Application of Palaeoecology and Geochemical Proxies in Tropical Peatlands' Degradation Studies

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1. Introduction

Tropical peatlands (TP) are undergoing large-scale degradation due to conversion of peatland forests to plantation, agriculture, logging, drainage and human resettlement[1,2,3]. In Southeast Asia, land use changes have resulted in ~3.1 Mha (1980 to 2010) of degraded peatlands[2]. The anthropogenic-driven degradation is exacerbated by droughts and wildfires from pronounced El Niño events[4]. Based on the TP studies in Southeast Asia, the impacts of degradation are numerous and these include carbon storage losses[4,5], carbon dioxide emissions[6,7], modifications in hydrology and drainage[8], forest fires[9], biodiversity losses[10] and health risks[11].

Majority of these impacts were studied based on short-term assessment of the observed data and did not consider the past degradation and the delayed impacts from the feedback mechanism between peat, hydrology and vegetation system[9]. Moreover, restoration works utilise these short-term data in their engineering solutions[12]. This can be counter-productive due to the lack of long-term data to conduct a comprehensive assessment of the degradation impacts and propose reliable restoration plans.

To provide long-term data, palaeoecological and geochemical proxies have been applied in temperate/boreal peatland studies[13,14] and are increasingly studied in TP[15,16]. Key proxies include: I) pollen and spores (palynomorphs), II) testate amoeba (TA), III) micro and macro charcoal, and IV) stable isotope and concentration of carbon and nitrogen.

As tropical and temperate/boreal peatlands thrive in different altitude, topography, climate and vegetation, this review paper will assess the application of these proxies in tropical peatlands to infer and explain the long-term trends and feedback mechanism of peat, hydrological, and vegetation responses to anthropogenic and climate drivers. To achieve this, this review will i) evaluate the methodology of the proxies; ii) assess the long-term trends in response to anthropogenic and climate drivers; and iii) investigate the long-term feedback mechanism between peat, hydrology and vegetation system.

2. Evaluation of proxies' methodology

The following table will evaluate the origins, methods, successful reconstruction and limitations of key proxies. The data from these proxies will be verified with each other using principal component analysis (PCA) to detect variability and correlations trends between the long-term data.

Proxies	Origin	Methods	Successful reconstruction	Limitations
Pollen and spores	- Released by plants and dispersed through wind, animals and water - Preserved : high decay-resistance capabilities [17]	- Counting (concentration) and identification to genus and species taxonomic levels [18] - Classification to vegetation groups (i.e freshwater swamp (wet), lowland mixed with swamp (fluctuating), peat swamp (wet), and open/invasive vegetation))[15,16] - Clustering analysis (CONISS): palynological zones [19]	- Past vegetation dynamics and vegetation/ecological communities[13,15,16,20] - Environmental changes such as water availability (i.e El Nino droughts, sea level), peat types and disturbances [16,20]	- Vegetation changes are less prominent in coastal peatlands compared to inland peatlands due to permanent humid rainfall regimes[20,21] - Low counts: gaps in chronology caused by anthropogenic or climatic drivers[20]
Testate amoeba (TA)	- Modern TA comprise up to 30% of the microbial biomass in peat [22] - Subfossil TA remains are preserved: gluing to organic and mineral particles [23]	- Sampling of subfossil and modern TA. - Counting (concentration) and identification to genus and morphospecies [16,22,23] - Transfer function model between modern TA and the measured environmental variables (reconstruct long-term measured data using subfossil TA) [24] - Classification to habitat groups[16]: peat moss TA (dry and fluctuating conditions), soil TA (dry) and water TA (wet)	- Long-term groundwater table level in ombrotrophic TP [16,22,23] - Long-term pH of peat in minerotrophic TP [24]	-Low preservation potential in river and basal mineral [16,22] - Some TA communities respond to extreme events but are insensitive to large natural variations [25]
Micro and macro charcoal	- Plant matter becomes inorganic carbon due to incomplete combustion and pyrolysis during fire [26] - Resistant to further oxidation and microbial activity [27] - Macro-charcoal (>125um) : local fires -Micro-charcoal (<125um): regional fires	- Counting to obtain charcoal concentration - CharAnalysis: calculate charcoal accumulation rate; fire intensity and frequency[28] -Charcoal/pollen concentration ratio: To ascertain the kind of human disturbance[4,20]	- Paleofire events and past fire frequency and intensity [16.20.21,29]	- Charcoal is rare in older peats in remote peatlands compared to the peatlands closer to rivers (accessible) [29] - Uneven spread of fires caused by spatial differences in hydrological and peat conditions
Stable isotope (δ13C & δ15N) ; Carbon (C) and Nitrogen (N)	- Organic C and N are internally derived in peat by precipitation (authigenic)[30] - δ13C: C3 (-30 to -20 %) & C4 (-16 to -9 %) plants [31] - δ13C is produced in C3 during dry conditions while δ15N is enriched during decomposition [31,32] - C and N are produced during anaerobic and aerobic conditions respectively[5]	-Concentration measured in the CN Elemental Analyser and Isotope Ratio Mass Spectrometry - Carbon/ Nitrogen ratio: degree of peat sequestration/decomposition [33] -Carbon density: carbon accumulation per area and year [16] - $\delta^{13}C$ and $\delta^{15}N$: calculated through dividing raw values with the PDB fossilised carbon and atmospheric nitrogen standards respectively[34]	- Distinguish between C3 and C4 vegetation [34] - Long-term trends of peat accumulation and decomposition [21] -Long-term information on water availability in peat [33]	- Remobilisation of C and N due to disturbances [30] - $\delta^{13}C$ in peat can also be produced from methanogenesis in peat, different plants and plants' parts and charred/burnt samples [35]

