Vulnerability of communities living on peatlands to climate change and peatland degradation: A case study in Tumbang Nusa Village, Central Kalimantan, Indonesia

Niken Sakuntaladewi[1], Daniel S. Mendham[2], Subarudi[3], Yanto Rochmayanto[4], Shokhrukh-Mirzo Jalilov[2], Deden Djaenudin[5], Rachman Effendi[1], Satria Astana[5], Ari Wibowo[6]

[1] Research Centre for Ecology and Ethnobiology, BRIN, Cibinong, Bogor, Indonesia
[2] Commonwealth Scientific and Industrial Research Organisation (CSIRO), Black Mountain, ACT, Australia
[3] Research Centre for Population, National Research and Innovation Agency (BRIN), Jakarta, Indonesia
[4] Directorate of Environment, Maritime, Natural Resources, and Nuclear Policy, BRIN, Jakarta, Indonesia
[5] Research Centre for Behavioural and Circular Economics, BRIN, Jakarta, Indonesia
[6] Centre for Standardisation for Disaster Management and Climate Change, Bogor, Indonesia

SUMMARY

Tropical peat swamp forest provides many ecosystem services to communities of local people in Indonesia, as well as to national and international communities. However, many Indonesian peatlands are degraded and thus susceptible to burning in the dry season and flooding in the wet season. Peat fires are a local, regional, national and international disaster, but the people most affected are those who live and work on peat at ground level whose livelihoods, health and children's education are highly vulnerable to such disasters. This article aims to assess the vulnerability of people and communities living on peatlands, and to understand the factors causing community vulnerability. We focused our study on the peat-dominated Tumbang Nusa Village in Central Kalimantan. The primary data for this study were collected by field observation and interviews with 52 villagers who were selected through stratified random sampling. We aimed to understand livelihoods, locations of the villagers' activities, agricultural technology applied in peatlands, community efforts to mitigate climate disasters, and participation in development programmes. Vulnerability was calculated as a function of exposure, sensitivity and adaptive capacity, using IPCC methodology. The results show that the Tumbang Nusa community has a high degree of vulnerability, primarily owing to fire and flood. Additionally, the community relies on ecosystem services from a damaged environment and employs land management practices that are often unsustainable. Understanding the causes of vulnerability will help improve rural communities' development programmes and the design of empowerment programmes to reduce vulnerability.

KEY WORDS: adaptive capacity, exposure, peatlands, rural communities, sensitivity, vulnerability

INTRODUCTION

While peatlands occupy only about 3 % of the land surface on Earth (Clymo *et al.* 1998, Blodau 2002), they play an outsized role in climate regulation through being an extensive, but vulnerable, store of carbon. South-east Asian peatlands provide tangible benefits to local communities in the form of both timber and non-timber forest products including food, medicine, resin and fish. They also provide broader public benefits in the form of ecosystem services such as carbon storage and regulation of water flows (Thornton 2018, Jessup *et al.* 2020). Peatlands are also home to unique and endangered species such as orangutan (The Orangutan Project 2023, Wetlands International 2023), and provide important habitat for migratory birds (UNEP 2022). Peatlands typically take hundreds or even thousands of years to form, but once they are drained they become susceptible to fires, subsidence and oxidation, resulting in globally significant carbon emissions.

Indonesia has 13.43 million hectares of peatlands, representing about 10 % of the total land area of Indonesia and around 36 % of the global area of tropical peatland. These peatlands are mainly peat swamp forests distributed across the islands of Kalimantan (Borneo), Sumatra and Papua (Nurbaya & Efransjah 2020, Anda *et al.* 2021) and store about 28 gigatons (Gt) of carbon or three times the total carbon stored in all forests in Indonesia (Warren *et*

al. 2017). Since 1969, peatlands in Indonesia have been widely converted to a range of land uses (e.g. agriculture, plantations, villages, offices, roads) for purposes of development and meeting the needs of an increasing human population. The drainage and clearing of peat swamp forests has resulted in large areas of dry and degraded peatland that nowadays releases 30–60 % of Indonesia's annual greenhouse gas (GHG) emissions, depending on fire severity (Hooijer *et al.* 2006). Therefore, activities to reduce or prevent GHG emissions from peatlands are important and potentially cost-effective options for climate change mitigation (Jessup *et al.* 2020). However, Indonesia still faces natural disasters and continued degradation of its natural resources including peatlands (Jessup *et al.* 2020). One of the reasons is the choice of land use by local people and communities, for whom environmental considerations are just one of several competing priorities, and livelihoods are often a more pressing issue than environmental services (Fleming *et al.* 2021, Jalilov *et al.* 2024).

Utilisation of peatlands for traditional agriculture and plantations (at both large and small scales) typically requires that the water table is at least 60 cm below ground level. The excavation of canals and subsequent drying of surface peat results in extensive peat soil decomposition and increased fire risk, resulting in massive fire events that have affected millions of hectares of land. Fires on this scale produce enormous GHG emissions and economic losses, with the biggest fire event in 2015 resulting in economic losses of more than USD 16 billion (Glauber *et al.* 2016). It is becoming more widely recognised that the benefits of peatland restoration far outweigh the costs (Kiely *et al.* 2021). However, the social benefits accrue mostly to the broader national and international community rather than to the communities on the ground whose livelihoods are directly linked to peatlands, and who are the most vulnerable to both peatland degradation and fire as well as to changes in the peatland and in policies surrounding it. This is the lived experience of the people of our study village, Tumbang Nusa in Central Kalimantan.

The purpose of this study was to understand and quantify the vulnerability of the Tumbang Nusa community in relation to their sources of income, their choice of adaptation strategies to survive under changing climate conditions with uncertain patterns of change, and the impact of climate change of unknown magnitude. The general aim was to achieve better targeting of support and assistance, especially for restoration of peatland areas, to increase resilience and reduce vulnerability in the community.

THEORETICAL FRAMEWORK

Climate change and vulnerability are two interrelated factors that affect the lives of millions of people around the world. Climate change refers to long-term changes in the Earth's climate system such as rising temperatures, melting ice caps, sea level rise and extreme weather events. Climate change increases the exposure and sensitivity of communities to hazards such as droughts, floods, heatwaves, storms and diseases. These hazards can undermine the livelihoods, health, security and wellbeing of people, especially those who are already marginalised or disadvantaged, making them vulnerable to climate change.

There is no consensus on the meaning of vulnerability (Gallopín 2006, Smit & Wandle 2006). In a climate-change context, vulnerability is defined as the degree to which a system is susceptible to, or unable to cope with, its adverse effects (e.g., extreme weather-related events); it is also a function of the character, magnitude and rate of climatic variation to which a system is exposed, and the system's sensitivity and adaptive capacity (IPCC 2022). Consequently, vulnerability depends on the buffering capacity of the landscape and its inhabitants and the intensity of shocks or hazards that exceed this capacity. While the shocks or hazards cannot be controlled, the potential buffering capacity can be addressed (Van Noordwijk *et al.* 2011).

