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Original Article

Cycles of renewal: Ecosystem regulation through shifting cultivation in Thai highlands

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Abstract

Shifting cultivation is often scrutinized for its environmental impacts, yet its role in providing ecosystem services remains poorly quantified. This study's objective was to measure and compare key regulating services across a land-use gradient in highland Thailand, including monoculture maize, active cultivation (upland rice), 3-year fallow, and conservation forest. Field and laboratory experiments assessed soil erosion, gaseous pollutants, Particulate Matter with diameter of less than 2.5 µm ($PM_{2.5}$) emissions, and particulate capture capacity. Results reveal that monoculture maize demonstrated severe soil degradation, with high sediment in runoff (2.39 g/L) and poor water infiltration (94.75%). Conversely, the 3-year fallow plot showed significant recovery, with erosion dropping to 0.90 g/L and infiltration rising to 97.28%. Furthermore, while burning for cultivation releases particulates, the fallow landscape provides a powerful counter-service, with vegetation sequestering an average of 22.95 kg of suspended particulates per rai. This research provides clear quantitative evidence that traditional shifting cultivation, with adequate fallow periods, functions as a resilient system whose regulating services can mitigate its own disturbances. These findings challenge one-dimensional views of the practice and argue for land policies that recognize and integrate the profound ecological value of managed agro-ecosystems

Keywords: Shifting cultivation, Land-use planning, Regulating ecosystem services, Erosion control, Gaseous air pollutants

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Introduction

Highland regions are globally recognized for their distinct ecosystems and rich biodiversity, providing critical ecosystem services. In Thailand, these uplands, often designated as protected forests, are vital watersheds. A predominant land management practice here is shifting cultivation, a traditional system supporting millions, including marginalized communities like the Karen in Mae San village, Lampang, for whom it underpins cultural identity, food security, and economic sustainability (Dressler et al., 2015). Criticism of shifting cultivation, especially in relation to deforestation, continues despite its deep cultural roots in highland societies. However, it's important to carefully distinguish its rotational nature, involving fallow periods for regeneration within a fixed landscape, from permanent forest loss caused by expansion into previously undisturbed areas (Martin et al., 2023; Thilde and Catherine, 2023). This difference matters when accurately assessing its environmental impacts.

The rationale for this research comes from growing pressures on traditional shifting cultivation systems. Environmental challenges arise from shortened fallow periods or practices on steep slopes, leading to soil degradation, nutrient depletion, and increased erosion (Kleinman et al., 1995). Biomass burning, integral to the process for soil fertility enhancement (Nakano and Syahbuddin, 1989; Kleinman et al., 1995), also generates greenhouse gases and $PM_{2.5}$ air pollution, posing significant health risks and economic costs (Mishra, 2022; Basith et al., 2022; Huang et al., 2023). Furthermore, national policies aimed at increasing forest cover, such as the 20-Year National Strategy (2018–2037), have reclassified traditional lands, limiting indigenous use, and forcing a shift towards continuous cultivation and monoculture systems. This transition has profound social, economic, and ecological repercussions (Mertz et al., 2013), necessitating a clearer understanding of the involved trade-offs.

Given the complex interactions between land-use change, ecosystem functions, and community well-being, this study hypothesizes that different land-use types within the highland agricultural landscape (monoculture, active shifting cultivation, community/conservation forest) exhibit measurably capacities to provide key regulating ecosystem services, thereby influencing environmental outcomes such as soil and air quality. To investigate this, the objective of this research is to quantify and compare key regulating services (soil erosion control, $PM_{2.5}$ sequestration) across the highland agricultural landscape. By doing so, this study develops and validates a comprehensive framework that explicitly links shifting cultivation practices, land-use transitions, and ecosystem services to measurable environmental outcomes such as soil erosion rates, $PM_{2.5}$ emissions, and dust sequestration. While prior research has separately addressed soil degradation, biodiversity loss, and carbon storage (Palm et al., 2004; Gogoi et al., 2020; Chandra et al., 2021; Mertz et al., 2021; Wapongnungsang et al., 2021; Abrell et al., 2024). This study synthesizes these elements into a coherent structure that captures the complex socio-ecological dynamics of highland landscapes. This provides empirical evidence to inform policy interventions that balance agricultural livelihoods with ecosystem conservation in highland regions.

Material and Methods

Study area

This research was carried out at various sites in and around the highland community of Mae San village, Thailand (18.62°N, 99.77°E). Mae San village, which is located in Ban Dong Sub-district, Mae Mo District, Lampang Province, sits between 500 and 1100 meters above sea level. The village is surrounded by a series of mountain ranges: the western ranges stretch from Chaeson National Park to Doi Khun Tan National Park, while the eastern ranges run through Mae Yom National Park and reach Wiang Kosai National Park, continuing beyond the Lampang Municipal Area.

The Karen Mae San community's livelihood is strongly dependent on this ecosystem, particularly their traditional shifting cultivation. This practice provides both food security and household income. The total annual economic value from natural resource use is around 6.5 million Baht. Major contributors include vegetables and mushrooms (about 3.14 million Baht), bamboo and plants (2.15 million Baht), and animals (around 1 million Baht), with the remainder coming from fruit gardens.

