 2015, Bonn *et al.* 2016, Rebelo *et al.* 2017, Van Deventer *et al.* 2019). Climate change drivers exacerbate these existing, multiple and interconnected pressures. Their extent and severity are not well documented or mapped for South African peatlands.

Ideally, the ecological condition of a peatland should be assessed infield, to determine the extent and degree of the multiple pressures as well as the responses of the peatland's hydrological regime, substrate, vegetation and fauna. While ecological condition assessments at this level are not available and the South African National Wetland Monitoring System not in operation, we can draw on available assessments and literature to obtain information about peatland condition. In the first subsection below, results for peatlands are extracted from the most recent (2018) National Biodiversity Assessment (NBA-2018). In the next subsection, we provide information on some of the peatlands that are affected by particular categories of pressures.

Assessed ecological condition from the National Biodiversity Assessment 2018

The South African National Wetland Monitoring System has yet to identify priority areas for sampling of wetlands, while a system for monitoring rivers is already in place at the South African Department of Water and Sanitation. In NBA-2018, the ecological condition of wetlands had to be modelled at a country-wide scale using available datasets which represented the above-mentioned pressures (see Van Deventer *et al.* 2019 for more information). For this review, the ecological condition was assigned to polygons of NWM5 and extracted for the peatlands considered here. The results show that the majority (80 %) of peatlands are considered heavily to critically modified, although the 11 % of polygons which were added subsequent to Van Deventer *et al.* (2019) were not assessed (Table 4).

There is widespread agreement that coastal swamp forests with peat substrates can be regarded as moderately to heavily-to-critically modified across

Table 4. Areal extent and areal percentage of peatlands according to peat ecoregion and ecological condition.

Peat ecoregion	Ecological condition category						Not assessed		Totals
	Natural and near-natural		Moderately modified		Heavily to critically modified				
	ha	(%)	ha	(%)	ha	(%)	ha	(%)	ha
Bushveld Basin	3.8	(100.0)							3.8
Cape Fold Mountains	16.4	(0.7)	12.0	(0.5)	2,200.9	(88.8)	249.4	(10.1)	2,478.7
Central Highlands	307.0	(5.8)	390.1	(7.3)	4,584.5	(86.0)	47.2	(0.9)	5,328.8
Eastern Coastal Belt	48.8	(0.9)	55.4	(1.0)	1,216.2	(22.2)	4,152.2	(75.9)	5,472.6
Eastern Uplands	1,526.8	(15.2)	68.8	(0.7)	8,439.0	(83.8)	36.5	(0.4)	10,071.0
Great Escarpment Mountains	619.1	(57.9)	14.3	(1.3)	436.4	(40.8)	–		1,069.8
Highveld	596.2	(4.8)	82.0	(0.7)	11,844.3	94.6)	–		12,522.5
Limpopo Plain	–		–		0.1		–		0.1
Lowveld	5.0	(5.9)	17.9	(21.2)	61.3	(72.9)	–		84.1
Natal Coastal Plain	2,612.2	(3.7)	4,405.5	(6.2)	56,246.9	(78.6)	8,251.2	(11.5)	71,515.7
Southern Coastal Belt	3.8	(0.03)			11,277.2	(94.0)	715.2	(6.0)	11,996.3
Western Coastal Belt	–		–		584.7	(100.0)	–		584.7
Totals	5,739.0	(4.7)	5,045.9	(4.2)	96,891.5	(80.0)	13,451.7	(11.1)	121,128.2

South Africa, as a result of timber plantations within their catchments reducing the availability of groundwater to the peatlands, along with other horticultural practices for food production (Grundling *et al*. 2000, Berliner 2005, Mucina & Rutherford 2006, Jewitt 2018). While these studies support the findings in Table 4 that peatlands are substantially modified, further work is required to assess the ecological condition of non-forested peatlands in South Africa.

Changes to the hydrological regime of peatlands

The demand for water to supply an increasing population and their inherent demand for water-intense food production is one of the main drivers of water table lowering in wetlands and their catchments (Mukheibir & Sparks 2003, Brown *et al.* 2019, Imasiku & Ntagwirumugara 2020). Excessive abstraction of groundwater from an aquifer results in lowering of the water table to the extent that no discharge of water to peatlands take place. Thus, increased water abstraction can reduce the availability of water to groundwater-dependent peatlands and can subsequently result in desiccation and smouldering of the peatland, eventually to a point of total collapse. South African peatlands are predominantly groundwater dependent and, thus, particularly susceptible to this type of degradation. Examples of peatlands where desiccation and collapse has followed over-abstraction of groundwater include the Rietvlei peatland in Gauteng Province (Grundling & Marneweck 1999), the Molopo peatland in North West Province (Abd Elbasit *et al.* 2020) and the Wadrif-Langvlei peatland in Western Cape Province (Bonthuis 2011, Die Burger 2011).

