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Review Paper

Toba Highland Peatlands: Exploring a Unique Ecosystem and its Environmental Significance

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Abstract

This paper provides a review of the Toba highland peatlands, focusing on their characteristics, environmental impacts and historical significance. The Toba area was influenced by a super volcano eruption around 74,000 years ago, which resulted in global cooling and the deposition of pyroclastic materials known as the Youngest Toba Tuff. The peatlands in the region formed south of the caldera and are characterised by varying extents and thicknesses. Radiocarbon dating indicates that the peat in Toba highland is approximately 20,000-30,000 years old, making it a valuable carbon stock and a record of the past. However, the drainage of peatlands has led to significant environmental degradation. It has resulted in increased CO_2 emissions, reduced water supply for local farmers, loss of biodiversity, air pollution from open fire burning practices, and an increased fire hazard. Understanding the environmental impacts and historical significance of Toba highland peatlands is crucial for conservation efforts and sustainable land management practices.

Keywords

Peatland, Climate Change, Greenhouse gas emissions

1. INTRODUCTION

Peatlands play a vital role in providing various ecosystem services, such as carbon storage, biomass production, and climate regulation. However, the combined effects of climate change and rapid land use changes are leading to the degradation of peatlands, resulting in the rapid release of stored carbon into the atmosphere (UNEP, 2022). According to the global peatland assessment conducted in 2022, the degradation of peatlands is responsible for emitting more than 3 billion tonnes of carbon dioxide CO_2 annually (UNEP, 2022). This emission is equivalent to approximately 10% of the global emissions generated from fossil fuels. These findings highlight the urgency and significance of studying peatlands, as we still have a long way to go in fully understanding the complex relationship between peatlands, carbon (C), and climate (Loisel et al., 2021).

Peatlands in Indonesia cover approximately 13.4 million hectares and are estimated to hold a carbon stock of around 36±6 Gt C (1 Giga ton or billion ton = 10^{12} kg) (Anda et al., 2021). These peatlands are mostly found in the three islands of Sumatra, Kalimantan, and Papua. However, Indonesian peatlands are facing significant environmental challenges, as environmental conservation clashes with the pressure for economic growth and livelihood support for smallholder farmers. One notable environmental issue is the occurrence of peatland fires during the 2015 El Niño season, which resulted in a substantial emission of 0.9-1.5 Gt of CO_2. This emission is equivalent to approximately 10% of the mean annual global carbon emissions from fossil fuels (Wiggins et al., 2018). The fires in 2015 and 2018 affected an estimated 1 million hectares of peatlands. Once burned, these areas are prone to subsequent fires, leading to progressive land degradation and continued release of carbon into the atmosphere. The future of Indonesia's peatlands is expected to face even greater challenges as temperatures rise and the region becomes drier. These changes in climatic conditions threaten the sustainability of peatlands and exacerbate the difficulties in managing and conserving these vital ecosystems.

Peatlands are not only a C store, but a record of our past environment. Peat preserves physical, chemical, and biological signatures of past environments and climates (Chambers et al., 2012). Studies on high-latitude northern peatlands indicate that warmer climates induced an increase in plant productivity, which may lead to an increase in C sink but it could be offset by increased soil respiration rates and lowered water tables (Maloney, 1980). Yet, there is limited information on the age and rates of accumulation of tropical highland peat deposits. There has been considerable attention paid to the lowland peats of Indonesia, including studies conducted in regions such as Riau,

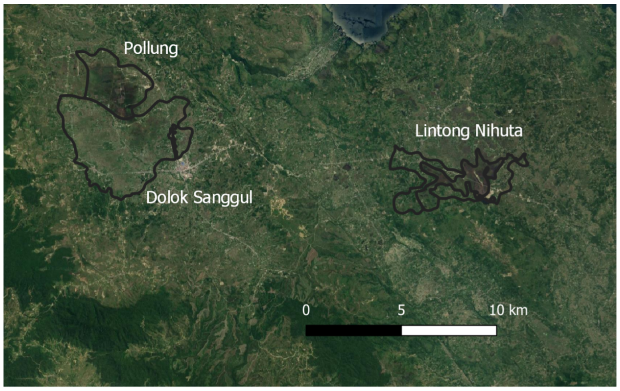

Figure 1. Approximate peatlands in the Toba highlands

South Sumatra, and Central Kalimantan (Ruwaimana et al., 2020). However, the country's tropical highland peats have not received a similar focus. Found in highlands in Sumatra, Sulawesi, and Papua, these peatlands remain poorly documented and understood.