Shifting cultivation is a carefully managed approach to resource use, deeply grounded in indigenous knowledge. Farming areas are chosen with care away from watershed zones, often guided by traditional beliefs such as seeking auspicious signs or seeking spiritual approval. Land preparation involves clearing and cutting—leaving some large tree stumps to encourage growth—followed by burning. This short-term land use incorporates long fallow periods, allowing natural vegetation to regrow, thereby restoring soil structure and fertility. The resulting secondary forests enhance carbon sequestration, regulate air quality, and trap $PM_{2.5}$ dust.

Typically, a mix of upland rice, diverse vegetables, and flowers is cultivated. After harvest, fields are left fallow for ecological recovery through secondary succession, with designations like "one-year fallow" up to "seven-year fallow" (or even 10-15 years). This process enhances soil fertility, enabling the ecosystem to provide services comparable to natural forests. Such rotational use of the same land promotes sustainable mineral and water cycling, contrasting with other farming methods that often lead to expansion into new, unplanned areas.

Assessment of soil erosion

This study examines the physical and chemical properties of soils, specifically bulk density, particle density, porosity, and organic matter. It also examines water infiltration rates and compares soil loss across different land use practices. Soil and water samples were collected from four representative plots (SW1-SW4, Figure 1), each characterized by distinct land use types, as detailed in Table 1. These plots have similar slopes with a gradient from 35 to 40. Sampling occurred from May 2023 (aligning with what is normally the beginning of the rainy season) to January 2024. The methods used for analyzing bulk density, particle density, and porosity followed the procedures outlined by Whittington et al. (2021). Soil organic matter content was measured by a modified Walkley-Black method (Nelson and Sommers, 2021). To quantify soil erosion, 2 × 10 m experimental plots were established, each bordered by 0.3 m wide galvanized iron sheets to prevent lateral soil movement. At the downslope end of each plot, two 200-liter tanks were installed to capture runoff and sediment (modified from Punyalue et al., 2018). Following each rainfall event, the total runoff volume was recorded, and three 0.5-liter subsamples of the sediment-laden water were collected within 24 hours. In the laboratory, these subsamples were allowed to settle before the supernatant was decanted. The remaining sediment was then oven-dried and weighed to determine soil loss.

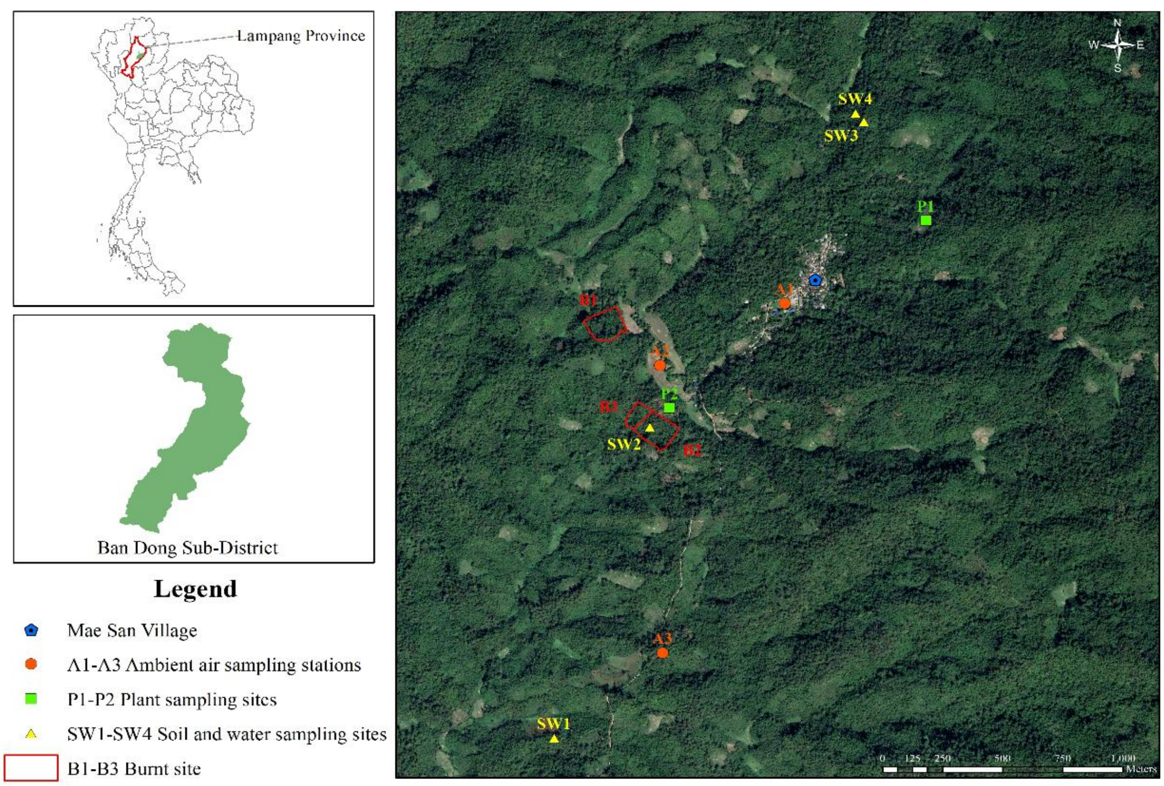

Figure-1. Topography of Thailand, Lampang province and Ban Dong sub-district and sampling sites.

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Table-1. Sample plots and their characteristics for soil erosion assessment.