Smit & Wandel (2006) suggested that climate vulnerability comprises three important factors, namely exposure, sensitivity and adaptive capacity. Exposure refers to the nature and extent to which a system is affected by significant variations in climate; sensitivity is the degree to which a system is affected, either adversely or favourably, by climate-related stimuli; and adaptive capacity is the ability of a system to reduce potential damage, take advantage of opportunities, or cope with the consequences. Exposure and sensitivity are almost inseparable properties of a community and dependent on the interaction between community characteristics and attributes of the climate stimulus (Smit & Wandel 2006). Adaptive capacity embraces coping ability, management capacity, stability, robustness, flexibility and resilience. Adaptive capacity is also context-specific, formed by interdependent scales, latent or potential adaptation, beyond coping ability, and dependent on access to resources (Jakku & Lynam 2010). It varies from country to country, from community to community, among social groups and individuals, and over time (McDowell & Hess 2012).

Vulnerability also changes over time because multiple stressors, such as land scarcity and delayed

seasonal rainfall, demand the expenditure of household assets for adaptation, including natural capital (water and land), human capital (including labour), and financial, physical, and social capital (McDowell & Hess 2012). In order to reduce vulnerability, constraints on access to key resources must be addressed, allowing rural communities the flexibility to reduce their exposure and improve their adaptive capacity.

METHODS

Study area

The study was conducted in the village of Tumbang Nusa, Pulang Pisau Regency, Central Kalimantan Province (Figure 1). Tumbang Nusa covers an area of around 200 km^2, of which around 90 % has deep peat, typically 4–8 m thick. The remaining 10 % is mineral soil alongside the Kahayan River (BRG 2018). Key metrics of climate change effects on communities include changes and irregularities in the rainfall pattern (see Figure 2 for Pulang Pisau Regency) and temperature, with Marlina *et al.* (2021) finding that nearly all of their respondents in Pulang Pisau Regency had experienced a rise in temperatures over the past decade.

The village comprises around 270 families. Families in Tumbang Nusa traditionally lived alongside the river but, in 1975 and 2018, peatland along the Trans-Kalimantan Road (initially an unsealed track) was allocated to community members for free. Early interest was very low because of distance from the river and challenges with managing peatland for agriculture or plantation cropping (Sakuntaladewi *et al.* 2021), and because the community livelihoods were traditionally river-dependent (BRG 2018, YTS 2019) trade (YTS 2019) and transport. In 1995 the government commenced a programme to convert 1.5 Mha of peatland in Central Kalimantan Province into agricultural land (the Mega Rice Project, Figure 3), of which 30.4 % (446,575 ha)

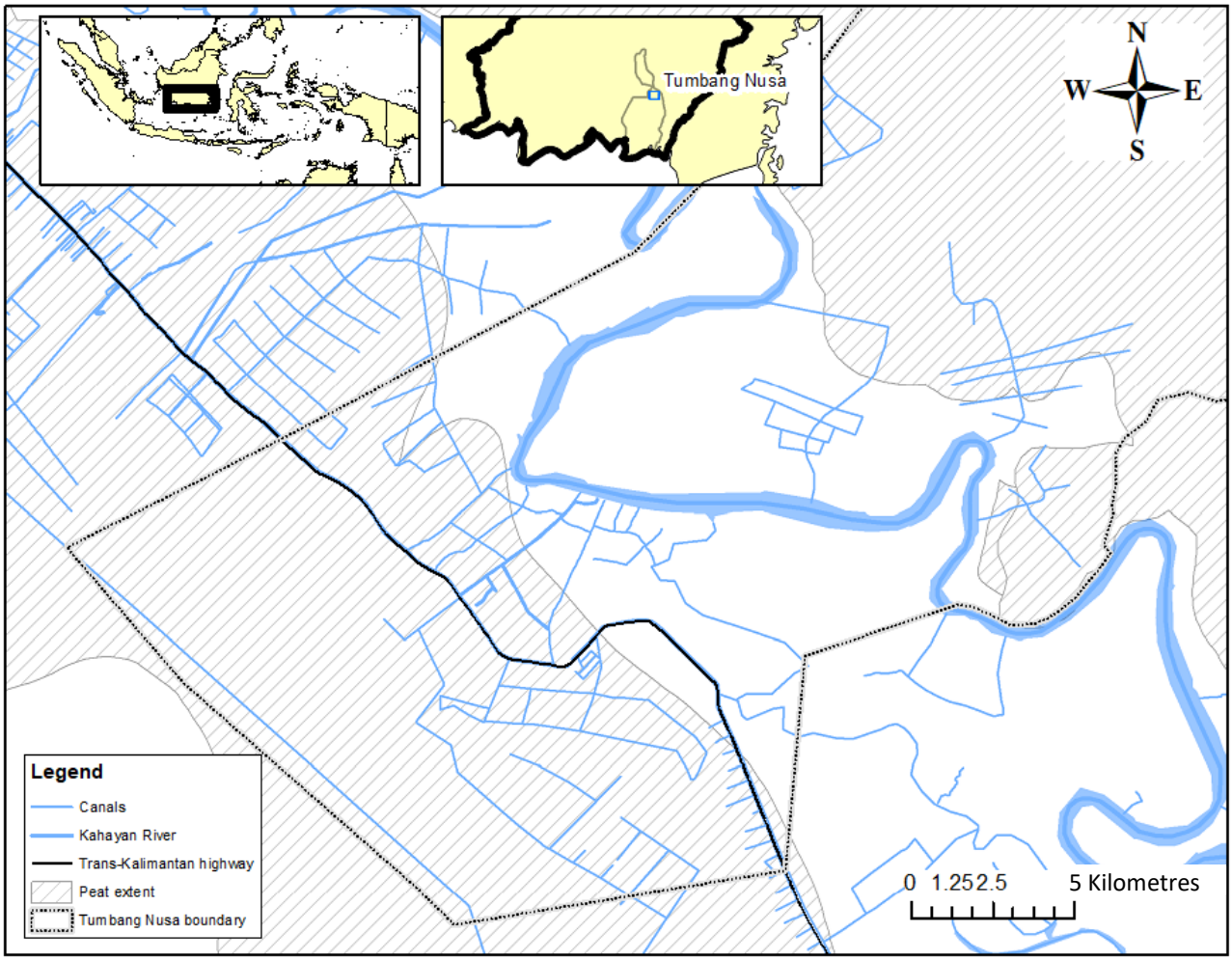

Figure 1. Map of Tumbang Nusa Village.

