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Article

Coevolutionary dynamics in tropical peat ecosystems: A case study of Sumatra peatlands biosphere reserve

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Abstract: Tropical peat swamp is an essential ecosystem experiencing increased degradation over the past few decades. Therefore, this study used the social-ecological system (SES) perspective to explain the complex relationship between humans and nature in the Sumatran Peatlands Biosphere Reserve. The peat swamp forest has experienced a significant decline, followed by a significant increase in oil palm and forest plantations in areas designated for peat protection. Human systems have evolved to become complex and hierarchical, constituting individuals, groups, organizations, and institutions. Studies on SES conducted in the tropical peatlands of Asia have yet to address the co-evolutionary processes occurring in this region, which could illustrate the dynamic relationship between humans and nature. This study highlights the co-evolutionary processes occurring in the tropical peatland biosphere reserve and provides insights into their sustainability trajectory. Moreover, the coevolution process shows that biosphere reserve is shifting toward an unsustainable path. This is indicated by ongoing degradation in three zones and a lack of a comprehensive framework for landscape-scale water management. Implementing landscape-scale water management is essential to sustain the capacity of peatlands social-ecological systems facing disturbances, and it is important to maintain biodiversity. In addition, exploring alternative development pathways can help alter these trajectories toward sustainability.

Keywords: biosphere reserve; coevolution; degradation; social-ecological system; tropical peatland; water management

1. Introduction

Peat swamp forest ecosystems are unique because natural forest grows on peat soil that is often flooded for long periods under normal conditions (Anderson, 1964). Globally, peatlands have experienced increasing degradation over the past few decades. Asian tropical peatlands are expected to continue to be the most degraded in the short and medium term (Urák et al., 2017). Moreover, Indonesia's peat swamp forest ecosystems are currently degrading at a rate of 3.6% per year (Miettinen et al., 2011) due to legal and illegal logging activities, large-scale forest, land use changes, and forest fires (Dohong et al., 2017).

Tropical peatlands play an important role as global climate regulators, with their carbon stocks estimated to account for 20% of the global total (Hans Joosten, 2009; Page and Hooijer, 2016). Human activities that alter peat hydrology have led to degradation and increased greenhouse gas (GHG) emissions (Dohong et al., 2017; Hergoualc'h et al., 2018; Prananto and Minasny, 2020; Urák et al., 2017). The tropical peat ecosystems also provide water, timber, and non-timber forest products (honey, resin, and rattan), as well as fishing and agricultural resources for local communities

(Hergoualc'h et al., 2018; Pertiwi et al., 2022). However, these environmental services are increasingly being lost due to land conversion and degradation (Dislich et al., 2017).

Environmental problems from peat degradation pose significant challenges to ecosystems, showing the extent of the damage caused by repeated governments policies. Field conditions show that land use issues need to be addressed urgently. Sumatran peatlands have experienced degradation over the past few decades, closely related to fire and land conversion (Miettinen et al., 2011, 2012). Currently, only 7% of the pristine peat swamp forest on the islands of Sumatra and Kalimantan remain (Miettinen et al., 2011). Riau Province on Sumatera Island has one of Indonesia's highest rates of peat swamp deforestation, reaching 6.5% per year due to the increase in industrial plantations and smallholder oil palm plantations (Miettinen et al., 2016). This loss continues to negatively affect the local communities depending on peat ecosystems services.

Implementing land planning and management processes has been closely related to the deterioration of the peat ecosystems. In Indonesia, the planning and management of tropical peat ecosystems are significantly influenced by positivist views. The current approach is linear and assumes that the system can be predicted, with the exception of unexpected disturbances. This is evident in the Indonesian Government's Regulation Number 71/2014, which is characterized by nuances of technical, managerial planning, and technocratic management. The dominance of positivism in planning is reflected in the allocation of at least 30% of the designated peat hydrological area as peat-protected areas. However, the 30% threshold was not often met by stakeholders, leading to injustice and imbalance in space distribution, and decreased system resilience (Afriyanie et al., 2020).

Positivism views tend to focus on the physical-ecological characteristics of peatlands, often overlooking the significant role of social factors in current challenges. The peat ecosystems planning process in Indonesia is divided into three stages, namely inventory, function determination, preparation, and determination of protection as well as management plans. The first and second stages use a technocratic method that only considers the physical factors of the land. Social issues related to community participation are accommodated by the government only in the last stage. Despite smallholders originating as key players in the peatlands landscape (Hergoualc'h et al., 2018), their engagement remains a minor aspect of the planning process for peat ecosystems. This shows technocratic rational planning still dominates the current planning process.

The interconnection and interdependence of human and ecosystems aspects require a paradigm shift to promote sustainability (Schoon and van der Leeuw, 2015). Unlike the positivist planning approach currently pursued by the Indonesian government, the current study described the role of the social-ecological system (SES) method in planning sensitive tropical peat ecosystems. SES thinking claims that humans are an inherent part of the biophysical world, where both entities are regarded as equal. Within this perspective, humans are no longer perceived as external elements in natural systems, and nature is not viewed as separate from social systems (Schoon and van der Leeuw, 2015). Instead of scrutinizing individual components within each system, SES focuses on the complex relationships and interactions among the elements of the human-natural system (Preiser et al., 2018).

The SES perspective fosters an awareness that humans and nature undergo co-evolution through interactions and feedback mechanisms (Biggs et al., 2021), making it a promising method for achieving sustainable development (Suroso and Kombaitan, 2018). The coevolutionary perspective prompts the reconsideration of development as a dynamic process, reflecting the coevolving relationship between humans and nature (Haider et al., 2021). Studies related to socio-ecological systems in tropical peatlands in the Asian region have started to emerge, with notable contributions from Grover et al. (2024) and Medrilzam et al. (2014). At the same time, there is still room for further exploration, particularly in understanding the co-evolutionary processes in this region. Highlighting the co-evolutionary processes in the tropical peatland ecosystems of Sumatra can provide valuable insights into the sustainable development trajectory. By analyzing development trajectories informed by co-evolutionary processes, we can identify and implement strategic interventions to guide the development of tropical peatlands towards a more sustainable future. Therefore, this study aimed to determine the extent to which the coevolution process in the SES of Indonesian tropical peat leads to sustainability, as well as explore how to address sustainability-related challenges.

2. Theoretical foundation

2.1. The social-ecological system

Natural resource management methods that focus on static models fail to create sustainable resource management (Berkes and Folke, 1998) and instead make ecosystems vulnerable (The Resilience Alliance, 2010). This leads to ecological uncertainty (Berkes and Folke, 1998), a consequence of the significant influence of positivism in natural resource planning. In contrast, management that considers social and ecological influences across scales has more significant potential to ensure sustainability and system resilience to disturbances (Berkes and Folke, 1994; The Resilience Alliance, 2010). These differences in perspective broaden the scope of understanding by incorporating social dimensions in dynamic ecosystems management (Folke et al., 2010). Social-ecological system (SES) thinking starts with the view that ecosystems are complex and adaptive (Preiser et al., 2021). This has led to a growing awareness that environmental problems cannot be approached from just one discipline. Therefore, an integrative, interdisciplinary approach that considers the interactions between social and ecological systems is needed (Binder et al., 2013).

Studies related to SES have expanded significantly, adopting various frameworks as guidance. There are at least ten types of frameworks applicable to SES research (Binder et al., 2013), one of which is human-environment system (HES). HES framework explicitly addresses the dynamics within social systems at different hierarchical levels. The framework introduced by Scholz and Binder (2003) is suitable for exploring environmental problems related to human behaviour in complex and hierarchical systems (Binder et al., 2013).

The perspective of SES is intricately connected to resilience thinking, prioritizing the capacity of complex adaptive systems in the face of change and disruption (Folke et al., 2016). Such systems respond to disturbances in three ways, namely persistence, adaptation, and transformation (Folke et al., 2010; Walker et al., 2004). In this context, using coevolution as an operational framework can implement resilience in SES and explain the developmental trajectory (Haider et al., 2021)

2.2. Indonesia's tropical peatlands: Issues

There is currently no agreement on the total area of Indonesian peatland. According to Wahyunto et al. (2010), the area is approximately 20.9 million hectares, while Anda et al. (2021) estimated it to be only 13.43 million hectares. The Indonesian government states that the hydrological area of peat reaches 24.6 million hectares (Regulation of the Minister of Environment and Forestry number 129/2017). These differences can be attributed to the variations in the definition of peatland, data collection methods, and the level of detail in the maps used. Peatlands are scattered across various regions of the world, and there is currently no agreement on the definition (Minasny et al., 2019) or total global area (Anda et al., 2021). The definition of peatlands can be grouped into two major parts, namely authoritative and scientific (Helmy et al., 2012). In Indonesia, the authoritative definition describes peatlands as areas with accumulation of partially decomposed organic matter with peat depths equal to or greater than 50 cm (Osaki et al., 2016). Other scientific definition describes peatlands as areas with accumulation of peat layers (consisting of 30%–65% dead organic material), with or without vegetation at the surface (Anda et al., 2021; Joosten and Clarke, 2002). The current study used the authoritative definition of peatlands.