Sample	Land use type	Explanation
Plot 1	Maize cultivation	This plot has grown maize continuously for 6 years. The slash-and-burn method was used to prepare the land each year.
Plot 2	Upland rice cultivation	Before slash-and-burn, this area was a 7-year fallow vegetation site of secondary forest.
Plot 3	3-years fallow vegetation	Areas that farmers have previously cultivated and have been allowed to naturally regenerate for 3 years
Plot 4	Forest/ conservation zone	This area is conserved for both environmental preservation and the collection of forest by-products.

Assessment of $PM_{2.5}$ dust generation

The dust sampling assessment was conducted in 2024, over three distinct periods: February (pre-burning season), March (burning season), and May (onset of the rainy season). March aligned with the peak of agricultural land preparation through burning, during which numerous hotspots of fire activity were reported across Thailand, Laos, Myanmar, and Cambodia, reflecting the seasonal cycle of shifting cultivation practices in these areas. Ambient air sampling stations (A1-A3) are shown in Figure 1. A total of 27 samples were collected over three days during each of these periods. It is important to note that prevailing wind patterns typically moved from south to north, transporting particulate matter from surrounding areas to Mae San village during this time. Consequently, sampling conducted during these three months facilitated a comprehensive evaluation of burning practices associated with shifting cultivation.

Three $PM_{2.5}$ samplers were employed for the collection of dust samples. This included a Met One model E-E-FRM-DC, which was installed at the Mae San School (center of the village), and two BGI PQ200 FRM Sampler units positioned in the rice field and upper hill area. All three instruments were designed based on the U.S. Environmental Protection Agency's Ambient Particulate Federal Reference Method (FRM) (CFR Part 50, Appendix L). Samples were collected at a consistent rate of 16.7 liters per minute, with built-in ambient temperature, pressure, and relative humidity sensors integrated into the equipment. The sampling process used 47 mm Polytetrafluoroethylene (PTFE) filter papers over 24-hour periods. The PTFE filter papers were dried in a desiccator for 24 hours before and after sampling to reduce residual moisture. Afterward, they were weighed using the gravimetric method to calculate the 24-hour concentration of $PM_{2.5}$.

In addition, the same filters were analyzed for water-soluble ions, including cations (NH_4^+, Na^+, Mg_2^+, K^+, Ca_2^+) and anions (F^-, Cl^-, Br^-, PO_4^{3-}, SO_4^{2-}, NO_3^-) using ion chromatography. Samples were sonicated in deionized water using an ultrasonic bath (Elmasonic S 30 (H)) for 30 minutes, and the extracts were filtered through 0.45-micron filter papers. Blank filters were extracted and passed through similar procedures. Both filtered samples and blank filters were stored below 4 °C to preserve sample integrity prior to analysis. Water-soluble ions were quantitatively determined using an S3000 Dionex ion chromatographic system (Thermo Scientific), equipped with an IonPac AS22 separation column and an IonPac AG22 guard column. Final concentrations of water-soluble ions extracted from the sample filters were corrected against the blank filters.

Measuring leaf surface retention of particulate matter (PM)

The ability of vegetation to trap airborne particulates was assessed in a plot left fallow for seven years, which reflects the typical fallow duration in dry evergreen forests before re-clearing. This timeframe was selected because it aligns with the local rotational cycle prior to re-cultivation, allowing for analysis of PM retention on mature leaf surfaces. Since the forest in Mae San village consists of dry evergreen trees, those left in fallow fields for six years will reach their seventh year by the next slash-and-burn cycle.

Two plots within the 7-year fallow area (P1-P2 in Figure 1) were selected along the southern wind direction in the Mae San areas. The first plot was situated near a burning site, while the second was located to the north of a village. From each plot, five dominant plant species, ranging from 0.6 to 2.0 meters in height, were randomly selected. Leaf samples, each measuring 400–600 cm², were collected from the selected species both before and after the burning event, with five replicate samples for each species. The leaf samples were placed in labeled, clean plastic bags for subsequent analysis.

Leaf sampling commenced in March, before the burning event, and was repeated 10 days after a heavy rainfall of 20 mm. A second sampling was conducted one day after the burning of the 7-year fallow plots.

To determine the PM capture capacity of the leaves, we followed a two-step approach. First, the leaf surface area of each species was measured using the Petiole mobile application. Then, the front surfaces of the leaf samples were washed thoroughly with distilled water. The resulting wash water was vacuum-filtered through a 0.45 µm nanopore filter paper. The filter paper was then dried at 60°C prior to and following filtration and weighed using a five-digit balance. The concentration of captured PM was expressed in grams per square meter (g/m^2) of leaf surface area for each species. This procedure was adapted from the method of Li et al. (2019).

Data collection and analysis

We began by holding a village meeting to respond to questions raised by community leaders and members, offering scientific knowledge to build mutual understanding. A team of seven Karen Mae San villagers was recruited to assist with data collection for a period of one year. Each member received three training sessions during that time.

All experiments were conducted in triplicate, and data were analyzed using Microsoft Excel 2010. Mean values were calculated for soil properties, surface runoff characteristics, and leaf dust-capturing capacity. Statistical analysis was assessed using one-way ANOVA followed by Tukey's post-hoc test (p< 0.05) to identify significant differences between treatment groups. All analyses were performed using IBM SPSS Statistics Version 29.

