

Breathing unequally through recurrent haze: community resilience and environmental health equity in Sarawak, Malaysian Borneo

Sam Froze Jiee  · Jyh Hann Lim · Siong Hee Lim · Romano Ngui · Winnie Johnny · Peter Ronald Bihos · Helmy Hazmi · Anselm Ting Su

Received: 24 July 2026 / Accepted: 12 October 2026

© The Author(s) 2026

Abstract

Background Recurrent haze is a persistent environmental health concern in Malaysian Borneo, arising from landscape and peatland fires and subsequent smoke transport under climate- and weather-sensitive conditions. Communities may differ in their capacity to prepare for and respond collectively to haze because access to protective resources, services, information and institutional support varies across settings. This study examined variation in perceived community haze resilience and its equity-relevant determinants among adults in Sarawak, Malaysian Borneo.

Methods We conducted a community-based cross-sectional study from June 2024 to May 2025 among 481 adults using multistage stratified cluster sampling. We measured community haze resilience across four domains: connection and caring, resources, transformative potential, and disaster management. Explanatory variables covered geographical, sociodemographic, household, health, psychosocial and informational factors. Independent-samples t-tests, one-way analysis of variance and Pearson correlations examined unadjusted associations. Hierarchical multiple linear regression with HC3 robust standard errors assessed adjusted associations and incremental explained variance; adjusted marginal means compared resilience across zones and settlement types.

Results Mean (SD) total resilience was 63.20 (7.86). Resilience differed across Sarawak zones ($F=22.09$, $p<0.001$, $\eta^2=0.085$) and settlement types ($F=9.53$, $p<0.001$, $\eta^2=0.038$), with urban respondents reporting lower mean resilience than suburban and rural respondents. At their entry step, haze-related psychosocial and informational factors increased explained variance by 35.2 percentage points; the final model explained 46.7% of variance (adjusted $R^2=0.442$). Higher haze knowledge was positively associated with resilience ($B=1.26$, 95% CI 0.98–1.55). Greater risk normalisation ($B=-0.40$, 95% CI -0.66 to -0.14), perceived economic and mobility costs ($B=-0.53$, 95% CI -0.87 to -0.18), and larger household size ($B=-0.47$, 95% CI -0.81 to -0.13) were associated with lower resilience. Compared with urban respondents, suburban ($B=5.31$, 95% CI 3.31–7.30) and rural respondents ($B=2.18$, 95% CI 0.63–3.73) had higher adjusted resilience.

Conclusions Perceived community resilience to recurrent haze varied across geographical and settlement contexts in the communities studied. Differences were associated with settlement context, household capacity, knowledge, risk normalisation and practical barriers, supporting an environmental health equity perspective. Preparedness

This Article in Press is shared early to give you faster access to new research. It is citable and carries a permanent DOI. The final edited version will replace it automatically.



strategies may benefit from targeted risk communication, support for vulnerable households and measures that reduce barriers to exposure reduction and collective response.

Keywords Environmental health equity · Community resilience · Recurrent haze · Sarawak · Malaysian Borneo · Haze preparedness · Smoke-related air pollution · Risk normalisation · Settlement inequity · Climate-sensitive hazards

Introduction

Recurrent haze is an increasingly important environmental health equity issue in fire-prone and climate-sensitive regions. Globally, wildfire and landscape-fire smoke are now recognised as a major population health threat because smoke-related fine particulate matter can travel across long distances, cross administrative boundaries and expose communities far from the fire source [1, 2]. The health effects of smoke exposure extend beyond transient eye, throat and respiratory irritation. Exposure to fine particulate matter with an aerodynamic diameter of 2.5 µm or smaller (PM_{2.5}) from wildfire and landscape-fire smoke has been associated with respiratory exacerbations, cardiovascular outcomes, increased healthcare utilisation and premature mortality, with disproportionate risks among people with chronic diseases, older adults, children, outdoor workers and populations with limited ability to avoid exposure or access timely care [2]. These features make haze not only an environmental exposure problem, but also an equity issue: the same smoke episode may produce different health risks when communities differ in baseline vulnerability, protective resources, access to services and collective capacity to respond.

In Southeast Asia, haze is closely linked to recurrent fires in vegetation, forests, landscapes and peatlands. Recent reviews have identified smoke haze from vegetation and peatland fires as a persistent regional public health problem, with evidence of respiratory and cardiorespiratory impacts and continuing gaps in exposure assessment, burden estimation and policy translation [3, 4]. The occurrence and transport of haze in Malaysian Borneo are strongly influenced by regional meteorological conditions. During the Southwest Monsoon, generally drier conditions over parts of the southern ASEAN region can favour increased landscape- and peat-fire activity, while prevailing southerly, southeasterly and southwesterly winds can transport smoke from Kalimantan toward Sarawak and other parts of Malaysian Borneo [5–7]. El Niño-related reductions in rainfall can further dry degraded peatlands, increasing their susceptibility to sustained combustion and prolonged smoke emissions [5, 6]. This climate-fire-transport pathway is evident during major regional haze episodes. In September 2015, the ASEAN Specialised Meteorological Centre reported 401 and 333 satellite-detected hotspots in Kalimantan on 4 and 5 September, respectively, with smoke from Kalimantan spreading into western Sarawak [8]. In September 2019, hotspot activity again escalated, with 114 and 459 hotspots detected in Kalimantan on 3 and 4 September, respectively; smoke from West Kalimantan was observed to be transported by prevailing winds toward western Sarawak [9]. These observations provide environmental context for the elevated API episodes shown in Fig. 1, although the present study did not conduct formal source apportionment or time-series analysis linking hotspot counts to API values.

The state may be affected by smoke generated by local and regional landscape and peatland fires, including fires elsewhere in Borneo and the wider Southeast Asian region, with emissions transported into and across Sarawak depending on prevailing meteorological conditions. Its geography also creates important equity concerns. Sarawak includes urban centres, suburban and semi-urban areas, rural villages, riverine settlements, interior communities and longhouse populations. These settings differ in access to health services, transport, information channels, household resources and local response capacity. As a result, the same haze episode may not translate into comparable risk or preparedness across communities. Communities with greater distance from health facilities, weaker transport access, fewer protective resources, larger household demands or higher health vulnerability may face greater difficulty converting public health advice into practical exposure-reduction action.

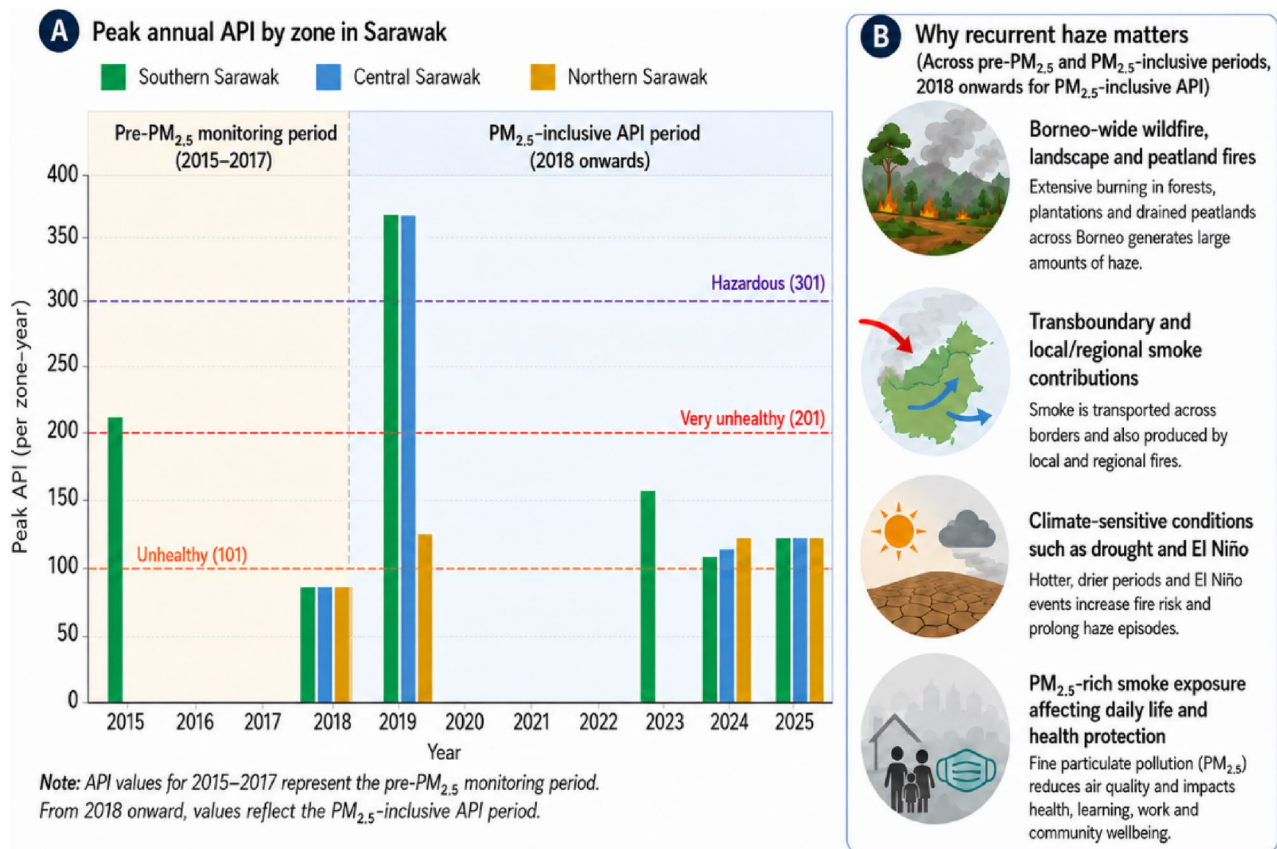


Fig. 1 Environmental context of recurrent haze in Sarawak. **A** Peak annual Air Pollutant Index (API) recorded across the Sarawak study zones, 2015–2025. The dashed vertical distinction separates the pre-PM_{2.5}-inclusive API period (2015–2017) from the period in which PM_{2.5} was incorporated into Malaysian API calculation (2018 onwards). Because the pollutant basis of the API changed, values across these periods are presented for descriptive historical context and should not be interpreted as a directly comparable longitudinal exposure series. Horizontal dashed lines indicate Malaysia's API categories for unhealthy (> 100), very unhealthy (> 200) and hazardous (> 300) air quality. **B** Key environmental-health pathways relevant to recurrent haze in Sarawak. Source: Malaysian Department of Environment, Air Pollutant Index Management System (APIMS)/official API records [10]; figure compiled by the authors.

Malaysia reports ambient air quality using the Air Pollutant Index (API), which is derived from pollutant-specific sub-indices; the highest sub-index determines the reported API for a given monitoring location and time [10]. PM_{2.5} was incorporated into Malaysia's API calculation from 16 August 2018, after expansion of the national monitoring network in 2017 [11]. This methodological change matters when interpreting historical API values because particulate pollution in the earlier period was represented primarily by PM₁₀, whereas PM_{2.5} may determine the API in the later period. Consequently, API values before and from 2018 onwards should not be regarded as a directly comparable homogeneous time series. Figure 1 therefore provides descriptive historical air-quality context for recurrent haze in Sarawak rather than an analysis of temporal exposure trends. Figure 1A presents the peak annual API recorded across the study zones from 2015 to 2025, with the pre-2018 and PM_{2.5}-inclusive periods explicitly distinguished. Episodes of elevated API illustrate the recurrence of poor air-quality conditions during the study period; differences between years should be interpreted in light of the change in API methodology. Figure 1B summarises why recurrent haze remains an environmental health concern in Sarawak, highlighting Borneo-wide landscape and peatland fires, transboundary and local or regional smoke contributions, climate-sensitive conditions such as drought and El Niño, and PM_{2.5}-rich smoke exposure that can disrupt daily life and health protection [3, 5–7].