More than half (56%) of the world's tropical peat area is in Southeast Asia (Rieley and Page, 2016). Indonesia has the most significant tropical peat ecosystems in Southeast Asia, accounting for about 47% of the world's tropical peat (Page et al., 2011). Peatlands are not evenly distributed throughout the region and are only found on the islands of Sumatera, Kalimantan, Papua (Wahyunto et al., 2010), and Sulawesi (Anda et al., 2021). Indonesia's tropical peat mainly comprises extensive forested peat domes between dominant rivers. Peat domes are not entirely decomposed mounds of dead organic matter overgrown by vegetation (Dommain et al., 2010). Peat domes in Southeast Asia have unique convex shapes, allowing for rapid radial drainage and preventing flooding (Takada et al., 2016). The existence of undisturbed peat domes is becoming increasingly scarce, necessitating urgent conservation efforts (Dommain et al., 2010).

Peatlands are part of the wetland ecosystems, playing a significant ecological role, and require proper regulation and management (Della Bosca and Gillespie, 2020). Globally, anthropogenic activities such as conversion to intensive agriculture, drainage, industrial, and residential uses have placed increasing pressures on wetlands (Birol and Cox, 2007). In Sumatra, both legal and illegal deforestation initially led to peatlands being repurposed for other uses (Dohong et al., 2017; Miettinen et al., 2011). The two primary causes of deforestation in peat swamp forest are logging activities and the pressure to develop large-scale plantations, such as oil palm and industrial plantations (Miettinen et al., 2011). Converting these areas for extensive agriculture or plantations requires hydrological engineering processes (Cobb et al., 2020; Dohong et al., 2017; Rydin and Jeglum, 2013; Wahyunto et al., 2010). These changes have made the peatlands in Sumatra vulnerable to repeated fires and increased carbon emissions (Miettinen et al., 2011).

The ecological condition of peat changes rapidly along with socio-economic changes. Both social and ecological systems experience various disturbances, reflecting a chaotic, complex, uncertain, and unpredictable system. The Indonesian government has attempted to conserve the country's remaining peatlands and has also encouraged both the restoration and sustainable management of peat. This was conducted by imposing a moratorium on peatlands use and establishing the Peat Restoration Agency in 2016 (Hergoualc'h et al., 2018). A major challenge in managing peat ecosystems is integrating and balancing the economic demands of exploiting peat swamp ecosystems with ecological and environmental sustainability, as well as fulfilling social functions for local communities. These efforts require a cross-sectoral communicative process between stakeholders to negotiate the complex trade-offs between ecological and socio-economic interests (Hergoualc'h et al., 2018). Another challenge is developing an integrated planning and management approach that balances the demands for peatlands use with the need for ecosystems sustainability (Wösten et al., 2008). Understanding this complex relationship is essential for effective peat management efforts.

3. Methods

3.1. Study site

This study was conducted in Giam Siak Kecil-Bukit Batu Biosphere Reserve (GSKBB-BR), a 705,271 Ha site in the Riau Province of Indonesia as shown in **Figure 1**. The location was chosen for two reasons. First, it is one of the last remaining blocks of peat swamp forest in Sumatra (Gunawan et al., 2012), with high conservation value (Jarvie et al., 2003), and has already been recognized by UNESCO since 2009 as a habitat for various endemic and endangered species (UNESCO, 2019). Second, there has been a significant increase in social activity in recent decades, marked by both legal and illegal logging of the remaining peat swamp forest. Furthermore, there has been a significant increase in the conversion of peatlands for various purposes, including housing, agriculture, oil palm plantations, and industrial timber plantations (Gunawan et al., 2012). This shows GSKBB-BR area has experienced intricate relationships among social actors at various levels, including the individual, community group, the private sector, and the government.

GSKBB-BR is divided into three zones, namely Core, Buffer, and Transition. The core zone (178,722 Ha) comprises two main conservation areas, namely the Wildlife Sanctuary of Giam Siak Kecil, and Bukit Batu. Both sanctuaries are managed by the Ministry of Environment and Forestry (MoEF). Another land use in the core zone includes the production forest concession area, managed by the private sector. The buffer zone (222,426 Ha), which surrounds the core zone, is dominated by industrial timber plantations. The transition zone (304,123 Ha) forms the outer area of GSKBB-BR. Many parties, including local communities, use the land in the transition zone for social-economic activities. About 77% of land use in this zone is focused on agriculture and oil palm plantations.

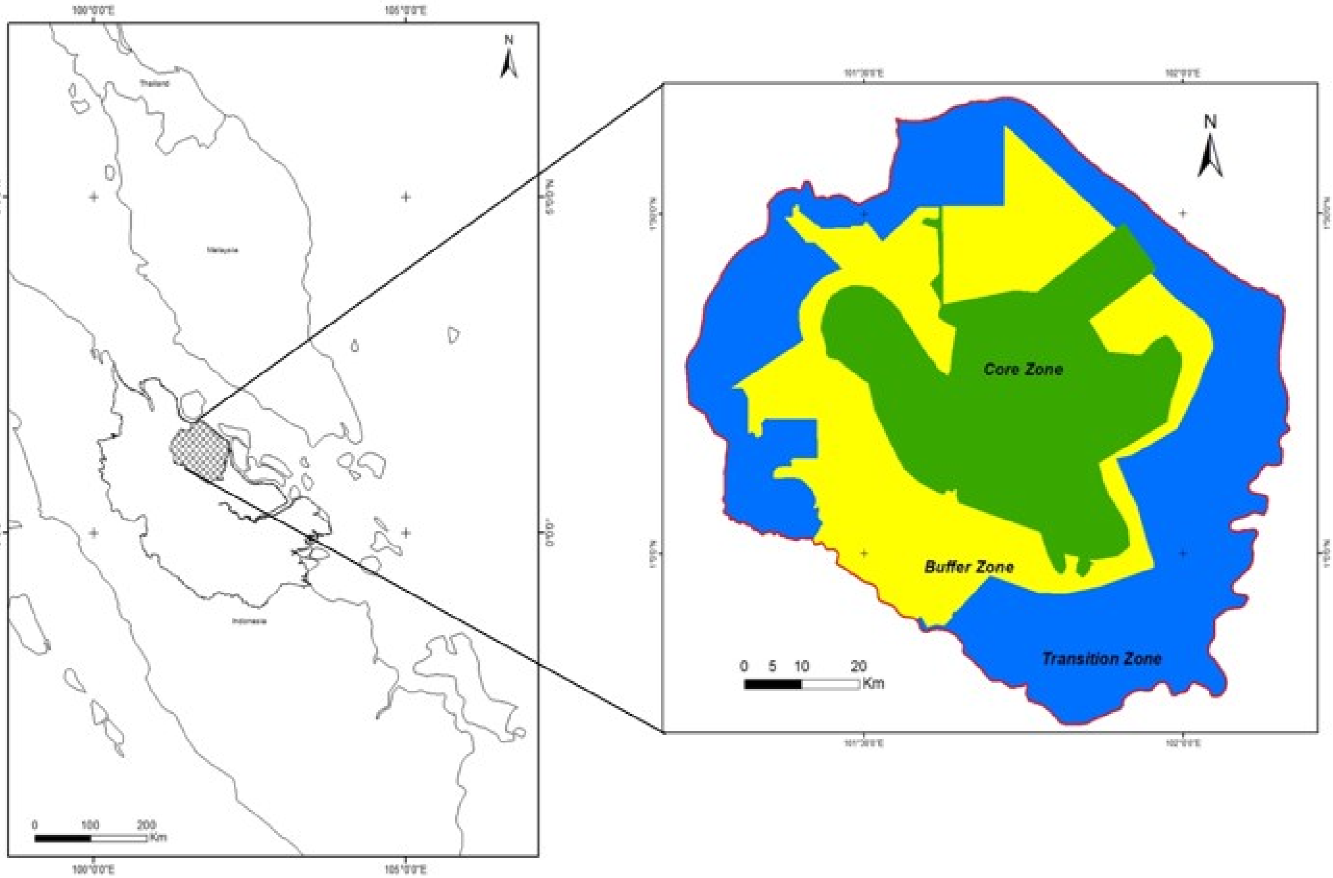

Figure 1. Study area of GSKBB-BR.

3.2. Data collection and analysis

Three main aspects were explored in this study, namely ecological and social conditions, as well as the interactions between social and ecological aspects of the study area. Both primary and secondary data were collected. Primary data were obtained through interviews with key respondents representing the five levels of the social sector, based on the Human Environment System (HES) framework.

The five levels of hierarchy in the social system analyzed in this case study were individual, group, organizational, institutional, and societal. Data were collected from various respondents with different perspectives and levels of knowledge to ensure data triangulation. Observations were also conducted to verify respondents' statements. The analysis of the social system followed HES method, which describes differences in interests either within the same hierarchical level or between levels. These differences can be seen in objectives, motivations for action, and strategies are chosen to achieve these objectives. In tropical peat ecosystems, objectives vary significantly between hierarchies, including interests focused on conservation, restoration, preservation of carbon stocks, agriculture, and plantations. Interview data were analyzed using transcribing, coding and interpretation techniques. The complex relationships within the area's social-ecology systems were analyzed using coevolution processes, specifically the coevolution analysis by Haider et al. (2021), proposing that the coevolutionary process advances through the phases of variation, selection, and retention.