The calculation of the water volume (Wv), runoff volume (Rv), sediment volume in runoff (Svr) and sediment volume (Sv) was performed using the following formula:

$$\boldsymbol{Wv(m|\,3/rai) = \frac{Rf(mm/y) * 1,600}{1000}}$$

In which Rf is the rainfall in the area.

$$\boldsymbol{Rv(m|\,3/rai) = \sum_{i=1}^{n}\left(\frac{Wt(L)}{1,000}\right) \times \left(\frac{1,600}{20}\right)}$$

Where, wt is the water in the collection tank in each rainfall event.

$$\boldsymbol{Sv(g/L) = \frac{\sum_{i=1}^{n}\left(\frac{\sum_{k=1}^{3} Sd(g/0.5\,L)}{3} \times 2\right)}{n}}$$

Where, Sd is dry sediment in 0.5 L of water in the collection tank in each rainfall event.

$$\boldsymbol{Svr(kg/rai) = \frac{((Sv \times 1,000) \times Wv)}{1,000}}$$

Sv denotes sediment volume, and Wv denotes water volume.

Ion chromatography was used to measure the concentrations of water-soluble ions in $PM_{2.5}$ samples; these concentrations, along with the extracted solution volume and the original $PM_{2.5}$ mass on the filter, were used to calculate the total mass of each ion.

Results

Land-use impacts on soil erosion and runoff

This research investigates how various land-use practices influence soil erosion and runoff. Specifically, it compares monoculture (maize), upland rice cultivation (with mixed vegetation), fallow land, and natural forest. Significant differences in both erosion and runoff were observed across the four examined land-use types: maize monoculture, upland rice systems, 3-year fallow plots, and natural forest. Total sediment volume ranged from 42.10 to 286.32 kg/rai, while sediment concentration in runoff varied from 0.48 to 2.39 g/L (Table 2). Monoculture maize plots exhibited the highest rate of soil erosion (286.32 kg/rai), which was significantly greater ($p < 0.05$) than all other land uses. This erosion corresponded with poor soil physical properties, including the lowest water infiltration rate (94.75%), the highest bulk density (1.04 g/cm^3), and the lowest porosity (59.05%).

In contrast, the sediment volumes from shifting cultivation plots (upland rice and 3-year fallow) were not significantly different ($p > 0.05$) from those of the natural forest, indicating superior soil stability compared to monoculture.

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Table-2. Sediment and surface runoff and properties of soil.

	Land use type			
	Maize (SW1)	**Upland rice (SW2)**	**3-year Fallow (SW3)**	**Forest (SW4)**
Surface runoff properties				
Rainfall (Rf) (mm/y)	1,426.60	1,426.60	1,514.30	1,514.30
Water volume (Wv)(m^3/rai)	2,282.56	2,282.56	2,422.88	2,422.88
Runoff volume (Rv)(m^3/rai)	119.80	54.57	65.85	87.71
Sediment volume in runoff (Svr) (g/L)	2.39[a]	1.71[a]	0.90[b]	0.48[b]
Infiltration volume (Iv) (percent)	94.75	97.61	97.28	96.38
Total Sediment volume (TSv) (kg/rai)	286.32[a]	93.31[b]	59.27[b]	42.10[b]
Soil properties				
Bulk density (g/cm^3)	1.04	0.98	0.98	0.87
Particle density (g/cm^3)	2.55	2.50	2.54	2.53
Porosity (percent)	59.05	60.59	61.31	65.68
Soil organic matter (percent)	3.62	3.94	3.62	4.05

Remarks: Values in the same row with different letters are significantly different ($p < 0.05$) according to Tukey's Test for Post-Hoc Analysis.

Particulate matter and gaseous air pollutants

$PM_{2.5}$ concentrations were measured in February, March, and May at three sampling sites in the Mae San area including, Mae San school, rice field, and upper hill. For comparative analysis, data on $PM_{2.5}$ concentrations recorded by the Pollution Control Department (PCD) in areas surrounding Mae San village are also included in Figure 2.

The graphs illustrate a distinct seasonal pattern, with peak $PM_{2.5}$ concentrations occurring during February and March, followed by a significant decrease at the onset of the rainy season in May. During the peak burning period in February and March, concentrations at all monitored locations consistently exceeded Thailand's national air quality standard of 50 µg/m³. In contrast, by May, levels at most sites had fallen below this standard. Remarkably, even during the peak season, the $PM_{2.5}$ concentrations measured within the Mae San community (Upper Hill, Rice Field, and Mae San School) were significantly lower than those recorded at the surrounding regional monitoring stations.

The data from Figure 2 can also be used for assessing the impact of burning on $PM_{2.5}$ levels in the Mae San community. While burning was associated with increased $PM_{2.5}$ levels during the burning season (February and March), the overall concentrations in Mae San were lower than those in nearby urban centers, such as Mueang Lampang district (Figure 2). $PM_{2.5}$ concentrations in the Mae San community and surrounding urban areas surpassed the 50 µg/m³ national air quality standard during the burning period. In contrast, by the onset of the rainy season in May, levels at the study site were compliant with this standard (Division of Air and Noise Quality Management, 2022). This indicates that while local burning contributes to air pollution, regional factors like biomass burning in several parts of Thailand and neighboring countries play a more significant role in long-term $PM_{2.5}$ levels (Chansuebsri et al., 2024).