Unequal access to healthcare is central to understanding environmental health equity in Sarawak and other parts of Borneo. Although Malaysia has invested in rural health services, including rural clinics, outreach services, mobile teams and flying doctor services, geographical remoteness, riverine or interior access, distance, transport constraints and service frequency continue to shape healthcare access for remote communities [12, 13]. This matters for haze preparedness because healthcare access is not only about treatment after illness occurs. It also affects the ability to obtain timely advice, respiratory assessment, medication, follow-up care and support for vulnerable households during haze episodes. In recurrent haze-exposed settings, unequal access to healthcare can amplify environmental health inequities by limiting some communities' capacity to prevent, recognise and manage haze-related health risks.

Sarawak-specific evidence supports the respiratory health relevance of poor air quality and haze-related particulate exposure. A Malaysian environmental epidemiology study reported significant associations between PM₁₀ exposure and childhood respiratory hospital admissions in Kuching, Sarawak [14]. Similarly, a time-series study in Bintulu found that short-term PM_{2.5} exposure was associated with increased childhood respiratory hospitalisation, particularly among younger children [15]. These findings are consistent with more recent Malaysian evidence showing associations between particulate exposure during haze periods and respiratory hospital admissions [16]. During the severe September 2019 haze episode, Ministry of Health sentinel surveillance in Sarawak also documented increases in asthma, conjunctivitis and upper respiratory tract infection presentations, with patterns varying across monitored locations [17]. Malaysia's National Health and Morbidity Survey 2023 reported a high burden of major non-communicable disease risk factors, including diabetes, hypertension, hypercholesterolaemia, overweight and obesity [18]. These conditions are clinically relevant because PM_{2.5}-rich smoke can aggravate cardiometabolic and respiratory vulnerability, making exposure reduction and early protection particularly important during haze episodes [1, 2]. Together, these findings reinforce the importance of preparedness measures that enable vulnerable households to reduce exposure and seek appropriate care during severe haze episodes.

Regional policy has increasingly acknowledged the need for sustained preparedness for haze. The Second Roadmap for ASEAN Cooperation on Transboundary Haze Pollution Control with Means of Implementation 2023–2030 emphasises prevention, monitoring, public awareness and health-risk reduction [19]. However, the ability to implement standard protective advice is shaped by the conditions in which people live and work. Reducing outdoor activity may be difficult for individuals whose livelihoods require outdoor work; maintaining cleaner indoor air may be constrained by housing conditions, household crowding or limited access to air filtration; and obtaining appropriate protective equipment may be affected by affordability and availability. Similarly, monitoring air quality and responding to advisories requires timely access to understandable and trusted information, while seeking healthcare when symptomatic may depend on geographical accessibility, transport and household resources. Households caring for children, older adults or people with chronic illness may also face greater protective demands. These constraints help explain why the same public-health recommendation may not be equally feasible across communities. From an environmental health equity perspective, the relevant concern is whether households have the resources and enabling conditions required to act on available advice. Such differences may influence opportunities to reduce smoke exposure and obtain timely care during haze episodes. The present study did not directly measure individual exposure or subsequent health outcomes; these pathways are therefore presented as plausible mechanisms linking social and material conditions with preparedness capacity rather than as causal effects demonstrated by the current data.

Most haze research in Southeast Asia has focused on pollutant exposure, health effects, economic impacts, knowledge, attitudes or individual protective behaviours [3, 4]. These perspectives are necessary but do not establish whether communities possess the collective capacities and enabling resources required to translate public-health advice into coordinated protective action. Individual knowledge, for example, cannot by itself ensure trusted risk communication, mobilisation of local resources, support for vulnerable households, continuity of assistance or effective linkages with health and emergency services. Community-level preparedness

therefore represents a distinct layer of health protection rather than simply the aggregation of individual protective behaviours.

This distinction is supported by broader community-resilience and health-emergency literature, including the Communities Advancing Resilience Toolkit (CART) [20]. A recent scoping review characterises community resilience through capacities to prepare, anticipate, prevent, self-organise, connect, adapt and cope, supported by social, economic, governance, communication, health and emergency-management resources [21]. The WHO South-East Asia strategic framework similarly identifies community engagement and resilience as core components of health-emergency preparedness and emphasises equity, access and inclusion of vulnerable and marginalised groups [22]. Public Health 3.0 resilience models further emphasise social connection, community resources, collective action and adaptive capacity [23]. Together, this literature supports treating lower perceived community resilience as a preparedness concern that may signal weaker collective capacity or enabling conditions, while not assuming a direct causal effect on smoke exposure or health outcomes.

This study therefore frames community haze resilience as an environmental health equity issue. Community haze resilience is defined here as the perceived capacity of communities to prepare for, adapt to, organise around and respond collectively to recurrent haze episodes in ways that may reduce smoke exposure, support vulnerable groups and protect population health. This framing differs from earlier work from the same Sarawak haze project, which examined individual haze-protective self-care behaviours as the primary outcome [24]. The present study shifts the focus from what individuals do during haze to variation in communities' perceived collective preparedness and response capacity. Recurrent haze, climate-sensitive fire risk, chronic disease vulnerability, settlement diversity and differences in healthcare access are converging public health concerns in Sarawak and Malaysian Borneo. An equity-oriented analysis can help identify where lower perceived resilience occurs, which measured factors are associated with that variation, and how public health preparedness can move beyond generic advisories toward locally appropriate support. Evidence on variation in community-level haze resilience can inform localised risk communication, strengthen community leadership, support vulnerable households, improve linkages with health services and guide practical measures to reduce barriers to exposure reduction.

Accordingly, this study conceptualised perceived community haze resilience as an equity-relevant preparedness capacity rather than as a direct measure of health protection. We do not assume that higher perceived resilience necessarily results in lower smoke exposure or better health outcomes, as these downstream outcomes were not measured. Instead, identifying variation in perceived resilience and its associated factors can indicate where preparedness capacity may differ and which potentially modifiable barriers or enabling conditions warrant further investigation or support. This study therefore assessed overall and domain-specific perceived community haze resilience, examined geographical and settlement-based variation, and identified social, environmental, economic, household, health-vulnerability, psychosocial and informational factors associated with resilience in Sarawak, Malaysian Borneo.

Footnote: For each calendar year, the zonal value represents the highest API recorded among DOE monitoring stations with available data within that study zone and therefore does not represent the mean API across stations or a population-weighted regional exposure estimate. Because the monitoring network changed over time, including expansion by 2017, Fig. 1A provides descriptive historical context rather than a fixed-station longitudinal comparison.

The pronounced haze episodes in 2015 and 2019 coincided with documented escalations in Kalimantan hotspot activity and regional smoke transport toward Sarawak; these historical observations provide contextual evidence rather than a formal statistical association between hotspot counts and API.

Methods

Study design and setting

This study used a community-based cross-sectional design to examine environmental health inequities in adults' resilience to recurrent haze in Sarawak, Malaysian Borneo. The analysis was derived from a larger state-level haze project conducted in Sarawak but addressed a distinct research question from the previously published analysis, which focused on individual haze-protective self-care behaviours [24]. In the present manuscript, the primary focus was perceived community haze resilience, interpreted through an environmental health equity lens. Sarawak, located in the northwest region of the island of Borneo, was selected as the study setting because it is repeatedly exposed to haze episodes associated with regional smoke transport, local and regional fire activity, and wider landscape and peatland fires affecting Borneo and Southeast Asia. The state is geographically extensive and socially diverse, comprising urban centres, suburban and semi-urban settlements, rural villages, riverine communities, interior areas and longhouse settlements. These characteristics make Sarawak a relevant setting for examining variation in communities' capacity to prepare for, adapt to, organise around and respond collectively to recurrent haze.

For geographical analysis, Sarawak was grouped into three broad study zones based on administrative divisions: Southern Sarawak (Kuching, Samarahan, Serian, Sri Aman and Betong), Central Sarawak (Sarikei, Sibul, Mukah, Kapit and Bintulu), and Northern Sarawak (Miri and Limbang). These zones served as broad contextual geographical groupings rather than measures of homogeneous haze exposure. For the environmental context presented in Fig. 1A, Department of Environment (DOE) air-quality monitoring stations were assigned to the three study zones according to geographical location. The Southern zone included Kuching, Samarahan and Sri Aman; the Central zone included Sarikei, Sibul, Kapit, Mukah, Bintulu and Samalaju; and the Northern zone included Miri, ILP Miri/Permyjaya and Limbang. Historical evidence indicates a 10-station Sarawak network during 2010–2016, while DOE records document Mukah and Samalaju in the expanded network by 2017 [11, 25]. Thus, annual zonal values were derived from stations with available data in each year rather than from an invariant panel of monitoring stations. Supplementary Table S1 provides the station-to-zone classification and historical network note.

Based on the 2020 Population and Housing Census, the administrative divisions comprising the Southern, Central and Northern study zones represented approximately 1.19 million, 0.81 million and 0.45 million residents, respectively [26]. The Southern zone includes Kuching, the state capital and largest urban centre, together with Kota Samarahan, Serian, Sri Aman and Betong; its economy encompasses government and commercial services, finance, education, tourism, agriculture and plantation activities. The Central zone includes Sibul, Bintulu, Sarikei, Mukah and Kapit as major centres and has a diverse economic base encompassing agriculture, timber processing, shipbuilding, hydropower, petrochemical and energy-intensive industries. The Northern zone is centred principally on Miri, Limbang and Lawas, with economic activities including petroleum and gas-related industries, services, tourism, agriculture and plantation activities [27]. These zones were used as broad geographical and contextual groupings rather than as proxies for uniform haze exposure. The frequency and severity of haze may vary within and between zones according to the location and intensity of fires, prevailing winds, meteorological conditions and local or regional smoke contributions. Previous haze experience was not measured at the individual level in this study and therefore was not assumed to be equivalent within each geographical zone. (Fig. 2).

