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CASE STUDY

Colonial legacy and traps in the social-ecological systems of forest management

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ABSTRACT

BACKGROUND AND OBJECTIVES: The persistence of colonial controls in present-day forest management has long been recognized as a potential threat to the resilience of social-ecological systems. These controls have created barriers that disconnect individuals from their land and diminish the forest diversity. In Mount Merapi, this maladaptation is manifested through the long-tailed macaque's invasion of farmlands, triggered by the state's failure to reforest the targeted 480 ha of damaged land after the 2010 eruption. This study aims to qualitatively interrogate factors that are hindering the swift restoration of Mount Merapi's social-ecological systems. This will be achieved by investigating the intricate dynamics of the area over various time frames, utilizing the panarchy framework developed by Holling and Gunderson. The framework is well-known for its capacity to facilitate a holistic understanding of social-ecological systems but is also intrinsically ambiguous to capture the complexity. The study's novelty lies in its adoption of Boyer's refined panarchy models and Boonstra and De Boer's systematic analysis to address the methodological concern toward a better understanding of social-ecological systems.
METHODS: This study utilizes various techniques for data collection, including semi-structured interviews, literature reviews, and field observations. The interviews involved informants who were selected through purposive sampling and focused on exploring Boyer's panarchy characteristics. In order to ensure the reliability of the data, triangulation was conducted prior to the development of panarchy models.
FINDINGS: The findings indicate that the strict forest controls embedded in the state's forest management since the colonial periods had created rigidity and poverty traps. The concept of the rigidity trap pertains to a reforestation strategy that utilized laborers and territories for ecological conservation, restricted local communities from utilizing forests, and diminished biodiversity by favoring the introduction of non-native *Acacia decurrens*.
CONCLUSION: To address traps, this study recommends the need to use a panarchy approach that facilitates a comprehensive understanding of social-ecological systems and to transfer governance to local people which must be based on an in-depth understanding of the local history, knowledge, and cultures.

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INTRODUCTION

Over time, indigenous communities maintain ecosystem balance (Berkes *et al.*, 2000) and predict disasters (Ford *et al.*, 2020); making them key sources of understanding the environment's behaviors (Everard, 2020). Contemporary resource management can gain valuable insights into environmental sustainability and restorations through their extensive knowledge (Everard, 2020). Nonetheless, the erosion of local knowledge persists as policymakers continue to overlook the customary rights of individuals over natural resources in their decision-making processes (Peluso, 1992; Wong *et al.*, 2020). This marginalization is inseparable from the colonial legacy brought by Europeans into indigenous lands worldwide. Their power's withdrawal, however, is not followed by a return to customary land tenure; instead, its legacies are retained by postcolonial governments (Peluso, 1992; Domínguez and Luoma, 2020). One of the enduring legacies is the notion that safeguarding biodiversity is most effectively achieved by establishing protected areas that are free from any human interference, allowing ecosystems to thrive undisturbed. Consequently, indigenous practices, such as slash-and-burn agriculture in the forest, are often considered irrational and destructive (Magome and Murombedzi, 2012; Domínguez and Luoma, 2020). Numerous studies have highlighted the paradoxical negative social-ecological consequences that arise from the colonial legacy, despite its conservation concern, in various natural resource settings (Table 1). Accordingly, this legacy promotes socio-economic disparities, a decline in local resilience, and deforestation that results in biodiversity loss, endemic extinction, and an increase in natural disasters.

Forests are the most susceptible to conflicts among natural resources given their common pool of resources (Agrawal, 2007), which are difficult to divide, control, and manage (Bruce and Mearns, 2001). In Indonesia, forests play a crucial role in the livelihoods of approximately 48.8 million individuals. Out of the total forest area of 120.50 million hectares (ha), Java accounts for nearly 2.10 percent (%), as reported by the BPS (2016). The Central Statistics Bureau highlights a significant rise in deforestation rates, especially from 2014 onwards (Table 2). This was inseparable from villagers' experience of environmental injustice before the reformation period that stimulated forest robbery and illegal logging (Ferdaus *et al.*, 2014).

Historically, the forest dwellers residing on this island have faced a multitude of physical challenges due to their engagement in the cultivation and logging of trees, as well as the laborious process of transporting them under the colonial rule (Kosuke *et al.*, 2023). Although Indonesia gained its independence in 1945, colonial regulations that marginalized people's customary rights in natural resource settings remain. As a consequence, individuals face the potential loss of their ancestral wisdom and the cultivation of a feeling of skepticism towards those in positions of power (Murtazashvili *et al.*, 2019). Local trust plays a pivotal role in mobilizing individuals towards environmental collective action, as it fosters reciprocity and facilitates cooperation across social, political, and economic domains. This crucial element is closely associated with reduced deforestation rates, highlighting its significance in promoting sustainable environmental practices (Murtazashvili *et al.*, 2019; Mihaylova, 2023). This study took place in the Mount Merapi region which in 2010, emitted a series of eruptions. The event damaged approximately 1,128 ha of land, claimed around 386 lives, and displaced nearly 15,366 residents (BNPB, 2011). Nevertheless, of 450 ha of damaged land targeted by the government, only about 90 ha were completely reforested until 2017. To solve this, the government decided to let the exotic *Acacia decurrens* invade the damaged land (Fig. 1) to expedite the forest succession (Hapsari, 2017). However, this approach may not only lead to water scarcity (FAO, 2022) disrupt ecosystem services and diminish the variety of forests (Souza-Alonso *et al.*, 2017). In Mount Merapi, this ecological imbalance problem has even forced long-tailed *macaques* to invade farmlands on the volcano's southern slope.

Across political regimes, Mount Merapi's forest management had experienced numerous changes from decentralization in which the traditional ruler of Yogyakarta endowed the right to manage the forest to the locals to centralization in which the national government holds the supreme power over forests and retains the colonial legacy to protect them from overuse. This study is aimed at interrogating factors that contribute to Mount Merapi's slow recovery after the violent eruption in 2010. The colonial legacy present in current forest management is believed to

Table 1: Colonial resource regulations and social-ecological impacts worldwide

Country	Colonial controls	Social-ecological impacts	Sources
Lesser Antilles, Caribbean	Sugar monoculture Introduction of exotic taxa	Depletion of native flora and fauna	Wallman, 2018
Yucatan	European/Spanish domesticates.	Altered mutualistic relations among people, plants, and animals; socioeconomic disparities	Alexander and Hernández, 2018
Congo	Limited access to forests through conservation policies of national parks Forced relocation	Poverty Deforestation Decline in the endemic animal and plant	Domínguez and Luoma, 2020
Kenya	Conservation measures, Ancestral lands' encroachment	Depletion of the Maur Forest	Domínguez and Luoma, 2020
India	British colonial regulation Adivavis people's limited access to forest	Discrimination Displacement Violence/human rights injustice Mass deforestation	Domínguez and Luoma, 2020
St. Vincent, Caribbean	Soil surveys Indigenous land encroachment Military force Sugar plantations Overexploited resources	Civil wars Displacement Social marginalization that leads to limited access to resources to recover from disasters	Scarlett, 2022
USA and Australia	Erasure of local practices of controlled burning	Increasing number and intensity of wildfires	Scarlett, 2022
Sierra Leone	British legacy of chieftaincy election	Deforestations	Mihaylova, 2023
Andes and Sierra Madre, South America and Mexico	Land and people exploitations	Damaged local ecosystems Extensive deforestation Declined soil fertility Increased soil erosions, flooding	Singh, 2023
Madagascar	Agricultural expansion	Deforestation Biodiversity loss Loss of 70% of primary forests Animal species extinction	Singh, 2023
Cameron	French's sedentarisation policy Forced relocation to forest periphery	Local conflicts with logging companies The risk of losing the native Baka's indigenous knowledge of managing forests	Carson *et al.*, 2018

Table 2: The Net Deforestation in forest areas in Java's Provinces in hectare (ha) (2013-2020) (BPS, 2022) adapted from the Central Bureau of Statistics, 2022

Year	West Java	Central Java	Yogyakarta	East Java	Banten
2013-2014	-10,979.5	-79.2	0.9	5,452.2	-237.3
2014-2015	1,750.5	1,589.5	51.8	3,621.0	1,282.2
2015-2016	0	0	0	0	0
2016-2017	-160.6	0	-163.8	0	-2,534.4
2017-2018	2,598.9	2,004.7	2.4	3,298.6	-523.6
2018-2019	3,782.4	1,859.6	141.4	5,066.4	67.3
2019-2020	0	0	0	0	0

be the primary factor hindering the ability of both the community (social system) and the forest (ecological system) to efficiently bounce back from various impacts. Numerous studies have been conducted to elucidate the impact of colonial heritage on the resilience of local systems. For example, using regression analysis, Mihaylova (2023) found that people's trust in traditional chiefs, the legacy of British colonialism in Sierra Leone, correlates with deforestation rates (Mihaylova, 2023). Marchand