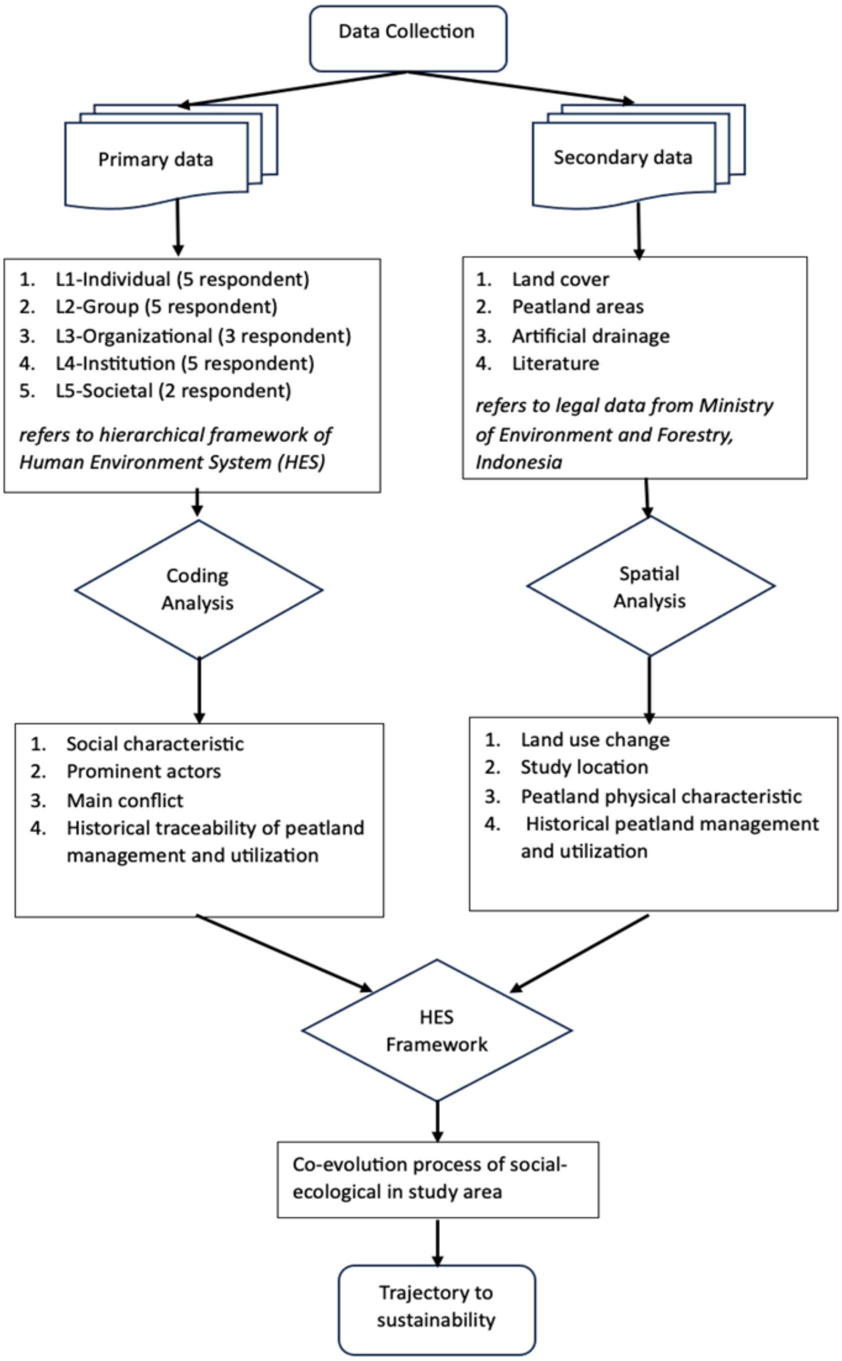

Figure 2. Research framework.

Primary data were also collected through general observations in the three zones of GSKBB-BR. Samples were selected using random start and snowball methods. Respondents represented the five levels of hierarchy, namely level-1 (L1) individuals; level-2 (L2) groups; level-3 (L3) organizations; level-4 (L4) institutions, and level-5 (L5) societal hierarchies. Interviews were conducted in five villages, namely Tasik Betung, Muara Bungkal, Sungai Pakning, Tanjung Leban and Temiang. An individual level respondent represented a local community member. Group-level respondents were represented by a forest farmer group or tribe figure. Organizational-level respondents were represented by the private sector. Institutional-level respondents included government parties such as the Centre of Natural Resource Conservation of Riau Province as part of MoEF's organizational structure, Peatlands and Mangrove Restoration Agency (PMRA) of Riau Province, Forest Management Unit as part of Provincial Government, and Agency of Development Planning of Riau Province. The highest hierarchy was the national level, represented by the MoEF and PMRA. A total of 20 key respondents participated, as shown in **Figure 2**. Secondary data were gathered from a review of existing literature and thematic maps acquired from various sources. The data focused on land cover, peatlands areas, and drainage canals.

4. Results and discussion

4.1. The ecological system of GSKBB-BR

The core area of GSKBB-BR is essential because it contains one of Sumatra's remaining peat swamp forest ecosystems. The protection of forest in the core zone is inseparable from the role of the Indonesian government in designating two wildlife sanctuaries, namely Giam Siak Kecil and Bukit Batu, established in 1986. These sanctuaries serve as essential habitats for various endemic and endangered fauna including Sumatran tiger (Panthera tigris Sumatrae), Sumatran elephant (Elephas maximus Sumatranus), Sun Bear (Helarctos malayanus), Tapir (Tapirus indicus), Clouded Tiger (Neofelis nebulusa), and Estuarine Crocodile (Crocodylus porosus) (Balai Besar Konservasi Sumber Daya Alam Riau, 2017). The core zone also protects various plant species, including mixed peat swamp forest and Bintangur Forest. The dominant plant families in this area are Myrtaceae, Ebenaceae, Clusiaceae, Sapotaceae, and Dipterocarpaceae (Gunawan et al., 2012), with the Dipterocarpaceae family being particularly significant for producing commercial timber in Indonesia, especially from the genus of Shorea.

The ecological system in GSKBB-BR is supported by a network of rivers, streams, and lakes. The Bukit Batu River, which divides the Bukit Batu wildlife sanctuary, and the Siak Kecil River in the Giam Siak Kecil wildlife sanctuary are the main rivers. These two conservation areas are connected by at least 26 lakes (Qomar et al., 2016), along with watershed systems and peat swamp forests. Collectively, these elements create a unique ecological system. This network of rivers and lakes has also long provided an essential source of livelihood for local people, offering abundant fishery products, including fish for human consumption.

The soil of GSKBB-BR consists of two main types, namely peat and mineral soil. Peat soil dominates the area, covering approximately 81% (568,041 Ha) of the total site, according to peat hydrological area data from the Ministry of Environment and Forestry (MoEF) (**Figure 3**). The peat soil is further categorized into peat domes (47%) and non-peat domes (53%). Peat domes are formed from the accumulation of partially decomposed organic material, are water-saturated, covered by vegetation, and appear as mounds (Dommain et al., 2010). These domes are unique to tropical Southeast Asia and play a crucial role in regulating the water supply to the surrounding areas due to their elevated position (Takada et al., 2016). Based on **Figure 3**, only a minor section of the two wildlife sanctuaries is within the peat dome areas, with most peat domes located around plantation forest companies.

Peat soil can also be classified into deep and shallow peat, with deep peat being predominant in this area. According to data from the Peat and Mangrove Restoration Agency, 68% of the peat is more than 3 m deep. The core zone is the most crucial area for deep peat, which shows higher carbon stocks. However, deep peat poses a significant challenge in case of fires which are often difficult to extinguish. Some parts of deep peatlands have undergone hydrological modification for industrial forest and oil palm plantations.

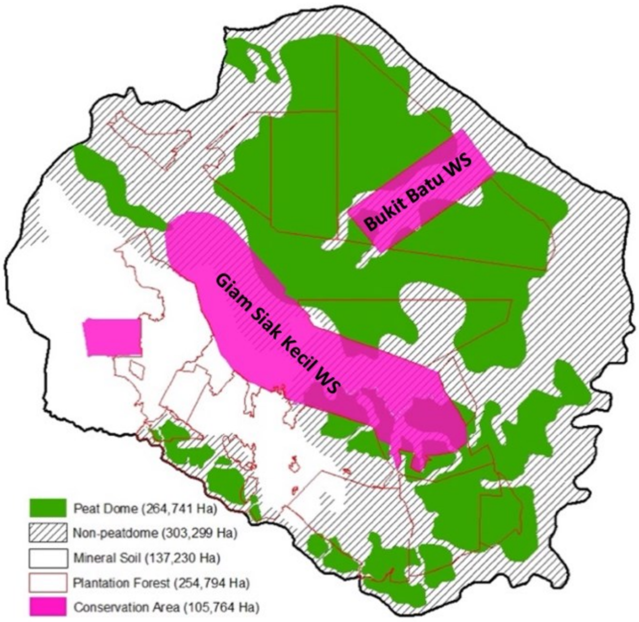

Figure 3. Intersection of peatland, peat dome, conservation, and plantation forest areas.