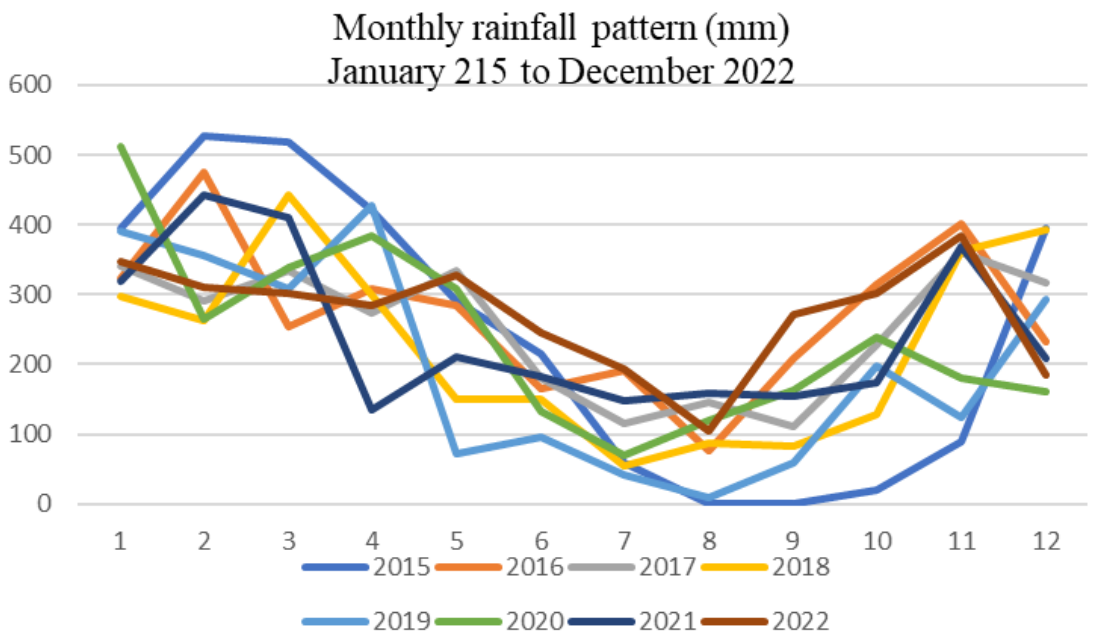

Figure 2. Monthly rainfall pattern in Pulang Pisau Regency from January 2015 to December 2022. Source: BPS (2023) (data processed).

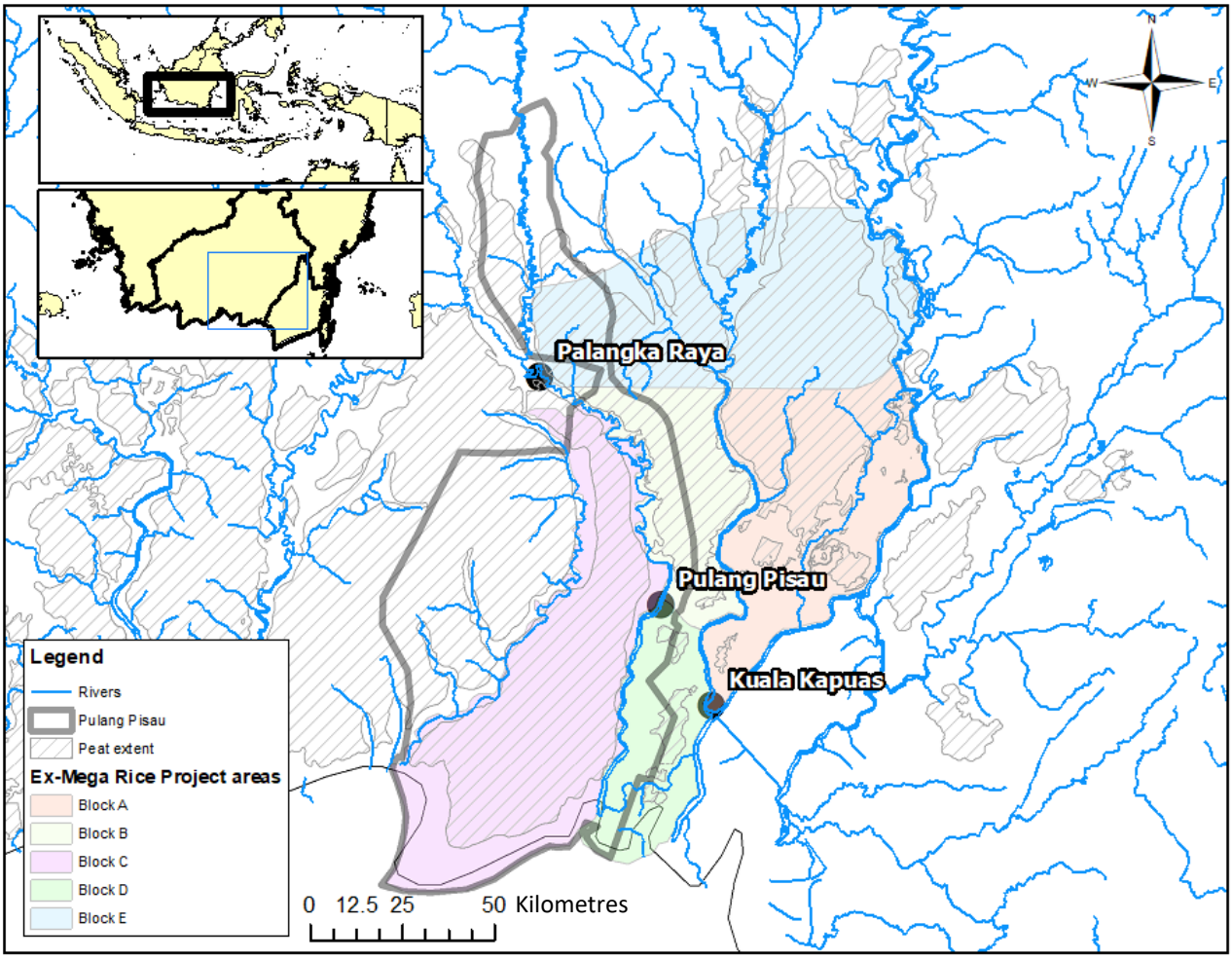

Figure 3. Maps of the ex Mega Rice Project (30.4 % or 446,575 ha were in Pulang Pisau District).

was located in Pulang Pisau District (KLHK 2020), within the same Peat Hydrology Unit (PHU) as Tumbang Nusa. Many canals were constructed to drain the Mega Rice Project area and many transmigrants were brought in to provide labour. Although this programme was unsuccessful and discontinued in 1998, some villagers have continued to experiment with techniques for cultivating peatland (Sakuntaladewi *et al.* 2022), including construction of a canal to connect to the existing canals on a Mega Rice Project area, approximately 2.5 km from their village.

Upgrading of the Trans-Kalimantan Road to a sealed highway and completion of the 10 km long Tumbang Nusa bridge in the village of Tumbang Nusa in 2014 have led to new economic opportunities and triggered higher migration from the river to the peatlands, with around 40 % of the village households now residing on peat, especially as traditional livelihoods near the river have become less attractive. Rattan and rubber plantations, as well as *purun* grass (*Lepironia articulata*) are abundant but as the selling price has generally been low (BRG 2018), they are economically unattractive. Families moving to peatlands typically earned their livelihoods by running a trading stall, some of them experimenting with farming and gardening on peatlands, and running or providing labour for nurseries. Another source of income that residents are strongly interested in is fishing. A participatory appraisal found that fishing was ranked as the primary source of livelihoods in Tumbang Nusa village in both 2009 (80 %) and 2019 (90 %) (YTS 2019). While a number of alternative livelihood programmes have been deployed in the village, very few of these have had any effect on the community (Mendham *et al.* 2024).

Of the peat area, about 20 % is currently utilised for economic purposes, housing and gardens (BRG 2018). However, many residents eventually sell peatland areas due to various challenges in managing them. It is estimated that 40–50 % of peatlands are already owned by outsiders and are not being managed. These unused peatlands are typically overgrown with shrubs, which can be a fire risk during the dry season.