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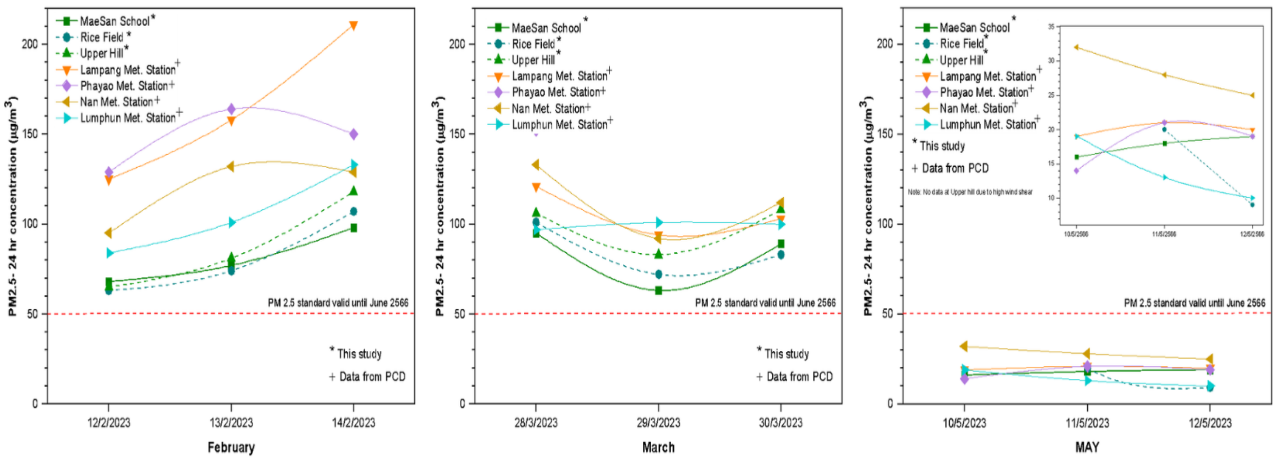

Figure-2. The Concentration of $PM_{2.5}$ measured in Ban Mae San area in different 3 months.

Water soluble ions

$PM_{2.5}$ samples collected on filters were analyzed for water-soluble ions, as described in section 2.3. Table 3 presents both positive and negative ions identified in $PM_{2.5}$. Given the diverse sources of $PM_{2.5}$ such as industrial emissions, transportation, and agricultural activities source apportionment is crucial to understand the origin of particulate matter in Mae San. Ion analysis indicated that positive ions included NH4+, Na+, Mg2+, K+, and Ca2+, while negative ions comprised F-, Cl-, Br-, PO43-, SO42--, and NO3. This initial assessment suggests that $PM_{2.5}$ in the area originates from multiple sources: (1) agricultural residue burning, (2) transportation, (3) industrial activities, (4) coal combustion, and (5) natural sources, such as wildfires.

The results of this study found that the four most abundant water soluble ions were Na^+ (8.69 ppm), Cl- (4.27 ppm), K^+ (3.93 ppm), and NO3- /SO42- (2.19 ppm) in descending order of concentration (Table 3). The detection of Cl- indicates a likely contribution from agricultural burning or coal combustion, while SO42- suggests inputs from industrial activities and coal use. NO3- is linked to emissions from transportation. The NO3-/SO42- ratio shows a higher proportion of NO3-, indicating that coal combustion is a more significant source than transportation in this case. Additionally, the presence of NH4+, Na+, Mg2+, and K+ supports the idea that agricultural burning contributes significantly to the observed $PM_{2.5}$.

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Table-3. Water-soluble ions identified in $PM_{2.5}$ in Ban Mae San area.

Water soluble ions	Amount (ppm)			Fingerprint	References
	Mae San School (A1)	Rice Field (A2)	Upper Hill (A3)		
F^-	1.5571	0.05536	0.0055		Hsu et al. (2008); Guo et al. (2023)
Cl^-	4.2726	0.1395	0.5298	Burning of vegetative material, Photochemical reactions, Coal combustion, Polyvinyl chloride plant, Petrochemical industrial district, and the Chlorine industry	Hsu et al. (2008); Guo et al. (2023)
Br^-	0.1052	-	0.0373		
PO_4^{3-}	0.3598				
NO_3^-	0.7881	0.2516	0.5341	Road dust, Petroleum vehicles, Anthropogenic emissions (e.g., industrial units, vehicle emissions), Regional transport processes	Dao et al. (2014); Saraga et al. (2017); Guo et al. (2023);
SO_4^{2-}	0.3598	0.1869	na	Coal combustion, Anthropogenic Emissions (e.g., industrial units, Vehicle emissions, Regional transport processes	Dao et al. (2014); Saraga et al. (2017)
NO^-_3/ SO_4^{2-}	2.1903	1.346	na	NO^-_3> SO_4^{2-} Coal Burning NO^-_3< SO_4^{2-}Vehicle Emission	Deshmukh et al. (2013); Dao et al. (2014)
Cl^-/Na^+	0.4915	na	na	Cl-/Na+>1.8 suggests Anthropogenic Sources for Cl-	Deshmukh et al. (2013)
Na^+	8.6928	0.5287	1.5972	Coal Combustion Process and Natural Sources from the Sea	Deshmukh et al. (2013)
NH_4^+	0.8176	na	0.7940	Fertilizer Usage	Dao et al. (2014)
K^+	3.9341	0.4326	0.9448	Biomass Burning, Burning of vegetative Material	Division of Air and Noise Quality Management (2022)
Ca^+	1.3254	0.2686	0.3657	Soil Dust and Desert Dust	Dao et al. (2014); Guo et al. (2023)
Mg	na	na	na	Soil Dust and Desert Dust	Guo et al. (2023)
K^+/ Na^+	0.4525	0.8182	0.5915	Excess K+ may be attributed to the combustion of biomass (e.g. wood for domestic heating) or engine exhaust (lubricant additives). In addition, K+ is a major constituent of fertilizers and is generally present in wind-blown soil. Vegetation is another possible source of K+	Deshmukh et al. (2013)