Study population, sample size calculation and sampling

The target population consisted of adults residing in Sarawak. Participants were eligible if they were aged 18 years or older, lived in the selected community during the study period, and provided informed consent. Individuals who were unable to complete the questionnaire or provide reliable responses were excluded. A multistage

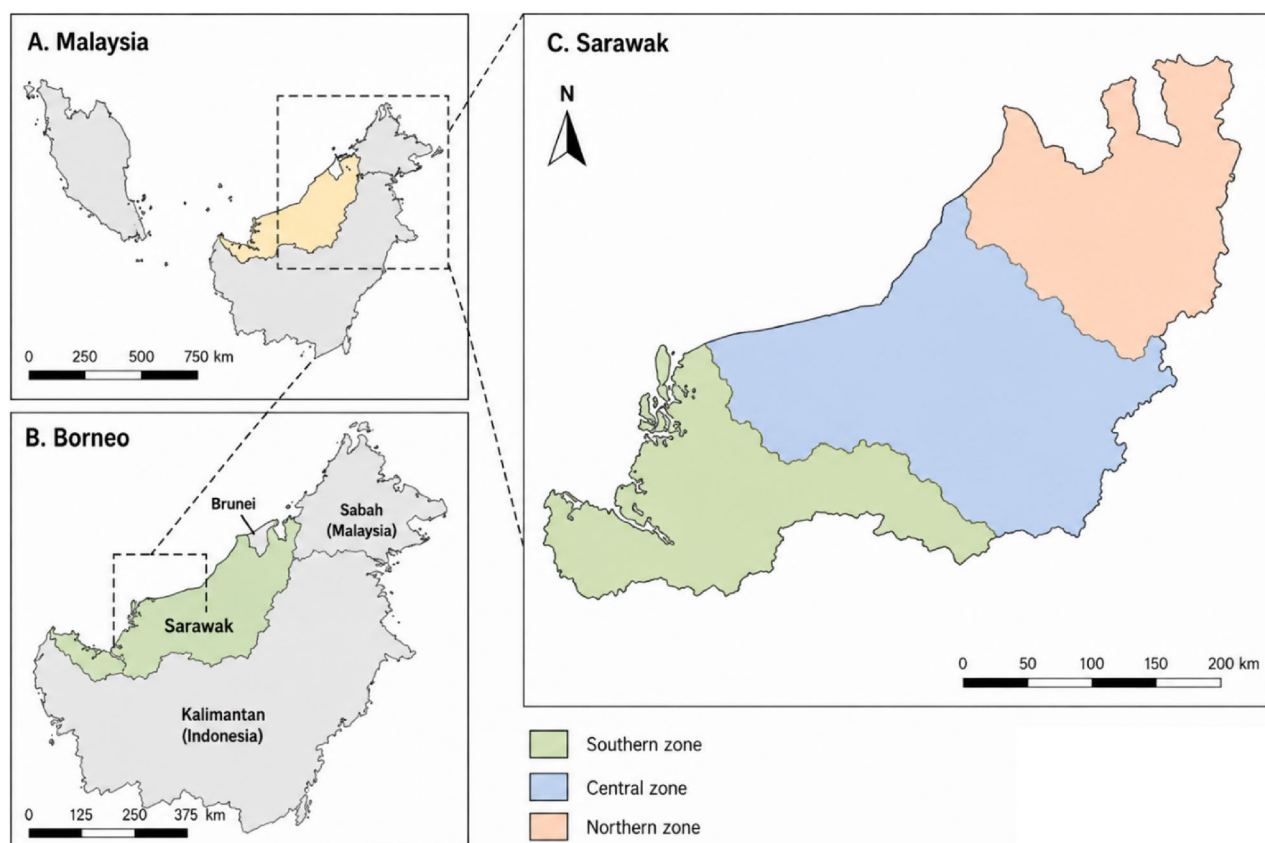


Fig. 2 **A** shows the location of Malaysia and the Borneo region within the broader national context. **B** highlights Sarawak within the island of Borneo, bordered by Sabah, Brunei and Kalimantan, Indonesia. **C** shows Sarawak divided into the three study zones used in this analysis: Southern, Central and Northern Sarawak

stratified cluster sampling design was used to recruit adults across Southern, Central and Northern Sarawak. The procedure comprised four stages. At Stage 1, Sarawak was stratified into the three geographical study zones. At Stage 2, districts were randomly selected within each zone, resulting in five selected districts in Southern Sarawak, three in Central Sarawak and two in Northern Sarawak. At Stage 3, community clusters comprising villages, residential areas and longhouses were randomly selected within the selected districts, yielding 15 clusters in the Southern zone, 10 in the Central zone and eight in the Northern zone. At Stage 4, official household lists obtained through the relevant district offices were used as sampling frames. Households were selected using systematic random sampling with a fixed sampling interval and random start. Field teams subsequently visited the sampled households and recruited one eligible adult per household. When more than one eligible adult was present, one participant was selected using a prespecified standardised within-household selection rule to ensure consistent selection across households. Up to two return visits at different times were made when sampled households could not initially be contacted. Refusals were not replaced; replacement was permitted only for closed or vacant dwellings after the specified return-visit procedure. Community liaison personnel assisted with wayfinding and verification of household listings but did not select participants [24].

We estimated the sample size using the Raosoft online sample size calculator for a cross-sectional survey. The calculation used a 95% confidence level, a 5% margin of error, a 50% response distribution, and the adult population of Sarawak as the reference population. We used a conservative 50% response distribution because no prior estimate of community haze resilience was available for Sarawak. The initial sample-size estimate was approximately 384 respondents, based on a 95% confidence level, 5% margin of error and 50% response distribution using the adult population of Sarawak as the reference population. A 20% allowance for potential non-response

was then applied, resulting in a target sample of approximately 462 respondents. The final achieved sample of 481 exceeded this target. Settlement type was operationally classified as urban, suburban or rural based on the sampled locality and field classification [28]. This classification followed the Malaysian statistical definition, which generally defines urban areas as gazetted and adjoining built-up areas with a population of at least 10,000 people and at least 60% of the population aged 15 years and above engaged in non-agricultural activities. Rural areas generally refer to settlements outside this urban classification. This study defined suburban areas as peri-urban or semi-urban localities at the urban fringe or in smaller developing townships with partial access to urban infrastructure and services. This operational classification was used as an equity-relevant variable to examine settlement-based differences in community haze resilience.

Conceptual framework

This study was guided by a study-specific conceptual framework integrating community resilience and environmental health equity perspectives. Community haze resilience was informed by the Communities Advancing Resilience Toolkit (CART), which conceptualises community resilience through capacities related to connection and caring, resources, transformative potential and disaster management [20, 29]. Broader public-health literature similarly conceptualises community resilience as a multidimensional capacity involving social relationships, resources, collective action, preparedness and the ability to respond to health emergencies [21–23]. Recurrent haze was conceptualised as the environmental hazard context, while perceived community haze resilience represented preparedness and collective response capacity. The environmental health equity perspective recognises that the consequences of environmental hazards are shaped not only by the hazard itself but also by differences in socioeconomic conditions, health vulnerability, access to protective resources, services, information and the capacity to undertake protective action [30–32]. From this perspective, the relevant concern is not whether all communities possess identical levels of resilience, but whether preparedness capacity, protective resources and institutional support are sufficient and proportionate to local needs and vulnerabilities [22, 32].

Accordingly, the study examined four broad groups of explanatory factors that may contribute to variation in community haze resilience. First, geographical and structural factors, including Sarawak zone, settlement type, distance to health facilities, transport access and household protective resources, were considered because they may influence the practical feasibility of protective action and access to support. Second, socioeconomic and household characteristics, including education, occupation, household income and household size, were included because they may affect access to information, protective resources and the capacity to sustain preparedness. Third, health vulnerability, including smoking status and diagnosed medical illness, was considered because individuals and households with greater health needs may require additional protection during haze episodes. Fourth, psychosocial and informational factors, including haze knowledge, risk normalisation, political trust and perceived economic or mobility costs, were included because they may influence risk appraisal and perceived capacity to respond. We conceptualised geographical zone as a distal contextual characteristic rather than a measure of haze exposure. We examined more proximal determinants of preparedness, including settlement context, socioeconomic and household characteristics, protective resources, health vulnerability, haze knowledge, risk normalisation, and perceived practical barriers, separately. This distinction allowed the analysis to assess whether geographical context remained associated with perceived community resilience after accounting for these measured factors.

Study instrument, data collection and questionnaire administration

Data were collected using a structured questionnaire developed specifically for this study to assess individual, household and community-level factors relevant to recurrent haze exposure. The complete questionnaire integrated study-specific items with selected constructs adapted from established instruments and developed questionnaires (Supplementary File 1). The first section collected information on sociodemographic characteristics,

household and healthcare access-related factors, medical history and smoking status. Items assessing haze tolerance or risk normalisation, political trust, perceived economic and mobility costs, and haze knowledge were adapted from a developed haze risk-perception questionnaire [24]. Items on haze-related protective practices were adapted from a developed questionnaire assessing self-protective behaviours during haze events [24] and refined to align with the objectives and context of the present study. Community resilience items were adapted to the haze context from the Communities Advancing Resilience Toolkit (CART), developed by Pfefferbaum et al., which assesses resilience across the domains of connection and caring, resources, transformative potential and disaster management [20, 29]. For this manuscript, the primary outcome was derived from the community resilience section of the questionnaire. In the present study, these domains were interpreted as community capacities that may support exposure reduction, protection of vulnerable households and collective response during recurrent haze.

To support the equity-focused interpretation of the measures, the instrument underwent translation, expert review, and pilot testing before the full survey. After translation into Malay, the questionnaire was reviewed by public health academics and Public Health Medicine Specialists to assess whether the items were relevant, clear and culturally appropriate for Sarawak's urban, suburban and rural communities. This review was important because the study involved communities with different settlement patterns, languages, socioeconomic backgrounds and levels of access to health services. Pilot testing was conducted with 45 respondents in Padawan District, selected to reflect heterogeneous field conditions and community profiles. Internal consistency reliability was assessed using Cronbach's alpha. The pilot results showed acceptable to excellent reliability for the multi-item domains used in the present analysis, including haze tolerance ($\alpha=0.718$), perceived costs ($\alpha=0.793$), political trust ($\alpha=0.920$), haze knowledge ($\alpha=0.952$) and community resilience ($\alpha=0.918$). The haze-protective self-care scale also demonstrated acceptable reliability ($\alpha=0.726$), although it was not the primary outcome in the present manuscript. These procedures supported the use of the adapted instrument for assessing community haze resilience and its equity-relevant predictors in the Sarawak context.

Data collection was conducted from June 2024 to May 2025. The questionnaire was administered through face-to-face, interviewer-assisted household interviews by trained researchers and Field Research Assistants. Interviewers followed a standardised field manual and used scripted questions and neutral prompts to promote consistency across study sites. Language support was available in Sarawakian Malay, Iban and Mandarin, enabling respondents to participate in their preferred language. Written informed consent was obtained before each interview, and interviews were conducted in a private area of the respondent's home to maintain confidentiality. Responses were recorded contemporaneously during the interview, and completed questionnaires were reviewed by field supervisors for completeness and consistency. Further details of the parent study field procedures have been reported previously [24].

Scoring of independent and outcome variables

The primary outcome was the total community haze resilience score, derived from the community resilience section of the questionnaire. The scale included items representing four domains: connection and caring, resources, transformative potential, and disaster management. Each item was scored on a five-point Likert scale, ranging from 1 = strongly disagree to 5 = strongly agree. Item scores were summed to generate domain-specific scores and the overall community haze resilience score. Higher scores indicated stronger perceived community capacity to prepare for, adapt to, organise around, and respond collectively to recurrent haze episodes. The total resilience score was analysed as a continuous dependent variable, while domain-specific scores were used in supplementary analyses.

The main independent scale-based variables were haze knowledge, haze tolerance or risk normalisation, political trust, and perceived economic and mobility costs. These constructs were also measured using five-point Likert-type items and scored by summing the relevant items within each construct. Higher haze knowledge scores indicated greater perceived knowledge and information-seeking orientation regarding haze causes, health

effects, control measures, and protective actions. Higher haze tolerance or risk normalisation scores indicated greater acceptance or normalisation of haze exposure. Higher political trust scores indicated stronger confidence in government information and haze-control responses. Higher perceived economic and mobility cost scores indicated greater perceived burden of haze-control or protective actions on employment, travel, mobility, and daily activities. All construct scores were analysed as continuous independent variables in the correlation and regression analyses.