Data collection and analysis

The study began in 2021 and continued until October 2023. The unit of analysis was the family. Fifty-two families were randomly selected from those living on mineral lands along the Kahayan River (35 families, 67 %) and on peatlands along the Trans-Kalimantan Highway (17 families, 33 %).

To assess vulnerability, a range of both quantitative and qualitative metrics were collected to understand the three aspects of vulnerability: exposure, sensitivity and adaptive capacity (Table 1).

Table 1. Data collected in Tumbang Nusa village to understand household vulnerability.

	Exposure	Sensitivity	Adaptive capacity
Primary data		• Type of family income (farming, fishing, trading, teacher, etc.) • Location of respondent's income (river, mineral land or peatland) • Potential source of income affected by floods and/or fires • Magnitude of the effect of floods and/or fires on their income	Community efforts towards: • Fire prevention/fighting • Flood control • Alleviating agricultural land drought • Technology applied to maintain their source of income
Secondary data	• Fire incidence between 2015 and 2020 • Flood incidence between 2019 and 2021 • History of peatland use in Pulang Pisau Regency and Tumbang Nusa Village	• Development programmes in the village	Related policy/government programmes: • Fire prevention/fighting • Flood prevention and control • Management of peatland drought

Primary data were obtained from respondents through in-depth interviews, and secondary data by field observations.

Vulnerability was assessed as a function of the exposure of respondents to climate change (climate exposure), how sensitive they were to climate change (sensitivity), and their capacity to adapt to climate change (adaptive capacity) (UNFCCC methodology; Kim 2018) as per the equation:

$$Vulnerability = Exposure + Sensitivity - Adaptive\ Capacity \quad [1]$$

Each data source was assessed and given a score of (-1) if the exposure, sensitivity or adaptive capacity was affected negatively by climate change, and (+1) if the factor would increase through climate change, reflecting the ability of the household to adjust to potential damage or seek opportunities to respond to the consequences of climate variability. Vulnerability was calculated per household. If the vulnerability score was greater than zero, the family was considered not vulnerable and if the sum was less than zero, then the household was considered vulnerable.

RESULTS

Characteristics of respondents

Of the 52 respondent families, 80 % were indigenous to the region and the remaining 20 % were immigrants from Sumatra, South Kalimantan or other districts in Central Kalimantan Province. Around 67 % of respondents lived on mineral soil along the Kahayan River and 33 % lived on peatland. Most of those living on peatland had relocated from the hamlet on the riverbank.

Respondents reported various sources of on-farm, off-farm and non-farm income. On-farm income includes earnings from mineral land, river and peatland and is typically seasonal; off-farm income includes processing to achieve additional value; and non-farm income includes all other activities that are not related to crop and livestock production, for example civil service, army/police or conducting a small business.

Approximately 38 % of the respondents relied solely on income from farming, 8 % solely on off-farm sources, 2 % on non-farm sources, 21 % on a combination of on-farm and off-farm activities, 19 % on a combination of on-farm and non-farm activities, and 12 % on a combination of on-farm, off-farm and non-farm income sources. Each family had daily expenses, medium term expenses (for example, celebrating Eid and paying vehicle taxes) and long-term needs (saving for children's education, buying a vehicle, getting married, as well as setting aside funds for emergencies such as medication costs and house repairs). Of the 52 families in our study, 12 % had just one type of livelihood, 42 % had two sources of income; 33 % had three, 12 % had four, and 2 % earned income from five sources.

Exposure to hazard

Land use practices that require the peat to be drained make it susceptible to fire in the dry season, flooding in the rainy season, and oxidation/subsidence at all times (Ikkala *et al.* 2021, Sakuntaladewi *et al.* 2021). Major fires occurred in Pulang Pisau Regency during the dry seasons of 2015 and 2019 (Figure 4). In the 2014–2015 fires, more than 50 % of village land was

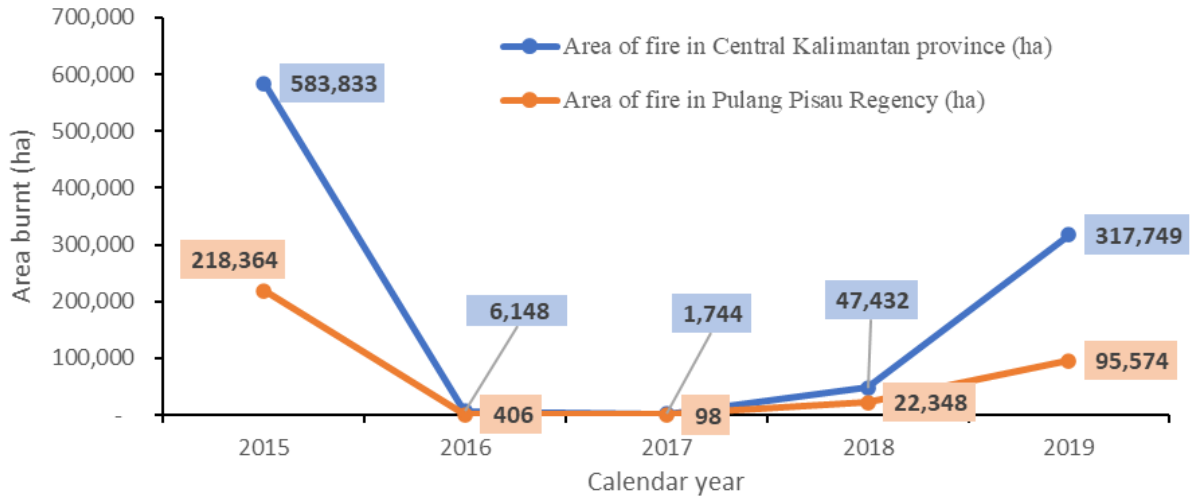

Figure 4. Areas burnt in Central Kalimantan and Pulang Pisau Regency, 2015 to 2019. Source: SiPongi (2019); data processed.

burned (BRG 2018), and in 2019 Tumbang Nusa was one of the starting points for fire. The main road connecting Central Kalimantan with South Kalimantan Province passes through the village and carries traffic at all times of the day and night. The respondents noticed that drivers and passengers often threw away cigarette butts that had not been extinguished. This village is also a destination for fishermen from outside the village, and fishing is a source of both accidental (e.g. from discarded cigarette butts) and non-accidental (e.g. clearing of vegetation around fishing holes) ignition. It is difficult to prevent those who pass through the village or visit to fish from starting fires, so the source of a fire is usually difficult to identify. However, all of the local fire hotspots are in areas that are accessible to people, and fires in this environment usually result from human actions.

In addition to fires, floods are a regular occurrence in Pulang Pisau Regency, including Tumbang Nusa Village. In Tumbang Nusa Village (Figure 5), eight flood events occurred between December 2019 and September 2022, each causing a period of inundation between 6 and 16 days and resulting in isolation from the road, submergence of dwellings on the banks of the Kahayan River, and loss of rambutan trees that were of fruit-bearing age as well as other agricultural crops and nursery stock. Floods can occur without warning during both the rainy season and the dry season, and vary in duration and intensity. In 2020 and 2021 there were flooding events at several times of the year. In response to these events, villagers received assistance from the government and NGOs, typically in the form of food and medicine.