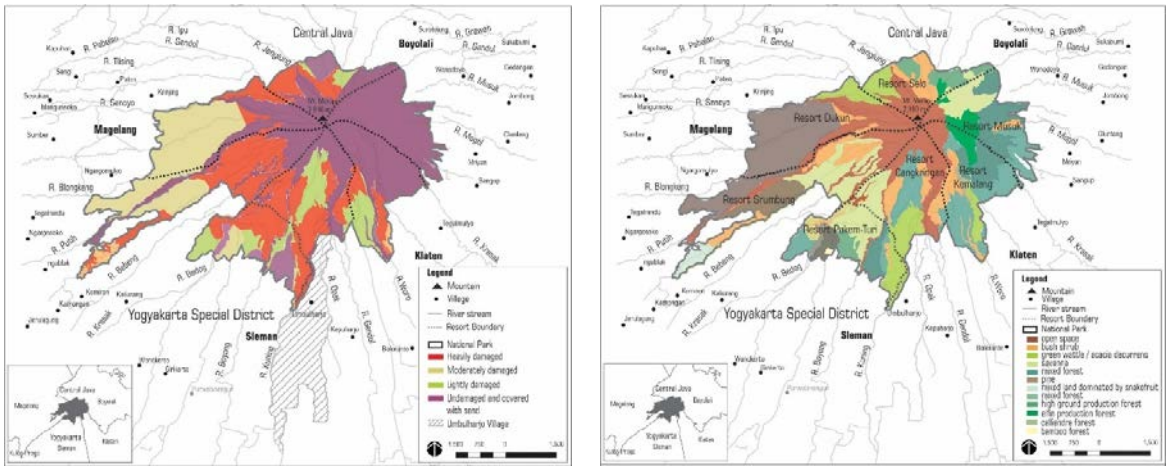


Fig. 1: The heavily damaged areas (red) after the 2010 eruption (a) and expansion of *Acacia decurrens* in the damaged areas (light green) (b)

(2016) found that deforestation in developing countries colonized by French is relatively less than that in countries colonized by British and Spanish after investigating whether inherited colonial legacies influence deforestation rates in 60 former colonialized countries (Marchand, 2016; Mihaylova, 2023). Nevertheless, a significant portion of these studies lack a comprehensive grasp of the intricate non-linear dynamics and interconnectedness of various systems. They also have a tendency to disregard additional factors that could potentially elucidate environmental issues, opting instead to construct rudimentary models for the analysis of resource-related challenges (Ostrom, 2009). To address this gap, this study offers Holling and Gunderson's *panarchy* framework to develop a comprehensive understanding of social-ecological systems' dynamics in the context of protected forest management in a post-colonial setting and unexpected disturbances. The novelty of this study lies in its adoption of a panarchy framework refined by Boyer (2020) and methodological steps developed by Boonstra and De Boer (2014) to reach the goal. These tools are instrumental for this study to explain Mount Merapi's Social ecological systems (SES) dynamics comprehensively and systematically. This study utilizes various techniques to gather data, including semi-structured interviews, literature reviews, and field observations. The data gathered were validated through cross-checking across these methods (i.e., triangulation) before being used to develop adaptive cycle models characterizing the notable panarchy framework. *Panarchy* originated from the name of a Greek God called *Pan*, and was first coined by Gunderson and Holling (2002) to illustrate the destabilizing nature that caused panic. *Panarchy* emerges as a fitting framework for strengthening the resilience of social-ecological systems (SES) by acknowledging the intricate interplay between human communities and the environment, illustrating their dynamic organization and interconnectedness across diverse scales of time and space. It accounts for hierarchical organizations, the connectedness of scales, and dynamics of system structure and grapples with systemic dynamics of change, including the possible collapse and emergence of novel systems as well as uncertainty such as a natural disaster (Sundstrom *et al.,* 2023). Although *panarchy* has been criticized for being too general and superficial (Holling and Gunderson, 2002), it is still widely used as a tool to study SES dynamics, identify environmental problems (Escamilla *et al.*, 2021; Rocha *et al.*, 2022), assess resilience, and identify opportunities and traps that can lead to novelty or collapse (Cox, 2016; Cumming, 2018). In this study, *panarchy* is useful for interrogating factors contributing to Mt. Merapi's slow recovery after the 2010 eruption by viewing the protected forest as a complex adaptive system, which is unpredictable, unstable, and non-linear across space and time. Studies on systems' resilience to natural disasters that used panarchy as their frameworks have been done progressively since its introduction in 2002 (Table 3). Nevertheless,

Table 3: Panarchy-based studies and their findings in the past ten years

Settings	Objective	Methods	Findings	Sources
Adirondack Park, New York	Identify patterns and dynamics operating in the policy network in Adirondack Park.	Qualitative (literature and documentative reviews)	Water, technology, and policies influenced land use	McNulty, 2023
Western Cape, South Africa	Understand and manage individual PAs for long-term sustainability	Mixed-methods	The dominant processes that shape and alter PA resilience are social and economic	Cumming *et al.*, 2015
South Dakota Prairie Porthole Region	Examine institutional adaptations to govern public access and use of non-meandered waters overlying private lands.	Qualitative (literature reviews)	Institutional Panarchy Framework that integrates Ostrom's SES and Gunderson and Holing's panarchy	May, 2021
The eastern Mediterranean at the end of the 2nd millennium BCE	Illustrate the collapse of the elite society as a result of its over-reliance on a hypernet-worked international system.	Qualitative (literature reviews)	Panarchy can help frame the impacts on the eastern Mediterranean and contextualize the differing effects	Newhard and Cline, 2022
All lakes in the boreonemoral ecoregion of southern Sweden	Test the premises of panarchy	Quantitative (time series modeling and correlation analysis)	The redundancy of liming footprints across scales in the physicochemical environment is not enough to create a self-organizing limed lake regime	Angeler *et al.*, 2021
Volcanic island of Surtsey	Provide a holistic analysis of the development of a vascular plant community	Mixed methods	The nutrients brought to the island by breeding gulls are the main driver of plant community development	Schrenk *et al.*, 2022
19 cases of disasters worldwide	Inform prepositions describing how inequalities can influence the reorganizations of SES after disasters.	Qualitative (case studies and literature reviews)	Inequalities influence the capacity of different individuals to reorganize after a disaster and that system connectedness can strongly interact with inequality.	Dade *et al.*, 2022
Flint, Cleveland, and Pittsburg	Analyze cross-scale dynamics of food systems in post-industrial Rust Belt cities after experiencing economic downturns	Qualitative (comparative studies)	Economic recovery in Pittsburgh was reflected in reorganization, while the lack of economic recovery in Flint and the uneven access to economic recovery in Cleveland placed their food systems in lock-in traps	Wentworth, *et al.*, 2022
Maumee River Watershed, Lake Eric, North America	Identify and document the social-ecological drivers associated with major changes over the last 200 years	Qualitative	Successful policy intervention must treat the MRW as a complex adaptive system operating at multiple scales	Siman and Niewiarowski, 2023
Selune River, northwestern France	Examine the landscape as an actor of ecological restoration projects rather than a resource; identify affordances recognized by local actors to understand human-river relations	Qualitative (observations, semi-structured interviews, photographic observations)	Decision makers should be sensitive to affordances A project cannot be fully constructed in advance in the absence of any interaction with the reality	Germaine and Gonin, 2024

there have been few advancements made in the context of Mount Merapi. By examining the gradual recuperation process of Mount Merapi subsequent to the eruption, this study endeavors to bridge the existing gap in understanding the complex dynamics of the volcano. The findings suggest that the state's forest regulations through reforestation over time are the major factors that contributed to the decline in forest diversity, leading to the ecological system's failure to rejuvenate itself after the eruption in 2010. The objective of this study is to analyze in detail the elements that hindered the gradual restoration of Mount Merapi following the volcanic eruption in 2010 by investigating the dynamics of its social-ecological systems using the panarchy framework developed by Holling and Gunderson. The study was conducted in Mount Merapi's Hazard Zone III, which is recognized as the most perilous region encompassing a protected forest, spanning from March 2021 to January 2022.

MATERIALS AND METHODS

Research context

Mount Merapi is a stratovolcano type that frequently emits a dense pyroclastic flow during eruptions (KESDM, 2010). Small eruptions typically happen at an average frequency of every 2-3 years, while larger eruptions tend to occur every 10-15 years. Furthermore, very large eruptions are infrequent, transpiring approximately every 50-60 years. Merapi the most active volcano in Indonesia, is located approximately 30 kilometers to the north of the bustling city of Yogyakarta (Donovan, 2010). Since the 1800s, more than 130,000 lives have been lost due to the eruptions of this volcano (Thouret *et al.*, 2000). However, despite this significant human toll, the area continues to be inhabited by approximately 1.6 million individuals (Surono *et al.*, 2012). The soil is very fertile for varying crops, enabling the harvest of plentiful agricultural products throughout the years and fine grass to grow along river streams. Spanning over 6,410 ha, Mount Merapi National Park can be divided into seven zones (Fig. 2), which are the core zone (+ 1,041.2 ha), wilderness zone (+2,980.19 ha), utilization zone (+461.73 ha), traditional zone (+1,504.62 ha), spiritual, cultural, and historical zone (+11.57 ha), rehabilitation zone (+418.42 ha), and mitigation and reconstruction zone (+189.88 ha). The hazard map of Mount Merapi divides the eruption threats into three zones, namely Hazard Zone III, Hazard Zone II, and Hazard Zone I, based on the level of risk. The initial release of the national park zone map took place in 2004; however, it underwent a revision in 2021 to incorporate the *ngarit-mugut* traditions within the boundaries of national park. In

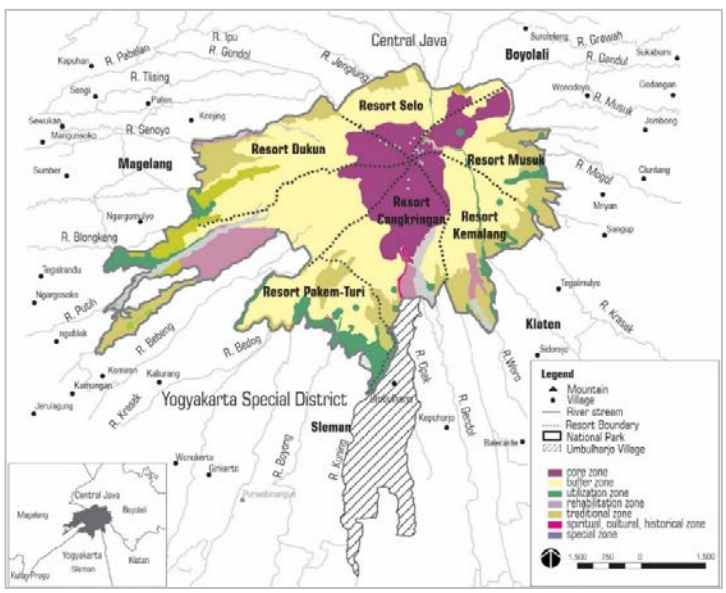


Fig. 2: The zonation of the Mount Merapi National Park. The image was redrawn based on the Mount Merapi National Park Agency's data in 2017

the same year, the state established the National Park Agency to enforce forest rules (Atmojo *et al.*, 2018).