Dust capturing capacity

Table 4 and Figure 3 present the dust-capturing capacity of leaves from different plant species. The dust retention values observed in plots located north of the burnt area, ranked from lowest to highest, are as follows: *Osbeckia stellata* Ham, *Macaranga denticulata* (Blume) Müll.Arg., *Zanthoxylum myriacanthum* Wall. ex Hook., and *Dendrocalamus hamiltonii* Nees & Arn. ex Munro. The dust retention ranged from 0.7 to 2.2 g of total dust per square meter of leaf area for each species.

M. denticulata exhibited the highest dust-capturing capacity per rai (14.8 kg/rai). This high capacity is attributed to its large quantity and abundance of leaves. *D. hamiltonii* demonstrated a capacity of 8.7 kg/rai, despite having fewer trees, due to its high leaf density and dust-capturing efficiency. *Z. myriacanthum*, although possessing strong dust retention capacity and a considerable number of trees, ranked third (5.1 kg/rai) because of its relatively lower leaf count.

In the plant sampling site number two adjacent to the burnt area (Figure 1), the species with the lowest to highest dust-capturing capacity were: *M. denticulata*, *Fernandoa adenophylla* (Wall. ex G.Don) Steenis, *Toona ciliata* M.Roem., *Ficus semicordata* Buch.-Ham. ex Sm, and *Z. myriacanthum*. The dust retention values for these species ranged from 0.33 to 3.03 g/m2 of leaf area (Table 4).

The total suspended particles (TSP) sequestration capacity referring to the total of all particulate sizes, including $PM_{2.5}$ and PM_{10} was found to be 28.8 kg/rai in site one (P1) and 17.11 kg/rai in site two (P2), resulting in an average dust sequestration capacity of 22.95 kg/rai (Table 4). In comparison, particulate emissions from burning released only 95.16 kg/rai of TSP, which is approximately 1.5 times lower than the lower-bound estimate of dust sequestration capacity in shifting cultivation areas (149.43 kg/rai across all fallow lands).

Our results showed that *Z. myriacanthum* had the highest dust retention capacity in this plot at 8.33 kg/rai, owing to its abundant leaves and large number of trees; *Z. myriacanthum* also features a dense covering of villi as well as minute glands and greater roughness of surface (Figure 3), allowing for higher adsorption amounts. Although *M. denticulata*, exhibited lower dust retention in this plot, it still captured 4.26 kg/rai, attributed to its high tree and leaf count. *F. semicordata*, despite having strong dust-capturing potential and a high leaf quantity, ranked lower at 3.88 kg/rai due to fewer trees.

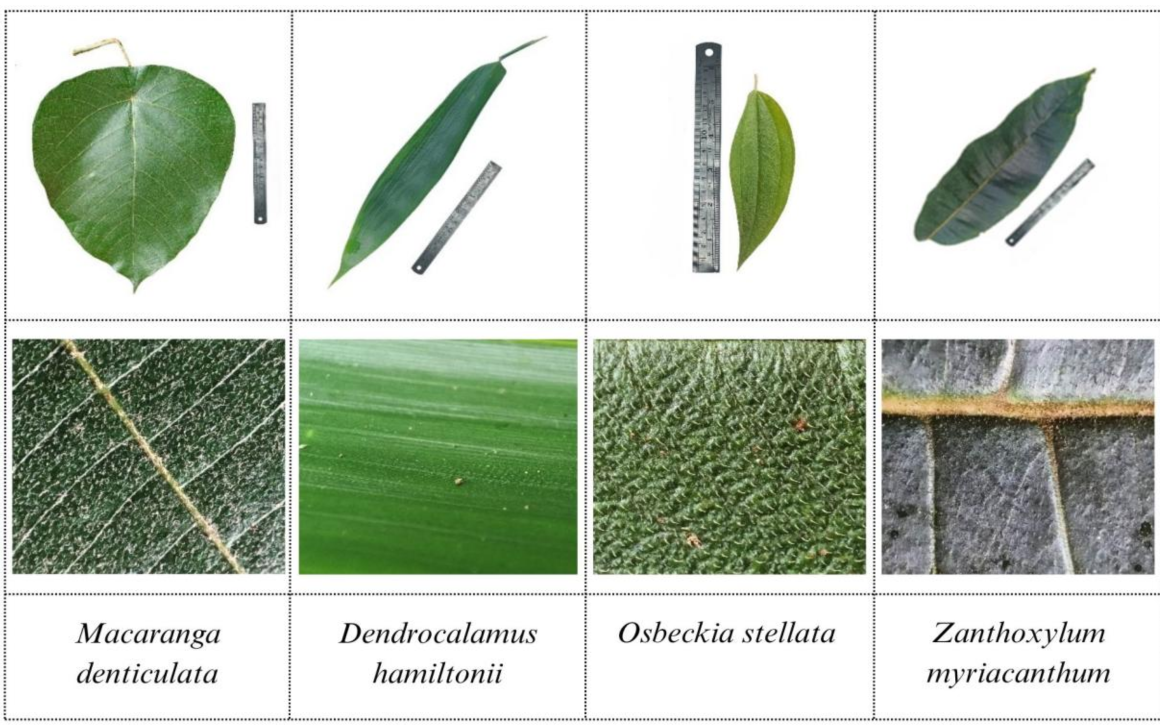

Figure-3. Leaf surface characteristics influencing particulate matter capture in four plant species.