Sensitivity ~ Financial security

Of the various sources of income noted by the respondents, there were that were used by more than 10 % of respondents (Figure 6). Each of these seven sources is described in more detail below.

Fishing

Of the seven sources of income, fishing in rivers, small lakes and canals was practiced by 34 respondents (65 %). Of those who had moved to live on peatland, 24 % still fished for livelihood purposes. Fish are considered to be quite abundant in the Kahayan River, with recent catches reported to be around 50 kg per visit in the wet season and 3–5 kg in the dry season (Sakuntaladewi *et al.* 2021). Fish can fulfil a family's protein requirement, as well as provide an income. Some fish products are marketed directly to neighbours, and some are bought by fish merchants in the village who sell on to Palangkaraya.

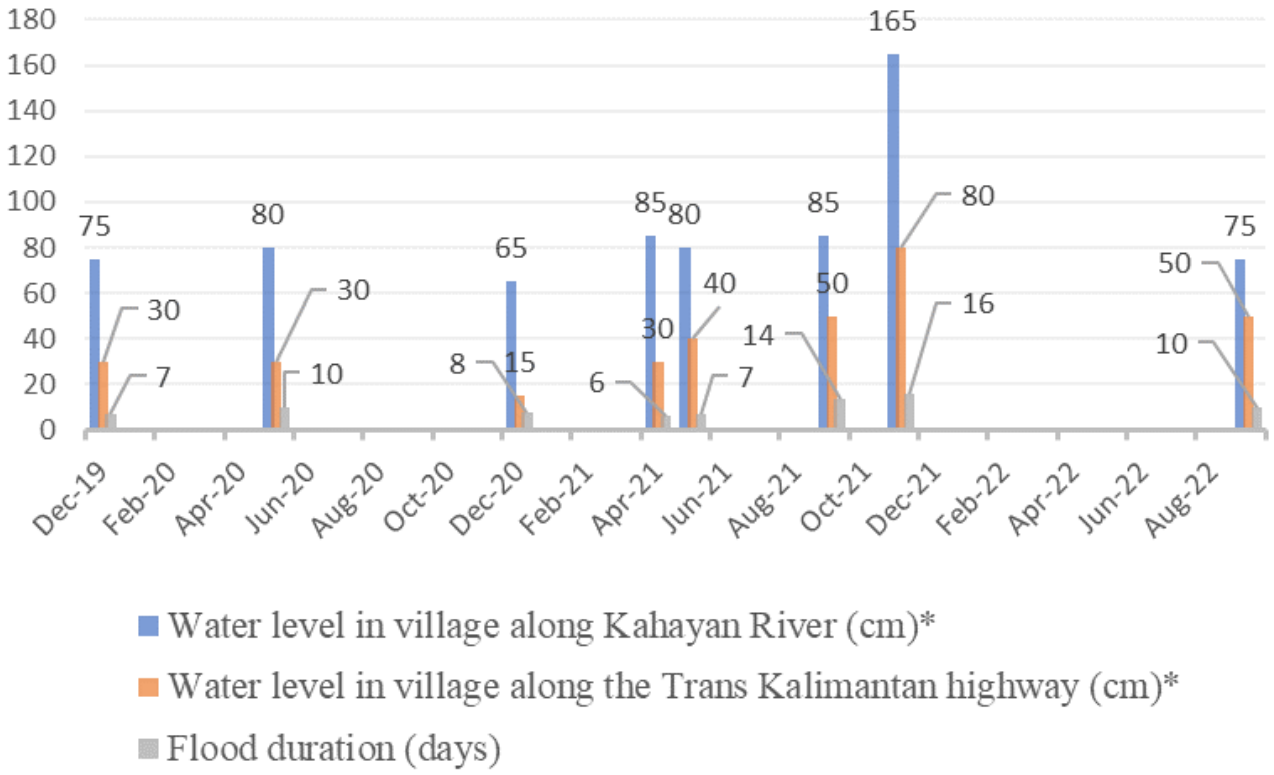

Figure 5. Flooding events in Tumbang Nusa between December 2019 and September 2022. The data are sourced from water level gauges in the village of Tumbang Nusa.

Recently, it was felt by respondents that income from fish was starting to decline because of overfishing (due to the unsustainable practice of electrocution) and increased vegetation growth in spawning ponds - with whole ponds sometimes becoming overgrown - owing to the ban on fire usage for clearing peatlands.

Trading

Around 14 households (27 % of respondents) earned income from trading in necessities, snacks, food and drinks. Of the 14 trading households, 43 % lived on peatland along the Trans-Kalimantan Highway, selling food and drinks. Their incomes were uncertain and varied greatly, from 100,000 to several million Indonesian rupiah per day. Their income could double or even triple before big holidays such as Eid, Christmas and New Year, or during floods that blocked roads meaning many travellers needed to wait for the water to recede. Fires and smoke haze resulted in lower trading income due to reduced traffic on the Trans-Kalimantan Highway.

Gold mining

Gold mining along the banks of the Kahayan River had increased in the previous two years, providing income to 23 % of respondents, 67 % of whom lived by the river. This activity employed many labourers, but the yield of gold (at 5–10 grams per week) was variable and uncertain. The price paid for gold in Palangkaraya was US$53–57 per gram, and around 15 litres of diesel costing US$1 per litre were used in producing one gram of gold. Gold mining can be affected by flooding because the mining process is regulated. At the time of our study, gold mining had been suspended by the government for four months because of concerns about:

(a) pollution from the use of mercury in processing; and
(b) increased silting of rivers because the gold-bearing soil was vacuumed up and dumped in the river after processing.

This ban was of concern to many of the villagers in Tumbang Nusa because they had lost a key source of income.