In 2016, approximately 107,488 individuals residing in seven villages bordering the National Park area depended on the forest for essential resources such as water, grass, and fuelwood. Water was the highest in rank based on the agency's survey on the annual local consumption. In 2018, there were at least 43 water sources identified within the national park, and five river streams, Boyong, Krasak, Opak, Gendol, and Kuning, are the primary sources of potable water for people in the province. Fuelwood and sand are the other two critical forest units for local livelihoods. In 2016, a significant proportion of the population, approximately 84.51%, relied on fuelwood either for their daily cooking needs or for producing charcoal for commercial purposes (Atmojo *et al.*, 2018). Sand, which could reach millions of m^3 during eruptions, creates abundant opportunities such as employment in the mining sector. However,once the resource is exhausted, miners frequently embark on a quest for sand within the woodland, delve further into the earth, or engage in the practice of excavating the river bank. (Umaya *et al.*, 2020). These practices have decreased the water table in the region, which has led to harvest failures in many villages (Sarrazin *et al.*, 2019).

Panarchy framework

An adaptive cycle illustrates the systems' dynamics comprising the phases of release (Ω), reorganization (α), exploitation (r), and conservation (k). Holling's expertise in studying managed ecosystems served as the foundation for this proposition. It functioned as a conceptual instrument that prioritized the processes of "destruction" and "reorganization" while also acknowledging the significance of other stages within a system, such as "exploitation" and "conservation" (Rocha *et al.*, 2022). The exploitation phase encompasses the system's capacity to disperse and its rapid expansion within a competitive environment. The conservation phase illustrates the gradual buildup and retention of resources within the system. The release phase is the tightly bound accumulation of resources that become fragile until they are suddenly released by external agents. The reorganization phase is the state where the system minimizes the loss of resources after a disruption and reorganizes the remaining resources for future exploitation (Holling and Gunderson, 2002). Holling and Gunderson (2002) introduced three adaptive cycle models in 2002 (Fig. 3). The first model focuses on "potential" and "connectedness". Potential denotes the ability of a system to undergo transformation, thereby influencing the range of choices accessible. Connectedness, on the other hand, signifies the extent of interconnectedness among internal governing variables and processes, establishing the system's adaptability. The subsequent model introduces "resilience" as an additional attribute. Resilience shows the extent to which a system is vulnerable to unpredictable disturbances. The panarchical adaptive cycle, which is the third model, depicts the progression of a complex system within social-ecological systems of varying scales. It showcases the transition from small and rapidly changing ecosystems to larger and slower ones.

The panarchical adaptive cycle has two main features: "hierarchy" and "connections". During the reorganization phase, the former promotes variety

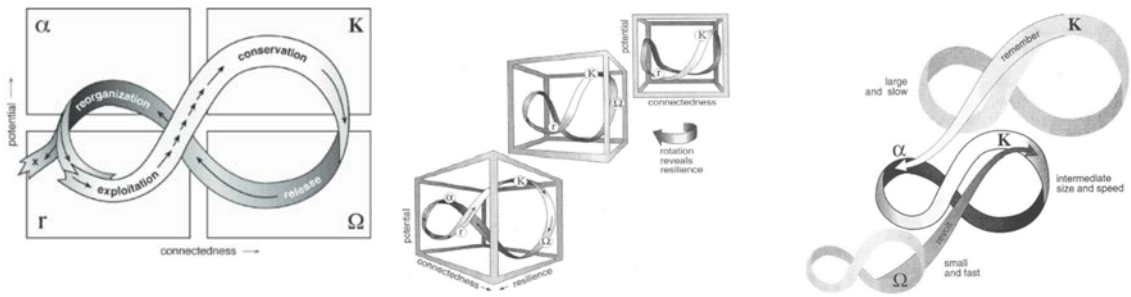


Fig. 3: The two-dimensional model (a), the three-dimensional model (b), and the panarchical model of adaptive cycles (c)

and generates new experiments at each level. The interaction takes place among scales symbolized by "revolt" and "remember". Revolt signifies a condition in which the factors leading to a significant shift in one cycle intensify to a precarious point in a broader, lengthier cycle. Remember serves as the mechanism that enables the system to rejuvenate, harnessing the amassed potential within a vast and gradual phase. Metaphorically, a *panarchical* adaptive cycle begins from a level that enters its release phase and undergoes a collapse. This subsequently leads to a significant and gradual intensification by triggering a crisis at its conservation phase or at the large level where the resilience is low. These effects are displayed by the "revolt" arrow that cascades to high, slow levels if they have accumulated vulnerabilities and rigidities at the conservation phases. The downward "remember" arrow indicates the second type of cross-scale interaction that is critical during times of change and renewal. Panarchy acknowledges the emergence of "novelty", which is the result of recombining existing elements and new inventions to create new opportunities and "collapse", which is instigated by external occurrences and intensified by the system's susceptibility. These two events determine the presence of "rigidity traps" and "poverty traps" in the systems' dynamics across scales. The former is the effect of a collapsing adaptive cycle where a system has high connectedness, high potential, and high resilience. It occurs when the systems' members are stable, highly connected, and self-reinforcing but inflexible and lack the adaptive capacity to find innovative solutions when new problems arise (Enqvist *et al.*, 2016; Cumming *et al.*, 2020). For instance, an excessively bureaucratic administration and a "command-and-control" approach within a system perceive each issue as if it were tightly constrained, precisely outlined, comparatively uncomplicated, and following a linear cause-and-effect pattern. The objective of this approach is to reduce the inherent diversity in the structure and operations of a system in order to enhance its predictability and stability, or to generate outcomes that are economically efficient and dependable for human requirements. In the forest context, the agency typically converts natural, multi-species, and variable-edged forests into monoculture, single-aged plantations; causing the forests to be susceptible to disturbances (Holling and Meffe, 1996). The agency's primary focus was solely on the scientific and technical facets of resource management, displaying minimal regard for local knowledge and a lack of comprehension regarding human behavior. Furthermore, their actions had a detrimental effect on the ability of indigenous communities to effectively manage their own resources (Acheson, 2006). On the other hand, the poverty trap is the effect of a collapsing adaptive cycle where the potential and diversity are destroyed by misuse or an external force, leading to the system's impoverished state marked by low connectedness, low potential, and low resilience (Holling, *et al.*, 2002). An example of this is a situation in which people are impoverished by circumstances beyond their control (Carpenter and Brock, 2008). This state is characterized by low connectedness, low resilience, and a lack of realization about its potential to change. Local people in this case may have abundant ideas and raw materials but cannot focus resources on a particular idea and move the system forward (Westley *et al.*, 2007). Consequently, the system's adaptive capacity experienced a significant decrease due to the gradual reduction in its sources of novelty. The depletion of natural resources by impoverished communities lacking assets can be attributed to their need for immediate sustenance, leading to the failure of conservation efforts aimed at preserving the resource (Cumming, 2018).

Methods

As described earlier, the current study is formulated on the premise that the enduring influence of colonialism in present-day forest management is the primary determinant that hampers the ability of the socio-ecological system (SES) to promptly recuperate from the consequences of the forceful volcanic eruption in 2010. With this assumption in mind, the analysis in this study utilizes the *panarchy* framework as its foundation. Given the heuristic and holistic nature of *panarchy*, studies using this framework typically employ qualitative methods. Table 3, for example, indicates that 7 out of 9 panarchy-based studies employ qualitative methods to assess the cross-scale dynamics of systems in varied natural resources. Despite the fact that quantitative approaches have unveiled fresh perspectives on the present comprehension of resilience, their availability remains limited (Angeler *et al.*, 2023). Within the qualitative research framework, this study employed

Table 4: Data collecting methods and sources

Period of the SES	Methods	Sources
Colonial	Literature reviews	Depdikbud, 1997; Peluso, 1992; Nugroho, 2017; Atmojo *et al.*, 2018; Kuswijayanti *et al.*, 2007; Ginaris, 2018
Old order regime	Literature reviews	Peluso, 1992; NYTimes, 1964a ; NYTimes, 1964b; Dwiyono, 2012; Kendal *et al.*, 2014
	Semi-structured interviews	Local informants
New order regime	Literature reviews	Isnaeni, 2021; Peluso, 1992; Atmojo *et al.*, 2018
	Semi-structured interviews	Local informants
Reformation	Literature reviews	Ulum, 2020; Ferdaus *et al.*, 2014; Hidayat, 2009; Wilson *et al.*, 2007; Donovan *et al.*, 2012; BLH, 2020; Isnaeni, 2021; Ferdaus *et al.*, 2014
	Semi-structured interviews	Local informants, National Park Agency
Post-reformation	Literature reviews	Zakaria, 2010; Suryawan *et al.*, 2015; Hapsari, 2017; Atmojo *et al.*, 2018; BTNGM, 2010; Utomo, 2022; FAO, 2022
	Semi-structured interviews	Local informants, National Park Agency
	Field observations	On-field

literature reviews, semi-structured interviews, and field observations (Table 1) as methods for data collection. The significance of the last two approaches cannot be overstated, given the scarcity of written records pertaining to the management of Merapi's forest from the colonial through reformation regimes. The semi-structured interview is due to its ability to acquire a comprehensive comprehension of the interactions between individuals and their environment from the viewpoint of the respondent. Consequently, it reveals unforeseen information that could be valuable in elucidating the maladjustment of the SES after the 2010 eruption. This qualitative data collection method employs open-ended questions and a flexible protocol, which is predetermined before the interviews and is supplemented by follow-up questions to garner an in-depth response over the course of conversations (DeJonckheere and Vaughn, 2019; Magaldi and Berler, 2020). By aligning the interview questions with the key parameters of adaptive cycles (Table 4) as defined by Boyer (2020), a comprehensive understanding was sought to be achieved. Using purposive sampling, the criteria for selecting trustworthy informants involve their residency in the Mt. area. The inhabitants of the Merapi region have likely depended on the forest resources for their livelihood since the colonial regime. This approach led to the recruitment of two local elders whose eligibility was further confirmed by the chief of the Pelemsari sub-village, a settlement situated less than five kilometers from Merapi's summit. Full consent was obtained from these informants after they received the researcher's explanations about the research's goal and procedure, their rights and obligations, and the researcher's promise to keep their identities confidential. Besides the two informants, interviews were also conducted with senior staff of the Mount Merapi National Park Agency. These specifically aimed to validate the data obtained from the local elders and enhance the researcher's comprehension of the practices related to forest management in Mt. Merapi from the state's perspective. The other method, literature review, is important in order to gather accurate information for the creation of adaptive cycle models. Data sources were selected by considering the credibility of the authors and publishers (e.g., reputed journals, books, newspapers).

