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Post-fire recovery of soil organic carbon, soil total nitrogen, soil nutrients, and soil erodibility in rotational shifting cultivation in Northern Thailand

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The hill tribes in Thailand traditionally depend on rotational shifting cultivation (RSC). However, insufficient understanding remains on post-fire soil properties and soil erodibility (*k*-values) with fallow years. To address this gap, the levels of soil organic carbon (SOC), soil total nitrogen (STN), soil nutrients, and soil erodibility after fire in RSC were investigated. Topsoil (0–10 cm) samples from sites with 4 (RSC-4Y), 5 (RSC-5Y), and 7 (RSC-7Y) fallow years in Chiang Mai Province, northern Thailand, were taken at four time points: before burning, 5 min after burning, 9 months after burning, and 2 years after burning. Soil pH, electrical conductivity, and soil nutrient (available P, K, and Ca) levels were increased after burning and remained higher than the pre-burning levels for at least 2 years. The SOC stock decreased after burning in all fallow fields. At 2 years after burning, the SOC stock in RSC-4Y was higher than before burning, whereas in RSC-5Y and RSC-7Y, the levels had not reached the pre-fire levels. The STN stocks of all studied fields significantly decreased after burning and had not reached the pre-burning levels after 2 years. After burning, the topsoil of RSC-4Y was most susceptible to erosion. However, only in RSC-4Y, the *k*-value was unchanged at 2 years after burning. Three different approaches are recommended for post-fire land management: 1) farmers should not cut and remove the weeds and grasses at the soil surface, 2) burning should be performed around late winter or early summer (November–February) to inhibit complete combustion, and 3) contour-felled log erosion barriers should be made by using the trunks remaining after the fire to trap the sediment and slow down surface runoff.

KEYWORDS

hill tribes, fire, soil recovery, soil properties, post-fire land management

1 Introduction

Fire is a fundamental factor in ecological systems (Francos and Úbeda, 2021). It alters several ecosystem components, such as soil, air, water, plants, and microorganisms (DeBano et al., 1998; Caton et al., 2019; Lucas-Borja et al., 2019), which affects the changes in soil nutrients and plant growth. Fire regimes (intensity and severity) are crucial for changing soil properties and the recovery after a fire (Nolan et al., 2021), as well as for frequency and seasonality (Jurvélius, 2004; Flannigan et al., 2009). Previous studies have investigated the direct and indirect effects of wildfire on soil and vegetation (Certini, 2005; Lucas-Borja et al., 2021), including nutrient losses after burning by runoff and erosion (Robichaud et al., 2000; Mataix-Solera et al., 2002). In South and Southeast Asia, fire is used as a tool for land preparation in shifting cultivation, supporting many ethnic minorities in terms of livelihood and food security (AIPP and IWGIA, 2014).

Shifting cultivation, also known as slash-and-burn or swidden agriculture, refers to a rotational farming technique in which the land is cleared by fire for cultivation and then abandoned to recover after harvest (Heinimann et al., 2017). In northern Thailand, shifting cultivation is a traditional farming practice in the mountainous area, and fire is normally used for burning vegetation residues after cutting (Arunrat et al., 2022a). Generally, there are two basic types of shifting cultivation, namely, pioneer and rotational shifting cultivation (Rerkasem and Rerkasem, 1994). In pioneer shifting cultivation, the primary forest is cleared, burnt, cropped, harvested, and abandoned, and subsequently, the village is moved to a new site, for which a part of the primary forest is being cleared. Rotational shifting cultivation (RSC) consists of a long fallow period, and the village is a permanent settlement and not moved to a new site after harvesting. The cultivated plots in RSC are managed as fallow cycles, while one plot is temporarily cultivated and then abandoned. This allows the recovery of the vegetation and soil fertility while the cultivator moves on to another plot. Currently, there are strict forest protection laws in Thailand, and the clearing of pioneer forests and the building of new settlements are prohibited. Thus, the existing shifting cultivation areas in Thailand are referred to as RSC.