Statistical analysis

Data were analysed using IBM SPSS Statistics version 29.0. Reporting for this cross-sectional study was guided by the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement [33]. All analyses were conducted with community haze resilience as the primary dependent variable. Prior to the main analysis, the study instrument and resilience scale were assessed for content validity and reliability. Content validity was established during instrument development through review by public health academics and Public Health Medicine Specialists with expertise in community medicine, environmental health and haze-related public health issues. The expert review focused on item relevance, clarity, cultural appropriateness and suitability for interviewer-assisted administration in Sarawak communities. The questionnaire was also pilot tested before full data collection to assess field feasibility, comprehension, and internal consistency. For the present dataset, the internal consistency of the total community haze resilience scale and each resilience domain was assessed using Cronbach's alpha. A Cronbach's alpha value of 0.70 or above was considered acceptable. Reliability was assessed for the total resilience scale and for the four domains separately: connection and caring, resources, transformative potential, and disaster management.

Categorical variables were summarised using frequencies and percentages, while continuous variables were described using means and standard deviations or medians and interquartile ranges, as appropriate. The distribution of the total community haze resilience score was assessed using histograms, normality plots, skewness, kurtosis and regression residual diagnostics. Bivariate analyses were then conducted to identify unadjusted associations between explanatory variables and total community haze resilience. Independent-samples t-tests were used to compare mean resilience between categorical variables with two groups, while one-way analysis of variance (ANOVA) was used for variables with three or more groups, with post-hoc pairwise comparisons where appropriate. Pearson correlation coefficients were used to assess crude linear associations between continuous explanatory variables and resilience. Non-parametric alternatives were considered where distributional assumptions were not adequately met. Geographical and settlement-based differences were specifically examined using ANOVA to compare mean resilience across Sarawak zones and urban, suburban and rural settlement types, with eta-squared reported to quantify the magnitude of between-group differences.

Hierarchical multiple linear regression was used to estimate adjusted associations between equity-relevant explanatory variables and total perceived community haze resilience and to quantify the incremental variance explained as conceptually defined blocks were introduced sequentially. The order of entry was specified a priori from the conceptual framework rather than determined empirically or through automated stepwise selection. Model 1 included sociodemographic and household characteristics to establish a baseline model of general background characteristics. Model 2 added settlement context, household protective resources and health-vulnerability indicators, representing more immediate material and health-related conditions relevant to preparedness. Model 3 added haze-specific psychosocial and informational factors, haze knowledge, risk normalisation, political trust and perceived economic or mobility costs, to assess their additional explanatory contribution after the preceding background and structural factors had been taken into account. Model 4 added Sarawak zone as a distal contextual characteristic to assess whether residual geographical variation remained after adjustment for the measured proximal factors. Geographical zone was not interpreted as a proxy for individual or cumulative haze exposure. For each step, model fit was summarised using R^2 , adjusted R^2 and ΔR^2 , and the statistical significance of the change in explained variance was assessed using the F-change statistic. ΔR^2 was interpreted as the additional

variance explained by the newly entered block conditional on variables already present in the model; because its magnitude depends on block order, it was not interpreted as a measure of the intrinsic or overall importance of a predictor block.

Potential multicollinearity was assessed using pairwise correlations among continuous predictors, tolerance values and variance inflation factors. Variance inflation factor values above 5 and tolerance values below 0.20 were considered indicative of potentially important multicollinearity. Covariates were selected a priori according to the conceptual framework and entered in conceptually defined blocks rather than through automated stepwise selection. Settlement type and distance to the nearest health facility were not included simultaneously because these variables were completely aligned in the dataset. Settlement type was retained in the primary model because it represented a broader contextual measure, while distance to the nearest health facility was evaluated in a sensitivity model. Standard regression diagnostics were used to examine influential observations, residual distribution, linearity and homoscedasticity. Because heteroscedasticity was identified during diagnostic assessment, heteroscedasticity-consistent HC3 robust standard errors were used for statistical inference. Adjusted marginal means were estimated to compare predicted community haze resilience scores across Sarawak zones and settlement types after adjustment for covariates. This analysis was included to support the equity interpretation by showing whether differences in resilience persisted after accounting for sociodemographic, household, health and psychosocial factors.

Adjusted marginal means were estimated to compare covariate-adjusted community haze resilience scores across Sarawak zones and settlement types, thereby assessing whether observed geographical and settlement differences persisted after adjustment for measured covariates. Separate multiple linear regression models were fitted for each resilience domain—connection and caring, resources, transformative potential and disaster management—to explore whether associated factors differed across dimensions of resilience. Finally, a sensitivity analysis replaced settlement type with distance to the nearest health facility to examine whether the main findings were materially altered when geographical accessibility was represented using this alternative measure.

Results

Participant characteristics

We approached 520 eligible adults, of whom 481 completed the questionnaire, yielding a response rate of 92.5%. We screened all completed responses for eligibility, completeness, and consistency before including them in the final analysis (Table 1). Respondents had a mean age of 39.56 years (SD 11.96) and a median age of 39 years (IQR 30–45). The largest age group was 30–45 years (53.2%), followed by respondents aged 46 years and above (24.3%) and 18–29 years (22.5%). Most respondents were male (64.7%), married (73.8%), had secondary education or above (79.4%), and were in formal employment (59.5%). The median monthly household income was RM1,700 (IQR RM1,350–RM2,800), and the mean household size was 5.30 persons (SD 1.80).

By geographical zone, 314 respondents (65.3%) were from Southern Sarawak, 90 (18.7%) from Central Sarawak, and 77 (16.0%) from Northern Sarawak. For settlement type, 121 respondents (25.2%) were classified as urban, 96 (20.0%) as suburban, and 264 (54.9%) as rural. More than half of the respondents lived more than 10 km from the nearest health facility (54.9%), while 78.0% reported no air purifier at home. Current smokers accounted for 35.8% of the sample, and 29.5% reported at least one diagnosed medical illness.

Profile of community haze resilience

The mean total community haze resilience score was 63.20 (SD 7.86), with a median of 64.00 and an interquartile range of 58.00 to 68.00. Observed scores ranged from 38 to 85. The distribution was approximately symmetrical, with minimal skewness (-0.03) and acceptable kurtosis (0.36). Although formal normality testing was significant,

Table 1 Characteristics of respondents, $n=481$

Characteristic	<i>n</i> (%)
Age, years	
Mean (SD)	39.56 (11.96)
Median (IQR)	39.00 (30.00–45.00)
18–29 years	108 (22.5)
30–45 years	256 (53.2)
46 and above	117 (24.3)
Gender	
Male	311 (64.7)
Female	170 (35.3)
Marital status	
Married	355 (73.8)
Unmarried/divorced	126 (26.2)
Education level	
Primary education and below	99 (20.6)
Secondary education and above	382 (79.4)
Occupation	
Not in the labour force	81 (16.8)
Self-sustained occupation	114 (23.7)
Formal employment	286 (59.5)
Monthly household income, RM*	
Mean (SD)	2,154.42 (1,804.49)
Median (IQR)	1,700.00 (1,350.00–2,800.00)
RM1,000 and less	91 (18.9)
RM1,100–RM2,000	216 (44.9)
RM2,100–RM3,000	89 (18.5)
RM3,100 or more	85 (17.7)
Household size	
Mean (SD)	5.30 (1.80)
Median (IQR)	5.00 (4.00–6.00)
Less than 5 members	174 (36.2)
5–6 members	187 (38.9)
7 or more members	120 (24.9)
Sarawak zone	
Southern Sarawak	314 (65.3)
Central Sarawak	90 (18.7)
Northern Sarawak	77 (16.0)
Settlement type	
Urban	121 (25.2)
Suburban	96 (20.0)
Rural	264 (54.9)
Distance to nearest health facility	
≤10 km	217 (45.1)
>10 km	264 (54.9)
Air purifier at home	
Yes	106 (22.0)
No	375 (78.0)
Smoking status	
Smoker	172 (35.8)
Non-smoker	309 (64.2)
Medical history	
Asthma	13 (2.7)
Tuberculosis history	1 (0.2)
Diabetes mellitus	14 (2.9)
Hypertension	92 (19.1)

Table 1 (continued)

Characteristic	<i>n</i> (%)
Age, years	
Hypercholesterolaemia	100 (20.8)
Kidney disease	7 (1.5)
Heart disease	7 (1.5)

RM Ringgit Malaysia (Malaysian currency)

Table 2 Descriptive profile of total and domain-specific community haze resilience scores

Scale/domain	Mean	SD	Median	IQR
Total community haze resilience	63.20	7.86	64.00	58.00–68.00
Connection and caring	18.75	2.72		
Resources	14.27	2.32		
Transformative potential	19.10	2.74		
Disaster management	11.09	1.64		

Higher scores indicate stronger perceived community haze resilience. The total community haze resilience score was derived from 17 items across four domains: connection and caring, resources, transformative potential, and disaster management

SD standard deviation, *IQR* interquartile range

Table 3 Community haze resilience by Sarawak zone

Sarawak zone	<i>n</i>	Mean resilience score (SD)
Southern	314	64.71 (7.95)
Central	90	61.91 (7.44)
Northern	77	58.57 (5.71)

One-way ANOVA showed significant differences across Sarawak zones. Post-hoc tests indicated that all pairwise zone comparisons were statistically significant. ANOVA: $F=22.09$, $p<0.001$, $\eta^2=0.085$

SD standard deviation, η^2 eta squared

ANOVA: $F=22.09$, $p<0.001$, $\eta^2=0.085$

visual inspection and distributional indices supported the use of linear regression, with robust standard errors applied in the final model (Table 2).

Respondents reported a moderately high level of community haze resilience. Among the four domains, transformative potential had the highest mean score, followed closely by connection and caring. The mean score for transformative potential was 19.10 (SD 2.74), while connection and caring had a mean score of 18.75 (SD 2.72). The resources domain had a mean score of 14.27 (SD 2.32), and the disaster management domain had a mean score of 11.09 (SD 1.64).

These findings suggest that respondents generally perceived their communities as having meaningful social cohesion and collective problem-solving capacity. However, resources and disaster-management capacity remain important areas for interpretation because these domains reflect practical preparedness, including access to leaders, services, resources, skills, priorities, and future planning.

Geographical variation in community haze resilience across Sarawak

Community haze resilience differed significantly across Sarawak's three geographical zones (Table 3). The highest mean resilience score was observed in Southern Sarawak, at 64.71 (SD=7.95). This was followed by Central Sarawak, with a mean of 61.91 (SD 7.44), and Northern Sarawak, with the lowest mean score of 58.57 (SD 5.71).

One-way analysis of variance showed a statistically significant difference in total community haze resilience across zones ($F=22.09$, $p<0.001$, $\eta^2=0.085$). The eta-squared value indicated a moderate effect size, suggesting that geographical zone accounted for a meaningful proportion of variation in community haze resilience. Post

hoc comparisons indicated significant differences among Southern and Central Sarawak, Southern and Northern Sarawak, and Central and Northern Sarawak.

These findings indicate geographical variation in unadjusted perceived community haze resilience, with respondents from Northern Sarawak reporting the lowest mean score. These unadjusted differences warranted further examination to determine whether they persisted after accounting for settlement, household, socioeconomic, health-vulnerability and psychosocial characteristics.

Settlement-based variation in community haze resilience

Community haze resilience also differed significantly by settlement type (Table 4). Urban respondents had the lowest mean resilience score, at 60.55 (SD 7.37). Suburban respondents had the highest mean score, at 64.28 (SD 6.37), while rural respondents had a mean score of 64.02 (SD 8.31). The difference across settlement types was statistically significant ($F=9.53$, $p<0.001$, $\eta^2=0.038$). Post-hoc analysis indicated that both suburban and rural respondents reported significantly higher resilience than urban respondents, while suburban and rural respondents did not differ significantly from each other.