All the data collected from interviews, observations, and literature reviews are displayed through the panarchy's adaptive cycle model developed by Holling *et al.* (2002) with specific events detailed by Boyer in 2020 (Boyer, 2020). This particular model has gained significant acceptance in a multitude of scholarly publications as a means to depict the adaptive cycle of social-ecological systems and pinpoint challenges across various natural resources and contexts (Fig. 4).

To investigate how the forest resource of Mt. Merapi is governed over periods and identify the system's poverty traps and rigidity traps, this study follows these steps: 1) *Describing the SES of the area of study.* This study follows Ostrom's general framework of social-ecological systems (SES) that consists of resource systems, resource units, governance

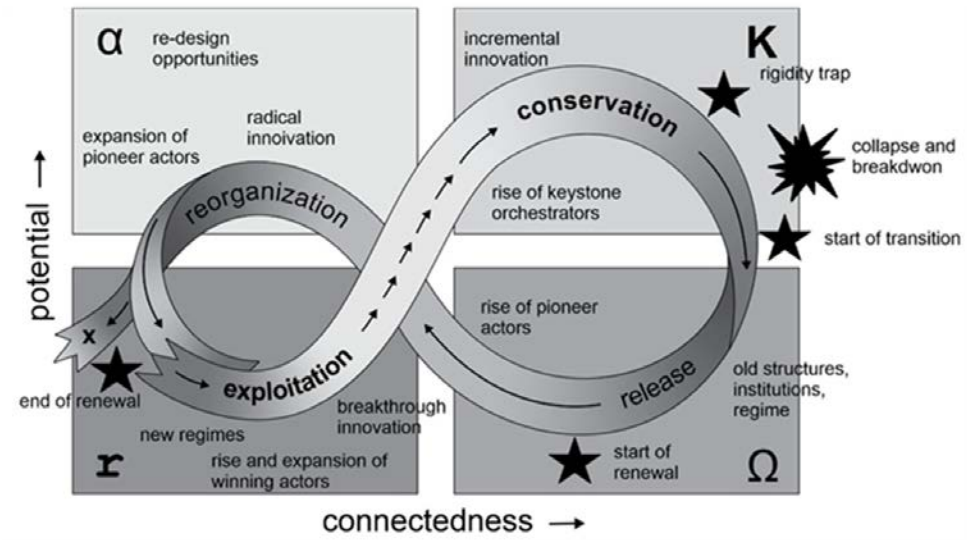


Fig. 4: The adaptive cycle's phases with their detailed events (Boyer, 2020)

Table 5: Boyer's key variables of an adaptive cycle and their characteristics as the research parameters.

The adaptive cycle's phase	Key variables	Characteristics
Conservation (K)	Potential	Incremental innovation Slow growth towards the accumulation peak. Resources are stored and used largely for the system's maintenance.
	Connectedness	Stability Certainty Rise of keystone orchestrators
	Rigidity	Lack of flexibility Lock-in and rigidity trap
	Resilience	Low and decreasing
	Unexpected destruction	Creative destruction Chaotic collapse
Release (ω)	Potential	Release of accumulated capital Uncertainty
	Connectedness	Old structures, institutions, breakdown Rise of Pioneer actors
	Resilience	Low and increasing
Reorganization (α)	Potential	Radical innovation Greatest uncertainty
	Connectedness	Redesign opportunities Expansion of Pioneer actors
	Resilience	High and increasing
Exploitation (r)	Potential	Breakthrough innovation Rapid accumulation of capitals Competitions
	Connectedness	Seizing of opportunities Rise and expansion of winning actors Rise of a new regime
	Resilience	Rising level of diversity and connections High and decreasing

Table 6: The specific events in each regime mark Mount Merapi's forest management

Periods	Year	Specific events
Colonial	1832	The Dutch implemented *cultuurstelsel*
	1870	The Dutch enacted the Agrarian Law
	1873	The Dutch introduced the *tumpang sari*
	1910	The Dutch's designation of the Law for Protection of Wild Mammals and Birds
	1919	European settlers proposed a hill station on Merapi's foot, Kaliurang district
	1931	The Dutch issued *Gouvernements Besluit* No. 4197/B
	1942	Japan occupied Java and implemented *romusha* and forest village programs
Old order	1960	The government passed a law regulating peasants' rights over the forest
	1964	Food crises due to failures of rice harvesting
New order	1966	Suharto's regime opened opportunities for timber companies and foreign investment in the forest
	1970s	State Forestry Corporation (SFC) launched community forest programs
	1990s	The state introduced dairy cows including fine grass seeds and *acacia decurrens*
Reformation	1999	The stipulation of Decree No. 41 in 1999 that all forests be managed by the state
	2004	The state enacted decree No. 134/Menhut-II/2004, which designated the forest as a national park
	2006	2-3 VEI scale eruption caused the protective wall around the crater to collapse
	2010	3-4 VEI scale eruption damaged the forest; the state envisioned decentralization in forest management and faced reforestation challenges

systems, and resource users (Ostrom, 2009); 2) Defining the timeline of the SES transformation. The SES transformation commences from the colonial era and extends to the post-reformation period, with political regimes playing a crucial role in shaping its timeline (Table 2); 3) Exploring the SES dynamics and specifying the events that contribute to each phase of transformation in each period. The system's dynamics are assessed regarding its resilience, potential, and connectedness (Table 5); 4) Developing the panarchical connections between the SES levels and discerning instances maladaptation. The nested adaptive cycles in this study comprise the state's forest management (large, slow system), Mount Merapi's ecosystem (intermediate size, speed system), and the local forest management (small, fast system) (Boonstra and De Boer, 2014).

RESULTS AND DISCUSSION

The results in this section are discussed by following the methodology of Boonstra and De Boer (2014), which are: 1) defining the timeline of the SES transformation; 2) exploring the SES dynamics per period; 3) developing the *panarchical* connections between the SES levels to identify traps.

Defining the timeline

The management of a natural resource plays a crucial role in determining the resilience of its SES. Developing the timeline of the SES dynamics, based on the political regime, is of utmost importance. The chronological representation of this timeline can be observed in Table 6.

Colonial period (1755-1945)

State's forest management

During their occupation, the Dutch implemented scientific approaches to oversee forest management and enforced regulations on land use, species preservation, and labor practices. One of their contributions involves the delineation of forest areas to differentiate the state's jurisdiction from local land tenures and to manage access to the forests. They also divided Java into nine prefectures in 1808 to intensify the *contingent*, a system that required people to pay taxes in the form of agricultural products (Depdikbud, 1997). The Dutch implemented a series of forest principles which emphasized that the advantages of forests should be directed towards the requirements of the entire populace, with the state assuming the role of the ultimate authority and overseer. Nevertheless, the aforementioned principles scarcely take into account the requirements of individuals residing in close proximity to the available resources. The rights of the local community pertaining to the forest were solely restricted to the gathering of non-timber items (Peluso, 1992). In 1812, the British took control of several Dutch East Indies posts in Java. The Dutch's forest policies were meticulously improved, with a focus on reserving the vast majority of the

forests to cater to their own interests. Additionally, they provided access to entrepreneurs and local elites, ensuring their involvement in the forest management. In 1816, the British returned control to the Dutch, who kept Raffles' forest rules. In 1832, the Dutch introduced the *cultuurstelsel,* which required people to plant the state's crops in the forest and subsidize the state with agricultural products. In 1865, the *blandongdiensten* was abolished in favor of a free labor system. This system required laborers to work in the forest and pay for the logs they cut (Nugroho, 2017). In 1870, the Dutch implemented an Agrarian Law to increase their control over land by transferring all unowned land to the ownership of the state. Three years later, a Dutch forester named Buurman van Vreede, imitating the Burmese *taungya* system, introduced the *tumpang sari* (Peluso, 1992; Depdikbud, 1997). The program's goal was to increase farmers' participation in overseeing the state's trees by granting them permission to cultivate non-timber crops in the forest as an incentive (Depdikbud, 1997). In 1942, Japan took over the Dutch administration and established the Japanese Forest Service. This agency neglected the Dutch's forestry practices and forced forest managers at the district level to organize reforestation on their own. Japan also implemented a forest village program to bolster their war efforts, requiring individuals to live in the forest and participate in reforestation efforts. However, the *romusha* labor system had negative social and environmental consequences. As a consequence, the excessive logging of forest trees resulted in both starvation and severe environmental degradation, irrespective of their age (Peluso, 1992). Japan withdrew from Indonesia after its defeat during WW II, which left a void in Indonesia's governance. Taking advantage of this situation, Soekarno and his colleagues declared Indonesia's independence on August 17, 1945 (Depdikbud, 1997).