3. Long-term trends in response to anthropogenic and climate drivers

The assessment of long-term trends (Fig 1) will be based on a specific case study in an inland peatland in Jambi Province, Central Sumatra, Indonesia using the palaeoecology and geochemical data (that have been smoothed using LOWESS)[36]. Other reconstruction used to verify palaeoecology and geochemical data are long-term rainfall data from Liang Luar cave in Flores, Indonesia[37] and sea level relative of the Malacca straits[38].

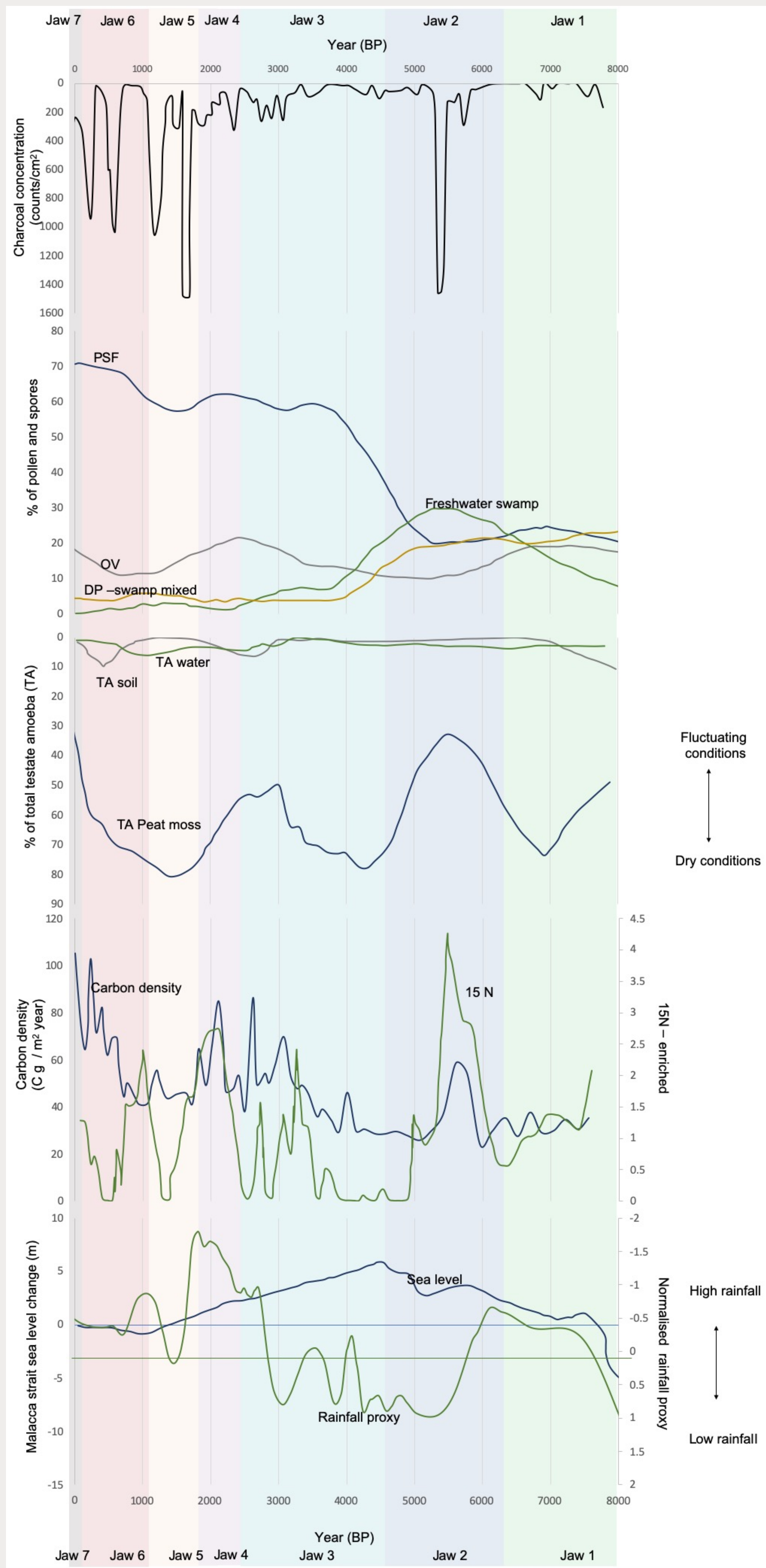

Figure 1: Palaeoecology and geochemical reconstruction of fire events (charcoal), past vegetation (pollen and spores), wet and dry phase (testate amoeba) and peat accumulation/decomposition (carbon density & δ15N) in TP in Central Sumatra (Indonesia)[36] were compared with regional rainfall reconstruction using speleothem (δ16O) in Liang Luar cave in Flores (Indonesia)[37] and Malacca strait sea level change[38]. Long-term data are grouped into palynological zones (Jaw 1-7).

Jaw 1 (6230 – 8000 BP) :
- Dipterocarp (DP)) - swamp mixed forest