Bivariate correlates of community haze resilience

In bivariate analyses, several geographical, settlement-related, household, health-vulnerability and psychosocial variables were associated with total community haze resilience. Geographical zone and settlement type were both significantly associated with resilience, consistent with the equity-focused framework. Respondents from Southern Sarawak reported the highest mean resilience score, while those from Northern Sarawak reported the lowest. Urban respondents had significantly lower mean resilience than suburban and rural respondents.

Distance to the nearest health facility was also associated with resilience, with respondents living more than 10 km from a health facility reporting higher mean resilience than those living within 10 km. However, distance to the health facility was closely aligned with settlement type and was therefore not included in the main regression model, which included settlement type. Air purifier ownership at home was associated with resilience, with respondents without an air purifier reporting a higher mean resilience score than those with one. Non-smokers also reported significantly higher resilience than smokers. The presence of any diagnosed medical illness was significantly associated with resilience, suggesting that health vulnerability may be related to perceived community preparedness capacity.

Among continuous variables, haze knowledge was positively correlated with total community haze resilience. Political trust was also positively correlated with resilience. In contrast, perceived economic and mobility costs, as well as haze tolerance or risk normalisation, were negatively correlated with resilience. Age showed a weak but statistically significant positive correlation with resilience. The full bivariate analysis is presented in Supplementary Table S2.

Table 4 Community haze resilience by settlement type

Settlement type	<i>n</i>	Mean resilience score	SD
Urban	121	60.55	7.37
Suburban	96	64.28	6.37
Rural	264	64.02	8.31

One-way ANOVA showed significant differences across settlement types. Post-hoc tests indicated that urban respondents had lower resilience than suburban and rural respondents

SD standard deviation, η^2 eta squared

ANOVA: $F=9.53$, $p<0.001$, $\eta^2=0.038$

Hierarchical regression analysis

We conducted hierarchical multiple linear regression to assess the incremental contribution of conceptually defined groups of variables to total perceived community haze resilience (Table 5). Model 1, comprising sociodemographic and household characteristics, explained 4.5% of the variance ($R^2 = 0.045$; adjusted $R^2 = 0.022$; F-change (11, 469)=2.01, $p=0.026$). Adding settlement type, air purifier ownership, smoking status and the presence of any diagnosed medical illness in Model 2 increased explained variance by 6.1% points ($R^2=0.106$; adjusted $R^2=0.076$; $\Delta R^2=0.061$; F-change (5, 464)=6.33, $p<0.001$). Model 3 added haze knowledge, risk normalisation, political trust and perceived economic and mobility costs; at this stage of the prespecified sequence, explained variance increased by a further 35.2% points ($R^2=0.458$; adjusted $R^2=0.434$; $\Delta R^2=0.352$; F-change (4, 460)=74.69, $p<0.001$). Sarawak zone was entered in Model 4 and increased explained variance by a further 0.9% points ($R^2=0.467$; adjusted $R^2=0.442$; $\Delta R^2=0.009$; F-change (2, 458)=3.87, $p=0.022$). These ΔR^2 values represent incremental contributions conditional on the variables entered in preceding models and therefore should not be interpreted as measures of the overall importance of the respective predictor blocks.

Collinearity diagnostics did not indicate problematic multicollinearity in the final model. Variance inflation factor values ranged from 1.21 to 3.06, while tolerance values ranged from 0.327 to 0.826. The highest correlation among the continuous predictors was observed between haze knowledge and political trust ($r=0.726$); however, their corresponding variance inflation factor values remained below 3.0. Settlement type and distance to the nearest health facility were completely aligned in the dataset and were therefore not entered simultaneously.

Final adjusted hierarchical regression model

In the final adjusted model, higher haze knowledge was positively associated with community haze resilience (Table 6). Each unit increase in haze knowledge score was associated with a 1.26-point increase in total resilience score ($B=1.26$, 95% CI 0.98 to 1.55, $p<0.001$). Settlement type also remained independently associated with resilience. Compared with urban respondents, suburban respondents had significantly higher adjusted resilience ($B=5.31$, 95% CI 3.31 to 7.30, $p<0.001$), while rural respondents also had significantly higher resilience ($B=2.18$, 95% CI 0.63 to 3.73, $p=0.006$).

Higher haze tolerance or risk normalisation was independently associated with lower community resilience. Repeated environmental hazards may become normalised when communities experience them over time, potentially reducing perceived urgency and preparedness. Previous research and reviews of air-pollution risk perception support the relevance of risk appraisal and normalisation in shaping responses to environmental hazards [34, 35]. In this study, risk normalisation was also negatively associated with several resilience domains, suggesting

Table 5 Hierarchical model-building summary for total community haze resilience

Model	Block entered	R^2	Adjusted R^2	ΔR^2	F-change	df1	df2	p for change
Model 1	Sociodemographic and household characteristics	0.045	0.022	0.045	2.01	11	469	0.026
Model 2	Settlement type, air purifier ownership, smoking status and presence of any diagnosed medical illness	0.106	0.076	0.061	6.33	5	464	<0.001
Model 3	Haze knowledge, risk normalisation, political trust and perceived economic/mobility costs	0.458	0.434	0.352	74.69	4	460	<0.001
Model 4	Sarawak zone	0.467	0.442	0.009	3.87	2	458	0.022

ΔR^2 represents the additional proportion of variance explained by the block entered at each step, conditional on variables already included in preceding models. F-change tests whether this increase in R^2 is statistically significant. Because ΔR^2 depends on the prespecified order of block entry, it should not be interpreted as a ranking of the overall importance of the predictor blocks

Table 6 Statistically significant predictors from the final adjusted hierarchical regression model for total community haze resilience

Predictor	B	95% CI	<i>p</i> -value
Haze knowledge	1.26	0.98 to 1.55	<0.001
Suburban vs. urban	5.31	3.31 to 7.30	<0.001
Rural vs. urban	2.18	0.63 to 3.73	0.006
Haze tolerance/risk normalisation	-0.40	-0.66 to -0.14	0.003
Perceived economic/mobility costs	-0.53	-0.87 to -0.18	0.003
Household size	-0.47	-0.81 to -0.13	0.007
Central vs. Southern	2.03	0.29 to 3.78	0.022
Non-smoker vs. smoker	1.37	0.03 to 2.71	0.046
No air purifier vs. air purifier	1.66	0.01 to 3.31	0.048

B values represent unstandardised coefficients from the final adjusted hierarchical regression model. Positive B values indicate higher total community haze resilience scores, while negative B values indicate lower scores. Robust standard errors were used to account for heteroscedasticity. Reference categories were urban residence, smoker status, air purifier ownership, and Southern Sarawak

CI confidence interval

Final model: $R^2 = 0.467$; adjusted $R^2 = 0.442$. $p < 0.05$ was considered statistically significant

Table 7 Adjusted marginal mean community haze resilience scores by zone and settlement type

Equity variable	Category	Adjusted mean	95% CI
Sarawak zone	Southern Sarawak	62.95	60.32 to 65.59
Sarawak zone	Central Sarawak	64.98	62.01 to 67.95
Sarawak zone	Northern Sarawak	62.14	59.10 to 65.17
Settlement type	Urban	60.95	58.13 to 63.77
Settlement type	Suburban	66.25	63.31 to 69.19
Settlement type	Rural	63.13	60.46 to 65.80

Adjusted means were estimated from the final multivariable model after controlling for sociodemographic, household, health-vulnerability, psychosocial, informational and geographical variables. Higher adjusted mean scores indicate higher predicted total community haze resilience. Urban residence and Southern Sarawak were used as reference categories in the regression model

CI confidence interval

that it may be relevant to both social and organisational aspects of preparedness; however, the cross-sectional design precludes causal interpretation.

After adjustment, Central Sarawak had higher resilience compared with Southern Sarawak ($B = 2.03$, 95% CI 0.29 to 3.78, $p = 0.022$). Northern Sarawak was not significantly different from Southern Sarawak after adjustment, suggesting that the lower unadjusted resilience observed in Northern Sarawak was partly explained by settlement type, household factors and psychosocial determinants.

Adjusted marginal means by zone and settlement type

Adjusted marginal means were estimated to examine whether differences in community haze resilience persisted after accounting for sociodemographic characteristics, household factors, health-vulnerability indicators, settlement type, psychosocial and informational variables, and the Sarawak zone (Table 7). This analysis was included to support the equity interpretation by showing the predicted resilience scores across key equity categories after multivariable adjustment. After adjustment, the predicted mean resilience score was 62.95 for Southern Sarawak, 64.98 for Central Sarawak, and 62.14 for Northern Sarawak. Central Sarawak showed the highest adjusted mean resilience score, while Northern Sarawak remained comparatively lower. However, the adjusted differences across zones were smaller than the unadjusted differences, suggesting that settlement type, household factors and psychosocial determinants explained part of the crude geographical variation.

For the settlement type, adjusted mean resilience remained lowest among urban respondents. The adjusted mean resilience score was 60.95 among urban respondents, compared with 66.25 among suburban respondents

and 63.13 among rural respondents. This indicates that settlement-based differences in resilience persisted after adjustment. The finding is particularly important for the equity framing because it suggests that lower resilience was not confined to rural or remote communities. Instead, urban respondents reported lower predicted resilience to community haze, even after accounting for other covariates.

Domain-specific predictors of community haze resilience

We ran domain-specific regression models to examine whether equity-relevant factors were associated with particular dimensions of community haze resilience (Supplementary Table S3). These analyses were important because total resilience may conceal differences across specific domains of community capacity, such as social cohesion, resources, collective problem-solving, and disaster management capacity. Overall, haze knowledge was the most consistent positive predictor across all four resilience domains. Higher haze knowledge was associated with stronger connection and caring, resources, transformative potential and disaster management. This indicates that informational capacity matters not only for overall resilience but also for multiple dimensions of community preparedness.

Settlement type was also important. Compared with urban respondents, suburban respondents showed stronger resilience across all four domains. Rural respondents showed higher scores than urban respondents, particularly in the transformative potential and disaster management domains, while differences in connection, caring, and resources were not consistently significant after adjustment. This suggests that the lower total resilience observed among urban respondents may reflect weaker perceived collective action, social organisation, or preparedness capacity rather than differences in access to formal infrastructure alone.

Higher haze tolerance or risk normalisation was negatively associated with connection and caring, transformative potential and disaster management. This suggests that normalising recurrent haze may weaken both social and organisational preparedness. Perceived economic and mobility costs were negatively associated with connection and caring and disaster management, while associations with resources and transformative potential were borderline or non-significant. Larger household size was negatively associated with several domains, indicating that household demands may reduce perceived capacity to organise and respond collectively. Geographical differences were also observed at the domain level. Northern Sarawak showed lower adjusted scores in the resources and disaster management domains compared with Southern Sarawak, suggesting potential gaps in practical support and preparedness capacity. Central Sarawak showed stronger adjusted scores in selected domains, particularly connection and caring and disaster management.

Sensitivity analysis

We conducted a sensitivity analysis by replacing settlement type with distance to the nearest health facility in the final regression model (Supplementary Table S4). The decision to exclude both settlement type and distance to the nearest health facility from the primary model was made because they were entirely aligned in the dataset. Specifically, all urban and suburban respondents resided within 10 km of a health facility, while all rural respondents lived more than 10 km away. Including both variables simultaneously would have introduced structural collinearity, which is why they were not included together in the model.