Local forest management

In 1909, the Dutch passed *Staatsblad 497* and *Staatsblad 594*, providing the foundation for the Law for Protection of Wild Mammals and Birds the following year. This led to the annexation of moorlands on Merapi's southern flank into the protected forest in 1912, with the Dutch claiming that it was intended to prevent floods and erosion caused by land clearance practices in the forest (Atmojo *et al.*, 2018). The legislation resulted in a shift in traditional farming methods among indigenous communities, transitioning from rotating cultivation to the fallow system and from grazing cattle to domesticating animals (Kuswijayanti *et al.*, 2007). The protected forest's designation was further strengthened by the Dutch settlers' intention to construct rest areas at the base of the volcano, dating back to 1919 (Ginaris, 2018). In 1931, the Dutch issued Gouvernements Besluit Number 4197/B, which stipulated about 6,472.1 ha of Merapi's land as a protected forest and specified forest services in Yogyakarta for hydrology, botany, and aesthetics. The Dutch implemented forest regulations concerning land use, water, plantation, agriculture, and forestry in order to uphold the law, based on a mutual agreement with the Sultan (Atmojo *et al.*, 2018). The law ended when Japan took over the Dutch's reign in 1945. Under their regime, Japan forced people in Mt. Merapi to build protective caves in the forest, participate in wars, and give up rice to the state. Japan's forest village program, nevertheless, played a crucial role in revitalizing the connection between farmers and forest land. However, the adverse effects of their occupation overshadowed any advantages.

Developing the adaptive cycle model

As Fig. 4 shows, the transition from the release phase (W) to the reorganization phase (α) is marked by the Dutch's oppressive scientific management which led to the collapse of indigenous forest management during their occupation (Fig. 5). In 1912, the Dutch issued a decree that annexed moorland to the protected forest, which was expanded in 1931. Over time, this legislation compelled individuals to alter their farming practices that were rooted in pre-colonial traditions. For example, the traditional shifting system with the slash-and-burn technique in the forest changed into the fallow system, which required manure for cultivation. Cattle grazing transformed into the domestication of cattle, necessitating farmers to collect grass for fodder.

Exploiting people, the Dutch exercised reforestation with mixed intercropping techniques and concession. Farmers were granted the privilege to cultivate the forest in order to sustain their livelihoods through their hard work. This practice not only enabled the Dutch to safeguard the forest ecosystem but also allowed them to reap the rewards of its resources, including

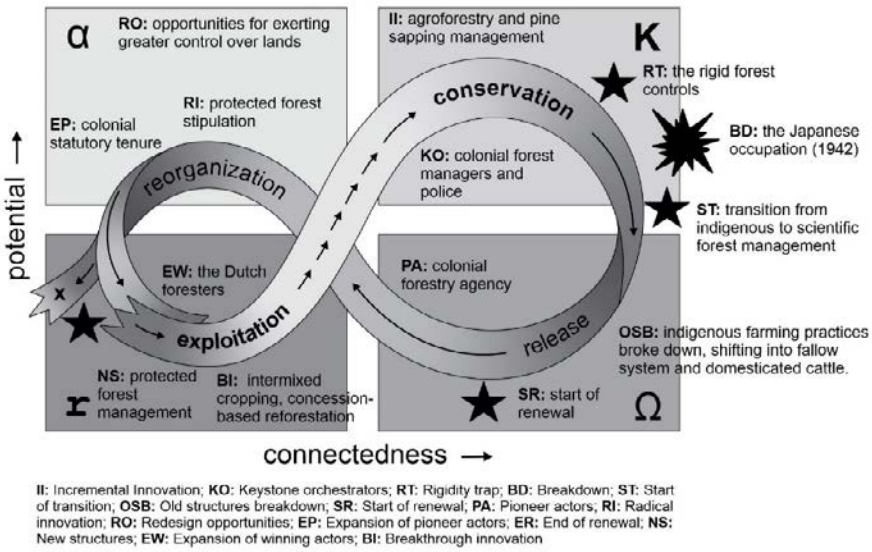


Fig. 5: The SES' adaptive cycle during the colonial regime

pine sap. In the transition from the reorganization phase (a) to the exploitation phase (r), traditional knowledge was replaced by scientific management, and the Dutch as the key orchestrators accumulated forest products towards the conservation phase (K). Over time, the forest's natural ability to anticipate unforeseen events was diminished due to the inflexible system resulting from the colonial regulations imposed on forest management. In 1942, the Dutch's forest management system broke down and the resource was managed by Japan. In the transition from the release phase (W) to the reorganization phase (a), Japan promoted a forest village program to support reforestation. The program allowed local farmers to resurrect their farming traditions and develop an awareness of their rights over the forest. In the transition from reorganization (α) to exploitation (r), Japan forced local people to build protective caves for military purposes in the forest under the *romusha* policy. During the reorganization phase, as the colonial administration gradually faded, reforestation continued to play a crucial role in advancing Japan's military objectives. In the exploitation phase, Japan, exercising *romusha*, forced laborers to devote harvested crops and rice to the Empire. This exploitation allowed Japan to accumulate agricultural products for its warfare towards the conservation phase. However, *romusha* and its rigid controls collapsed after Japan was defeated by the Allies in 1945.

Old order period (1945-1965)

State's forest management

Soekarno declared Indonesia's independence in response to the void of governance after Japan's defeat in WW II (NYTimes, 1964b). However, this was overshadowed by the Dutch's attempts to reoccupy the country. In response to the Dutch's aggressive actions, the government decided to relocate the administration of the National Forest Agency from Bogor to Yogyakarta. Here, they developed forestry policies despite the internal disputes on whether the Dutch forestry routines should be retained (Peluso, 1992). The conflicting political ideologies of its members, including the Indonesian Communist Party, the Darul Islam and the Islamic Army of Indonesia, and the Indonesian Nationalist Party, further heightened the internal tensions. In the view of the Communist Party, the forestry agency was an extension of a colonial bureaucracyThe supporters of this cause encompassed individuals such as squatters, landless peasants, forest laborers, and the Union of Forestry Workers associated with the organization. The Union of Forestry Workers made efforts to broaden its membership to include individuals at the managerial level (Peluso, 1992). This party along with the Darul

Islam and the Islamic Army of Indonesia even openly challenged the government through guerilla warfare and used forests as their covert places. In order to eradicate the rebels, the government tried to secure the backing of the populace by providing them with the opportunity to use the forest for a limited period in return for assisting in the cultivation of the state's crops. However, this failed due to people's fear of encountering the rebels in the forest. As a result, land tracts became untended and covered with wild grass (Dwiyono, 2012). During this period, the Forestry Agency classified landless peasants as squatters and exclusively sold the finest timber to manufacturers. In 1960, a law regulating peasants' rights over the forest was passed, which allowed peasants to be evicted from state land without a court order and authorized the state to use military force to enforce rules. Another law was passed in 1961, declaring the foundation of the State Forest Enterprise that managed the commercialization of forest products (Peluso, 1992). In 1964, a food crisis occurred. Approximately 2 million individuals residing in Java are currently confronted with food shortages as a result of the president's initiative to restrict rice imports. Unfortunately, this policy was not accompanied by an adequate focus on enhancing domestic rice production, leaving impoverished villagers with no choice but to resort to begging on the streets of urban areas. The failure to maintain rice production forced Soekarno to forgo rice in favor of cassava and corn (NYTimes, 1964a). In Mount Merapi, this order was actualized through reforestation in which people were mandated to cultivate cassava and corn under pine stands and regularly deliver the harvested products to the state. The outcome of this practice led to a monoculture characterized by pine stands and corn as the dominant species in the forest composition.

Local forest management

During this period, people's rights over the forest were oppressed by the state, which prevented them from exercising their farming traditions and expanding their local knowledge. According to a local source, the primary focus of people's activities was centered on fulfilling the state's requirements of growing cassava and corn in pine stands. In return for their efforts, they would then deliver the harvested crops to obtain their entitlement to the products.

Developing the adaptive cycle model

As Fig. 6 shows, the release phase (W) is marked by the end of the *romusha* program due to the rise of the old order that replaced Japan's regime. The renewal phase commences with the creation of the initial national forestry agency. However, the agency was forced to sustain colonial forest controls due to the predominant influences of its conservative members. The agency's restructuring of the forest led to a decrease in cohesion among the members, especially due to their varying political beliefs and the impact of the communist party (Fig. 6). From the

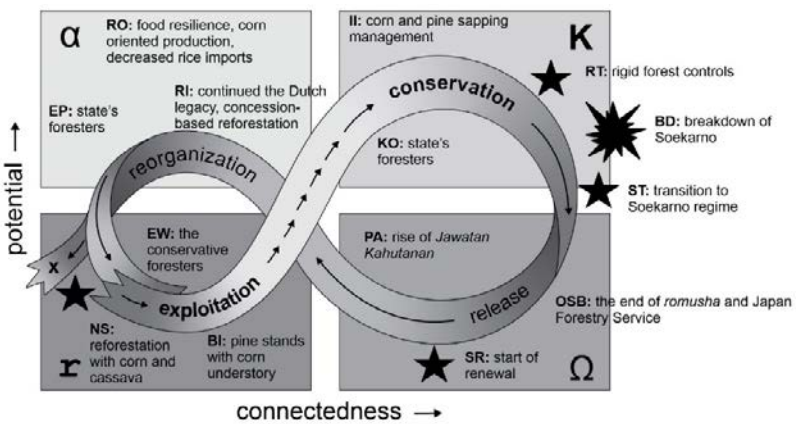


Fig. 6: The SES adaptive cycle during the old-order regime

reorganization phase (a) to the exploitation phase (r), the state proceeded with the colonial legacy and concession-based reforestation. In the exploitation phase (r), the state pioneered reforestation with corn and cassava, forming a new structure of agroforestry that was rigid in its control. Towards the conservation phase (K), the agency accumulated cassava, corn, and pine sap , leading to a decrease in forest diversity and ultimately impacting the ecosystem's ability to withstand disturbances (Kendal *et al.,* 2014).