Demand for water from timber plantations has resulted in lowering of the water table in the cases of the KwaMbonambi and Manzengwenya plantations in KZN Province (Kelbe *et al.* 2016) and Lakenvlei in Mpumalanga Province (Grundling & Marneweck 1999). The exotic trees such as pine (*Pinus* spp.) and blue gum (*Eucalyptus* spp.) used in South African timber plantations not only tap into groundwater, lowering the water table, but also extensively alter the land cover on aquifer recharge areas such that the infiltration of rainwater is retarded (Walters *et al*. 2011, Elshehawi *et al*. 2019b). The combined effects mean that peatlands in and adjacent to timber plantations are often desiccated to such a degree that they may ignite, smoulder and burn. Kelbe *et al.* (2016) found that clones of *Eucalyptus grandis*, with root depths of up to 28 m (Dye 1996) and high evapotranspiration rates, can draw down the water table over a horizontal distance of more than 2 km from the edge of the plantation. In addition to effects within the peatland, adjacent aquatic ecosystems are also negatively affected, as for the Vasi Pan peatland in the Manzengwenya plantation (Grundling & Blackmore 1998, Elshehawi *et al*. 2019a). Here, pine trees were planted on the peatland in the early 1960s, which resulted in artificial lowering of the groundwater table. The peatland has subsequently dried out several times over the past three decades, with associated ignition and smouldering of the peat substrate (Grundling & Blackmore 1998). The peatland first ignited in 1996, whereupon the former Department of Water Affairs and Forestry (DWAF) ordered the removal of plantation trees within about 100 m of the edges of the wetland. Regardless of this directive, the peatland continued to dry out and suffered another two severe peat fires. The pine (*Pinus* spp.) plantation trees were later substituted with blue gum (*Eucalyptus* spp.) and planting expanded farther into the peatland in 2011. This resulted in an increase of water abstraction by the exotic trees, thereby continuing the artificial lowering of the water table and exacerbating the extent and degree of desiccation not only across the Vasi Pan peatland but also in other peatlands on the outskirts of the Manzengwenya plantation. In these areas, both commercial and subsistence timber plantations have reduced water availability and the ecological condition of peatlands (Elshehawi *et al*. 2019a). During the past two decades, indiscriminate small-scale subsistence growers and illegal timber plantations, supplemented by commercial and state forestry, have caused widespread lowering of groundwater levels across the MCP, where peatland ecosystems have been shown to be primarily aquifer-dependent (Grundling *et al*. 2014). The resultant desiccation and burning of peat has resulted in a negative effect on the biodiversity of the MCP (Janse van Rensburg 2019).

An increase in water can also negatively affect peatlands. The addition of water to peatlands from Waste Water Treatment Works (WWTW), irrigation, increased runoff from urban and overgrazed areas, etc. results in an increased flow of water in peatlands. Peatlands are naturally low-energy systems and the introduction of higher-energy flows can result in severe erosion and degradation. The Colbyn (Kotze *et al.* 2019) and Rietvlei peatlands in Pretoria (Ayine 2007), Kliprivier south of Johannesburg (McCarthy & Venter 2006) (all three in Gauteng Province) and several palmiet peatlands in the Cape Fold mountains (Western Cape Province) are examples of peatlands where erosion of peat has resulted from disturbance to their hydrological regimes through artificial water inputs (Haig *et al*. 2002, Rebelo 2012).

Water and soil pollution

Mining waste can contaminate the water flowing through peatlands, from which pollutants are absorbed by the peat. For example, the spring that feeds the Gerhard Minnebron peatland with a perennial discharge of groundwater originates from a karst aquifer that is polluted with uranium through the filling of caves and sinkholes with uraniferous waste rock from deep-level gold mining (Winde 2010, Winde & Erasmus 2011). The peatland found along the Kliprivier is not only exposed to mining related discharges (McCarthy & Venter 2006) and elevated heavy metal loads, but also receives around 253 million m^3 yr^{-1} of treated sewage and industrial water (Davidson 2003, Kotze 2005). The discharge of water loaded with mine effluent into some peatlands has resulted in the attenuation of elevated levels of trace metals such as Co, Ni, Zn, Pb, Cu and U, thus improving water quality downstream of the peatlands (Winde 2011, Humphries *et al.* 2017). Elevated levels of trace metals resulting from mine water pollution have a negative effect on vegetation health and, therefore, on the ecological condition of the wetland (Van Deventer & Cho 2014). Many peatlands across South Africa are also exposed to elevated nutrient levels originating from agriculture; one example is the palmiet wetlands in the Western Cape (Rebelo *et al*. 2018). Spillages of raw sewage effluent have been recurring events in the urban Colbyn peatland in Pretoria (Mulders 2016, Ngobeni 2019). Nutrients such as phosphates result in species composition change and can also accelerate peat degradation (Oberholster *et al.* 2008, Sokolowska *et al.* 2011, Mettrop *et al.* 2015).

Habitat transformation and clearing of vegetation

Drainage and clearing of vegetation cover are particularly problematic in coastal swamp and floodplain forest with peat substrates across the northern and eastern parts of the country including KZN Province (Janse van Rensburg 2019). Degradation follows the alteration of hydrological flows resulting from the clearance of vegetation cover and subsequent drainage of the peatland for subsistence and commercial cultivation. Clearance of vegetation not only results in a loss of biodiversity, but also exacerbates erosion of the peat. The iSiyaya and Swamanzi peatlands (Grundling *et al.* 1998) flowing into Kosi Bay (KZN Province) (Grundling *et al.* 1998), Lakenvlei near Dullstroom (Mpumalanga Province) (Grundling & Marneweck 1999) and palmiet wetlands such as the Kromme in the Langkloof (Haig *et al.* 2002) and Riviersonderend downstream of the Theewaterskloof Dam (Western Cape Province) (Rebelo 2012) are examples.

Peat extraction

Peat extraction for commercial gain occurred extensively in the interior of South Africa from the 1980s until 2011, especially in the karst-related peatlands in North West Province and Gauteng Province, with some peat mining also reported in the Soutpansberg mountains (Limpopo Province) and the George area in Western Cape Province (Grundling & Grobler 2005, Grundling & Marneweck 1999). Peat mining ceased in 2011 but its legacies linger as erosion of drainage channels (e.g. in the Kliprivier, Rietspruit and Rietvlei wetlands in Gauteng Province) and as open water bodies unable to support revegetation that result in increased runoff, reducing the probability of further peat accumulation (in the Kliprivier and Gerhard Minnebron peatlands) (Grundling & Marneweck 1999, Grundling & Grobler 2005). These factors also diminish water storage, base flow maintenance, C sequestration, storage, filtration and biodiversity functions in the affected wetlands.