In the sensitivity model, distance to the nearest health facility was not independently associated with total community haze resilience after adjustment. However, haze knowledge, haze tolerance or risk normalisation, perceived economic and mobility costs, household size, smoking status, air purifier ownership and Sarawak zone retained similar patterns of association. This supported the decision to use settlement type as the primary equity variable in the main model, as it appeared to capture a broader social and contextual dimension of inequity than distance to a health facility alone.

Overall, the findings indicate that a combination of informational capacity, settlement context, risk perception, perceived practical barriers, household structure and geographical context shaped community haze resilience in

Sarawak. The results support framing recurrent haze as an environmental health equity issue, in which communities differ in their capacity to prepare, adapt, organise, and respond collectively.

Discussion

Community haze resilience as an environmental health equity concern

The present study found that perceived community capacity to prepare for, adapt to, organise around and respond to recurrent haze varied across Sarawak. Total community haze resilience differed significantly by geographical zone and settlement type, with Northern Sarawak showing the lowest unadjusted resilience and urban respondents reporting lower resilience than suburban and rural respondents. In the adjusted model, higher haze knowledge was positively associated with resilience, whereas greater haze tolerance or risk normalisation, higher perceived economic and mobility costs and larger household size were associated with lower resilience. These findings suggest that recurrent haze preparedness is associated not only with the environmental hazard context but also with informational, psychosocial, household and settlement-related conditions. This extends previous haze research in Southeast Asia, which has largely emphasised exposure, acute health effects, economic impacts, knowledge, attitudes or individual protective practices [3, 24], by examining perceived community resilience as an equity-relevant dimension of environmental health preparedness.

These findings complement, but also move beyond, existing haze literature. Earlier reviews of Southeast Asian haze have highlighted the health impacts of smoke from vegetation, forest and peatland fires, while also noting gaps in exposure assessment, burden estimation and public health translation [3, 4]. The previously published analysis from this Sarawak project examined haze-protective self-care behaviours as an individual-level outcome [24]. In contrast, the present analysis shifts the unit of interpretation from individual behaviour to perceived community capacity. This distinction is important because repeated smoke exposure requires not only that individuals know what to do, but also that communities have trusted information, local leadership, social support, access to resources and practical mechanisms to protect vulnerable households. This aligns with wildfire-smoke and environmental justice literature showing that smoke-related health risks and the capacity for protection are shaped by housing, income, occupational flexibility, healthcare access and trusted communication, not merely by ambient air pollution levels [30, 31].

These findings matter for equity because recurrent haze is experienced not only as an environmental event but also through the conditions that determine whether communities can protect themselves. Smoke-related PM_{2.5} exposure from wildfire, landscape fire and peatland fire activity is known to affect respiratory and cardiovascular health, healthcare utilisation and population morbidity [1–6]. Environmental justice and health-equity literature further emphasise that low-income, marginalised and medically vulnerable communities may face greater difficulty reducing exposure or accessing protective resources [30–32]. In Sarawak, recurrent haze therefore raises an environmental health equity concern because communities may differ in their practical capacity to reduce exposure, seek care, organise support and protect vulnerable households.

Geographical and settlement-based inequities in resilience

The unadjusted geographical pattern, where Southern Sarawak had the highest resilience and Northern Sarawak the lowest, suggests that community preparedness capacity may vary across the state. This is plausible given Sarawak's vast geography, dispersed settlements and unequal access to healthcare and public services. Previous Malaysian evidence has shown that access to healthcare can differ in rural populations [13], while recent reports on Sarawak's Flying Doctor Services highlight the continuing importance of mobile and outreach services for geographically remote communities [12]. These access issues matter for haze preparedness because health services are needed not only after symptoms develop but also for risk communication, medication continuity,

respiratory assessment and follow-up support during haze episodes. The attenuation of the crude zonal differences after multivariable adjustment is important for interpreting geography. The lower unadjusted resilience observed in Northern Sarawak should not be interpreted as an intrinsic geographical effect or as evidence of greater haze exposure. Rather, part of the crude geographical variation was accounted for by measured settlement, household and psychosocial characteristics. Geographical zone therefore appears to function primarily as a contextual marker, while more proximal determinants provide greater insight into the mechanisms associated with resilience.

The settlement-based findings were particularly notable. Urban respondents had lower resilience than suburban and rural respondents, both before and after adjustment. This challenges a simple assumption that rurality always equates to weaker preparedness. Many equity discussions emphasise rural disadvantage due to remoteness, transport barriers, and limited access to healthcare, which remain important concerns in Sarawak and other parts of Borneo [12, 13]. However, resilience is not determined by infrastructure alone. Rural communities may face service-access barriers, but they may also possess stronger social familiarity, mutual assistance networks and local leadership structures that support collective response. Conversely, urban communities may have better formal infrastructure but weaker perceived neighbourhood cohesion, less collective organisation or greater dependence on individual household-level coping.

Community resilience is increasingly recognised as a public health capacity that links social connection, local leadership, health systems, trust and emergency preparedness [21–23]. This interpretation is consistent with CART-based community resilience frameworks, which emphasise connection and caring, community resources, transformative potential and disaster-management capacity [20, 29]. Recent health-emergency literature similarly emphasises that community resilience relies on social networks, local trust, leadership, learning and system linkages, not only formal service availability [21, 22]. Therefore, the lower adjusted resilience among urban respondents may reflect differences in perceived neighbourhood cohesion or collective organisation despite better physical access to formal services. This finding suggests that urban haze preparedness should not be assumed to be adequate simply because services and infrastructure are more concentrated.

Informational equity and the central role of haze knowledge

Higher haze knowledge was positively associated with total community haze resilience and was consistently associated with all four resilience domains. This finding suggests that informational capacity may be a modifiable component of preparedness. Knowledge may help communities interpret air-quality warnings, recognise vulnerable groups, identify feasible exposure-reduction actions and coordinate local response. The association should nevertheless be interpreted as cross-sectional and does not establish that increasing knowledge alone will cause improvements in resilience.

This finding is consistent with previous haze studies showing that knowledge and risk perception influence protective behaviour during smoke haze episodes [3, 4, 24]. However, the present study adds that knowledge is not only associated with individual self-care, but also with perceived community resilience across connection and caring, resources, transformative potential and disaster management. This suggests that knowledge may operate as a collective preparedness resource. In recurrent smoke settings, knowledge helps communities interpret air-quality warnings, recognise vulnerable groups, identify feasible exposure-reduction actions and coordinate local response. Recent wildfire-smoke risk communication literature also emphasises that effective communication must be tailored, trusted, actionable and equity-focused, particularly for communities facing repeated smoke events or practical barriers to response [31].

From an equity perspective, haze knowledge should be treated as a community resource rather than only an individual attribute. Generic air-quality advisories may improve awareness, but they may not sufficiently reach communities with lower health literacy, limited internet access, language diversity or weaker connections to formal institutions. Recent wildfire-smoke risk communication research has highlighted the need for equity-focused communication, as low-income and marginalised communities may be disadvantaged in their ability to receive,

interpret and act on smoke-related health messages [31]. In Sarawak, this means that haze communication should be localised, repeated, culturally appropriate and linked to feasible action. Practical approaches may include community-level haze preparedness briefings, locally tailored air-quality alerts, school- and workplace-based exposure-reduction plans, and engagement of village leaders, community health volunteers and primary care teams. The ASEAN haze roadmap emphasises public awareness and health risk reduction [19], and the present findings support translating that regional priority into targeted informational equity strategies.

Risk normalisation and perceived costs as barriers to equitable preparedness

Higher haze tolerance or risk normalisation was independently associated with lower community resilience. This finding is important because recurrent environmental hazards may become normalised when communities experience them repeatedly over time. If haze is perceived as routine, unavoidable or simply part of seasonal life, communities may be less likely to organise collective preparedness, demand protective resources or respond early to worsening air quality. Risk normalisation may therefore reduce the perceived urgency of reducing exposure, even when haze poses known respiratory and cardiovascular risks [1–4]. In this study, risk normalisation was also negatively associated with several resilience domains, suggesting that it may weaken both the social and organisational components of preparedness.

Perceived economic and mobility costs were also associated with lower resilience. This indicates that preparedness is constrained not only by knowledge, but also by practical barriers. Haze-related protective actions may affect work attendance, transport, outdoor livelihoods, schooling, childcare and household income. For lower-resource households, reducing exposure may compete with the need to work, travel or maintain daily activities. This is where equity becomes central: the same public health advice may be easier for some households to follow than others. Advising people to stay indoors, reduce outdoor exertion or use protective equipment is necessary. Still, it may be insufficient for those whose livelihoods, housing conditions or caregiving responsibilities limit their ability to comply. Equity-focused risk communication literature similarly cautions that messages are less effective when they do not address practical barriers faced by disadvantaged communities [31].

The negative association between perceived economic and mobility costs and community resilience is consistent with an equity interpretation of environmental risk. In practice, haze-related advice may be easier to follow for households with flexible work arrangements, adequate housing, air-conditioned or filtered indoor spaces, access to transport and greater financial capacity. By contrast, households dependent on outdoor work, informal employment, daily wages or regular travel may face greater difficulty reducing exposure even when they understand the health risks. Wildfire-smoke and environmental justice literature similarly describes constraints related to housing, work, transport, caregiving and access to protective resources [30, 31]. This suggests that haze preparedness should not rely solely on changing attitudes or improving knowledge; it should also consider the practical costs of protective action.

These findings suggest that public health messaging should avoid assuming that poor preparedness reflects indifference or lack of awareness. Some communities may understand the risks of haze but still perceive protective actions as economically or socially costly. Policy responses should therefore combine risk communication with enabling support, such as workplace guidance for outdoor workers, clean-air community spaces during severe haze, support for schools and childcare settings, access to appropriate masks, and protection of vulnerable households. Without such enabling measures, haze preparedness may remain inequitable because higher-resource households can act on advice while lower-resource households cannot.

The observed associations with perceived economic and mobility costs, household size, haze knowledge and settlement context are consistent with the proposed implementation pathway: public-health recommendations may be widely communicated, but the practical capacity to act on them can differ across households and communities. Because individual exposure and health outcomes were not measured, these associations should be interpreted as differences in preparedness capacity rather than evidence that these factors directly altered smoke exposure or disease risk.

Household vulnerability and community capacity

Larger household size was independently associated with lower community haze resilience. This may reflect the greater practical burden of organising protection for multiple household members, especially where households include children, older persons, persons with chronic diseases or individuals engaged in outdoor work. Larger households may require more resources to reduce exposure, including masks, transport, indoor space, medication, health information and caregiving support. In recurrent haze situations, these demands may reduce perceived capacity to organise and respond effectively. This finding is relevant to equity because household structure can influence the feasibility of translating public health advice into action.

Although direct comparisons are limited because few haze studies have examined community resilience as the outcome, this finding is plausible from a household-capacity perspective. Larger households may need to protect multiple members with different vulnerabilities, including children, older adults, people with chronic disease and those engaged in outdoor work. This is consistent with the broader smoke-exposure literature showing that vulnerability is shaped not only by biological susceptibility but also by household and social conditions that influence the ability to avoid exposure [2, 30]. In Sarawak, where some households are large and multigenerational, haze preparedness may require household-level support rather than advice directed only at individual respondents. Such support may include medication preparedness, indoor clean-air planning, identification of vulnerable household members and community follow-up during severe haze episodes.