- Increase in sea level and rainfall is accompanied by the slight growth of PSF after 7000 BP
- Beginning of minerotrophic peat

Jaw 2 (6230 – 4500 BP):
- Freshwater swamp forest with increasing sea level
- Sharp increase to PSF between 4800 to 4500 BP
- Shift to dry: large-scale fire event and peat disturbances (5200 to 5400 BP)
- Minerotrophic peat with moderate carbon

Jaw 3 (4500 – 2500 BP):
- Dominated by PSF
- Peat disturbances, small-scale and frequent fire, and open vegetation between 3200 to 2500 BP (not due to dry phase)
- Shift to ombrotrophic peat due to decreasing sea level and fluctuating wet and dry phase

Jaw 4 (2500 – 1900 BP):
- Dominated by PSF and wet phase
- Peat disturbance and small-scale, frequent fire (not due to dry phase)
- Ombrotrophic peat with increasing carbon

Jaw 5 (1900 – 1100 BP):
- PSF and fluctuating wet and dry phase
- Large- scale but less frequent fire due to sharp shift to dry phase
- Peat layers with low 15N

Jaw 6 (1100 – 120 BP):
- PSF and wet conditions
- Large-scale fire and open vegetation (not due to dry phase)
- Delayed peat disturbances from fires in Jaw 5
- Ombrotrophic peat with high carbon