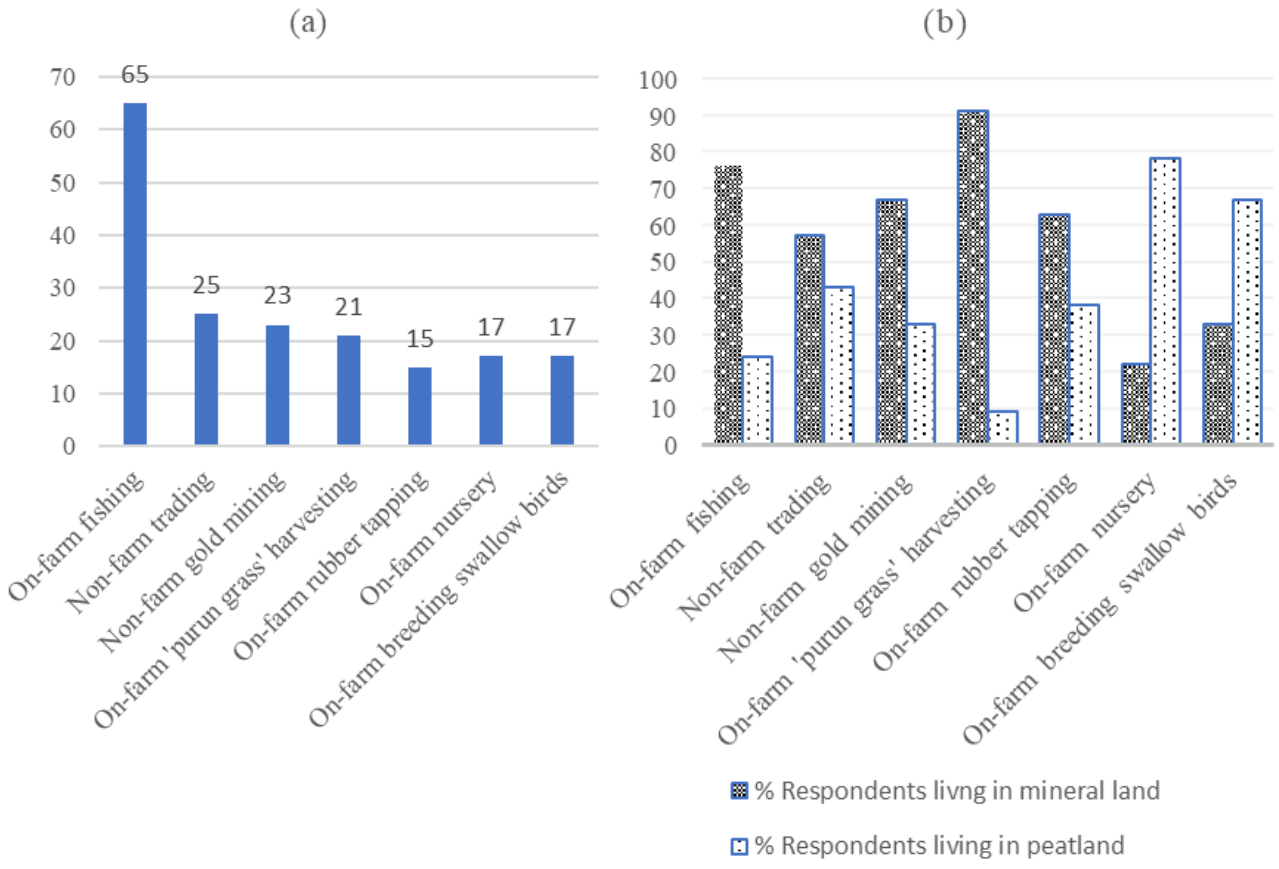

Figure 6. The proportion of respondents practising the most common livelihoods reported in Tumbang Nusa (a) and the proportion of those livelihoods practised by respondents living on mineral soil and peatland (b).

Purun grass collection

21 % of respondents (91 % of whom lived along the river) earned income from purun harvesting or selling purun products (woven baskets and biodegradable drinking straws). The location for purun collection was approximately two hours from the village by boat and accessible only during the wet season. After being washed and dried in the sun the purun could be sold at only US$0.27 per bunch (IDR 4000), meaning that harvesting was conducted to meet orders. There was significant domestic and international demand for purun drinking straws, but prices returned to the were low (around US$0.015 per straw), meaning that only two households in our study were conducting this business activity.

Rubber tapping

Rubber tapping was carried out by eight respondents, of whom 62 % lived along the river and 38 % lived on peatland. The low price of latex (US$420 per tonne) in recent years had reduced community interest in rubber tapping (Sakuntaladewi *et al.* 2022). Rubber grows well on peatland but produces a lower yield of sap than rubber grown on mineral soil. It cannot be tapped when it rains or during floods.

Nursery production

Nursery production was conducted by nine of the respondents, most of whom (78 %) lived along the Trans-Kalimantan Highway. The nurseries had varying capacities, from tens of thousands to several hundred thousand seedlings. Prices at farm level were US$0.027 for seedlings 10 cm tall, US$0.034 for 10–20 cm seedlings, and US$0.04–0.05 for seedlings over 20 cm. On average, a nursery could raise 1–2 lots per year, with gross income varying from US$700 to over US$7000 per year (Sakuntaladewi *et al*. 2022).

There had been significant demand for seedlings of native peatland species such as belangiran (*Shorea belangeran*) and jelutung (*Dyera* sp.) due to the government-led restoration programmes. Nursery producers used peat soil mined from the village of Tumbang Nusa as the medium for plant growth. Planting beds in the gardens (yards) behind the residents' houses along the Trans- Kalimantan Highway made for convenience in building and maintaining their nurseries, as well as in bringing seedlings to the road for transport. Flooding in the rainy season presents a major challenge for nursery cultivation and heavy losses of seedlings can be incurred during floods (Figure 7). Fires are also a significant threat to nursery operations and recent fires (September–October 2023) had reached residents' gardens, causing many seedlings to wither in the heat and eventually die.

Swallow nest production

This business was practised by nine (17 %) of the respondent households. Of these, 67 % lived on peatland. The first swallow-nest business had been established in around 2009 and started returning an income after about two years. This original swallow house was currently producing about seven ounces per week, returning a gross weekly income of around US$470. While substantial initial capital (US$10,000 –30,000) is required to build a swallow house, the time to first production is unpredictable, and the price of swallow nests fluctuates markedly (from US$250 to US$1000 per kilogram), this business was regarded as quite lucrative, and villagers were willing to take out loans of US$10,000 to $27,000 to construct a swallow house. About 50 swallow houses (owned by 37 families) had been built in Tumbang Nusa by 2021. The swallow-nest production business faces risks of both theft and loss of production and quality in the event of smoke haze from fire.

Figure 7. Floods in Tumbang Nusa in November 2021, and their effects on community nurseries and planted trees.

It was clear that respondents faced several challenges in relation to the livelihood options detailed above. The challenges can be broadly grouped into those that are affected (directly and indirectly) by climate change, and those caused by human actions that lead to environmental degradation (Table 2). Increased challenges increase community vulnerability because household incomes are susceptible to reduction or loss.

Adaptative capacity

It was apparent that the livelihoods of people living in Tumbang Nusa were threatened by fire and flooding, both of which were exacerbated by peatland degradation caused by logging, drainage and repeated fires. To mitigate community vulnerability in Tumbang Nusa, various parties had intervened to assist, including external bodies (government, NGOs) and the community (Table 3).

Fires and floods not only degrade the environment, but also affect livelihood and social activities (including school children's activities) and the health of residents. Dense smoke haze reduces visibility to only a few metres. While fires, floods and environmental degradation are of key national and international concern, the most vulnerable people are those in the communities at the ground level.

Efforts to prevent and extinguish fires encompass policy, technical and institutional aspects. The government-issued ban on burning had changed the behaviour of the Tumbang Nusa community because they feared being sent to prison if found guilty. In this village (along with many other fire-prone villages), a Fire Care Community Group was formed to help prevent fires from occurring, as well as to extinguish small fires before they got out of control. The village head (elected in 2019) had taken several measures to prevent fire, including monitoring visitors who came to fish, signage, financial support for fire care groups, coordination with fire control agencies, ensuring that fire suppression and pumping equipment was well maintained, and that boreholes were ready for use.

There were about 400 deep wells and 15 canal blocks in the village of Tumbang Nusa (Figure 8). Deep wells were used to prevent fires, while canal blocks were intended to slow down drainage so that the peatland remained wet. The construction of deep wells and canal blocks was funded by the Peatland Restoration Agency (BRG), which is now the Peatland and Mangrove Restoration Agency (BRGM), in collaboration with the University of Palangkaraya, UNOPS, the Palangkaraya Provincial Environmental Service and the Central Kalimantan Provincial Public Works Office. The construction of

Table 2. Sensitivity of income sources to climate change and environmental degradation.