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Table-4. The dust capturing capacity of leaves (leaf area in m^2).

Plant species	TSP capturing capacity (kg TSP/m^2)	TSP captured (kg/1 Tree)	TSP capturing capacity (kg TSP/rai)
Plant sampling site 1 (P1) (1.3 km north of open-burning plot)			
Macaranga denticulata	1.1	0.65	14.8
Zanthoxylum myriacanthum	2.2	0.17	5.1
Osbeckia stellata	0.7	0.04	0.2
Dendrocalamus hamiltonii	2.2	1.30	8.7
Total			**28.8**
Plant Sampling Site 2 (P2) — 0.1 km from Shifting Cultivation Plot			
M. denticulata	0.33	0.25	4.26
Toona ciliata	2.35	0.04	0.17
Z. myriacanthum	3.03	0.15	8.33
Fernandoa adenophylla	1.68	0.12	0.47
Ficus semicordata	2.66	0.97	3.88
Total			**17.11**
Average			**22.95**

Discussion

Several studies have shown an immense interest in shifting cultivation, as particularly seen in multiple angles: its effects on soil quality, biodiversity, and carbon sequestration in soils and forests (Palm et al., 2004; Gogoi et al., 2020; Chandra et al., 2021; Mertz et al., 2021; Wapongnungsang et al., 2021; Abrell et al., 2024). However, equal emphasis has not been fully placed on the important role of ecosystem services in alleviating the environmental repercussions of this practice (Millennium Ecosystem Assessment, 2005; Fisher et al., 2009). It is empirically known that literature has predominantly concentrated on discrete ecological aspects, as seen in soil degradation or particulate matter emissions (Tsegaye, 2019; Alves et al., 2023), the comprehensive suite of ecosystem services furnished by shifting cultivation remains largely overlooked. As a result, its capacity to alleviate erosion and reduce air pollution deserves to be given more attention. This study is thus aimed at remedying these challenges by presenting a holistic analysis of the regulating functions of ecosystem services. It sheds light on their roles in curbing soil erosion and $PM_{2.5}$ emissions across diverse land-use configurations.

With regards to the findings, they clearly note a statistically significant difference ($p < 0.05$) in soil erosion and runoff across land-use types, with monoculture (maize). This exhibits the greatest rates of soil erosion (286.32 $kg.rai^{-1}$) and runoff (119.80 $m^3.rai^{-1}$). Being characterized by cyclical fallow periods and heterogeneous vegetation of the shifting cultivation systems exhibited improved soil structure, superior water infiltration, and attenuated erosion. The depletion of carbon from the soil profile under shifting cultivation was markedly lower when compared to that under intensive cultivation (Lal and Logan, 1995). Natural forests yielded the most favorable outcomes in terms of soil bulk density and porosity. However, they paradoxically exhibited slightly higher surface runoff than fallow land, which is likely because of the accumulation of organic matter on the forest floor (Hazarika et al., 2024). At first, water infiltration is fundamentally affected by soil properties: texture, porosity, bulk density, and compaction levels. These factors have some significant effects on hydraulic conductivity (Alves et al., 2023). The findings of this study are also congruent with previous studies of

Tsegaye (2019) and Alves et al. (2023); they underscore the role of vegetative cover in mitigating soil erosion and facilitating water infiltration by reducing compaction and surface crusting. The adoption of management practices, as seen in no-tillage systems, contour plowing, and pasture-based crop rotation, all have strong links to the reduction of both soil and water losses. Whilst monoculture systems, particularly maize, were prone to compaction and reduced porosity, shifting cultivation demonstrated more sustainable land use, which supported the conclusions of studies that accentuate the value of agroforestry systems in preserving ecosystem services (Hazarika et al., 2024).

Recent research has demonstrated that specific water-soluble ions can reliably function as indicators of $PM_{2.5}$ emission sources (Xie et al., 2020; Chansuebsri et al., 2024). Our study emphasizes the deleterious effects of burning practices on air quality in Mae San. Intriguingly, even though there were localized combustion activities, $PM_{2.5}$ concentrations are still lower than those observed in nearby urban areas. Ion analysis further reported that $PM_{2.5}$ levels were modulated by a confluence of sources, including agricultural burning, transportation, and industrial operations. These results are consistent with the study of Amnuaylojaroen and Parasin (2023), showing that as biomass burning is adopted throughout Southeast Asia in general it gives rise to increasing air pollutant levels in Thailand. In addition, Chansuebsri et al. (2024) and Phairuang et al. (2019) emphasize that air quality in Thai cities such as Chiang Mai and Bangkok is also influenced by open burning related pollution within the wider region.