The Toba peatland, situated in the Humbang Hasundutan regency on the southern side of Lake Toba, is an example of an under-studied highland peatland. Despite its long-standing recognition, the Toba peatland has experienced significant deforestation, resulting in the loss of its natural vegetation. Presently, large portions of the peatland are dedicated to agricultural activities such as horticulture, coffee production, and rice cultivation. As a consequence of extensive land clearance, some areas remain abandoned or have become overgrown with sedges and grasses.

The aim of this paper is to provide an overview of Toba highland peats by examining the existing body of knowledge. The paper begins by presenting an analysis of the extent and current status of the peatlands, as well as delving into the historical studies conducted in the area. Furthermore, the paper explores the various characteristics of the peats, including their composition, age, and formation rates. Subsequently, the paper delves into a thorough discussion on the environmental issues associated with Toba highland peats.

2. PEATLANDS IN TOBA HIGHLAND

2.1 Area and extent

The Toba area was influenced by the super volcano eruption that occurred around 74,000 years ago. The eruption ejected around 2800 km^3 of pyroclastic materials, known as the Youngest Toba Tuff, causing global cooling for six to ten years (Chesner, 2012). After the super eruption of rhyolitic tuffs, volcanic activity continued, and eruptions continued episodically for another 6 to 24,000 years, progressing westward across the caldera. The area in Padepur, south of the caldera, was dated around 63,000 years (Mucek et al., 2017).

The peatlands formed south of the caldera, including Dolok Sanggul and Pollung to the west and Lintong Nihuta to the east (Figure 1). The mean annual temperature is 20^{o}C with a range between 14 to 24^{o}C. The annual rainfall is around 2000 – 2100 mm. These peatlands are primarily located in depressions, with remnants of past vegetation accumulating and remaining saturated over time. The Lintong Nihuta area is at elevation around 1410 m above sea level (a.s.l.), composed of several peatlands. The total area of Lintong Nihuta is about 2000 ha, with around 1700 ha of peatland. Dolok Sanggul is at about 1400 m a.s.l. around 2000 ha, but much of it has been developed. The relatively large peatland is in Pollung about 1500 ha. It is uncertain how many of these peatlands are intact.

The composition of these peats predominantly originates from tree matter, with discernible large, undecomposed woods still visible. The thickness of the peat layers varies from 1 to 3 meters. However, areas that have been exploited are considerably thinner now, measuring less than 1 meter in places.

2.2 Historical studies

German botanist Franz Wilhelm Junghuhn noted the occurrence of peats on the Toba highland in his publication Die Battaländer auf Sumatra (1847), where he encountered swamps with a coffee-brown coloured water.

The most comprehensive description was by Elisabeth Polak in her book "Ueber Torf und Moor in Niederlandisch Indien" published in 1933. She examined mountainous peats on the Toba Plain, Telaga Saat in West Java and Dieng Plateau. Polak mentioned that raised bogs in the tropics are always forest bogs, which are not composed of sphagnum. However, above 1200 m sphagnum is very common.

Polak (1933) noted that the Toba Plain is mostly devoid of trees, but once covered in forests, evidenced by the presence of resinous wood in the soil. Local inhabitants extract tree trunks, stumps, and root masses from the area to use as fuel. The peat soils are former forest soils that have dried up but retain high levels of organic matter. The deforestation of the area was already documented by Junghuhn in 1847 and later by Ruttner in 1930. The steppe-like vegetation observed in the Toba Plain is therefore a secondary characteristic resulting from the absence of tree cover, leading to soil drying and increased exposure of plants to direct sunlight.

Polak (1933) further noted three types of bog-like formations: 1. Marshy areas where the ground is slightly sunken and moist, and where sparse scrub, grasses, Cyperaceae, orchids, ferns, and Nepenthes tobaica, with the soil layer completely occupied by Sphagnum. Sphagnum grows almost directly on hard rock. 2. Small ponds in the process of being filled in. Typical boggy areas often covered with Sphagnum. 3. Bare peat, partially cultivated as rice fields or covered with herbaceous vegetation. The latter are fossil forest soils, abundant with wood. Polak (1933) recorded peatland in Lintong Nihuta, Dolok Margu and Dolok Sanggul. Below are some of her descriptions from 1933.