Livelihood activity	Issue	Sensitivity		
		Affected by climate change		Environmental degradation
		directly	indirectly	
Fishing	Electrocution			✓
	Reduced spawning grounds		✓	
Trading	Haze, floods affect community income	✓		
Gold mining	Flood	✓		
	River silting			✓
	Mercury			✓
	The activity was stopped by the authorities			✓
Purun collection	Not possible when water level is low	✓		
	Dependent on customer orders			✓
Nursery production	Flood, fire	✓		
Swallow nests	Fire	✓		

canal blocks began in 2017, using the basic materials of wood, cement or a mixture of wood branches and sacks filled with soil. The last option was intended to allow tree roots to grow into the construction so that it remained strong enough to hold water.

The policy that was still a challenge for the people of Tumbang Nusa was the protection of peat more than 3 m deep whilst cultivating peat less than 3 m deep. Peatlands in Tumbang Nusa Village are generally deep so fall into the protection category, but the community did not necessarily understand the restrictions and provisions for cultivating peatlands. Some respondents continued to cultivate peatlands using various techniques including canal construction to drain peat so they could plant trees or crops to meet their family needs. They realised that cultivating peatlands was expensive and risky, but they did it anyway for their survival. To prevent or minimise the risk of fire to tree nurseries, the farmers maintained these businesses in the gardens of their houses, which they could actively protect from fires.

Tumbang Nusa experienced major flooding at the end of 2021, which wiped out some nursery businesses and many existing crop plants including rambutan, pineapple and various kinds of vegetables that people had planted in their gardens. The respondents had employed various kinds of agricultural technology to minimise the effects of

Table 3. Programmes aimed at reducing environmental degradation and community vulnerability.

Institution / organisation	Activities	Expected effects (direct and indirect)
Central government	a. Zero burning policy for fire prevention. b. Formation of Indonesian forest fire control brigade 'Manggala Agni' to patrol and extinguish fire. c. Zonation of peat into protection (depth > 3m) and cultivation (< 3m deep) areas. d. Restoration of degraded peatland (rewetting, revegetation and revitalisation).	• no fire • improved peatland • improvement of the community's economy
Local government	e. Coordination of various parties to prevent or extinguish fires. f. Community economic improvement programme.	
NGOs	Assistance to increase people's incomes.	
Police and army	a. Help to extinguish forest and land fires.	
The Tumbang Nusa Community	b. Formation of the 'Fire Care Society' group. c. Allocation of village funds for Fire Care Community activities. d. Cross-sectoral coordination to prevent and extinguish fire.	

Figure 8. Deep well (left); canal blocks using concrete material (centre) and timber/logs (right).

flooding on the crops, such as growing vegetables and rice in polybags, and fruit trees on mounds. Floods also caused many honey bees to drown, so respondents had learned to put a net or gauze under each beehive to prevent the bees from falling into the water (Figure 9).

Flood is a disaster that cannot be prevented or avoided by the people of Tumbang Nusa Village. For residents living along the Kahayan River, flooding can exceed 1 m in depth and submerge their gardens and houses (which are built on stilts). For residents farther from the river, flooding is less severe, particularly for those on the other side of the highway, which acts as a partial levée. Respondents whose businesses were unable to survive the floods had changed their type of business from vegetable farming to livestock (chickens, pigs, goats) or other businesses.

Non-Governmental Organisations (NGOs) also provide some assistance to the people of Tumbang Nusa, such as helping to provide community training in how to manufacture purun straws as a substitute for plastic straws. Local government has also carried out community economic empowerment, including training on the development of stingless bee honey and fish processing. Their intention is to increase community resilience in dealing with the effects of climate change, but Mendham *et al*. (2024) found that many of these programmes had few follow-on effects in the community due to a mismatch with community needs and lack of adoption.

Vulnerability assessment

The majority of respondents (62 %) were considered to be vulnerable, while 38 % were not (Table 4). The vulnerable group had greater exposure to the agricultural sector, even though they typically had more than one source of income. The respondents who lived on mineral soil along the Kahayan River had higher vulnerability (71 %) than those living on the peatland (41 %). This was because their livelihoods were generally more dependent on natural capital, which is affected more negatively by climate change and peatland degradation. The peatland dwellers typically had livelihoods such as teaching, police, trading, kelulut honey and swallow nests, that were less affected by climate-change induced disasters, and there was also less inundation in their gardens so their land-based livelihoods were more protected.

Figure 9. Several technologies are applied to keep plants and bees alive during flooding, such as planting trees on mounds to avoid flooding (left), crops planted in polybags to save plants from flooding (centre), and nets to stop bees from drowning (right).

Table 4. Proportion of respondents considered vulnerable in the Tumbang Nusa Community.

Respondents	Number of respondents	% vulnerable	% not vulnerable
All respondents	52	62	38
Respondents living on peatland	17	41	59
Respondents living on mineral soil along the river	35	71	29

DISCUSSION

Vulnerability

More than 60 % of respondents from Tumbang Nusa were considered vulnerable to climate change and peatland degradation. Key factors that increase their vulnerability include magnitude of climate risk, low adaptability and low adoption of various external assistance programmes. Highly vulnerable households were characterised by having a high proportion of livelihoods dependent on natural resources - such as cultivation of land for agricultural activities - as was found in Ghana by Armah *et al.* (2010). Cultivation of the land exposes communities directly to risk from fire and flooding; and the problem is exacerbated by the unpredictable occurrence and duration of floods, which make it very difficult for farmers to find low-risk land-based options. Smallholder farmers are already known to be particularly exposed to climate change (Harvey *et al.* 2014), and climate variations have been shown to greatly affect the success of land-based community businesses in other situations (Habib-ur-Rahman *et al.* 2022). Fishing, including the continued use of electrocution, is also susceptible to climate change (Rahardjo 2011, Barbarossa *et al.* 2021) and degradation-induced changes in peatland (Thornton *et al.* 2018), so is also one of the livelihoods that results in higher community vulnerability.

The development of peatlands in and around Tumbang Nusa for economic purposes has contributed substantially to their degradation. Peatlands are very fragile (Wulandari *et al.* 2021), and the construction of canals and drainage to make them more accessible and behave more like mineral soil when under agricultural use has exposed them to degradation and risk. Even though the respondents know that farming on peatlands is very risky, they still attempt to avoid and overcome the challenges. Substantial efforts have been made to prevent and overcome fire disasters, at both individual family and village government levels, through policy, technical and institutional routes as well as coordination with various relevant agencies at sub-national and national levels. From 2020 to 2022 the village of Tumbang Nusa was free from fire, although this coincided with a run of wet years. In the dry/El Niño year of 2023, peatland fire occurred again in the village of Tumbang Nusa. Fire spread from the edge of the highway into the residents' gardens. Firefighters, along with the local community, attempted to extinguish the fire for four days, drawing water from boreholes, bringing in water from outside the village, and even employing water bombing. However, they could only manage to put out the surface fires. Fires continued within the peat, releasing substantial quantities of smoke. Firefighters were uncertain of the fire's depth within the peatland and how much fuel remained.