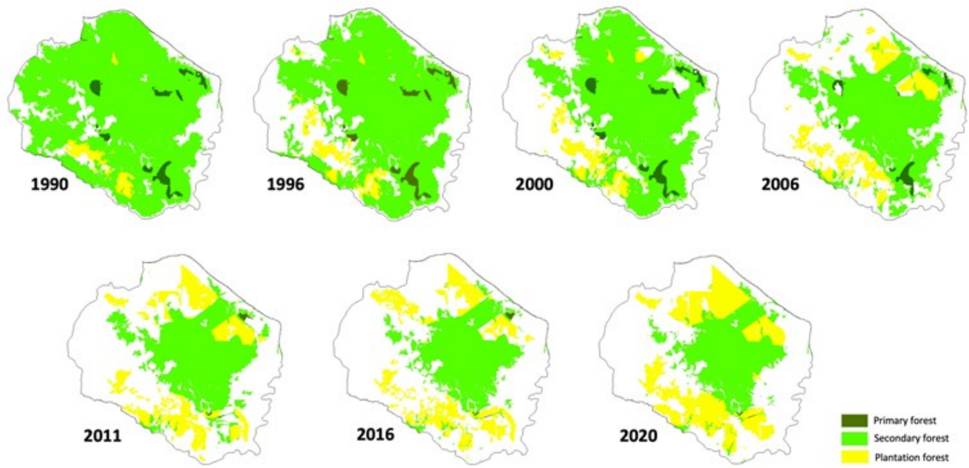

Figure 4. Land use changes between 1990 and 2020.

GSKBB-BR area has experienced a significant decline in natural forest cover over the past thirty years, as shown in **Figure 4**. During this period, almost all the remaining primary forest has disappeared, and secondary forest also drastically declined. In total, natural forest cover has been reduced by 389,870 ha at a rate of 18,565 ha/year. These changes are closely related to logging activities, drainage, and fires, which are intermediate phases leading to the development of oil palm and forest plantations (Miettinen, 2012). The use of fire for land clearing is closely associated with the occurrence of wildfires in plantation forest estates, smallholder plantations, and unmanaged lands in Riau Province (Miettinen, 2017). Significant additions have occurred in plantation cover (rubber and oil palm); to 10,803 ha/year, meanwhile, the plantation forests estate has been increasing at a rate of 6326 ha/year. Rubber and oil palm plantations in 2020 exceeded the natural forest cover in the GSKBB-BR area. This trend showed peat ecological factors were not adequately considered when allocating forest concession permits.

Land cover degradation that occurs in the study area requires regular monitoring, a task well-suited to machine learning algorithms. Machine learning has demonstrated high accuracy and reliability in estimating the research variables (Bartold and Kluczek, 2023). Since peatlands play a crucial role in maintaining global carbon balance, the presence of peatland areas needs to be preserved naturally. Some of the essential variables related to carbon balance are climate and biodiversity. The global community currently places significant emphasis on the importance of acquiring physical, chemical, or biological data variables that are critical features in climate change mitigation and biodiversity preservation. Several environmental concern group like the European Space Agency's that build the Global Monitoring for Essential Climate Variables (ECVs), also The Group on Earth Observations Biodiversity Observation Network (GEO BON) who developed Essential Biodiversity Variables (EBVs), and the Ecosystem Services Working Group (ESWG), are provide valuable data to monitor those variable changes.

4.2. The social system of GSKBB-BR

Biosphere reserves are managed using a zoning mechanism to support their three main functions, namely conservation, sustainable development, and logistical support for research and monitoring (UNESCO, 1996). Many actors are interested in utilizing peatlands in GSKBB-BR area. Based on analysis using HES framework (**Table 1**), these actors tend to have different interests. Local communities living in and around GSKBB-BR's core zone are particularly interested in land use, especially around the two wildlife sanctuary areas.

Table 1. Overview of actors and conflicts faced in each biosphere reserve zone.

Zones	Prominent actor	Main Conflicts
Core	L1—Fisherman, farmers L2—Farmers group L5—MoEF	Illegal logging activity Land occupation and conversion Wildlife conflict Peatlands fires
Buffer	L1—Farmers L2—Farmers group L3—Private sector on plantation forest L4—Provincial Government (Forest Management Unit) L5—MoEF	Land occupation Wildlife conflict Water management conflict Peatlands fires
Transition	L1—Farmers L2—Farmers group L3—Private sector on oil palm plantation L4—Provincial and District Government L5—PMRA	Water management conflict Peatlands fires Land productivity

L1 (individual level); L2 (groups level); L3 (organizations level); L4 (institutions level); L5 (national level).

The core zone is a conservation area comprising important ecosystems and essential habitats, which have experienced minimal disturbances and low impact uses. These areas are recognized and protected through local government legal mechanisms for educational and research purposes (UNESCO, 1996). Forest areas in Indonesia are divided into three functions, namely conservation, protection, and production (Law number 41 of 1999 on Forestry). The core zone is entirely state forest land, designated as both conservation and production forests. The production forest in this area was previously a forest concession granted to the private sector (L3). However, it was later handed back to the state (L5) to serve as the core zone of the biosphere reserve. Production forest areas within the core zone are vulnerable to illegal logging and land occupation by the communities (L1 and L2) as open-access areas. The two wildlife sanctuaries and former concession areas in the core zone are experiencing disturbances, as peat swamp forest is being converted into oil palm plantations due to increasing land demands. The need for plantation land is the main issue threatening the sustainability of the wildlife reserves.

In the buffer zone, there are also state forest areas where legal access can only be granted by MoEF (L5). These lands tend to be open-access and not actively managed by any specific party. Consequently, the community eventually took over this area. FMU (L4), designated as the stakeholder authorized to manage the production forest area, appears incapable of restraining the pace of land occupation. Since the early 2000s, the communities started cultivating oil palm commodities in the open-access area, lending to land-buying and selling transactions for oil palm plantations. This is a new phenomenon for the communities (L1 and L2), as land ownership was previously communal. These transactions occur not only on land owned by the communities but also on open-access land. In plantation forest areas, cultivated plants are starting to grow, and the communities have begun building canals independently of those constructed by plantation forest companies (L3).

The transition zone is located downstream of GSKBB-BR, while the core and buffer zones are located upstream. In the transition zone, state forest areas are few, land tenure patterns are mainly dominated by individuals (L1) and groups (L2). Non-state-owned land is typically used for cultivating food crops and oil palm plantations. This zone also includes a transmigration area initiated by the government in the 1970s (Tirtosudarmo, 2021). The transmigrant communities from Java Island initially cleared peatlands to cultivate food crops, especially rice and vegetables, while indigenous Malays preferred to clear land around the coastline and work as fishermen. In the transition zone, some locations serve as rice barns to meet the food needs of the communities. The Regional Government (L4) has identified several locations in Siak District for this purpose. However, the success of the program has been challenging due to local limitations in rice cultivation on peatlands (L1 and L2). There have also been cases of sulfuric acid contamination on agricultural land. Tropical peatlands generally contain layers of pyrite sedimentation, which are not dangerous when waterlogged (Haraguchi, 2016). Another significant issue is water management between the buffer and transition zones. PMRA (L5) has attempted to address water issues in the transition zone through a rewetting program by creating canal blocks in non-concession peatlands areas. However, the lack of integrated water management between peat-domes and downstream areas can lead to recurring peatlands fires.

4.3. The co-evolution processes of the social-ecological system in GSKBB-BR

GSKBB-BR has a complex social system that significantly affects the peat ecological system. The Indonesian government's policy attributes most changes to the ecological system in this area to forest exploitation activities. **Table 2** describes the process of coevolution of social-ecological systems in GSKBB-BR. Initially, peat swamp forest dominated this area. The earliest human influences date back to the late Holocene period, involving the harvesting of forest products, both timber and non-timber, and hunting. In the early Anthropocene period, the local Malay community viewed peatlands as a primary source of food through shifting cultivation, growing crops, fruits, and spices (Nursyamsi et al., 2016). Before intensive land management, the local Malay community only practiced shifting cultivation, with livelihoods varying according to the seasons. During the dry season, when peatlands experience high water loss, the land is primarily cultivated for agricultural purposes. During the rainy season, when the water level in peatlands increases, the communities engaged more in traditional hunting and fishing.

In the 1970s, a change in Indonesian government policy resulted in the granting of Forest Concession Rights to the private sector. This transition encouraged large-scale logging operations, leading to significant forest exploitation (Gunawan et al., 2016). Consequently, Indonesia became the largest timber exporter in the 1980s (Brockhaus et al., 2012). The plywood industry rapidly expanded due to the abundant supply of raw wood materials from natural forests. During this period, forestry companies operating in peat swamp forest areas started constructing drainage systems to transport logs.

The government subsequently issued Industrial Plantation Forest permits in the 2000s (Gunawan et al., 2016). Over the past two decades, several licenses have been granted in peat ecosystems regions, particularly for industrial forest plantations (Dohong et al., 2017). Most of the land used for these plantations is located in GSKBB-BR buffer zone. Cultivating forest plants for industrial purposes necessitates changes to the peat hydrological system to maintain timber productivity. It also requires the creation of more structured drainage canals. Artificial drainage remains the primary enabling factor for industrial forest plantations in tropical peatlands. According to data from the MoEF, nine companies affiliated with two large groups in Indonesia have been granted the rights to exploit forest areas. These companies cultivate fast-growing species (*Eucalyptus pelita* and *Acacia crassicarpa*) for the pulp and paper industry. The first plant is cultivated on mineral soils, while the second is cultivated on peatlands. The extensive utilization of peat for cultivation activities has made the enforcement of protected area demarcations increasingly challenging.