In conjunction with tree canopy density, the capacity of plant species to sequester dust has also been found to be strongly contingent upon the anatomical characteristics of their leaves. This includes the presence of trichomes, wax layers, broadleaf structures, and surface roughness (Mo et al., 2015; Chen et al., 2017). Younis et al. (2013); Song et al. (2015); and Chen et al. (2017) all indicate that leaf roughness and trichome density play an important part in a species' dust-capturing capacity. This is also consistent with our own findings, which suggest that surface roughness—dependent on leaf hairs, scales, glands, furrows, or veins — plays a major role.

In this study, the greatest total suspended particulate (TSP) retention appeared in *Macaranga denticulata* (14.8 kg.rai-1) and *Dendrocalamus hamiltonii* (8.7 kg.rai-1). It is of particular importance that the dust-capturing efficacy of certain species, such as *Zanthoxylum myriacanthum*, exceeded the particulate emissions which are produced by burning. This leverages efficiency, which is attributed to surface roughness and trichome density, aligns with earlier findings of previous studies (Mo et al., 2015; Chen et al., 2017; Li et al., 2019). These results bring to the forefront the potential of vegetation within shifting cultivation systems to lower particulate emissions, which could present a valuable but underexamined avenue for ecosystem services research.

The present study is circumscribed by methodological limitations, most notably the reliance on field measurements confined to a single burning season. This constraint suppresses the full potential of a comprehensive evaluation of $PM_{2.5}$ concentrations and soil property variability across seasonal and interannual timescales. In addition, the geographically limited area in this study further restricts the full potential for broad extrapolation of the findings.

Integrating ecosystem services into land-use planning is of importance for executing sustainable agricultural strategies that could develop ecological functionality. The adaptation of shifting cultivation principles to conventional farming shows a promising paradigm for bolstering environmental resilience across both highland and lowland agricultural systems. Among the policy interventions, the practice of land-use rotation originates as particularly salient, which exerts a massive impact on soil structure quality and could better climate resilience. Furthermore, the integration of perennial trees into agricultural systems can diminish the adverse effects of environmental stressors. These cover particulate matter mitigation, organic soil matter accumulation, and erosion control. This integrated approach largely supports both farmers and the environment by reducing production costs whilst having a link with both ecological sustainability and improving agricultural resilience. Clearly, this becomes crucial in the context of increasing global climate variability.

These findings have important implications for land use policy and sustainable agricultural development in highland regions. The study shows the great benefit provided by traditional shifting cultivation systems, particularly when managed with adequate fallow periods. These practices provide critical regulating ecosystem services that alleviate soil erosion. They also enhance water infiltration and reduce particulate air pollution through dust capture. In contrast, the transition towards monoculture and increasingly shortened fallow cycles has had detrimental consequences. In monocultures ecosystem services are compromised that result in an exacerbation of land degradation and air quality. Consequently, policy frameworks need to more actively support community-based land management. Therefore, having the consideration on the ecological value of fallow areas and secondary forest is of use and help to inform sustainable policies regarding land use and conservation efforts. The change in policy direction would more profoundly and clearly address the need to strike the perfect balance on the conservation goals with indigenous livelihoods. This could cover the formal designation of rotational farming zones and the provision of incentives to support longer fallow periods. Policy frameworks should also help with the adoption of integrated agroforestry practices. Consequently, it could establish the presence of dust-capturing vegetation. Furthermore, greater emphasis must be placed to associate with local communities so as for the decision-making processes and institutionalizing participatory governance mechanisms. At this point, the engagement and rapport would help to affirm that knowledge, which is central to rotational farming systems, is fully supported. This approach may largely help to execute initiating and supporting land management strategies that are more adaptive, culturally contextualized, and ecologically sustainable. Based on prioritizing both forest conservation policies and ecosystem service provision, policymakers are likely to potentially further advance environmental protection objectives. Apart from the early mentioned points, they may more substantively contribute to farmers' livelihoods and to the long-term sustainability of the highland agricultural landscapes on which these communities live on.

Conclusion

Shifting cultivation contributes to the maintenance of ecosystem services in highland agricultural systems, notably for indigenous communities like those in Mae San, limiting soil degradation and air pollution. It supports regulating services such as erosion control, water management, and air quality through carbon sequestration. Compared to monoculture, its biodiversity-rich fallow systems maintain soil health, limit soil loss, and facilitate water infiltration. While agricultural burning produces $PM_{2.5}$ and gaseous emissions, these are lower than urban sources. Vegetation in fallow lands and forests traps airborne particles, with TSP sequestration approximately 1.5 times higher than burning emissions, underscoring agroforestry's role in reducing particulate pollution.

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Contribution of Authors

Teanma J: Conceptualized the research, validated calculations, curated data, and edited the manuscript.
Kanchanaroeak Y: Wrote original draft, contributed to its editing and manuscript conceptualization, and data curation.
Putkham A: Was responsible for the methodology of air pollution analysis, contributed to data curation, and edited the manuscript.
Tanee T: Conducted soil erosion analysis, performed calculations, contributed to data curation, and edited the manuscript.
Kanchak A, Kengchuwong M, Putkham AI & Chidburee P: Provided essential equipment for the study, assisted in analysis.
Muangkot P: Performed experiments and collected data.

All authors read and approved final draft of the manuscript.

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