Health vulnerability should also be interpreted within this wider household and community context. The study retained the presence of any diagnosed medical illness as the main health-vulnerability variable in the analysis, while individual conditions were reported descriptively. This avoids over-interpreting small disease-specific subgroups while recognising that chronic disease burden matters for haze preparedness. Malaysia continues to face a substantial burden of non-communicable disease risk factors [18], and smoke-related PM_{2.5} exposure is clinically relevant for individuals with cardiometabolic or respiratory vulnerability [1, 2]. Although this study did not examine clinical outcomes, these overlapping vulnerabilities support prioritising households with chronic disease, respiratory vulnerability or limited access to timely care during haze preparedness.

Sustainable development relevance

The findings are relevant to the Sustainable Development Goals (SDGs), particularly because recurrent haze sits at the intersection of environmental exposure, health protection, inequality, community resilience and climate adaptation. Strengthening community resilience to haze aligns with SDG 3 on health and well-being, SDG 10 on reducing inequalities, SDG 11 on resilient human settlements, and SDG 13 on climate action [36]. The lower adjusted resilience among urban respondents, and the attenuation of crude zonal differences after adjustment, further suggest that preparedness should not be designed as a uniform intervention but should address the specific barriers associated with lower capacity.

These linkages indicate that haze preparedness should not be treated narrowly as an episodic air-pollution response but as part of a wider sustainable-development agenda involving health equity, resilient communities and climate-health adaptation [36].

For Sarawak, recurrent haze intersects with chronic disease vulnerability, urban-rural and interior settlement diversity, differences in healthcare accessibility and variable community preparedness capacity. These issues align with the broader SDG principle that health, inequality reduction, sustainable communities, and climate action are interdependent [36]. The World Health Organization's operational framework for climate-resilient and low-carbon health systems further emphasises strengthening health-system capacity to protect communities under changing climate conditions while maintaining equitable access to quality care [37]. Applied to recurrent haze, this supports integrating preparedness into primary care outreach, local government planning, community risk communication, school health programmes, occupational protection for outdoor workers and emergency

preparedness systems. Recent SDG resilience scholarship likewise highlights the need for integrated, shock-responsive policies to protect well-being during crises and environmental disruptions [38].

Implications for equitable haze preparedness and policy

The findings have several implications for policy and public health practice. First, haze preparedness should move beyond uniform, individual-level advisories to community-centred, equity-oriented strategies. Public messages remain important, but local mechanisms should support them by helping communities act collectively. These may include strengthening local leadership, improving community-level risk communication, identifying vulnerable households before haze episodes, and linking community preparedness plans with primary care and public health services. This aligns with resilience frameworks that view community capacity as a combination of connection, resources, transformative potential, and disaster management ability [20, 29], and with health emergency and disaster risk management approaches that emphasise the role of health systems in preventing and reducing health consequences from natural and technological hazards [22].

Second, interventions should prioritise modifiable factors associated with variation in resilience. Haze knowledge, risk normalisation and perceived practical costs are actionable targets. Risk communication should therefore do more than provide air-quality readings. It should clearly explain health risks, counter the normalisation of repeated haze exposure, and provide feasible actions to reduce exposure across different household and occupational contexts. For communities facing economic or mobility constraints, preparedness strategies should include practical support rather than relying solely on behaviour-change messages. This is especially important because communities may understand haze risks but still lack the resources, household flexibility or occupational protection needed to act on public health advice.

Third, haze preparedness should be integrated into broader environmental health and climate adaptation planning. Tropical peatland fire haze in Southeast Asia is linked to land-use pressures, drought, El Niño-related conditions and regional smoke transport [5–7]. As climate-sensitive fire risks evolve, communities will need sustained preparedness rather than ad hoc responses during severe haze episodes. The ASEAN roadmap provides a regional policy platform for haze prevention, monitoring, and health risk reduction [19], but local implementation must be sensitive to inequities across settlement contexts, household capacities, access to information, and community organisation. In Sarawak, this means embedding haze preparedness within primary care outreach, local government planning, school health programmes, workplace health protection and community-based disaster preparedness.

Strengths and limitations

This study has several strengths. First, it provides a distinct equity-oriented analysis of recurrent haze by examining community haze resilience as the primary outcome, rather than individual haze-protective self-care behaviour. This allowed the study to move beyond personal protective practices and to examine the broader community capacity to prepare, adapt, organise, and respond collectively during recurrent haze episodes. This distinction matters because reducing exposure during haze depends not only on individual knowledge or motivation but also on social cohesion, local leadership, access to resources, trusted communication, and community-level preparedness mechanisms. Second, the study used a state-level community sample from Sarawak and included both geographical zone and settlement type, enabling the analysis to examine two complementary dimensions of environmental health equity. Including urban, suburban, and rural settlement categories was particularly important because the findings showed that lower resilience was not confined to rural communities but was also evident in urban settings.

Third, the study used a study-specific conceptual framework integrating community resilience and environmental health equity perspectives and a hierarchical analytical approach to examine the incremental contribution of conceptually defined groups of determinants. Haze-related psychosocial and informational factors substantially

increased explained variance after sociodemographic, household, and settlement-related factors were considered. Fourth, the study examined both total and domain-specific community resilience, providing a more nuanced understanding of how variation may appear across social cohesion, resources, transformative potential and disaster-management capacity. Finally, the study used a structured questionnaire that underwent translation, expert review and pilot testing, with the community resilience items adapted from established CART measures [20, 29].

Several limitations should also be acknowledged. First, the cross-sectional design limits causal interpretation. Although the findings suggest plausible relationships between settlement context, haze knowledge, risk normalisation, perceived costs and community resilience, the temporal direction of these associations cannot be confirmed. Longitudinal or repeated-measures studies would help determine whether improvements in risk communication, local preparedness, or community mobilisation lead to measurable gains in community haze resilience over time. Second, the study relied on self-reported data, which may introduce recall bias, social desirability bias or perception-based measurement error. Community haze resilience was measured as perceived community capacity, rather than through direct observation of preparedness activities, emergency response performance, local resource inventories or actual community behaviour during haze episodes.

Third, this study did not include individual-level PM_{2.5} exposure estimates, real-time air-quality monitoring data, previous individual haze experience, frequency or severity of past haze exposure, or clinical outcome measures. Previous haze experience and cumulative exposure severity may influence risk perception, knowledge and preparedness and could therefore partly account for geographical variation in perceived community resilience. Geographical zone should consequently not be interpreted as a surrogate for historical or cumulative haze exposure. The findings should also not be interpreted as evidence of an exposure-response relationship between haze and health outcomes. Instead, the study should be interpreted as an equity-focused analysis of perceived preparedness capacity within a recurrent haze-exposed setting. Future studies incorporating participant-level exposure histories, locality-specific monitoring data and temporally resolved exposure measures would help distinguish the effects of environmental exposure from those of social and contextual determinants.

Fourth, cultural determinants were not directly operationalised as a separate construct. Sarawak is culturally and ethnolinguistically diverse, and cultural norms, language, community leadership traditions and collective practices may influence risk perception, information exchange and community response. Although we incorporated translation, culturally appropriate expert review, and multilingual interviewer support into data collection, the study cannot determine the independent contribution of cultural determinants to perceived community haze resilience. Future studies should measure these dimensions explicitly. Fifth, settlement type was operationally classified from sampled locality and field classification. Although this followed Malaysian statistical definitions, it may not fully align with formal census-based urban-rural classifications. Settlement type and distance to the nearest health facility were also completely aligned in the dataset and therefore were not included simultaneously in the primary model. We conducted a sensitivity analysis using distance in place of settlement type, but residual confounding by access-related factors remains possible.

Sixth, the study retained the presence of any diagnosed medical illness as the primary health-vulnerability indicator in the analysis, while reporting individual diagnoses only descriptively. This approach avoided sparse-category instability and overadjustment, but it also means that the study could not determine whether resilience differed by specific conditions such as asthma, diabetes, hypertension, cardiovascular disease or previous tuberculosis.

Finally, although respondents were recruited from Southern, Central and Northern Sarawak using multistage stratified cluster sampling, the achieved sample was regionally imbalanced, with 65.3% recruited from Southern Sarawak. The sample was therefore not population-proportional across zones, and overall unweighted descriptive estimates may disproportionately reflect the characteristics of Southern respondents. Although geographical zone and settlement type were included separately in the multivariable analysis, statistical adjustment cannot fully address residual selection or unmeasured contextual differences associated with unequal regional representation. The findings should therefore be generalised cautiously, particularly to under-represented and highly remote

communities, communities not accessible during fieldwork, and groups with limited participation in community-based surveys.

Conclusion

This study found that perceived community resilience to recurrent haze varied across geographical and settlement contexts among the communities studied in Sarawak, Malaysian Borneo. Urban respondents had lower adjusted resilience than suburban and rural respondents. Higher haze knowledge was positively associated with resilience, whereas greater risk normalisation, higher perceived economic and mobility costs, and larger household size were associated with lower resilience. These findings suggest that community preparedness for recurrent haze is associated not only with geographical and settlement context but also with informational, psychosocial, household and practical conditions that may enable or constrain communities' capacity to prepare, adapt, organise and respond collectively. Viewed through an environmental health equity lens, these differences highlight whether communities have adequate access to the information, resources, support, and enabling conditions needed for effective haze preparedness.

Public health preparedness may therefore benefit from locally tailored risk communication, support for vulnerable households, measures to reduce practical barriers to protective action, and stronger linkages among communities, local leadership and health services. Further longitudinal and community-level research is warranted to determine how differences in perceived community resilience translate into protective behaviours and health outcomes during recurrent haze episodes.

Abbreviations

ANOVA	Analysis of variance
API	Air Pollutant Index
ASEAN	Association of Southeast Asian Nations
B	Unstandardised regression coefficient
CI	Confidence interval
CART	Communities Advancing Resilience Toolkit
F	F-statistic
IQR	Interquartile range
NCD	Non-communicable disease
PM _{2.5}	Particulate matter with an aerodynamic diameter of 2.5 micrometres or smaller
p	Probability value / statistical significance value
R ²	Coefficient of determination
ΔR ²	Change in the coefficient of determination
SD	Standard deviation
SE	Standard error
STROBE	Strengthening the Reporting of Observational Studies in Epidemiology
η ²	Eta squared: effect size in analysis of variance
α	Cronbach's alpha: internal consistency reliability coefficient
β	Standardised regression coefficient, if reported
r	Pearson correlation coefficient
t	T-statistic

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1186/s12889-026-29927-0>.

Acknowledgements We would like to express our sincere appreciation to all respondents who participated in this study. We also acknowledge the support of Universiti Malaysia Sarawak and the relevant community leaders and field personnel who assisted with access to study localities and data collection. We are grateful to all research team members, enumerators and administrative staff involved in field coordination, questionnaire administration, data management and logistical support throughout the study. Their contribution was essential in enabling data collection across diverse urban, suburban and rural communities in Sarawak.

Authors' contributions SFJ conceived the study idea, served as project leader, and provided overall supervision, including conceptualising the manuscript, interpreting findings, and critically revising the intellectual content. SFJ also contributed substantially to drafting and refining the manuscript. LJH, LSH, RN, WJ, and PRB contributed to data collection, management, organisation, verification of study variables, interpretation of findings, and manuscript writing. They also helped refine the presentation of the study findings and ensure the results were reported clearly and accurately. HH and AST contributed to the statistical analysis, interpretation of the regression findings, development of the analytical narrative, and manuscript writing. They also helped ensure that the statistical outputs were appropriately interpreted in relation to the study objectives and conceptual framework. All authors contributed to the final manuscript, reviewed and critically revised the draft, approved the final version for submission, and agreed to be accountable for the work's accuracy and integrity.