Damage and sedimentation resulting from erosion

Land use and its associated land cover in a catchment are likely to alter the flows into wetlands and will directly affect a wetland's ecological condition (Winter 2000). Apart from the changes in hydrological inputs, secondary effects such as erosion and siltation also become prevalent (Grundling 2004). For example, wetland catchments that are degraded and erosion-prone will be characterised by high sediment loads entering the wetland with subsequent siltation (e.g. in the Watervalspruit mire, Kgaswane Ramsar Site; Smakhtin & Bachelor 2005). Alternatively, intense storms in degraded catchments will result in adverse stormflow into wetlands resulting in erosion, desiccation and high clastic sediment flows that could disrupt peat accumulation (e.g. the Matlabas mire; Grundling *et al.* 2015, Bootsma *et al.* 2019). Furthermore, wetlands in temperate regions of southern Africa will compete with humankind for water resources (especially groundwater) and are thus likely to become desiccated. An example is provided by the palmiet peatlands, which have become increasingly fragmented by gully erosion as a result of land-use change (Rebelo *et al*. 2017).

PEAT DESICCATION AND PEAT FIRES

A total of 51 sites on 20 peatlands, across six of the 16 peat ecoregions and seven of the nine provinces of South Africa, have burned between 1988 and May 2020. Two of the peatlands (Lakenvlei and Verlorenvlei) also have desiccated areas (Figure 3,

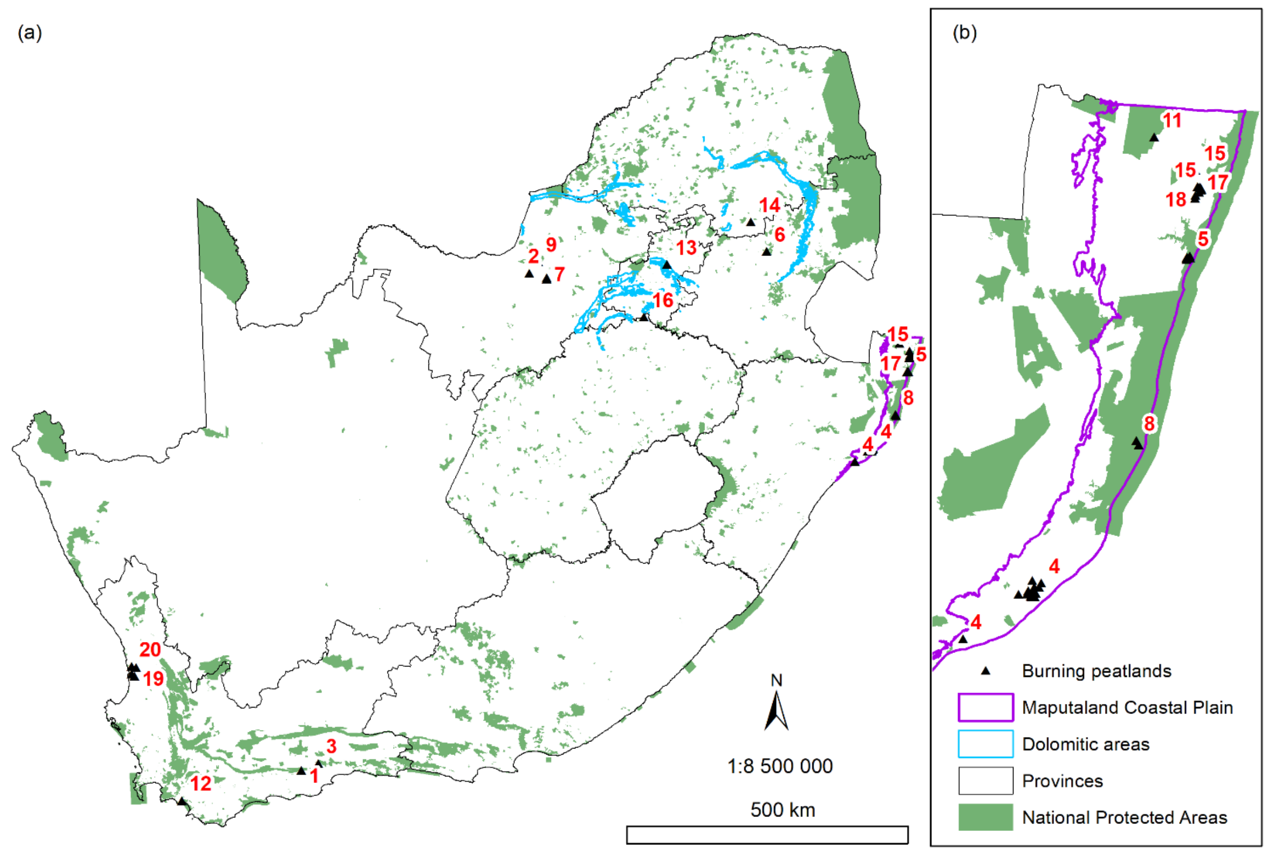

Figure 3. Location of burning peatlands across (a) South Africa and (b) the Maputaland Coastal Plain. Number labels refer to the site numbers shown in Table A2 (see Appendix).

Table A2). Seven of the burnt peatlands were observed in the Natal Coastal Plain peat ecoregion in KZN Province, where all 34 sites within the MCP (67 % of all sites) have burned (Figure 3). In Western Cape Province, seven sites of fires within five peatlands were recorded across three peat ecoregions (Cape Fold Mountains, Southern and Western Coastal Belt). The remaining ten sites on seven peatlands were located inland across two peat ecoregions (Central Highveld and Highveld) and five provinces.