Jaw 7 (120 – 0) BP
- Not described due to lack of data

4. Long-term feedback mechanism

Majority of the long-term trends and PCA correlations (Fig 2) fit into the theoretical feedback mechanism[39] between peat, hydrology and vegetation system except for the following:

1) Small fires (J3 & 4) and recent fire (J6) occurred in wet phase while large fires (J2 & 5) in dry phase (low negative correlation in Dim2) →anthropogenic fire (followed by increase in OV)

2) Peak in 15N is delayed during large fires in J5 and 6 (but not in J2, 3 & 4) (no correlation in Dim1) → Wet conditions and burnt peat layer resulted in delayed decomposition for deeper peats

3) PSF and peat moss TA had no correlation with rainfall proxy
→ peat moss TA represents groundwater level (high positive correlation with PSF in Dim1)
→Rainfall proxy is linked to sea level

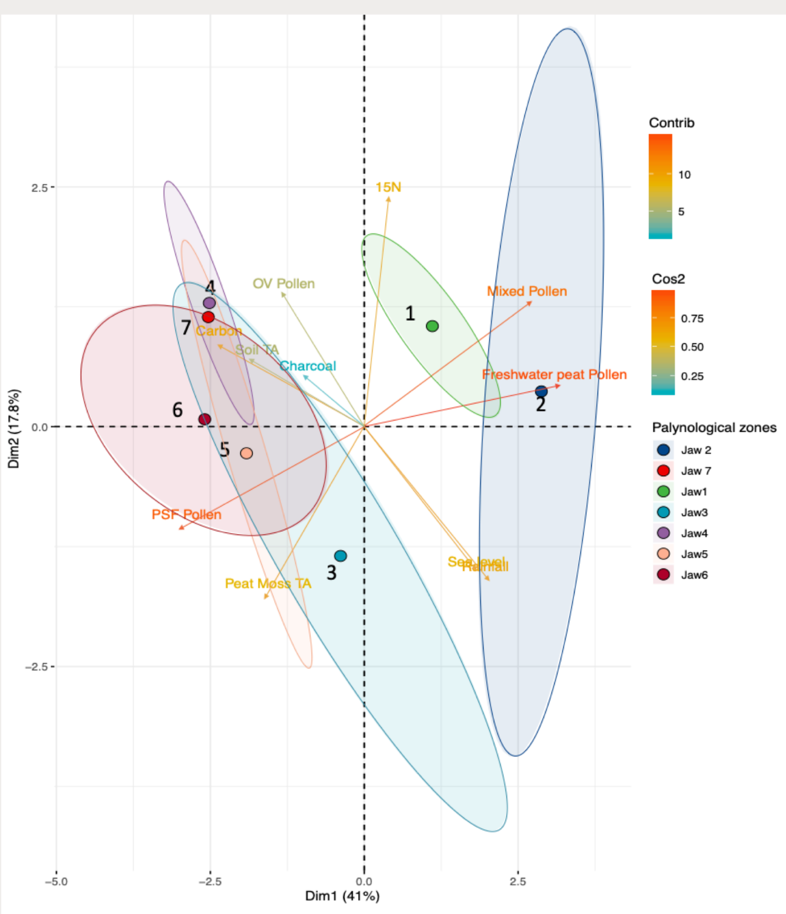

Figure 2:. Dim1 and Dim2 explain 41% and17.8% of the variables' variances respectively. The contribution and correlation of each variables (arrows) and the scores of all long-term data for each palynological zones (ellipses) are shown.

5. Conclusion

- Multi-proxies are needed to verify the reconstruction of peat, hydrology and vegetation system.
- Pollen and spores showed clear changes in vegetation dynamics and peat types which are supported by sea level changes.
- Fire event are not only due to climatic-drivers (low rainfall) - evidence of anthropogenic burning.
- Peat decomposition can be delayed if fires are large in scale and conditions are wetter.
- Carbon density can reflects charcoal concentration: peat disturbances instead of accumulation

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