The most recent climate disaster that has affected respondents to the greatest extent is flooding. Floods have negatively affected many land-based sources of income, and farmers have suffered significant losses. The community has adapted by applying various technologies to avoid flooding or changing their source of livelihood. However, these adaptations are necessarily small scale, such as growing crops in polybags, and would not work on a large scale. Flood disasters are often exacerbated by peatland degradation (Lupascu *et al.* 2020, Ikkala *et al.* 2021), as the high-water holding capacity in its natural state helps it to buffer the water flows in the system and reduce flooding in the surrounding area (Agus & Subiksa 2008, Lupascu *et al.* 2020). To restore the ability of peatland to absorb water requires takes a long time and success is not guaranteed. While efforts are being made to restore peatlands, the lives and livelihoods of communities who are dependent on peatland need to continue, so adaptation is a critical step for them. Several forms of adaptation have been implemented by the Tumbang Nusa village community, but many of their actions are still focussed around land-based activities and the risk of failure is still high because their adaptation actions are not always accompanied by mitigation actions. Given our findings in this study, the best options for peatland communities to reduce their vulnerability are (1) to transition from land-based to sustainable on-farm options that do not involve cultivation of the land (such as stingless bees and swallow nests production), off-farm (purun drinking straws, processed products such as fish crackers) and non-farm (eco-tourism) livelihood options; or (2) to focus on land use options that can return an income while also being compatible with sustainable peatland restoration. Options that allow for full rewetting such as Payment for Environmental Services (e.g. carbon services, biodiversity services; Van de Sand 2012) and agrosilvofishery are likely to be critical to allow the community to reduce its vulnerability.

Only a minority of the community have professions as government employees, teachers, and police/army members whose incomes are not affected by climate change or peatland degradation. Some of the respondent families have chosen to generate income from more sustainable peat-friendly options that combine conservation and a return on investment, such as swallow-nest production and stingless honey bee (*Trigona*, locally called kelulut bees) production. Both of these businesses require

that the peatland environment is well maintained because they require a diverse range of plants growing in the local area in order to be able to produce bird nests and honey, and products are spoiled by smoke. Swallow nest businesses require substantial capital investment, but the *kelulut* honey business is more accessible to those with less capital because the investment is smaller and regular harvesting can provide cash flow every two weeks. The main challenge for kelulut honey producers is the marketing of the product - they do not have a cooperative marketing arrangement, so their bargaining position is poor. While cooperatives have been found to improve farmer livelihoods and agricultural performance in some situations (Ofori *et al.* 2019), often communities do not optimally utilise farmer groups because they can reduce autonomy and require a degree of cooperation that communities are not accustomed to (Mendham *et al.* 2024).

The reality for most people on the ground is that they need to derive an income from the land that they manage. A significant opportunity is for the broader national and international community to pay for those services that are provided when peat is rewetted (like carbon and biodiversity), such that the local community gets a net benefit from ecosystem restoration instead of a net disbenefit (Locatelli *et al.* 2014). Some payments from ecosystem services are starting to occur at the community level in Tumbang Nusa, as the village has started to become a destination for domestic and foreign tourists. Tourists are interested in seeing the processes of purun crafts (making purun straws and baskets), kelulut honey production, and raising seedlings in the tree nurseries. They buy purun products and can drink kelulut honey straight from the hive using purun straws. Additionally, in the last two years, several carbon traders/aggregators who are interested in developing a carbon trading business have visited Tumbang Nusa, but the community has not responded because they do not understand this business. If it is done well, recognition of (and payment for) ecosystem services could be a significant pathway towards helping the peat restoration effort, as it will drive restoration by the community from the community level (Van de Sand 2012, Locatelli *et al.* 2014), but examples of successful Payment for Ecosystem Services (PES) initiatives are rare because of the multiple problems associated with implementation (Chan *et al.* 2017).

Peatland restoration to reduce community vulnerability

Rewetting through the construction of canal blocks has succeeded in reducing hotspots (Yuliani 2017). Thus, rewetting is the key action that can prevent fire and CO_2 emissions. The longer-term aim is to return the water absorbing ecological function of peatlands and help reduce flooding, but peatlands are fragile ecosystems that can become very difficult to wet again once the moisture content falls below 100 g water per gram of peat soil (Lestari & Mukhlis 2021). However, rewetting must be integrated with revegetation in degraded areas and with revitalisation of the community's economy because the community must be able to thrive in rewetted peatlands. Its implementation must benefit the local communities and related stakeholders.

Policy improvements are needed at the site level to increase community resilience in the face of climate change and their degraded peatland environment. Focus needs to be placed on strategies to reduce the risk of biophysical exposure, while increasing the adaptive capacity of villagers to reduce their sensitivity. Strengthening peat revegetation, rewetting and management of the water table greatly contributes to reducing the risk of exposure and part of the mitigation potential of natural climate solutions pathways (Griscom *et al.* 2017, 2020), but communities need to be supported to manage their land through sustainable means. PES offers an opportunity to do this, but such payments need to benefit the people on the land the most, such that they are encouraged to lead the restoration effort rather than resist it. Accordingly, local government should promote and encourage alternative livelihood options, as well as the marketing of produce, in villages where a combination of mitigation and adaptation is a priority. Assistance is needed to facilitate value chains and marketing of both products and environmental services.

The high proportion of vulnerable people in Tumbang Nusa demonstrates the threats to their livelihoods that they face on a day-to-day basis. The international and national repercussions of peatland degradation make the policy environment difficult for those on the ground. For example, the no-burn policy, which was intended to reduce the number of fires, has had the follow-on effect of increasing vulnerability of the local people, because it has contributed to a reduction in fish spawning areas and increased the capital and labour inputs required to use the land for agricultural production. Many assistance programmes aiming to reduce vulnerability have been provided to communities, but these can become part of the problem if they are not conceived and implemented with long-term sustainability in mind. One example is the establishment of new oil palm plantations that require the lowering of the water table. Aid programmes often do not result in

community adoption beyond the initial assistance phase (Mendham *et al*. 2024). A win-win solution is required, that promotes economic development of the village community whilst simultaneously minimising and repairing damage to the peatland, so that the restoration effort is driven from community level because people are internally motivated by achieving a net benefit from the transition.

Fires and/or floods repeatedly affect the village of Tumbang Nusa, posing an ongoing threat to the livelihoods of the land-based communities. To reduce this community's vulnerability, activities in the village of Tumbang Nusa must provide promising economic benefits, contribute to environmental improvement, and empower the community to actively protect peatlands from further degradation.

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AUTHOR CONTRIBUTIONS

NS and AW initiated the research; NS and YR designed the sampling protocol and collected the data; NS, DSM and DD analysed the data. All authors (NS, DSM, S, YR, SMJ, DD, RE, SA, AW) contributed to interpretation of the results and writing of the final manuscript.

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Author for correspondence: Dr Niken Sakuntaladewi, Research Centre for Ecology and Ethnobiology, National Research and Innovation Agency (BRIN), Kawasan Sains dan Teknologi Soekarno, Jl. Raya Jakarta–Bogor KM 46, Cibinong, Bogor, Jawa Barat 16911, Indonesia. E-mail: niken_sakuntaladewi@yahoo.co.uk