Table 2. The overview of coevolution process.

Time Period		**Ecological System**	**Social Systems**
Pleistocene	60,000 YBP	Peat in the Southeast Asian region stars to form (Anderson, 1964).	
	35,000 YBP		Humans are believed to have been in the Indo-Malayan region, but the influence on the peat in Sumatra was minimal (Cole et al., 2022).
Holocene	6000–5000 YBP (Cole et al., 2022; Omar et al., 2022)	Peat accumulated rapidly due to the development of a transitional ecosystems from mangroves to swamp.	Human influence on peat ecosystems started increase in Kalimantan, but there was influence on Sumatra Island.
Holocene/Paleoantropocene	5,000–200 YBP (Cole et al., 2022).	There is evidence of fire in the peat ecosystems related to human activities (Hapsari et al., 2018).	The existence of the Malay Kingdom (1000–600 YBP) began to influence the peat ecosystems of Sumatra, but were unfamiliar with drainage canals (Hapsari et al., 2018).
Anthropocene	200 YBP–1980s	Deforestation increases due to demand for other land uses. Ditches are made and used as transportation routes and boundaries for land ownership.	The Malay community used peat to shift cultivation and carry out traditional hunting and fishing activities. The transmigration program started in the tidal swamp area of Riau Province (Tirtosudarmo, 2021).
	1970s–1990s	The rate of deforestation increased sharply due to the issuance of forest exploitation permits.	In 1986, two conservation areas were designated, namely the Giam Siak Kecil Wildlife Reserve, and the Bukit Batu Wildlife Reserve (Balai Besar Konservasi Sumber Daya Alam Riau, 2017). Land conflict was not prominent.
	1990–2009	Changes in the peat hydrological system increased due to the construction of large-scale drainage canals for industrial plantation forests.	Indonesian government began to push policies with regards to Industrial Plantation Forest Concession Rights. There were intensive interactions between local people and immigrants who introduced palm oil. Illegal logging activities increased pressure on natural forests.
	2009–2016	Deforestation started to slow down. Artificial drainage increased not only in industrial plantation areas but also in community-controlled areas. Biodiversity declined sharply due to the loss of natural forests.	UNESCO established the GSKBB BR. Indonesian government began to pay special attention to peat ecosystems by issuing a policy related to the protection and management of peat ecosystems.
	2016–current	Peat hydrology started becoming a concern because it is directly related to wildfires. Rewetting is carried out by constructing canal blocks in essential areas. The conservation of biodiversity activities focuses on the biosphere reserve's core zone as well as in high conservation value (HCV) area.	Increasing the price of palm oil commodities is one of the main driving factors for changes in the functioning of the peatlands. Applying peat restoration policies through rewetting has experienced several challenges. The effectiveness of biosphere reserve management is also experiencing challenges as the institutions formed need to run effectively. During this period, the government issued many regulations to accelerate peat restoration efforts.

Historically, GSKBB-BR area was predominantly inhabited by Malay people, whose primary livelihood centered on fishing in the sea, rivers, and lakes. Some Malay groups acknowledged initially lacking expertise in crop cultivation. Only a limited range of commodities, such as rubber, were cultivated by clearing land in peat forest since the colonial era. During the early 1990s, a significant wave of population migration from Java Island to various parts of this region occurred through the Indonesian government's transmigration program (Tirtosudarmo, 2021). Most of these Javanese migrants were experienced in cultivating mineral-rich soil but had little to no knowledge of peatlands cultivation. The learning process of peatlands cultivation is often marked by trial and error. It is evident that there was a lack of local knowledge regarding peatlands management from both indigenous communities and the migrant population within GSKBB BR area. Substantial transformations in community-managed land swiftly unfolded following the introduction of oil palm cultivation in the late 2000s, driven mainly by the influence of migrants from North Sumatra Province. Currently, local communities prefer cultivating palm oil due to its market stability and ease of cultivation.

Deforestation and the construction of drainage canals have impacted a series of forest fires in peatlands (Dohong et al., 2017; Januar et al., 2021; Miettinen et al., 2012, 2017). In 2015, Riau Province became one of the areas with the largest peatland fires on Sumatra Island (Miettinen et al., 2017). The biosphere reserve area has experienced a series of land fires in recent years (**Figure 5**). Hotspot data shows that fires occur in all zones of the biosphere reserve, although the transition zone has the most hotspots. This data indicates that the transition zone, which is mostly managed by the community, has a higher fire risk potential. The wildlife sanctuary area in the core zone also faces a fire risk, closely related to land claiming activities. Land claim in state forest areas through illegal logging and fire-based land clearing is a common activity in Riau Province, leading to the conversion of peatlands into plantations (Purnomo et al., 2017).

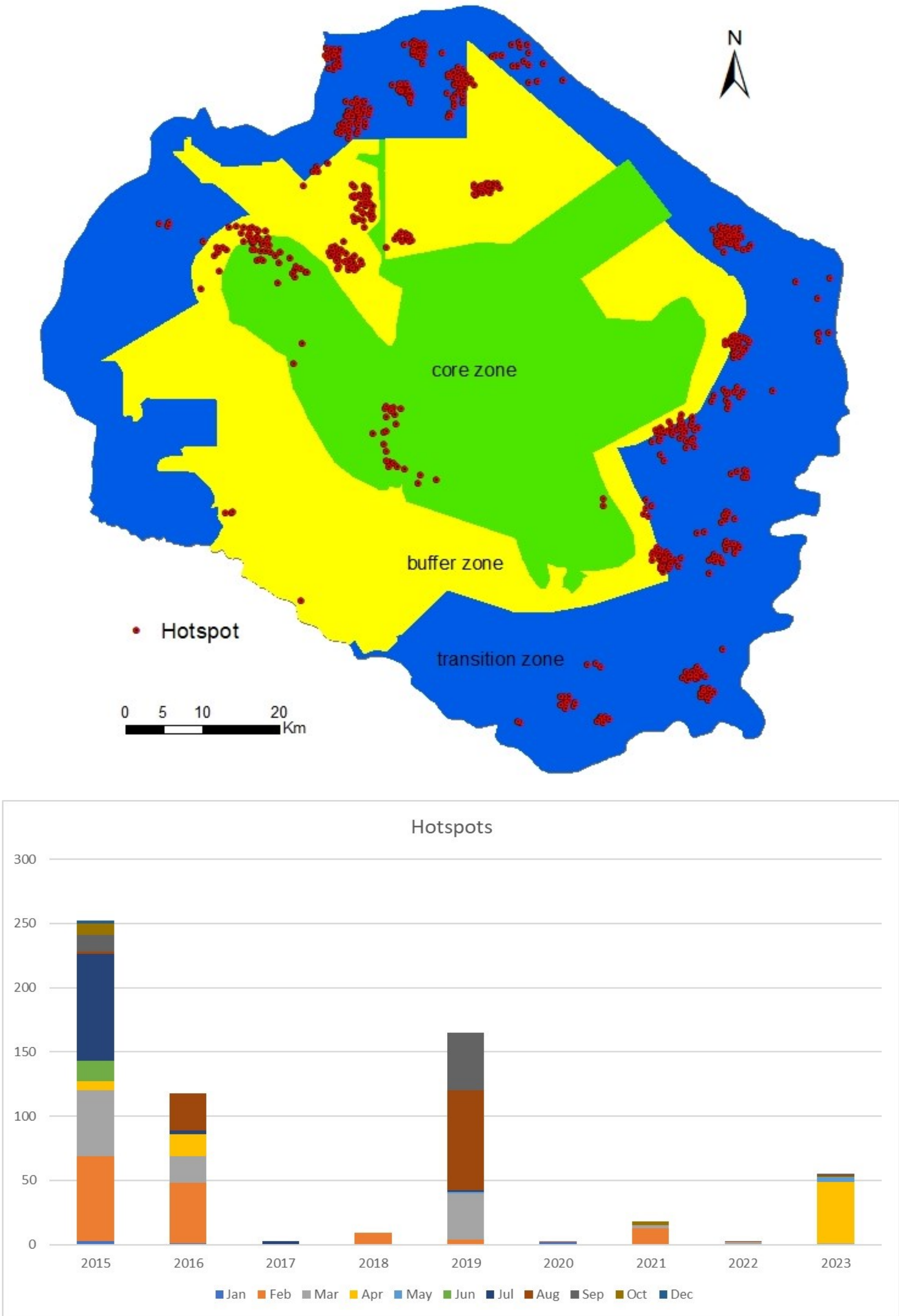

Figure 5. Hotspot data from 2015–2023.

This data is obtained from the MoEF Government of Indonesia based on National Aeronautics and Space Administration—National Oceanic and Atmospheric Administration (NASA-NOAA), Suomi National Polar-orbiting Partnership (SNPP) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (MoEF, 2024).