New order period (1965-1998)
State's forest management

Soekarno's political influence diminished, resulting in the transition of leadership to Suharto, who held the position of commander of the armed forces during that period. During his regime (1966-1998), Indonesia experienced impressive economic growth but faced devastating ecological destruction. The destruction was mainly attributed to the Right of Forest Utilization, which the central government granted to timber companies and foreign investors (Isnaeni, 2021). Exercised by the Forest Service agency, which later became the SFC, this right imposed strict forest control and disregarded local farming traditions. The agency perceived the villagers as lacking knowledge and understanding about the ecological benefits provided by the forest, and frequently resorted to military intervention to combat the issue of illegal logging. In 1983, the SFC, which was once under the Ministry of Agriculture's administration, became an independent institution. The SFC continued the Dutch control and routine patrols and, in the 1970s, promoted community forest programs to alleviate poverty and end forest encroachment. These, however, were hardly successful as they focused on lessening people's reliance on the forest (Peluso, 1992). In 1960, after a significant eruption, the authorities mandated the relocation of residents living in close proximity to the peak of the volcano. The state annexed abandoned settlements and farmlands, replacing them with pine forests, and mandated those who remained in the villages to tap pine and hand in the sap to the agency. From 1988 to 1993, the National Agriculture Enterprise Unit launched a reforestation program. During the initial three years, people had the opportunity to cultivate various crops amidst pine forests and gather grass by assisting in tapping pine trees. In the 1990s, the government brought in dairy cows to the area, enticing locals to engage in livestock farming of this kind. To support this sector, the agency introduced new grass species such as *brachiaria mutichathat* into the forest. In Cangkringan, the Yogyakarta Forestry Agency Unit also introduced an exotic tree species, *acacia decurrens*. During this time period, reforestation was implemented alongside an agreement that allowed individuals to enter the state's forest areas in return for their efforts in cultivating the state's crops. These forest areas, known as sanggeman by the locals, can be passed down to future generations of farmers, granting them the right to utilize the land. When dividing the land tracts among farmers, on-field supervisors were obliged to handle the process (Atmojo *et al.*, 2018).

Local forest management

Under the reforestation program, the forest composition was dominated by the state's tree species such as teak, pine, and *acacia decurrens*, intended for large-scale production and commercialism. The responsibility of providing the seeds fell upon the agency, while individuals were obligated to engage in cultivation activities in return for their entitlement to sow crops beneath tree stands and gather grass, fuelwood, or leaves from trees that had reached a minimum age of ten years. In running the reforestation, the agency determined when trees should be cut off. Certain crops such as papaya and banana that could impede the trees' growth were prohibited from being cultivated. In addition to overseeing plant species, the agency also regulated the trade of forest commodities. As an illustration, individuals who sell the state's cultivated species on their privately-owned farmlands are obligated to remit a certain fee to the agency. Forests during this regime were marked by expansive deforestation for timber business and the use of military support to address illegal logging. For example, forest police caught-handed and imprisoned a resident who cut bamboo in the forest. The fear instigated by this specific case deterred individuals from breaking forest regulations. Despite the agency's efforts to encourage community initiatives during this time, the deep-rooted skepticism towards the government resulted in the failure of these programs (Peluso, 1992).

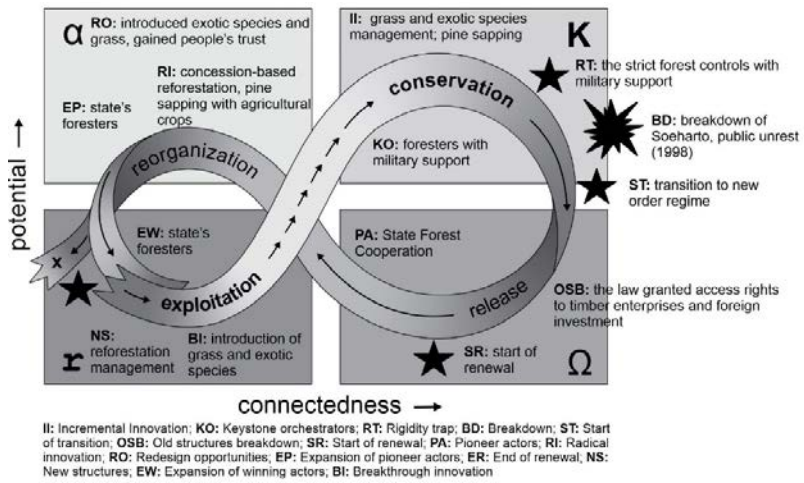


Fig. 7: The SES adaptive cycle during the new order regime

Developing the adaptive cycle model

In contrast to the previous leader's emphasis on economic nationalization, Suharto implemented a policy that welcomed foreign investments in Indonesia and prioritized export-driven economic development. In the adaptive cycle (Fig. 7), the fall of Soekarno thus would mean the collapse of his policy of economic nationalization and the rise of capitalism; marking the release phase (W). The State Forest Cooperation was an innovative entity that significantly contributed to the restructuring of reforestation initiatives through the advocacy of pine cultivation and other economically viable crops. In the 1990s, dairy farming saw a rise, and the state introduced fine grass into the forest to support it. *Acacia decurrens*, which could be transformed into charcoal, were also introduced. During the exploitation phase (r), farmers were granted permission to grow grass beneath the state's tree stands, thereby substituting the previously prevalent crops like cassava, corn, and Arabica coffee. As people exploited grass for fodder, the state accumulated pine saps and agroforestry products towards the conservation phase (K). However, the strict forest controls over labor, land, and species during Suharto's regime created rigid agroforestry management practices,-which formed a monoculture forest and reduced the forest diversity. This, consequently, increased the SES vulnerability of Mt. Merapi to natural disturbances.

Reformation period (1998-2004)

State's forest management

During the new order regime, Indonesia faced an economic crisis that led to public unrest. This ultimately caused Suharto's resignation in 1998. Nevertheless, the period of transition was riddled with uncertainties as political machinations persisted in influencing market-oriented strategies that capitalized on the utilization of natural resources (Ulum, 2020). In 1999, the Indonesian government passed Decree No. 41, which mandated that all forests be managed by the state for the prosperity of the entire population (Ferdaus *et al.*, 2014). State-owned enterprises were responsible for overseeing the management of production forests in various regions including Sumatra, Kalimantan, Sulawesi, Nusa Tenggara, Maluku, Papua, as well as certain areas of Java and Bali. In the case of Mount Merapi, forest management was split between two agencies operating in separate jurisdictions. The Yogyakarta Provincial Agency of Forestry and Plantation was responsible for managing the production forest, which covered an area of 13,851 ha. The Ministry of Forestry's General Directorate of Forest Protection and Conservation was responsible for managing the protected forest, which covered an area of 2,057.90 ha. During Susilo Bambang Yudhoyono's administration, forest management was marked by tensions between the state and the people. This was particularly evident with the enactment of the Ministry of Forestry's

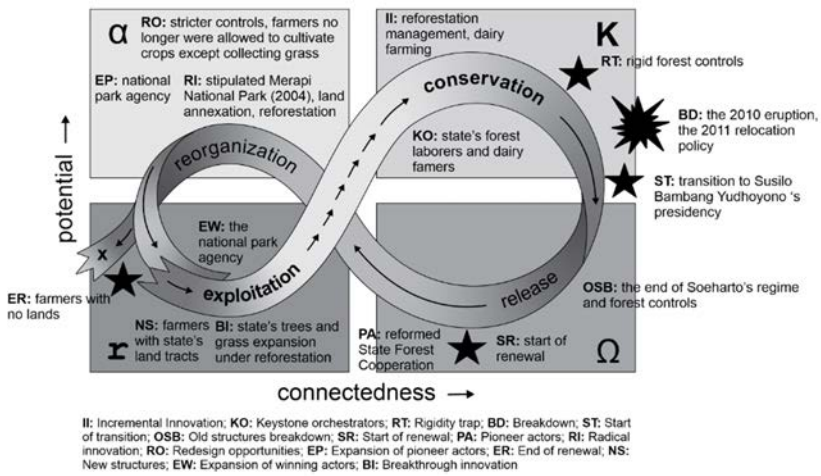


Fig. 8: The SES adaptive cycle during the reformation period

Decree No. 134/Menhut-II/2004, which designated Mount Merapi forest as a national park. This decree was intended to address ecological degradation in the Nature Reserve Plawangan Turgo, sedimentation of two river streams, volcanic eruptions, and illegal sand mining. Nevertheless, inadequate communication and a failure to engage with the local community resulted in apprehensions that the policy would impose additional limitations on their long-standing reliance on the forest.