Figure 2. Various land uses on peatlands in Dolok Sanggul: open peatland, grassland, paddy rice, onion field, and coffee plantation.

"At Lingtang Nihoeda, there was a marshy area where a type of peat was visible on the surface. It turned out that the vegetation had been destroyed by fire; the dead layer had a resemblance to Sphagnum peat but was only 50 cm thick. New vegetation was already growing, including Sphagnum, ferns, and Juncus. The area is very moist and soft, and the peat-like mass is still slightly decomposed and has a pale yellow color."

"A relatively large swamp is found in Si Gelapang, near Si Borong-Borong. The bog is shallow and moist, with the soil layer occupied by Sphagnum. ... The humus layer is less than 30 cm thick. Rüttner (1930) suggests that these swamps formed after the forest was cleared, indicating that the short period of growth is responsible for the lack of peat formation."

"At the roadside near Dolok Margoe, there is a small pond with water that is white in color from the washed-out liparite tuff. The depth is only a few meters, and there is a floating mat of vegetation on the water's surface. Under the floating mat, wood remnants can be found, and small shrubs also grow interspersed among the herbaceous plants."

"The ladangs in Negri Djandi, Dolok Sanggoel District, are cultivated on peaty humus. Below the cultivation layer, there is approximately 30 cm of peat composed of reeds and roots, embedded in brown plastic humus. This is followed by a light yellow layer, which, according to the locals, can reach a thickness of about three men's heights. According to the claims of the Bataks, this layer has the highest heat effect, and they use the material as a household fuel for cooking. It is also applied and burned in the ladangs, as the ash is believed to improve the soil. The yellow color of this soil darkens quickly in the air and turns brown. When burned, this "peat" leaves behind yellow ash with many quartz crystals."

Historical observations noted that the area has been cleared from forest in 1930s when Polak conducted the survey. Maloney (1980) conducted a pollen analysis of a 9.76 m peat core from Pea Sim Sim, south of Lintong Nihuta, and found evidence that forests were cleared since 7,500 yr BP. There was evidence of vegetation change around 17,800 yr BP, but it could be due to climate. Based on several peat deposits, Maloney (1980) suggested that around 2000-2600 years ago, rice was cultivated in the area.

2.3 Peat Characteristics

The extent and thickness of the peat in the region is variable. Research conducted by Maloney (1980) in the 1970s documented areas with peat thickness up to 10 meters. Meanwhile, Tarigan (2011) reported peatland in Nagasaribu village in Lintong Nihuta with an average thickness of 2.5 meters, with a surface bulk density of 0.28 g/cm^3 and an average carbon content of 56%.

A study by Munawaroh et al. (2022) surveyed peatlands in Pollung and Dolok Sanggul with various land uses: open peatland, grassland, paddy field, onion field, and coffee plantation (Figure 2). The topsoil analysis shows that the organic C content has declined, with a maximum of 22% on an open peatland (with no vegetation) and 5% on coffee fields (Table 1).

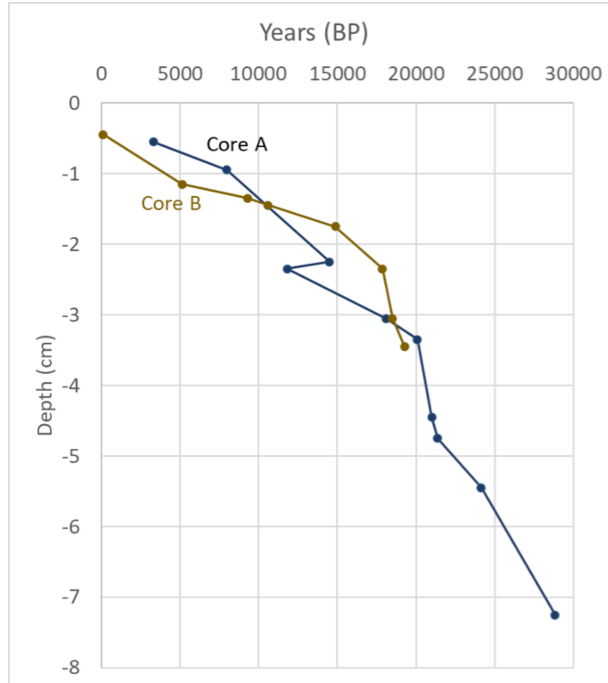

Figure 3. Radiocarbon peat age at the Pea Bulolock site (data from Maloney and McCormac (1996)