The numbers of sites and peatlands that have burned and their frequency of burning are increasing (Figure 4). To our knowledge, two peat fires - at the Lichtenburg Game Breeding Centre (LGBC) and Rietvlei - were noted before the 1991–1995 decadal drought, which was considered the third most extreme drought recorded between 1921 and 2014, affecting 33 % of the country (Malherbe *et al.* 2016). For the 24-year period from 1991 to December 2014 (prior to the most recent drought of 2015–2016), 21 sites across eleven peatlands, five peat ecoregions and five provinces were recorded as having been affected. Since January 2015, acknowledged as the start of the most recent extreme drought (Johan Malherbe, personal communication 23 Apr 2020), the number of burnt sites has more than doubled, with 49 sites within 13 peatlands having burned in only five years. This constitutes a doubling in the number of peat fires in the past five years compared to the previous 24 years.

The 1991–1995 and 2015–2016 droughts had similarly low averages of mean monthly rainfall (42 and 40 mm, respectively) compared to the 31-year national average of 48 mm; with maximum mean monthly rainfall recorded during the droughts at 105 and 87 mm, respectively, compared to the 31-year national maximum mean of 164 mm (ARC-SCW 2020). Yet, according to a climatological expert of South Africa, Dr Johan Malherbe (ARC-SCW; personal communication 23 Apr 2020), the 1991–1995 drought was more extreme and extensive than the 2015–2016 drought. Therefore, the increase in the number, frequency and geographical distribution of peat fires suggests that regional droughts could have affected particular peatlands. Considering that the 1991–1995 drought was more extreme than that of 2015–2016 leads to the inference that anthropogenic influences may have contributed to causing greater numbers of peatlands to burn in recent years.

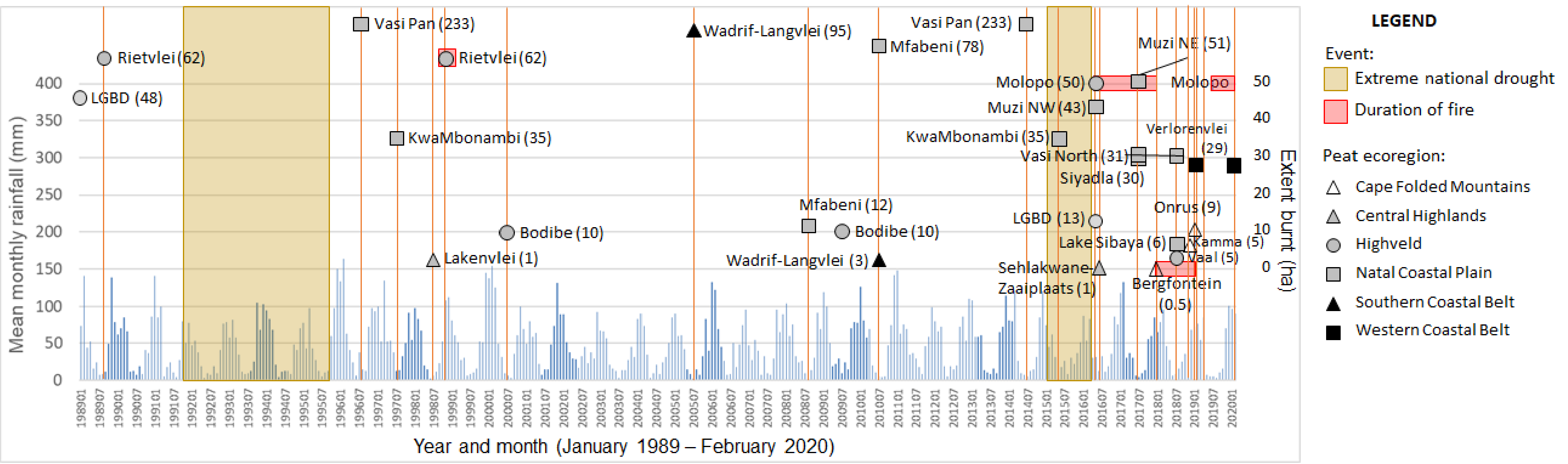

Figure 4. The sequences of mean monthly rainfall for South Africa (below) and observed peat fires (plotted per peat ecoregion; above) for the 31-year period January 1989 to February 2020. The areal extents (ha) of the fires are shown in brackets. The timings of extreme decadal droughts which affected >25 % of the areal extent of South Africa (Malherbe *et al.* 2016) are also shown. The extents of peat fires were summarised from publications listed in Table A2; rainfall data were obtained from ARC-SCW (2020); and drought information from Malherbe *et al.* (2016). Where only the year of a fire is recorded in Table A2, the fire is assumed to have occurred in the driest month of the year.

At provincial level, KZN Province contains the largest number (eight) of observed smouldering peatlands and showed an increase in the number of burning peatlands after onset of the most recent decadal drought in January 2014 (Figure 4). Thirteen sites across three peatlands (Vasi Pan, KwaMbonambi, Mfabeni) burned in the 24-year interval between the two extreme decadal national droughts of 1991–1995 and 2015–2016, whereas burning of a total of 34 sites (67 % of all sites) has been recorded on the MCP within the past five years. Poor land use planning - in particular extensive plantation of exotic trees - is the primary candidate cause of desiccation and burning of the Vasi Pan peatland, which has the largest burnt area (233 ha) of all the burnt and desiccated peatlands across SA (Grundling & Blackmore 1998, Elshehawi *et al*. 2019). The largest peatlands (including Vasi Pan and Mfabeni) that burned in the 20-year period between the two decadal droughts did not ignite during or immediately after the 5-year cyclic droughts listed by Malherbe *et al.* (2016). Rather, the increasing trend in peat fires within the past five years suggests that the cumulative effects of both anthropogenic pressures and increasing temperatures, heatwaves and intensified droughts associated with climate change have resulted in the peatlands on the MCP losing their resilience to a tipping point of collapse. Since the 1970s, several scientists have recommended the complete eradication of timber plantations from the MCP (Bate *et al.* 2016, Kelbe *et al.* 2016). To reduce the risk of complete collapse of the peatlands in this region, urgent intervention is now required to regulate timber plantations to an extent that is appropriate to the available groundwater sources on the MCP.