Local forest management

In 2004, the national park decree caused public unrest because the government did not properly inform them about the plan, and the community was not involved in the decision-making process. In order to contest the decree, individuals collaborated with environmental advocates and established communal forums (Hidayat, 2009). In 2006, there was a major eruption that caused the collapse of a volcano's lava dome. This resulted in deadly pyroclastic flows that traveled southeastward for 4 km towards the Gendol Valley. Consequently, the neighboring villages suffered significant destruction, leading to the displacement of approximately 15,000 individuals from their residences. However, despite the evacuation orders, a few individuals, along with their livestock, chose to remain steadfast and refused to abandon their homes (Wilson *et al.*, 2007; Donovan *et al.*, 2012). The eruption also caused damage to major parts of the national park and created arid land that was suitable for the growth of the exotic species, *Acacia decurrens.* Studies suggest that this species could eventually grow into a pure stand and become weeds, thereby preventing the growth of native species. Consequently, the invasion of this species has altered the original composition of the forest, which was once dominated by endemics such as *schima waliichi* (BLH, 2020). The local informant contended that prior to the eruption, long-tailed macaques had access to a wider range of forest foods, linking this issue post-eruption with the habits of these primates. Among the native food plants the informant referred to are *Gnetum gnemon sp., Ficus Variegata sp.,* and *Musa acuminata, sp.*

Developing the adaptive cycle model

In the reléase phase (W), the fall of Soeharto's regime was marked by deforestation, which increased at an alarming rate (Isnaeni, 2021). This problem was partly attributed to the environmental injustice that local farmers had experienced prior to Susilo Bambang Yudhoyono's administration (Fredaur et al., 2014) (Ferdaus et al., 2014) (Fig. 8). During the transition to the reorganization phase (a), the state took action by restructuring forest management and enlarging the area of protected forests. As part of this effort, Mount Merapi was officially designated as a national park in 2004. This designation meant stricter forest controls imposed by the state to protect the forest from local access. Consequently, demonstrations emerged across the region, leading to the formation of public

platforms such as the People Caring Merapi Forum and the Merapi's Victims Forum. People accused the government of wanting to annex their farmland and further marginalize their rights over the forest. The government finally allowed people to continue accessing the forest, which helped ease the tension between the people and the government.

During this phase, the government implemented changes to the management of forests and the granting of reforestation concessions. The objective was to engage local farmers in the cultivation and supervision of the state-owned trees within the national park. As an incentive, these farmers were granted access to the forest and permitted to utilize its resources, such as grass and dry wood found beneath the tree stands. The state through the Mount Merapi National Park Agency played a pioneering role in expanding forest control towards the reorganization phase. However, the state's vision to expand forest controls faced resistance from the people. In the exploitation phase (r), the state continued exploiting forest lands and people to preserve the forest, particularly, after the 2006 eruption which had significantly damaged the forest lands. The event forced the state to further accelerate reforestation which would mean a demand for a large number of laborers. As the conservation phase (K) approaches, laborers, land tracts, and predetermined species are accumulated under the stricter reforestation procedure. These rigid forest controls, much like those in the previous periods, may potentially degrade the resilience of Mount Merapi's ecosystem and the community, particularly in the face of unpredictable disturbances such as eruptions.

Postreformation period (2004-onward)
Developing the adaptive cycle model

The volcanic eruption in 2010 resulted in the total breakdown of the strict regulations enforced by the national park officials. Consequently, the emphasis transitioned from preservation to the recovery stage of the adaptive cycle (Fig. 9). Almost 43% of the forest land covering an area of nearly 6,410 ha was severely damaged. Experts estimated that it would take around 40-50 years to fully restore the forest land (Zakaria, 2010). During the release phase (W), the eruption caused significant damage to the forest and had a traumatic impact on the people who lived there. Out of the 450 ha of land damaged on the slopes of the volcano, only about 20 percent had been restored by 2017 (Suryawan *et al.*, 2015; Hapsari, 2017). Throughout the reorganization phase,

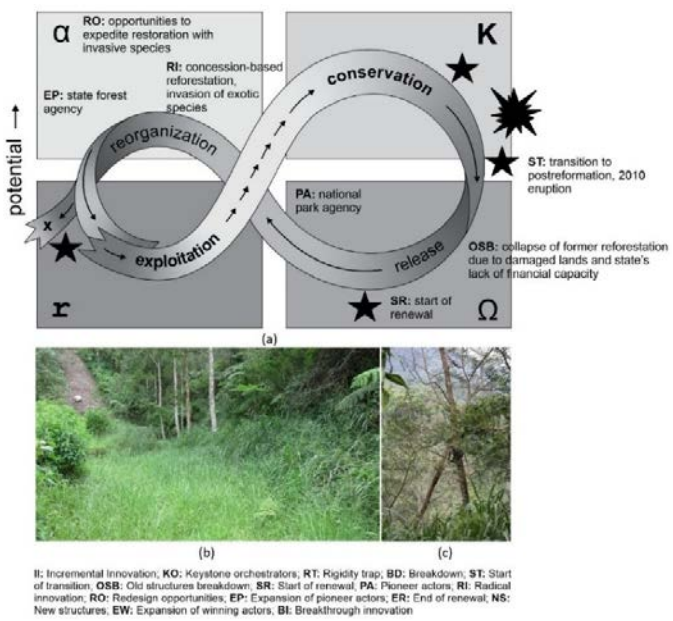


Fig. 9: The SES adaptive cycle during the reformation period (a), monoculture forest (b), and long-tailed *macaques* observed in the southern flank (c).

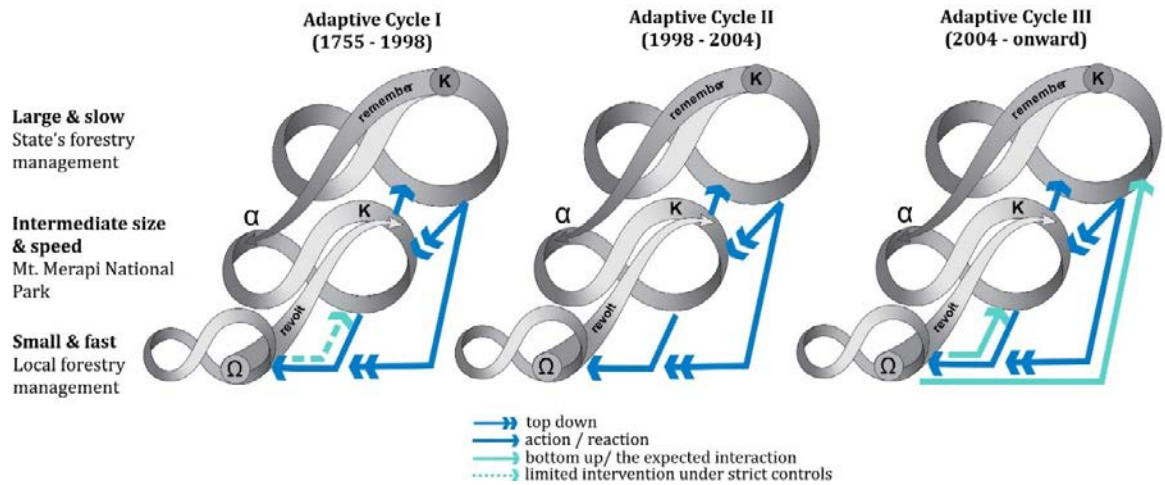


Fig. 10: The SES adaptive cycle during the reformation period

the government sought to expedite the reforestation process. However, due to financial constraints, it had to be divided into phases. Authorities decided to allow the invasive species, *acacia decurrens,* to expand in the damaged áreas. Prior studies show that damaged lands in the Cangkringan and Pakem-Turi resorts in Yogyakarta have become monoculture due to the rapid invasion of *Acacia decurrens*, which was introduced by the state in the 1980s (Atmojo *et al.*, 2018). In Resort Cangkringan, the non-indigenous species prevailed over the native trees, compelling the long-tailed macaques to relocate towards the lower elevation and venture into agricultural lands situated on the southern side in search of sustenance (BTNGM, 2010; Utomo, 2022). The agency's attitude of allowing the species' invasion has not only threatened forest biodiversity but also water availability that has long supported the adjacent communities (FAO, 2022) and as described by a local informant, damaged grass needed by their domestic cattle.

Identifying maladaptations

The adaptive cycle models of Mount Merapi throughout political regimes indicate that the colonial-style forest control embedded in concession-based reforestation had created a rigidity trap in the SES's resilience (Fig. 10). These models show the heuristic dynamics of SES in Mount Merapi across spatial scales (local community, Mount Merapi region, state) and temporal scales (colonial-new order, reformation-postreformation, and post-reformation-onward). The division of these models' periods into three categories was based on two significant events: the national park designation in 2004 and the eruption in 2010, both of which had a substantial impact on forest management and interactions between people and the land.

Model I (colonial-new order) highlights the significant impact of colonialism on local farming traditions in the forest. Before the colonial era, the traditional ruler decentralized forest management that enabled the locals to practice shifting cultivation with slash-and-burn techniques. These helped optimize soil fertility, enrich forest biodiversity, and improve its natural capacity to rejuvenate after eruptions. When the Dutch arrived, these traditions were entirely excluded from forest management. The Dutch implemented a system of scientific forest management in order to utilize the forest resources for their own benefit. As part of this strategy, they declared Mt. Merapi as a protected forest area. Reforestation was extensively carried out to preserve the forest resources and the rules they imposed to facilitate this include determining the types of crops and the plantation techniques. The colonial rules embedded in reforestation represent the "remember" feature of the large and slow system (state forest management) which influences the reorganization phase of the small and fast system (local traditions).