The coevolution of social-ecological systems is a series of variation, selection and retention processes manifested in daily practices (Haider et al., 2021), as presented in **Figure 6**. The government prioritized logging and intensive cultivation as the primary development activities in the study area based on various peat ecosystems utilization options. However, conservation was not a primary choice, as shown by the small conservation area. The unnatural, box-shaped Bukit Batu Wildlife Sanctuary appears to be an area designated for peat conservation. Oil palm plantations have become the primary economic activity for local communities, replacing fisheries and shifting cultivation. Due to declining fish production, fisheries are no longer economically viable. Interviews with fishermen in Temiang and Tasik Betung support this observation, and also corresponded with Qomar et al. (2016). Artificial drainage systems in plantation forest are suspected to be a source of river pollution, causing siltation and increased water turbidity, leading to a decrease in fish catches. In addition, the culture of shifting cultivation for food crops is being abandoned in favor of converting forest land into oil palm plantations.

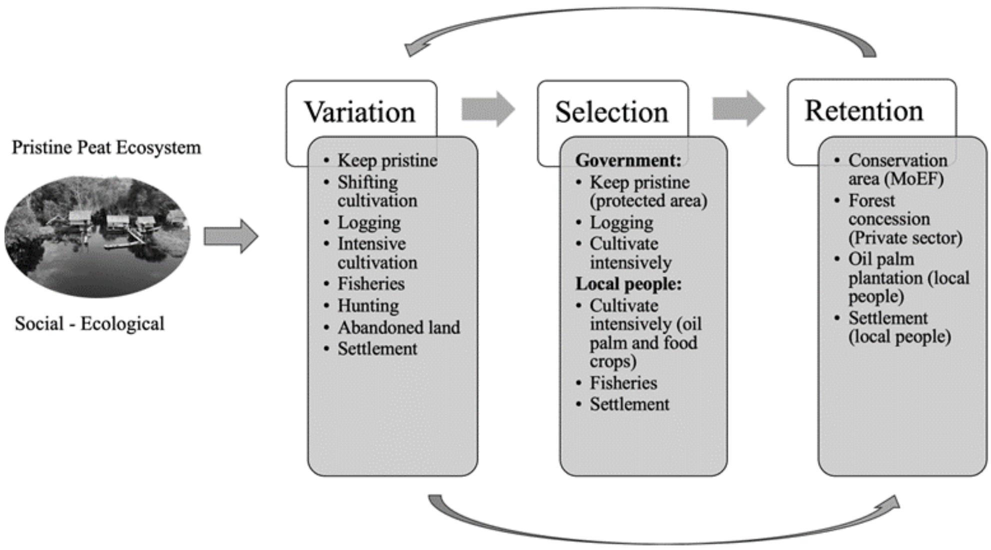

Figure 6. SES coevolution process on tropical peatlands based on variation, selection, and retention processes.

Adapted from Haider et al. (2021).

4.4. Toward a new trajectory in tropical peat development

The coevolutionary standpoint offers an opportunity to redefine development as a dynamic process that can be influenced and guided toward novel outcomes (Haider et al., 2021). From this perspective, coevolution focuses on the capacity of social-ecological systems to persist, adapt, and change rather than a single outcome. The examination of the coevolutionary process presented in **Table 2** and **Figure 5** shows that significant interventions are necessary for tropical peatlands development. Coevolution in GSKBB-BR is progressing toward an unsustainable trajectory for the following reasons:

4.4.1. The ecological condition of the peat in the buffer and transition zones has significantly deviated from its natural waterlogged state

Peatlands are naturally waterlogged, which slows down the decomposition of organic matter (Anderson, 1964; Furukawa et al., 2005; Prananto and Minasny, 2020). However, peat degradation in GSKBB-BR was historically driven by land use policies that neglected peat ecological systems. The Indonesian government issued its first policy regarding peat through the Presidential Decree number 32 of 1990, categorizing areas with peat deeper than 3 m as protected. Despite this, there were no detailed criteria for managing spatial planning in peat ecosystems for several years after the decree. It was only after a series of peat fires that the government introduced more progressive policies for peatlands management and protection, as outlined in Government Regulation No. 71/2014 on peat ecosystems protection and management, as well as the establishment of the Peatlands Restoration Agency (PRA) in 2016. Previously, the issuance of peatlands management licenses to the private sector lacked sufficient regulatory oversight to preserve the natural state of peatlands. The true importance of peatlands was only recognized after a series of catastrophic forest and land fires. However, current on-site conditions show excessive spatial utilization in areas that should be protected.

In accordance with Government Regulation No. 71/2014, the Indonesian government established a water table threshold of 40 cm below the peat surface. To support this mandate, the Indonesian government initiated a restoration program overseen by the PRA. During its implementation, PRA constructed numerous canal blocks with spillways in areas managed by local communities situated outside the peat dome peak. In addition, a ministerial-level regulation specifies that the primary protected area is the peat dome peak, and any damage to this area requires restoration. This decision is rooted in the high degree of spatial utilization observed in the peat dome region.

In contrasting approaches to peatlands ecosystems restoration, Finland has been actively engaged in restoration efforts since the 1990s. Regulatory modifications in Finland aimed to balance ecological and social sustainability, biodiversity protection, and the sustainability of forest products (Kuuluvainen et al., 2004). This initiative has targeted the restoration of over 10 million hectares of peatlands, utilizing techniques such as canal filling to restore the hydrological system and removing industrial crops in their original form (Komulainen et al., 1999; Kuuluvainen et al., 2004). From a policy perspective, Finland has undergone a significant regulatory transformation, while policies in Indonesia appear to prioritize economic interests.

4.4.2. The core zone represents the remaining pristine tropical peat area facing ongoing challenges from land use changes, mainly driven by local communities

Increased land demand was driven by increased population and land transactions with migrants. As a result, the communities tended to improve welfare by clearing peatlands for oil palm plantations. The high income generated from palm oil has increased pressure on other commodities including rubber, sago, food crops, and fishery products. This has also changed the local mindset from fulfilling daily needs to accumulating wealth personally and for the descendants.

As more land is converted to oil palm plantations, the number of canals constructed in peatlands increases. This not only heightens the risk of land fires but also threatens biodiversity, a concern often overlooked due to the difficulty in quantifying its economic value. The loss of peat swamp forest cover accelerates habitat degradation and reduces environmental services. Endemic flora and fauna are increasingly confined to the core zone and high conservation value areas in the buffer zone. Should this pattern continue, biodiversity would be at the risk of extinction, and conflicts between humans and wildlife could escalate. Therefore, policies and practices are needed to offer greater protection to habitats and maintain the condition of the remaining peat swamp forests.

4.4.3. Current policy tools and knowledge need a framework capable of effectively implementing landscape-scale tropical peat ecosystems management

Presently, peat management remains fragmented, corresponding with the individual interests of various land-controlling actors. Large-scale peatlands management by the private sector indirectly influences local communities, shifting land use patterns from cultivation to more intensive land management. Consequently, communities have modified peat's natural hydrological system by creating unstructured ditches, as shown in **Figure 7**. These drainage canals lower the water table, increasing the risk of forest fires on peatlands (Dohong et al., 2017).

The interconnected canals constructed by plantation forest companies and the ditches built by the communities create an upstream-downstream water flow relationship. Peat dome areas, situated at higher elevations, have been allocated for plantation forest activities. Conversely, the local communities' cultivated plants are primarily at lower elevations. This independent water management in different areas increases the risk of fires during extreme climate events. During the rainy season, water is directed downstream through artificial drainage channels to prevent upstream flooding, making downstream areas more prone to flooding. In contrast, during the dry season, private companies maintain the water supply in their areas, causing downstream areas to become drier and more vulnerable to wildfire.

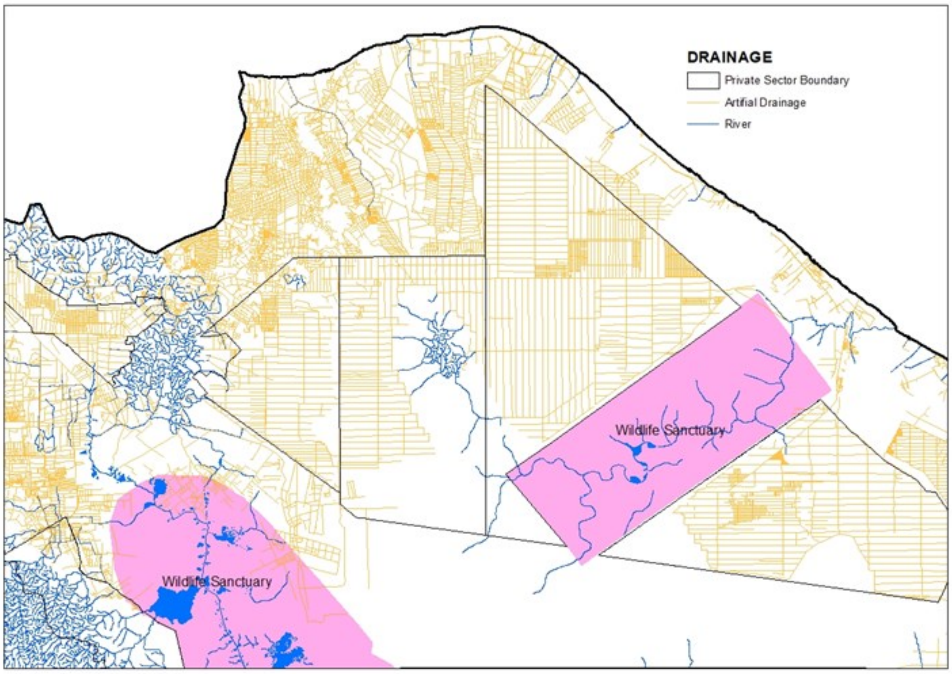

Figure 7. Differences between community and plantation forest company canal structures.