Similar to the peatlands of the MCP, the peatlands in Western Cape Province that burned during the past ten years exhibit combined and cumulative effects of increasing anthropogenic pressure and climate change (Figure 4). Within the Wadrif-Langvlei, two sites (95 ha and 3 ha) burned between 2006 and 2011, whereas four additional peatlands (Bergfontein, Kamma, Onrus, Verlorenvlei; seven burnt sites) have burned in the past three years. In the arid Verlorenvlei catchment, substantial increases in groundwater abstraction and dams in ephemeral streams during the past two decades can be inferred from the 67 % (9,542 ha) increase in centre pivot irrigation fields between 1998 (14,285 ha) and 2020 (23,827 ha).

We have estimated that the peat fires in South Africa since 1988 have resulted in a carbon loss (from peat deposits) of 280,513 tons, equivalent to a CO_2 emission of 1,036,822 tons (Table A2). To arrive at this estimate, carbon loss was calculated by combining wetland area mapped with scar thickness recorded from infield sampling to estimate the volume of peat lost, then converting to C loss using available values for the bulk density and C content of peat (*sensu* Agus *et al.* 2011, IPCC 2014). The C content and bulk density values determined previously for the Muzi North peatland (Grundling *et al.* 2000) yielded high-confidence values of 17,505 tons of C lost and 64,245 tons of CO_2 emitted for that site (Table A2). However, C content and bulk density values for all other burnt peatlands had to be extrapolated from Mulders *et al*. (2017). The results showed that Vasi Pan lost the most C (55,920 tons) and emitted the most CO_2 (205,226 tons) amongst the 20 burnt peatlands considered. Overall, the Natal Coastal Plain peat ecoregion lost 111,737 tons of C and emitted 410,074 tons of CO_2 as a result of peat fires. Considering that this region has the greatest number of peat fires and the number of its peatlands burning has increased within the past five years, there is now a critical need for intervention to determine the water reserves required for the functioning of peatlands, and to regulate water abstraction accordingly, in this region.

ASSESSMENT OF THE PROTECTION OF SOUTH AFRICAN PEATLANDS

In most South African peat ecoregions, less than 5 % of the total extent of peatland lies completely within protected areas (Table 5). The two exceptions where much higher percentages of total peatland extent lie within National Protected Areas (NPAs) are the Limpopo Plain (100 %) and Lowveld (43 %) peat ecoregions. However, these ecoregions host very few peatlands. Moreover, being situated within an NPA does not guarantee protection from pressures within the catchment, as 13 (65 %) of the 20 burnt peatlands across South Africa are situated within an NPA and/or a Ramsar Site. In fact, 34 (67 %) of the 51 burnt sites within the 20 known burnt peatlands are located on the MCP. Therefore, the question that arises is: are NPAs effective in securing conservation and wise use of peatlands in South Africa?

To be effective, the protection given to South African peatlands needs to address the increasing anthropogenic pressures and effects of climate changes (increasing temperatures, heatwaves, intensified droughts and high-intensity rainfall events). Habitats that are associated with peatlands, such as coastal swamp and floodplain forests (Van Deventer *et al.* 2021), and palmiet wetlands, are easy to map and consider for red listing as ecosystems under the International Union for Conservation of

Table 5. Extent of peatlands within National Protected Areas (NPAs) across peat ecoregions of South Africa.

Peat ecoregion	Degree of inclusion within NPA						Totals
	complete		partial		none		
	ha	(%)	ha	(%)	ha	(%)	ha
Bushveld Basin					3.8	(100.0)	3.8
Cape Fold Mountains	14.5	(0.6)	2,060.0	(83.1)	404.3	(16.3)	2,478.7
Central Highlands	173.7	(3.3)	3,489.6	(65.5)	1,665.5	(31.3)	5,328.8
Eastern Coastal Belt	66.0	(1.2)	1,109.2	(20.3)	4,297.4	(78.5)	5,472.6
Eastern Uplands	–		3,220.0	(32.0)	6,851.0	(68.0)	10,071.0
Great Escarpment Mountains	28.8	(0.01)	618.6	(79.9)	422.4	(20.1)	1,069.8
Highveld	1.5		10,005.2		2,515.8		12,522.5
Limpopo Plain	0.1	(100.0)	–		–		0.1
Lowveld	35.8	(42.5)	–		48.3	(57.5)	84.1
Natal Coastal Plain	5,653.8	(7.9)	56,913.5	(79.6)	8,948.4	(12.5)	71,515.7
Southern Coastal Belt	–		11,286.2	(94.1)	710.1	(5.9)	11,996.3
Western Coastal Belt	–		–		584.7	(100.0)	584.7
Totals	5,974.2	(4.9)	88,702.2	(73.2)	26,451.7	(21.8)	121,128.2

Nature (IUCN) guidelines (Bland *et al.* 2017). In contrast, non-forested peatlands will be more challenging to map and red list because improved mapping of their areal extent across the country is required, along with a detailed representative ecological condition assessment across the peat ecoregions. To devise appropriate management plans and monitoring for these peatlands, information on their true areal extent, peat thickness sampling, and calculations of peat volume and rate of peat accumulation would be needed. It would be critical to understand how extant pressures affect their (groundwater dependent) hydrological regimes; and to develop a framework to determine the vulnerability of all peatlands in terms of proximity to their tipping points into a potential collapsed state. Effective protection would constitute the regulation of pressures not only in the immediate vicinity of a peatland's boundary (e.g. within 5 km in the case of NPA peatlands that have burned), but also within the full groundwater catchment.