Table 7: Comparing the research results with prior studies concerning traps in SES

Case	Problems	Results/ findings	Sources
Provinces in Cameroon	French colonial legacy limits local access to forests Economic crises Illegal logging Decentralization issues	Decentralized forest management must ensure the security of transfer, recognize institutional choices, show accountable representation, and equally distribute costs and benefits	Oyono *et al.*, 2007
Forests in semi-arid regions in Asia and Africa	Scientific forestry imported by Europeans disregarded local practices in semi-arid forests. Lack of forest resilience	The colonial legacy remained via the principles of demarcation of the forests and strict silvicultural rules. Power transfer to the local level is limited by technical problems, ineffective, and partial. Forest management requires a landscape approach that encompasses multiple systems and actors	Gautier *et al.*, 2015
Akwapim-Togo mountain range, Ghana	Colonial rules weaken customary institutions. Rural populations were trapped in persistent resource dependence. Forest management is constrained by a lack of capacity to enforce policies, tension between customary and state, and ambiguity in resource tenure	Governance reform should improve: linkages between customary and state institutions, new and nonlocal actors, investments in capacity building and training	Baker, *et al.*, 2018
Gabon, Central Africa	French and English colonial and current laws forced the shift from customary closed-access to open-access systems of bushmeat extraction Wildlife declines. Erosion of local hunting governance system.	Decentralized management should consider: an understanding of the history of the governance of natural resources via long-term engagement to gain trust the heterogeneous nature of local communities	Walter and Hamilton, 2014
Central Coast First Nations, Canada	Social marginalization and environmental degradation are driven by colonial practices. The loss of indigenous management rights and stewardship capacity	Integrate indigenous knowledge into management plans and education systems, cultural revitalization, and recovery of depleted species	Eckert *et al.*, 2018

Consequently, people were compelled to undergo institutional adaptations, transitioning from a nomadic lifestyle to that of settled farmers, and further transforming from conventional farmers to laborers in plantations. Responding to colonial strict rules, people resisted by illegally logging and stealing wood from the forest; representing the 'revolt' feature of the adaptive cycle. Model II (reformation-post-reformation) illustrates the major social and environmental implications of Mount Merapi's designation as a national park following the enactment of the Ministry of Forestry's decree in 2004. The agency has implemented more stringent regulations for forest management, which now prohibit the cultivation of crops and the collection of plants other than grass within the state's tree stands. People are bound to the concesión that they must cultivate and manage the state's tree species in exchange for the grass-collecting right. The impact was exacerbated by violent eruptions in 2006 and 2010, which forced the government to expedite reforestation. To solve its lack of financial capacity, the government continued reforestation, divided it into phases, and decided to let the exotic *acacia decurrens* invade the damaged lands. Consequently, the decrease in forest diversity resulted in the encroachment of long-tailed *macaques* into agricultural areas. Model III (post-reformation-onward) shows the state's reformed policy, which envisioned decentralized forest governance. The failures of reforestation forced the state to transfer forest management from the central government to regional and local governments, private sectors, non-governmental organizations, and community-based

organizations (Nuesiri, 2016). To facilitate this, the National Park Agency has developed two models of community partnerships. The initial model focuses on enhancing the utilization of natural resources beyond the boundaries of the national park by providing support to the local community through the implementation of the "mentored village" initiative. The second model aims at legitimizing people's *ngarit mugut* practices in the forest by incorporating these in the national park map under the label "traditional zone." It is expected that these partnerships can help gain people's trust and motivate their voluntary participation in reforestation through silviculture (Atmojo *et al.*, 2018). Nevertheless, the stringent forest regulations imposed during the colonial era in relation to reforestation have fostered a sense of skepticism towards the government, thereby highlighting the inflexibility of the system and the entrapment in poverty. The former is represented by the highly connected, self-reinforcing, and inflexible state (Holling and Gunderson, 2002; Tidball *et al.*, 2016) of the national-level forestry systems via concession-based reforestation, which exploited laborers and lands for water and ecological preservation and consequently limited the local capacity to adapt to unexpected changes. Reforestation, while aiming to restore degraded forests and improve watershed functions, can have unintended consequences on the environment due to the stringent regulations on species selection, land use, and labor practices. Most reforestation in Southeast Asia relies on exotic species such as *Eucalyptus sp.,* pine, and *Acacia sp*., due to its readily available seeds from international seed banks and long-established nursery protocols. Planting exotic species monocultures may change natural habitat conditions and degrade biodiversity (Chechina and Hamann, 2015), which in this case materialized through the invasion of long-tailed macaques after the 2010 eruption. Strict forest controls embedded in reforestation, the legacy of the colonial era, that impoverished local people would promote distrust of the government. The poverty trap resulting from this legacy often motivates forest crimes at the local level, such as illegal logging, stealing wood (Peluso, 1992), and resistance to the state, such as avoidance from reporting forest crimes to authorities. In the absence of local trust, the government would fail to engage people in reforestation programs. The poverty trap can also be associated with community resources beyond just the economy, including traditional knowledge. The historical breakdown of relationships between people and forests due to colonial influences has led to the decline of indigenous forestry knowledge. However, local people and land interaction is still sustained through *ngarit mugut* and the cultural rite of *Labuhan Merapi* in the protected forest zone, which is aimed at appeasing deities to protect villages from disasters. In addition to these, individuals who prioritize environmental preservation have also rallied others to safeguard the forest and its biodiversity through the establishment of community organizations such as the Kaliurang Village Environment Awareness Community and the Women's Agriculture of Merapi Asri Group. To address the systemic traps in the SES' dynamics of Mount Merapi's forest management, this study recommends the need for scholars and policymakers to consider the use of panarchy framework as it has been evident effective in numerous studies (Table 3) in facilitating a comprehensive understanding of the complex dynamics of SES and factors interplayed. The comprehensive adaptive cycle proposed by Boyer and the systematic methodology developed by Boonstra and De Boer, as utilized in this research, have the potential to enhance the ability to achieve the stated objective and minimize the risk of neglecting crucial factors in statistical analysis. Using these tools, this study found SES problems are highly associated with colonial legacy. To address them, prior studies (Table 7) that also explained similar SES problems recommended decentralized forest management as the strategy. Decentralization is advantageous because it provides effective service delivery, reduces administrative transaction costs, increases local participation, facilitates stronger powers for local governments, develops a sense of responsibility amongst local actors, and promotes equity in access and profits as well as environmental sustainability (Oyono *et al*., 2007). However, it is imperative to approach the transition with careful consideration. In certain regions such as Dharmasraya and West Sumatera, numerous traditional elites possess authority over the forested areas, claiming them as customary land. These elites have been observed to sell the land to interested buyers at considerably reduced rates (Mutolib, *et al.,* 2024). In Jharkhand, India, decentralization leads to

socioeconomic disparities where the wealthy groups gain greater benefits from the program than the poor. Such unexpected drawbacks signal the need for state intervention to a considerable degree (Balooni and Inoue, 2007) and an in-depth understanding of the local history, knowledge, and cultural characteristics (Walter and Hamilton, 2014; Gautier *et al.*, 2015; Eckert *et al.*, 2018) and assurance of secure and effective transfer of power (Oyono *et al*., 2007; Baker, *et al.,* 2018).

Reforestation through silviculture that considers local knowledge of forestry and endemics has been considered by Mount Merapi National Park Agency (the state) since 2012 and needs to be encouraged. Nevertheless, it is imperative that the procedure guarantees the active involvement of the community throughout every stage, starting from the initial inventory, continuing through the implementation, and concluding with the monitoring phase.

CONCLUSION

The study confirms the assumption that the strict, bureaucratic, and inflexible colonial controls (i.e., rigidity traps) had negative implications on the resilience of Mount Merapi's SES. In panarchy models, the strict colonial controls represent the cycle's "remember" feature; a legacy that provides a blueprint of forestry procedure with little regard to "novelty" and "surprises". The local level is plagued by the perpetuation of "poverty traps" due to the legacy, making it extremely challenging for individuals to enhance their livelihoods, foster the growth of forestry practices, and acquire expertise in disaster risk management. The oppressive scientific management via via controls of forest species (e.g., *Acacia decurrens*) reduced forest diversity, leading to the failure of the forest (i.e., intermediate scale) to naturally rejuvenate after the eruption. The local community's gradual recuperation (i.e., at the local scale) and the forest's restoration (i.e., at the intermediate scale) act as the cycle's "revolt" that compelled the state (i.e., at the large scale) to restructure the forest governance, shifting it from a top-down approach to a bottom-up approach. Based on these empirical findings, the study recommends the decentralization of forest governance whose transfer of rights to local communities should be secure and effective. Decentralizing forest governance offers a multitude of advantages, including the promotion of local stewardship and the preservation of forest diversity. The novelty of this study lies in its adoption of Boyer's detailed adaptive cycle and Boonstra and De Boer's systematic methodology, which have not yet been considered in prior studies but have enabled this study to interrogate factors contributing to Merapi's slow recovery by examining the SES dynamics comprehensively and systematically. Policymakers should carefully contemplate the utilization of such tools in relation to panarchy when embarking on future initiatives aimed at tackling environmental issues. Despite the limitations, this study has effectively showcased the capability of *panarchy* in identifying maladaptations within social-ecological systems in a postcolonial context. First, this study relied mostly on literature reviews, signaling the need for future studies to integrate varied methods such as focus group discussions besides interviews and observations. Second, the lack of written records of forest management, spatially and non-spatially, warrants the need for more in-depth interviews and rigorous documentative reviews. In conclusion, this study focused on the comprehensive and theoretical notion of panarchy, which makes it susceptible to concerns regarding its reliability and validity. In order to tackle this matter, forthcoming studies should contemplate the utilization of mixed methods that combine qualitative and quantitative methodologies.

AUTHOR CONTRIBUTIONS

C.D.A. Depari has been responsible for all the current work, including writing, work plan preparation, defining the bibliographic search, searching the bibliography, selecting the relevant references, coding the references, writing the initial draft, synthesising the manuscript, and revising the final version.

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CONFLICT OF INTEREST

The author declares that there is no conflict of

interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
BD	Breakdown
BI	Breakthrough innovation
EP	Expansion of pioneer actors
ER	End of Renewal
EW	Expansion of winning actors
II	Incremental Innovation
KO	Keystone orchestrators
OSB	Old structures' breakdown
NS	New structures
PA	Pioneer actors
RI	Radical Innovation
RO	Redesign opportunities
RT	Rigidity traps
SES	Social-ecological systems
SFC	State forest cooperation
SR	Start of renewal
ST	Start of transition
WW II	World War II

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