Based on the preceding depiction, the private sector holds more influence than local communities. However, both groups are at risk of peatlands fires. Interviews conducted in Tanjung Leban with key respondents from both the private sector and local communities show that fires outside concession areas can easily spread inside concession boundaries. Consequently, both groups require a sufficient water supply during the dry season. Implementing landscape-scale water management is an essential measure that should be undertaken promptly.

5. Conclusions

In conclusion, the perspective of the social-ecological system (SES) underscored the interdependence of social and ecological systems. It showed the existing limitations in the management of peat ecosystems, where the primary focus was on ecological aspects, often overlooking social complexities. This ecological-centric approach frequently resulted in implementation difficulties due to conflicting stakeholder interests. In contrast, socio-economic management practices in tropical peatlands tended to disregard the unique characteristics of peat ecosystems while engaging in various forms of dryland cultivation activities. The scope of positivist planning still lagged in fully grasping the complex dynamics inherent in these social-ecological relationships.

Planning for tropical peatlands ecosystems could no longer adhere to a positivist paradigm that was linear and assumed systems were predictable. Instead of setting potentially unattainable objectives, peatlands ecosystems planning should shift toward improving the system's ability to endure, adapt, and transform. This could be achieved by first comprehending the complex relationships within the SES of tropical peat.

The coevolutionary perspective used to describe the trajectory of the GSKBB-BR suggests that this area is moving towards unsustainable pathways and requires intervention. landscape-scale water management interventions are crucial to redirect the development paths. Government action is needed to establish detailed frameworks for implementing landscape-scale water management, which are currently lacking. The government plays a regulatory role in balancing various stakeholder interests. However, we argue that water management alone is not sufficient. Overemphasizing a minimum water level threshold as a primary water management can be misleading, neglecting the intricate relationships within social-ecological systems. Social-ecological systems can build resilience through maintaining biodiversity. Therefore, biodiversity in the core zone area must be preserved by mitigating the conversion pressure on the remaining peat swamp forests. Similarly, enhancing ecosystem diversity in buffer and transition zones is crucial for increasing resilience capacity. Thus, monitoring of water management and biodiversity is crucial and requires reliable data. For future research, we propose that machine learning can be a powerful tool to address these issues.

6. Research limitation

This study had specific limitations in uncovering and clarifying power dynamics associated with the collaboration among actors and stakeholders, a phenomenon likely to exist both at the research site and the national level. Revealing these informalities and underlying power dynamics would provide a more comprehensive insight into the complex nature of relationships, specifically within social systems connected to peatlands.

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MA; data curation, MA; writing—original draft preparation, MA; writing—review and editing, MA, DSAS and TFS; visualization, MA; supervision, DSAS and TFS. All authors have read and agreed to the published version of the manuscript.

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References

Afriyanie, D., Julian, M. M., Riqqi, A., et al. (2020). Re-framing urban green spaces planning for flood protection through socio-ecological resilience in Bandung City, Indonesia. Cities, 101(10), 102710. https://doi.org/10.1016/j.cities.2020.102710

Anda, M., Ritung, S., Suryani, E., et al. (2021). Geoderma Revisiting tropical peatlands in Indonesia: Semi-detailed mapping, extent and depth distribution assessment. Geoderma, 402, 115235. https://doi.org/10.1016/j.geoderma.2021.115235

Anderson, J. A. R. (1964). The Structure and Development of the Peat Swamp of Sarawak and Brunei. The Journal of Tropical Geography, 18.

Balai Besar Konservasi Sumber Daya Alam Riau. (2017). Bukit Batu Wildlife Sanctuary. Available online: https://bbksda-riau.id/index.php?r=post&id01=4&id02=22&id03=46&token=460ca5c691fc591de6f363493449911f (accessed on 7 March 2024).

Bartold, M., & Kluczek, M. (2023). A Machine Learning Approach for Mapping Chlorophyll Fluorescence at Inland Wetlands. Remote Sensing, 15(9). https://doi.org/10.3390/rs15092392

Berkes, F., & Folke, C. (1994). Linking Social and Ecological Systems for Resilience and Sustainability. Sciences New York, 52.

Berkes, F., & Folke, C. (1998). Linking social and ecological systems for resilience and sustainability. Linking Social and Ecological Systems, 1, 13–20.

Biggs, R., Clements, H., de Vos, A., et al. (2021). What are social-ecological systems and social-ecological systems research? In: Biggs R., de Vos A., Preiser R., et al. (editors). The Routledge Handbook of Research Methods for Social-Ecological Systems. Routledge. pp. 1–494. https://doi.org/10.4324/9781003021339

Binder, C. R., Hinkel, J., Bots, P. W. G., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. Ecology and Society, 18(4). https://doi.org/10.5751/ES-05551-180426

Birol, E., & Cox, V. (2007). Using choice experiments to design wetland management programmes: The case of Severn Estuary wetland, UK. Journal of Environmental Planning and Management, 50(3), 363–380. https://doi.org/10.1080/09640560701261661

Brockhaus, M., Obidzinski, K., Dermawan, A., et al. (2012). An overview of forest and land allocation policies in Indonesia: Is the current framework sufficient to meet the needs of REDD+? Forest Policy and Economics, 18, 30–37. https://doi.org/10.1016/j.forpol.2011.09.004

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? Ecosystems, 4(8), 765–781. https://doi.org/10.1007/s10021-001-0045-9

Cobb, A. R., Dommain, R., Tan, F., et al. (2020). Carbon storage capacity of tropical peatlands in natural and artificial drainage networks. Environmental Research Letters, 15(11), 23–25. https://doi.org/10.1088/1748-9326/aba867

Cole, L. E. S., Åkesson, C. M., Hapsari, K. A., et al. (2022). Tropical peatlands in the anthropocene: Lessons from the past. Anthropocene, 37, 100324. https://doi.org/10.1016/j.ancene.2022.100324

Davoudi, S., Shaw, K., Haider, L. J., et al. (2012). Resilience: A Bridging Concept or a Dead End? "Reframing" Resilience: Challenges for Planning Theory and Practice Interacting Traps: Resilience Assessment of a Pasture Management System in Northern Afghanistan Urban Resilience: What Does it Mean in Planni. Planning Theory and Practice, 13(2), 299–333. https://doi.org/10.1080/14649357.2012.677124

Della Bosca, H., & Gillespie, J. (2020). Bringing the swamp in from the periphery: Australian wetlands as sites of climate resilience and political agency. Journal of Environmental Planning and Management, 63(9), 1616–1632. https://doi.org/10.1080/09640568.2019.1679100

Dislich, C., Keyel, A. C., Salecker, J., et al. (2017). A review of the ecosystem functions in oil palm plantations, using forests as a