Funding This research was supported by the Pilot Research Grant Scheme of Universiti Malaysia Sarawak (UNIMAS), Project ID UNI/F05/PILOT/86115/2024.

Data availability All data generated or analysed during this study are included in this published article and its supplementary materials.

Declarations

Ethics approval and consent to participate The Medical Research Ethics Committee, Universiti Malaysia Sarawak (UNIMAS), approved this study (Reference: FME/24/129, 7 May 2024). The study followed the ethical principles of the Declaration of Helsinki and relevant institutional guidelines. All participants were informed about the study objectives and procedures, the voluntary nature of their participation, the confidentiality of their responses, and their right to decline participation or withdraw at any time without penalty. We obtained informed consent from all participants before data collection.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Gould CF, Heft-Neal S, Johnson M, Aguilera J, Burke M, Nadeau K. Health effects of wildfire smoke exposure. *Annu Rev Med*. 2024;75:277–92. <https://doi.org/10.1146/annurev-med-052422-020909>.
2. World Health Organization. Wildfires. <https://www.who.int/health-topics/wildfires>. Accessed 16 Sep 2026.
3. Phung VLH, Uttajug A, Ueda K, Yulianti N, Latif MT, Naito D. A scoping review on the health effects of smoke haze from vegetation and peatland fires in Southeast Asia: issues with study approaches and interpretation. *PLoS ONE*. 2022;17(9):e0274433. <https://doi.org/10.1371/journal.pone.0274433>.
4. Cheong KH, Ngiam NJ, Morgan GG, Pek PP, Tan BYQ, Lai JW, et al. Acute health impacts of the Southeast Asian transboundary haze problem: a review. *Int J Environ Res Public Health*. 2019;16(18):3286. <https://doi.org/10.3390/ijerph16183286>.
5. Kuwata M. Atmospheric emissions, processes, and impacts of tropical peatland fire haze in Equatorial Asia: a review. *Atmos Environ*. 2024;331:120575. <https://doi.org/10.1016/j.atmosenv.2024.120575>.

6. Grosvenor MJ, Ardiyani V, Wooster MJ, Gillott S, Green DC, Lestari P, et al. Catastrophic impact of extreme 2019 Indonesian peatland fires on urban air quality and health. *Commun Earth Environ*. 2024;5:649. <https://doi.org/10.1038/s43247-024-01813-w>.
7. Latif MT, Othman M, Idris N, Juneng L, Abdullah AM, Hamzah WP, et al. Impact of regional haze towards air quality in Malaysia: a review. *Atmos Environ*. 2018;177:28–44. <https://doi.org/10.1016/j.atmosenv.2018.01.002>.
8. ASEAN Specialised Meteorological Centre. Upgrade of Alert Level 2 to Alert Level 3 for Kalimantan. 8 September 2015. <https://asmc.asean.org/asmc-alerts/>. Accessed 20 Sep 2026.
9. ASEAN Specialised Meteorological Centre. Activation of Alert Level 3 for Kalimantan. 5 September 2019. <https://asmc.asean.org/alert20190905-activation-of-alert-level-3-for-kalimantan/>. Accessed 20 Sep 2026.
10. Department of Environment Malaysia. Air Pollutant Index (API). <https://www.doe.gov.my/2021/10/04/english-air-pollutant-index-api/>. Accessed 20 Sep 2026.
11. Payus CM, Nur Syazni MS, Sentian J. Extended air pollution index (API) as tool of sustainable indicator in the air quality assessment: El-Nino events with climate change driven. *Heliyon*. 2022;8(3):e09157. <https://doi.org/10.1016/j.heliyon.2022.e09157>.
12. Lim SH, Giee SF, Johnny W, Lai HY. Flying Doctor Services in Sarawak: a medical frontline experience. *Air Med J*. 2024;43(5):392–4. <https://doi.org/10.1016/j.amj.2024.05.001>.
13. Lim KK, Sivasampu S, Mahmud F. Equity in access to health care in a rural population in Malaysia: a cross-sectional study. *Aust J Rural Health*. 2017;25(2):102–9. <https://doi.org/10.1111/ajr.12298>.
14. Sahani M, Othman H, Kwan SC, Juneng L, Ibrahim MF, Hod R, et al. Impacts of climate change and environmental degradation on children in Malaysia. *Front Public Health*. 2022;10:909779. <https://doi.org/10.3389/fpubh.2022.909779>.
15. Ibrahim MF, Hod R, Ahmad Tajudin MAB, Wan Mahiyuddin WR, Mohammed Naw A, Sahani M. Children's exposure to air pollution in a natural gas industrial area and their risk of hospital admission for respiratory diseases. *Environ Res*. 2022;210:112966. <https://doi.org/10.1016/j.envres.2022.112966>.
16. Mohd Zulkifli SWH, Samsudin HB, Majid N. Association between PM₁₀ and respiratory diseases admission in peninsula Malaysia during haze. *Sci Rep*. 2024;14:21030. <https://doi.org/10.1038/s41598-024-63591-x>.
17. Ministry of Health Malaysia. Current situation of haze-related illnesses in Sarawak. 20 September 2019. <https://www.moh.gov.my/media-kkm/arkib-kenyataan-media/2019/kenyataan-akhbar-ketua-pengarah-kesihatan-malaysia-20-september-2019-situasi-terkini-penyakit-berkaitan-jerebu-di-sarawak>. Accessed 16 Sep 2026.
18. Institute for Public Health. National Health and Morbidity Survey (NHMS) 2023: Non-Communicable Diseases and Healthcare Demand - Key Findings. Shah Alam: Institute for Public Health, National Institutes of Health, Ministry of Health Malaysia; 2024.
19. ASEAN Secretariat. The Second Roadmap for ASEAN Cooperation on Transboundary Haze Pollution Control with Means of Implementation (2023–2030). Jakarta: ASEAN Secretariat; 2024.
20. Pfefferbaum RL, Pfefferbaum B, Van Horn RL, Klomp RW, Norris FH, Reissman DB. The Communities Advancing Resilience Toolkit (CART): an intervention to build community resilience to disasters. *J Public Health Manag Pract*. 2013;19(3):250–8. <https://doi.org/10.1097/PHH.0b013e318268aed8>.
21. van Kessel G, Milanese S, Dizon J, de Vries DH, MacGregor H, Abramowitz S, et al. Community resilience to health emergencies: a scoping review. *BMJ Glob Health*. 2025;10(4):e016963. <https://doi.org/10.1136/bmjgh-2024-016963>.
22. World Health Organization, Regional Office for South-East Asia. Strategic Action Framework for Strengthening Community Engagement and Resilience to Health Emergencies in the WHO South-East Asia Region (2025–2029). New Delhi: WHO Regional Office for South-East Asia; 2024.
23. Ellis WR, Dietz WH, Chen KLD. Community resilience: a dynamic model for Public Health 3.0. *J Public Health Manag Pract*. 2022;28(Suppl 1):S18–26. <https://doi.org/10.1097/PHH.0000000000001413>.
24. Jiee SF, Hann LJ, Hee LS, Ngui R, Joseph TA, Seling NR, et al. Haze-protective self-care behaviours in Sarawak, Malaysia: a state-representative cross-sectional study. *Sci Rep*. 2026;16:18384. <https://doi.org/10.1038/s41598-026-49870-9>.
25. Department of Environment Malaysia. Kenyataan Media: Indeks Pencemar Udara (IPU), 19 Ogos 2017. <https://www.doe.gov.my/wp-content/uploads/2021/09/13.-Kenyataan-Akhbar-NRE-Haze-Indeks-Pencemar-Udara-IPU-19-Ogos-2017.pdf>. Accessed 20 Sep 2026.
26. Department of Statistics Malaysia. Key Findings Population and Housing Census of Malaysia 2020: Administrative District. Putrajaya: Department of Statistics Malaysia; 2022. <https://www.dosm.gov.my/portal-main/release-content/key-findings-population-and-housing-census-of-malaysia-2020-administrative-district>. Accessed 20 Sep 2026.
27. Sarawak Development Agency. Sri Aman Masterplan (2020–2030) Study. Sarawak: Sarawak Development Agency. https://sada.sarawak.gov.my/modules/web/pages.php?id=4&mod=publicationC=publication_show. Accessed 20 Sep 2026.
28. Department of Statistics Malaysia. Household Income and Basic Amenities Survey Report 2022: Technical Notes. Putrajaya: Department of Statistics Malaysia; 2023.

29. Pfefferbaum RL, Pfefferbaum B, Zhao YD, Van Horn RL, McCarter GSM, Leonard MB. Assessing community resilience: a CART survey application in an impoverished urban community. *Disaster Health*. 2016;3(2):45–56. <https://doi.org/10.1080/21665044.2016.1189068>.
30. D'Evelyn SM, Jung J, Alvarado E, Baumgartner J, Caligiuri P, Hagmann RK, et al. Wildfire, smoke exposure, human health, and environmental justice need to be integrated into forest restoration and management. *Curr Environ Health Rep*. 2022;9(3):366–85. <https://doi.org/10.1007/s40572-022-00355-7>.
31. Sandoval S, Bui J, Hopfer S. Wildfire and smoke risk communication: a systematic literature review from a health equity focus. *Int J Environ Res Public Health*. 2025;22(3):368. <https://doi.org/10.3390/ijerph22030368>.
32. World Health Organization. Operational framework for monitoring social determinants of health equity. Geneva: World Health Organization; 2024.
33. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Lancet*. 2007;370(9596):1453–7. [https://doi.org/10.1016/S0140-6736\(07\)61602-X](https://doi.org/10.1016/S0140-6736(07)61602-X).
34. Zhou L, Wu X, Xu Z, Fujita H. The influencing factors of haze tolerance in China. *Int J Environ Res Public Health*. 2019;16(2):287. <https://doi.org/10.3390/ijerph16020287>.
35. Bahrami Z, Sato S, Yang Z, Maiti M, Kanawat P, Umemura T, et al. The perception of air pollution and its health risk: a scoping review of measures and methods. *Glob Health Action*. 2024;17(1):2370100. <https://doi.org/10.1080/16549716.2024.2370100>.
36. United Nations. Transforming our world: the 2030 Agenda for Sustainable Development. New York: United Nations; 2015. A/RES/70/1.
37. World Health Organization. Operational framework for building climate resilient and low carbon health systems. Geneva: World Health Organization; 2023.
38. Henrysson M, Bali Swain R, Swain A, Fuso Nerini F. Sustainable Development Goals and wellbeing for resilient societies: shocks and recovery. *Humanit Soc Sci Commun*. 2024;11:1513. <https://doi.org/10.1057/s41599-024-03973-8>.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Sam Froze Jiee¹  · Jyh Hann Lim² · Siong Hee Lim¹ · Romano Ngui³ · Winnie Johnny¹ · Peter Ronald Bihos^{1,4} · Helmy Hazmi¹ · Anselm Ting Su¹

✉ Sam Froze Jiee
fjsam@unimas.my

¹ Department of Community Medicine and Public Health, Faculty of Medicine and Health Sciences, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak, Malaysia

² Environmental Health Sector, Disease Control Division, Ministry of Health Malaysia, Putrajaya, Malaysia

³ Department of Paraclinical Sciences, Faculty of Medicine and Health Sciences, Universiti Malaysia Sarawak (UNIMAS), Kota Samarahan, Sarawak, Malaysia

⁴ Sarawak State Health Department, Ministry of Health Malaysia, Kuching, Sarawak, Malaysia