RESPONSES TO PEAT FIRES, DESICCATION AND PRESSURES

South Africa is a signatory to the Ramsar Convention. Since the 6th Ramsar Conference of the Parties (CoP) in 1996, various resolutions (also adopted by South Africa) have urged parties to prioritise peatland conservation (e.g. Recommendation 6.1, Resolution VIII.17 and XII.11). The latest relevant resolution (Resolution XIII.13), adopted at the 2018 CoP in Dubai, urges contracting parties to restore degraded peatlands in order to mitigate and adapt to climate change, enhance biodiversity and reduce disaster risk. Thus, it is recognised that conservation and restoration of peatlands can contribute to the fulfilment of multiple obligations or commitments under different multilateral environmental agreements such as the Ramsar Convention on Wetlands, Convention on Biological Diversity, United Nations Framework Convention on Climate Change, the Paris Agreement, and the United Nations Convention to Combat Desertification. Furthermore, the Constitution of the Republic of South Africa (Act 108 of 1996) states in Section 24 that everyone has the right a) to an environment that is not harmful to their health or wellbeing; and b) to have the environment protected for the benefit of present and future generations through reasonable legislature and additional measures that, amongst other purposes, prevent pollution and ecological degradation. In other words, intervention on peatlands is now critical and obligatory within the terms of the South African Constitution.

The protection of peatlands as types of wetlands is facilitated by South African legislation including the National Water Act (NWA; Act No. 36 of 1998) and the National Environmental Management Act (NEMA; Act No. 107 of 1998), in Listing Notice 1 (Activity 19) of the Environmental Impact Assessment [EIA] Regulations 2014 as amended). Utilisation of and development on peatlands (e.g. peat extraction, damming, excavation, draining, cultivation and infilling) are governed by Sections

21c and 21i of the NWA and as a listed activity of the EIA Regulations (Listing Notice 2, Activity 24 of 2014) as well as Article 7 of the Conservation of Agricultural Resources Act (CARA; Act No. 43 of 1983). In accordance with these regulations, activities affecting peatlands such as altering the beds and banks of the wetland, and diverting or impeding water flow, additionally require a water use licence under the terms of the NWA.

The NWA also allows for the classification of water resources within the nine Water Management Areas (WMAs) as per Government Gazette No. 40279 of 16 September 2016. This process requires Reserve Determination of the WMA to identify the amount of water resources (rivers and wetlands), followed by a Classification of the sources according to their quality. This process influences water use licences and their regulation and management. Only limited water ecological reserve studies have been commissioned for wetlands in the WMAs to date, and none specifically for peatlands as far as could be assessed by the authors using databases compiled by the South African Department of Water and Sanitation. The ecological reserve is, according to Van Wyk *et al.* (2006, page 404), “an allocation of water specified as a volume and quality underpinned by flow and duration requirements to sustain the specified [wetland] ecosystem”. Water use during droughts needs to be curbed, particularly in karst areas in the Highveld and Central peat ecoregions as well as in the sandy MCP of the Natal Coastal Plain peat ecoregion (Figure 4). Hydrological modelling of the water budget and ecological reserve determination for wetlands (including peatlands) is required before appropriate land uses can be permitted in these areas. Another regulation to consider is the incorporation of peatlands into national or provincial Strategic Water Source Areas (SWSAs; Le Maitre *et al.* 2018). Water licensing should allow a more flexible approach to the percentage reduction of use at times of severe and intense drought. We postulate that this should be enacted through the Disaster Management Act of South Africa when required to prevent ecosystem collapse.

Peat within draining wetlands becomes hydrophobic during desiccation and, if left to burn and/or erode extensively, will become nearly impossible to restore. It is more cost effective to prevent these peatlands from degrading by ensuring - through good land use practices, compliance and enforcement - that their hydrological functioning is maintained in both the short term and the long term, rather than trying to rewet them after they have become degraded. Extinguishing peat fires and building weirs or other structures to prevent erosion are expensive measures which are not always cost effective (Kotze *et al.* 2019).

Presently, the roles and responsibilities for intervention in the case of peat fires (as for wetlands in general) are non-existent. A response plan is required to address peat fires as emergencies, and planning is needed to implement the subsequent rehabilitation of burnt peatlands. Cooperative governance within the catchment areas of peatlands is critical and can be achieved through capacity building, training and awareness amongst stakeholders including government institutions and landowners. Emergency response plans are critical for municipalities with peatlands that have collapsed historically and where collapse is imminent. Furthermore, South Africa’s constitution and international obligations require national and provincial departments to support municipalities and landowners with the technical and institutional infrastructure that is required to prevent peatland degradation and manage degraded peatlands; as well as to enforce legislative compliance when required.

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AUTHOR CONTRIBUTIONS

The methodology was conceived by PLG, ATG, HVD and JlR. Data collection was executed by PLG, ATG and JlR, while HVD facilitated the consolidation and analysis in Geographical Information Systems (GIS). Data curation will be facilitated by ATG and HVD. PLG and ATG were responsible for obtaining the original funding for the project, while HVD attained additional funding for compilation and analysis of the journal article. HVD coordinated the structure of the manuscript, for which all authors wrote sections. The final review and editing was done by all four authors.