reference system. Biological Reviews, 92(3), 1539–1569. https://doi.org/10.1111/brv.12295
Dohong, A., Aziz, A. A., & Dargusch, P. (2017). A review of the drivers of tropical peatland degradation in South-East Asia. Land Use Policy, 69, 349–360. https://doi.org/10.1016/j.landusepol.2017.09.035
Dommain, R., Couwenberg, J., & Joosten, H. (2010). Hydrological self-regulation of domed peatlands in south-east Asia and consequences for conservation and restoration. Mires & Peat, 6, 1–17.
Folke, C., Biggs, R., Norström, A. V., et al. (2016). Social-ecological resilience and biosphere-based sustainability science. Ecology and Society, 21(3). https://doi.org/10.5751/ES-08748-210341
Folke, C., Carpenter, S. R., Walker, B., et al. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. Ecology and Society, 15(4). https://doi.org/10.5751/ES-03610-150420
Furukawa, Y., Inubushi, K., Ali, M., et al. (2005). Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands. Nutrient Cycling in Agroecosystems, 71(1), 81–91. https://doi.org/10.1007/s10705-004-5286-5
Grover, S., Treby, S., Mendham, D. S., et al. (2024). Social and Ecological Dimensions of Tropical Peatland Restoration. Mires and Peat, 30, 1–8. https://doi.org/10.19189/MaP.2023.OMB.Sc.2114019
Gunawan, H, Kobayashi, S., Mizuno, K., & Kono, Y. (2012). Peat swamp forest types and their regeneration in Giam Siak Kecil-Bukit Batu Biosphere Reserve, Riau, East Sumatra, Indonesia. Mires and Peat, 10, 1–17.
Gunawan, H., Kobayashi, S., Mizuno, K., et al. (2016). Sustainable Management Model for Peatland Ecosystems in the Riau, Sumatra. In: Osaki, M., Tsuji, N. (editors). Tropical Peatland Ecosystem Springer.
Haider, L. J., Schlüter, M., Folke, C., & Reyers, B. (2021). Rethinking resilience and development: A coevolutionary perspective. Ambio, 50(7), 1304–1312. https://doi.org/10.1007/s13280-020-01485-8
Hapsari, K. A., Biagioni, S., Jennerjahn, T. C., et al. (2018). Resilience of a peatland in Central Sumatra, Indonesia to past anthropogenic disturbance: Improving conservation and restoration designs using palaeoecology. Journal of Ecology, 106(6), 2473–2490. https://doi.org/10.1111/1365-2745.13000
Haraguchi, A. (2016). Discharged Sulfuric Acid from Peatland to River System. In: Osaki, M., & Tsuji, N. (editors). Tropical Peatland Ecosystem. Springer.
Helmy, F., Osaki, M., Hirose, K., et al. (2012). Peatland Definition: From Uncertainty to Certainty. Available online: https://issuu.com/i_c_c_c/docs/pm01_082012_en/32 (accessed on 8 March 2024).
Hergoualc'h, K., Carmenta, R., Atmadja, S., et al. (2018). Managing peatlands in Indonesia: Challenges and opportunities for local and global communities. Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF). p. 205. https://doi.org/10.17528/cifor/006449
Januar, R., Sari, E. N. N., & Putra, S. (2021). Dynamics of local governance: The case of peatland restoration in Central Kalimantan, Indonesia. Land Use Policy, 102, 105270. https://doi.org/10.1016/j.landusepol.2020.105270
Jarvie, J., Jeyaraj, K., Hardiono, M., et al. (2003). A High Conservation Value Forest Analysis of the Giam Siak Kecil Landscape, ÄìRiau, Sumatra. A Report to WWF International.
Joosten, H., & Clarke, D. (2002). Wise use of mires and peatlands -Background and principles including a framework for decision-making. Available online: http://www.gret-perg.ulaval.ca/fileadmin/fichiers/fichiersGRET/pdf/Doc_generale/WUMP_Wise_Use_of_Mires_and_Peatlands_book.pdf (accessed on 9 March 2024).
Joosten, H. (2009). The Global Peatland CO_2 Picture. Africa. p. 11.
Komulainen, V. M., Tuittila, E. S., Vasander, H., & Laine, J. (1999). Restoration of drained peatlands in southern Finland: Initial effects on vegetation change and CO_2 balance. Journal of Applied Ecology, 36(5), 634–648. https://doi.org/10.1046/j.1365-2664.1999.00430.x
Kuuluvainen, T. T., Tukia, H., Aapala, K. (2004). Ecological restoration of forested ecosystems in Finland. In: Restoration of Boreal and Temperate Forests. CRC press.
Medrilzam, M., Dargusch, P., Herbohn, J., & Smith, C. (2014). The socio-ecological drivers of forest degradation in part of the tropical peatlands of Central Kalimantan, Indonesia. Forestry, 87(2), 335–345. https://doi.org/10.1093/forestry/cpt033
Miettinen, J., Hooijer, A., Wang, J., et al. (2012). Peatland degradation and conversion sequences and interrelations in Sumatra. Regional Environmental Change, 12(4), 729–737. https://doi.org/10.1007/s10113-012-0290-9
Miettinen, J., Shi, C., & Liew, S. C. (2011). Two decades of destruction in Southeast Asia's peat swamp forests. Frontiers in Ecology and the Environment, 10(3), 124–128. https://doi.org/10.1890/100236

Miettinen, J., Shi, C., & Liew, S. C. (2016). Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Global Ecology and Conservation, 6, 67–78. https://doi.org/10.1016/j.gecco.2016.02.004

Miettinen, J., Shi, C., & Liew, S. C. (2017). Fire Distribution in Peninsular Malaysia, Sumatra and Borneo in 2015 with Special Emphasis on Peatland Fires. Environmental Management, 60(4), 747–757. https://doi.org/10.1007/s00267-017-0911-7

Minasny, B., Berglund, Ö., Connolly, J., et al. (2019). Earth-Science Reviews Digital mapping of peatlands – A critical review. Earth-Science Reviews, 196, 102870. https://doi.org/10.1016/j.earscirev.2019.05.014

MoEF. (2024). Hotspot Distribution Hotspot Data Information (Indonesian). Available online: https://sipongi.menlhk.go.id/sebaran-titik-panas (accessed on 21 June 2024).

Nursyamsi, D., Noor, M., & Maftu'ah, E. (2016). Peatland Management for Sustainable Agriculture. In: Osaki, M., & Tsuji, N. (editors). Tropical Peatland Ecosystem. Springer. pp. 493–511.

Omar, M. S., Ifandi, E., Sukri, R. S., et al. (2022). Peatlands in Southeast Asia: A comprehensive geological review. Earth-Science Reviews, 232, 104149. https://doi.org/10.1016/j.earscirev.2022.104149

Osaki, M., Hirose, K., Segah, H., & Helmy, F. (2016). Tropical Peat and Peatland Definition in Indonesia. In: Osaki, M., & Tsuji, N. (editors). Tropical Peatland Ecosystems. Springer. pp. 137–147.

Page, S. E., & Hooijer, A. (2016). In the line of fire: the peatlands of Southeast Asia. Philosophical Transactions of the Royal Society B: Biological Sciences, 371(1696), 20150176. https://doi.org/10.1098/rstb.2015.0176

Pertiwi, N., Tsusaka, T. W., Nguyen, T. P. L., et al. (2022). Nature-based Carbon Pricing of Full Ecosystem Services for Peatland Conservation—A Case Study in Riau Province, Indonesia. Nature-Based Solutions, 2, 100023. https://doi.org/10.1016/j.nbsj.2022.100023

Prananto, J. A., Minasny, B., Comeau, L., et al. (2020). Drainage increases CO2 and N2O emissions from tropical peat soils. Global Change Biology, 26(8), 4583–4600. https://doi.org/10.1111/gcb.15147

Preiser, R., Biggs, R., De Vos, A., et al. (2018). Social-ecological systems as complex adaptive systems: organizing principles for advancing research methods and approaches. Ecology and Society, 23(4). https://doi.org/10.5751/es-10558-230446

Preiser, R., Schlüter, M., Biggs, R., et al. (2021). Complexity-based social-ecological systems research: philosophical foundations and practical implications. In: The Routledge Handbook of Research Methods for Social-Ecological Systems. Routledge. pp. 27–46. https://doi.org/10.4324/9781003021339-3

Purnomo, H., Shantiko, B., Sitorus, S., et al. (2017). Fire economy and actor network of forest and land fires in Indonesia. Forest Policy and Economics, 78, 21–31. https://doi.org/10.1016/j.forpol.2017.01.001

Qomar, N., Basuni, S., Soekmadi, R., et al. (2016). Local Institution in Utilization of the Water Resources of The Giam Siak Kecil—Bukit Batu Biosphere Reserve, in Riau, Indonesia. MIMBAR, Jurnal Sosial Dan Pembangunan, 32(2), 421. https://doi.org/10.29313/mimbar.v32i2.1862

Rieley, J., & Page, S. (2016). Tropical peatland of the world. In: Osaki, M., & Tsuji, N. (editors). Tropical Peatland Ecosystems. Springer. https://doi.org/10.1007/978-4-431-55681-7_1

Rydin, H., & Jeglum, J. K. (2013). The Biology of Peatlands, 2nd ed. OUP Oxford.

Scholz, R. W., & Binder, C. R. (2003). Principles of Human-Environment Systems (HES) Research. In: Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society. Brigham Young University. pp. 791-796.

Schoon, M., & van der Leeuw, S. (2015). About nature/society relationships—The shift toward social-ecological systems perspectives: insights into the human-nature relationship (French). Natures Sciences Sociétés, 23(2), 166–174. https://doi.org/10.1051/nss/2015034

Suroso, D. S. A., & Kombaitan, B. (2018). Social-ecological resilience for the spatial planning process using a system dynamics model: Case study of Northern Bandung area, Indonesia. International Journal of Sustainable Society, 10(1), 42. https://doi.org/10.1504/ijssoc.2018.092650

Takada, M., Shimada, S., & Takahashi, H. (2016). Tropical Peat Formation. In: Osaki, M., & Tsuji, N. (editors). Tropical Peatland Ecosystem. Springer. pp. 127–136.

The Resilience Alliance. (2010). Assessing resilience in social-ecological systems: Workbook for practitioners. Available online: http://www.resalliance.org/3871.php (accessed on 9 March 2024).

Tirtosudarmo, R. (2021). From Colonization to Nation-State. In: From Colonization to Nation-State. Springer Singapore. https://doi.org/10.1007/978-981-16-6437-3

UNESCO. (1996). Biosphere reserves: The Seville Strategy and the Statutory Framework of the World Network. Landscape and

Urban Planning, 84(1), 21.
UNESCO. (2019). Giam Siak Kecil-Bukit Batu Biosphere Reserve, Indonesia. Available online: https://en.unesco.org/biosphere/aspac/giam-siak-kecil-bukit-batu (accessed on 9 March 2024).
Urák, I., Hartel, T., Gallé, R., & Balog, A. (2017). Worldwide peatland degradations and the related carbon dioxide emissions: the importance of policy regulations. Environmental Science and Policy, 69, 57–64. https://doi.org/10.1016/j.envsci.2016.12.012
Wahyunto, Dariah, A., Agus, F., & Cheng, Z. S. (2010). Distribution, properties, and carbon stock of Indonesian peatland. Available online: https://www.naro.affrc.go.jp/archive/niaes/marco/bogor2010/proceedings/14.pdf (accessed on 8 March 2024).
Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. Ecology and Society, 9(2). https://doi.org/10.5751/ES-00650-090205
Wösten, J. H. M., Clymans, E., Page, S. E., et al. (2008). Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena, 73(2), 212–224. https://doi.org/10.1016/j.catena.2007.07.010