2.4 Peat Age

Bernard Maloney, from the Paleoecology Centre at Queen's University in Ireland, conducted several studies in the 1970s as part of his PhD thesis at Hill University. His research centered around investigating changes in climate and vegetation over the past 100,000 years, with several study sites on peat deposits located near Lintong Nihuta.

One site, referred to as "Pea Bullock," is situated north of Siborong Borong and is approximately 1,400 meters above sea level. The current location of this site is untraceable, and local inhabitants do not recognise the "Pea Bullock" name. In the Batak language, "Pea" means swamp or pond, and it is surmised that the correct term could be "bulok". The closest probable location is Huta Gambut (2o 13′ 45″, 98o 58′ 35″), sitting at an elevation of 1,322 meters and about 2 kilometers north of Siborong Borong. This site is associated with the oldest date of 28,840 ± 460 years BP, recorded at a depth of 7.25 meters. Maloney hypothesised that this location could be an extinct volcanic crater. The radiocarbon dating shows that, at the bottom of the peat (8 m), the age is close to 30,000 years BP (Figure 3).

Radiocarbon dating on other sites near Lintong Nihuta (Figure 4) include: • Pea Sim Sim from Maloney (1980), at

Table 1. Soil properties of peatland in Pollung and Dolok Sanggul with different land uses (Munawaroh et al., 2022)

Land use	Organic C (%)	pH	C/N	Field water content (%)
Open peatland	22.05	2.7	37.37	98
Grassland	19.32	4.1	30.18	42.8
Paddy field	14.15	4.2	22.46	28.1
Onion field	15.64	3.7	22.66	32.8
Coffee field	5.23	3.6	10.25	14.3

elevation 1450 m, about 3 km south of Lintong Nihuta, with age of 18,497 ± 95 years BP at the basal depth of 9.75 m. Pollen analysis from the study suggests that human cleared the forest in the area 7500 years ago.

• Tao Sipinggan, described Maloney (1985), an extinct crater, about 1 km south of Lintong Nihuta, the site was at elevation 1445 m, and was dated at 12,116 ± 140 years BP at a depth of 12 m. Tao means lake in Batak language, suggesting a former lake,

• Pea Sijajap at about 100 m lower altitude in the Simamora rift (Maloney, 1985), and infilled volcanic crater, about 1300 m altitude in a downfaulted rift valley, not on the plateau. An unreclaimed herbaceous swamp was at the centre, surrounded by wet-rice fields and low scrub vegetation. The upper 1.15 m was dated at 3900 years BP.

The radiocarbon dating from Maloney's work suggests the peat age in Toba highland is between 20,000-30,000 years. This is 3 times older than lowland coastal peatland in Riau, which was dated to be 6500 years BP (Fujimoto et al., 2019). Coastal peatland mainly formed after sea level stabilisation around 8000 years BP. Inland peat could form earlier with some data suggesting 47,000 years BP in the Upper Kapuas of Kalimantan (Ruwaimana et al., 2020).

The average peat accumulation rate of the Toba peatlands is very slow, between 0.1-0.6 mm/year: • Pea Bullock: 0.12 mm/year (0.1 Mg C/ha/yr) during the past 17,000 years and 0.40 mm/year (0.2 Mg C/ha/yr) from 17,000-30,000 years. • Tao Sipinggan: 0.44 mm/year (0.2 Mg C/ha/yr). • Pea Sim Sim and Pea Sijajap: 0.27 mm/year (0.1 Mg C/ha/yr) for the past 10,000 years and 0.69 mm/year (0.4 Mg C/ha/yr) for the past 10-20,000 years.

In summary, these peats are high-value carbon stock and stores record of our past 30,000 years.