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Appendix

Table A1. South African datasets relating to peatlands or their associated vegetation cover.

Province or South Africa (SA)	Citation	Study	Extent description	Point or polygon dataset	Type of sampling or mapping	Description of incorporation of data into a national peatlands map	Ramsar wetland or peatland type	Confidence in representing peatland areal extent
SA	Adams *et al.* 2016	Estuarine habitats, updated also for the National Biodiversity Assessment of 2018 (NBA 2018)	South Africa	Polygons	Desktop, heads-up digitising from orthophotos or other space-borne satellite images	Polygons of estuarine habitats, in some instances, to species level, were extracted and integrated with other datasets	Coastal swamp forests were classified as Xp - forested peatlands	High
	Grundling *et al.* 2017	National Peatlands Database (NPD)	South Africa	Points	Infield auguring	Swamp and peatland points were used to extract polygons from available datasets or map from aerial photography	Swamp forests were classified as Xp - forested peatlands and others as U - non-forested peatlands	N.A.
	Mucina & Rutherford 2006, Dayaram *et al.* 2019	Vegetation map of South Africa, Lesotho and Swaziland (Mucina & Rutherford 2006) with updates from Dayaram *et al.* (2019)	South Africa	Polygons	Desktop, heads-up digitising from orthophotos or other space-borne satellite images	Polygons of swamp forests were extracted and integrated with other datasets	Coastal swamp forests were classified as Xp - forested peatlands	Medium
	Sieben *et al.* 2014	National Wetland Vegetation Database (NWVD)	South Africa	Points	Collation of coordinates from infield surveys	Swamp and peatland points were used to extract polygons from available datasets or map from orthophotos	Coastal swamp forests were classified as Xp - forested peatlands and others as U - non-forested peatlands	N.A.

Province or South Africa (SA)	Citation	Study	Extent description	Point or polygon dataset	Type of sampling or mapping	Description of incorporation of data into a national peatlands map	Ramsar wetland or peatland type	Confidence in representing peatland areal extent
KwaZulu-Natal (KZN) Province	Grobler 2009	Swamp forest at Kosi Bay, KZN	Sub-catchment scale	Points: Coordinates of relevé points	Infield floristic-based sampling of vegetation	Points were used to extract polygons from available datasets or map from orthophotos photography	Swamp forests were classified as Xp - forested peatlands	N.A.
	Scott-Shaw & Escott 2011	KZN	Provincial	Polygons	Desktop, heads-up digitising from orthophotos	Polygons of swamp forests were extracted and integrated with other datasets	Coastal swamp forests were classified as Xp - forested peatlands	Medium
	Sliva 2004	Swamp forest at Kosi Bay, KZN	Sub-catchment scale	Points	Global Positioning System (GPS)		Coastal swamp forests were classified as Xp -- forested peatlands	N.A.
	Venter 2003	Mfabeni Swamp	Wetland extent	Points (coordinates of relevés) and polygons of wetland vegetation communities	Infield Braun-Blanquet sampling of vegetation	Polygons were used to distinguish between swamp forests and non-forested wetlands	Coastal swamp forests were classified as Xp - forested peatlands and others as U - non-forested peatlands. Communities dominated by *Barringtonia racemosa* were removed since they were not considered peatlands	High
Western Cape Province	Rebelo *et al.* 2017	Four palmiet wetlands in Western Cape Province	Four wetlands	Polygons of the extent of the four wetlands	Infield Braun-Blanquette sampling of vegetation and auger samples	Polygons were used as-is	Palmiet wetlands were integrated as U - non-forested peatlands	High

Table A2. Number and areal extent (ha) of peat fires observed between 1988 and May 2020 (see Figure 4).

Name of system (number of sites)	Peat ecoregion	Province[1]	Extent of wetland (ha)[2]	Peat thickness (m)	Date burned or duration[3]	Extent burnt (ha)[4]	% burnt	Extent desiccated (ha)	% desiccated	Depth burnt / desiccated (m)	Volume burned (m^3)[5]	Volume desiccated (m^3)[6]	Carbon loss (t)[7]	CO$_2$ emitted (t)[8]	Pressures within immediate catchment	Cause of ignition (natural / anthropogenic)
1.Bergfontein	Cape Fold Mountains	WC	22.0	2.4	2018 to 2020	3	13.0			1.5	45,000		2,340	8,588	Wattle trees in wetland and overgrazing.	Veld fire from adjacent catchment.
2.Bodibe	Highveld	NW	26.3	7.0	Between 2000 and 2009	9.9	37.6			7	693,000		33,551	130,472	Overgrazing and township.	Anthropogenic (veld set afire for grazing purposes).
3.Kamma	Cape Fold Mountains	WC	97.0	5	24 Nov 2018	5	6.0			2.5	2,500		6,500	23,855	Wattle trees in wetland and overgrazing.	Veld fire from adjacent catchment.
					14 May 2020	2	2.1			2.5	50,000		2,600	9,542	Wattle trees in wetland and overgrazing.	Veld fire from adjacent catchment.
4.KwaMbonambi (13 sites)	Natal Coastal Plain	KZN	103.8	1-1.5	1997, 2015	35.0	33.7			0.5–1	174,850		8,393	30,802	Timber plantations within and surrounding the wetland.	Anthropogenic (Honey hunter started fire).
5.Lake Sibaya (eight sites)	Natal Coastal Plain	KZN	29.8	1.0	2018	5.6	18.7			0.5	27,750		1,332	4,888	Timber plantations, overgrazing and water abstraction.	Anthropogenic (burning of garden refuse).
6.Lakenvlei (two sites)	Central Highlands	MP	4.3	1.0	1998	1.07	24.9	4.3	100.0	0.5–1	5,350	21 500	271	994	Timber plantations, grazing, two mines (diamond and coal), dams and artificial drainage.	Veld fire (anthropogenic).
7.Lichtenburg Game Breeding Centre (LGBC) (two sites)	Highveld	NW	1,171.0	4.0	1988	48	4.1			1.0–2.0	480,000		24,624	90,370	Water abstraction for irrigation, town and industry, plus agriculture.	Veld fire (anthropogenic).
					28 May 2016	13	1.1				130 ,000		6,669	2, 475		
8.Mfabeni (two sites)	Natal Coastal Plain	KZN	1,445.0	10.0	2008	11.5	0.8			0.5	57500		2,762	10,135	Timber plantations before 2007; the wetland was 1,500 m from the edge of the plantation.	Natural (veld fire originated from lightning).
					2010	77.7	5.4				388,500		18,646	68,431		
9.Molopo (two sites)	Highveld	NW	113.0	3.0	From 08 May 2016 to 09 Jan 2018	50	44.2			0.5–1	250,000		12,825	47,068	Water abstraction, overgrazing, agriculture, resorts and bluegum plantations.	Veld fire (anthropogenic).
10.Muzi North-East	Natal Coastal Plain	KZN	377.0	3.5	2017	50.6	13.4			0.5	253,000		9,453	34,694	Cultivation inside, overgrazing and timber plantations.	Anthropogenic (burning of garden refuse).
11.Muzi North-West	Natal Coastal Plain	KZN	493.0	3.5	2016	43.1	8.7			0.5	215,500		8,052	29,551	Cultivation inside upstream and timber plantations.	Veld fire (anthropogenic).
12.Onrus	Cape Fold Mountains	WC	33.0	7.0	22 Jan 2019	9	27.3			1–1.5	90,000	330,000	4,680	17,176	Dam, water abstraction, blue gums, wattle and agriculture.	Veld fire (anthropogenic).

Name of system (number of sites)	Peat ecoregion	Province [1]	Extent of wetland (ha) [2]	Peat thickness (m)	Date burned or duration[3]	Extent burnt (ha) [4]	% burnt	Extent desiccated (ha)	% desiccated	Depth burnt / desiccated (m)	Volume burned (m^3) [5]	Volume desiccated (m^3) [6]	Carbon loss (t) [7]	CO_2 emitted (t) [8]	Pressures within immediate catchment	Cause of ignition (natural / anthropogenic)
13.Rietvlei	Highveld	GT	467.0	1.5	Dry season of 1988, 1989 or 1990, 1998 (for 180 days)	62	13.3			0.5–1	310,000		14,607	53,608	Water abstraction, dams, agriculture, artificial drainage, poplar, bluegum and wattle plantations, urban and industry upstream.	Veld fire (anthropogenic).
14.Sehlakwane Zaaiplaats	Central Highlands	LP	5.2	1.2	25 Aug 2016	1	19.3			0.5	5,000		253	929	Townships, overgrazing and abstraction.	Anthropogenic (veld set afire for grazing purposes).
15.Siyadla (six sites)	Natal Coastal Plain	KZN	114.0	1.5	2017	29.8	26.2			0.5	149,560		7,179	26,347	Timber plantations within 1,300 m of the edge of the wetland, overgrazing and cultivation inside.	Anthropogenic (veld set afire for grazing purposes).
16.Vaal River Tributary (racecourse)	Highveld	FS	64.0	0.5-1	04 Sep 2018	5	7.8			0.5	25,000		1,283	4,707	Mine water abstraction, urban development and mining.	Veld fire (anthropogenic).
17.Vasi North	Natal Coastal Plain	KZN	304.9	7.0	2017, 2018	31.3	10.3			0.5–1.5	156,500		7,512	27,569	Commercial timber plantations within and surrounding the wetland.	Management and veld fire (anthropogenic).
18.Vasi Pan (two sites)				3.8	1996, 2014	233	76.4				1,165,000		55,920	205,226		
19.Verlorenvlei (two sites)	Western Coastal Belt	WC	1,636.0	6.0	Apr 2019, Feb 2020	29	1.8	430	26.3	0.5–1	145,000	2,150,000	6,380	23,415	Water abstraction, dams, cultivation, wattle and blue gum plantations.	Natural (lightning).
20.Wadrif-Langvlei (two sites)	Southern Coastal Belt	WC	95.0	2.0	Before 2005	95	100.0			1	950,000		43,225	158,636	Overgrazing, water abstraction for irrigation and urban requirements of Lambertsbaai, as well as blue gum plantations and damming.	Veld fire (anthropogenic).
			21.0	2.0	2010	3.2	15.2			1	32,000		1,456	5,344		

[1] Abbreviations for provinces: FS = Free State, GT = Gauteng, KZN = KwaZulu-Natal, LP = Limpopo, MP = Mpumalanga, NW = North West, WC = Western Cape.
[2] Calculated from National Wetland Map version 5 (Van Deventer *et al*. 2020) or, where missing, captured specifically for this article.
[3] Where the month of the fire was recorded but no date, only the month and year are shown.
[4] Either recorded from publications or captured by experts in Google Earth Pro (Google LLC 2020).
[5] Volume of peat burned = extent burnt (ha) × average depth of burn × 10,000 (to convert ha to m²).
[6] Volume of peat desiccated = extent desiccated (ha) × average depth desiccated × 10,000 (to convert ha to m²).
[7] Carbon loss = volume of peat burned × bulk density × % carbon content. Calculated using extrapolated values for peat ecoregions from Grundling *et al*. (2017).
[8] Carbon loss × 3.66 (based on the atomic mass of carbon dioxide in relation to carbon).