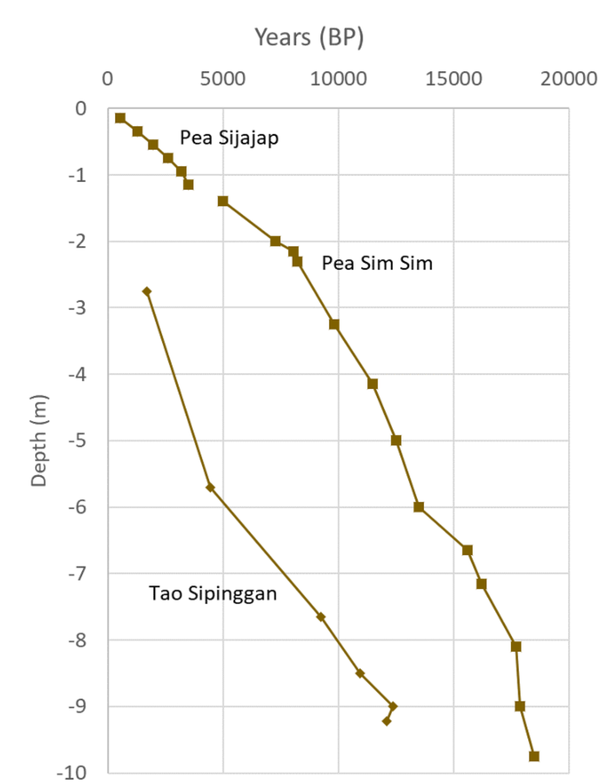

Figure 4. Peat age of Pea Sijajap, Pea Sim SIm and Tao Sipinggan (Maloney, 1985)

2.5 Environmental Degradation

The Desa Nagasaribu in Lintong Nihuta was previously mined for fuel by locals to supply a local pulp and paper mill in 1996. This process involved draining the area, which is still evident as water continues to flow out from the drain (Figure 5).

The drainage of the peatlands has given rise to a range of environmental issues, including: - Increased CO_2 emissions: The drainage has exposed the peats to oxidation and subsidence, resulting in significant emissions of carbon dioxide (CO_2) into the atmosphere. - Reduction in water

Figure 5. Water running over degraded peats in Lintong Nihuta

Figure 6. Woods being collected from peats at Lintong Nihuta to produce charcoal

supply: The drainage has led to a reduction in the water supply available to local traditional paddy fields. As a consequence, some farmers have experienced the drying out of their fields, impacting agricultural productivity. - Biodiversity loss: The drainage of the peatlands has resulted in the loss of biodiversity within the affected areas. The disruption of natural habitats and the alteration of hydrological regimes have negatively impacted various plant and animal species. - Air pollution from open fire burning: The practice of utilising open fire burning to produce charcoal from collected wood contributes to air pollution (Figure 6). This release of pollutants into the atmosphere further exacerbates the environmental impact of the peatland drainage. - Increased fire hazard: The drained peatlands, in their dry condition, pose a significant fire hazard. The accumulation of dry peat and the prevalence of flammable materials increase the likelihood of uncontrolled fires, posing risks to both the environment and human settlements.

The local government enacted a regulation in 2013 to safeguard these peatlands from further exploitation. This regulation stipulates that peatlands deeper than 1 meter must not be utilised, thereby offering some level of protection to these valuable ecological areas.

3. CONCLUSION

Peatlands in Humbang Hasundutan are a unique tropical ecosystem primarily formed from accumulated tree matter. They exhibit significant variations in peat layer thickness. Unfortunately, large areas of these peatlands remain exploited and degraded, leading to various problems such as peat oxidation, CO_2 emissions, reduced water supply, biodiversity loss, and increased fire hazards. Studies have indicated that abandoned peatlands have lost approximately 50% of their carbon stock, while those used for agriculture have experienced a staggering 90% loss in C content.

The Toba peatlands encompass several extensive areas, however, the exact extent of these peatlands remains unconfirmed due to limited research. A study conducted in the 1970s suggested that the bottom layer of the peat is approximately 30,000 years old. Additional sites have provided valuable data on peat age and accumulation rates, indicating a slow formation rate of 0.1-0.6 mm/year, underscoring the gradual development of these ecological resources.

These upland peatlands represent invaluable carbon reservoirs that store records spanning the past 30,000 years. Importantly, they are significantly older than the coastal lowland peatlands found in South Sumatra. Preserving and conducting further studies on these peatlands are crucial for enhancing our understanding of historical climate and vegetation changes and their significance in shaping the present and future environment.

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