Several studies have reported the variation in soil properties after a fire. Giovannini et al. (1988) reported that organic matter (OM) was completely oxidized at about 460°C during a fire. This can lead to changes in nutrient availability to plants (Phillips et al., 2000; Zhu et al., 2021), facilitating the recovery of ecosystem processes (Pellegrini et al., 2018). With specific regard to soil nutrient losses and recovery, fire consumes vegetation, increases the surface runoff and soil erosion rates, and transports nutrients downslope (Cawson et al., 2012; Vieira et al., 2015). The factors determining nutrient loss are erodible soil particles, rainfall, and topographic characteristics. Pierson et al. (2019) reported that fire caused the loss of soil carbon and nitrogen, which was related to erosion rates. To date, a study by Arunrat et al. (2022a) investigated the impacts of fire on soil properties in RSC in northern Thailand. The authors found that soil pH and electrical conductivity significantly increased after a fire, whereas soil organic carbon (SOC), soil total nitrogen (STN), and some soil properties [soil texture, available P, exchangeable K, exchangeable Ca, exchangeable Mg, bulk density, and organic matter] were not significantly changed due to the low fire intensity and short fire duration. The OM at the soil surface has been reported as being most susceptible to high fire intensity, resulting in changes in soil properties. However, the effects of fire on post-fire recovery in RSC in northern Thailand are still unknown.

Fire and erosion interact with the change of soil physical and chemical properties after the fire due to the losses of vegetation and litter at the surface layer (Larsen et al., 2009). In the most concerning case, these losses of vegetation and litter usually occurred during intense rainfall periods on the hillslopes (Carroll et al., 2007). The Universal Soil Loss Equation (USLE) is a widely used model for assessing soil loss, elaborated by Wischmeier and Smith (1978) and later modified in the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997; 2017). The five erosion factors in the RUSLE model are soil erodibility (*k*-factor), rainfall erosivity (R), topography (LS), land cover (C), and practice (P). The *k*-factor is the most suitable factor for assessing soil susceptibility to erosion (USDA, 1954; Wischmeier and Smith, 1965; Wischmeier and Smith, 1978; Kyveryga et al., 2004), as organic carbon (OC) content and different-sized soil particles are the main parameters affecting soil erodibility, especially in hillslopes (Emadi et al., 2009). Soil erodibility is related to the granulometry, structure, and stability of soil aggregates, indicating that the soils with higher silt contents are more erodible than clayey soils. Meanwhile, OM also plays an important role in soil erodibility by maintaining the stability of soil aggregates (Deng et al., 2018). However, fire may alter the changes of these properties, which may increase or decrease the level of soil erodibility. A study by Arunrat et al. (2022b), studying terraced paddy fields and upland rice fields in northern Thailand, found that the increase in soil erodibility was consistent with a decrease in SOC stock. Unfortunately, the effect of post-fire on soil erodibility in RSC is still not well understood.

To fill the research gaps and extend the previous investigation in RSC, this study focused on deepening our understanding of post-fire recovery in RSC, with the following two objectives: 1) to examine the recovery of soil organic carbon, soil total nitrogen, and soil nutrients after a fire and 2) to assess soil erodibility changes in RSC. The results of this study provide a scientific reference for the minimization of post-fire risks and can contribute to implementing suitable management and restoration, which can help reduce soil degradation in RSC.

2 Materials and methods

2.1 Study area and RSC field selection

The study was conducted at Ban Mae Pok, Ban Thab subdistrict, Mae Chaem district, Chiang Mai province, northern Thailand (Figure 1). The terrain is mountainous, with an elevation of 700–1,000 m above sea level. The average annual temperature is 25.4°C. The winter season is from October to February, with a minimum temperature of 15°C, and the maximum temperature in summer is 39°C, from February to May. The rainy season is from September to October, with an average annual precipitation of 1,140.2 mm (Department of Mineral Resources, 2015). In the highlands (slope >35%) of Thailand, soils are classified as slope complex series (LDD, 1992; Arunrat et al., 2022c). The soil is mostly

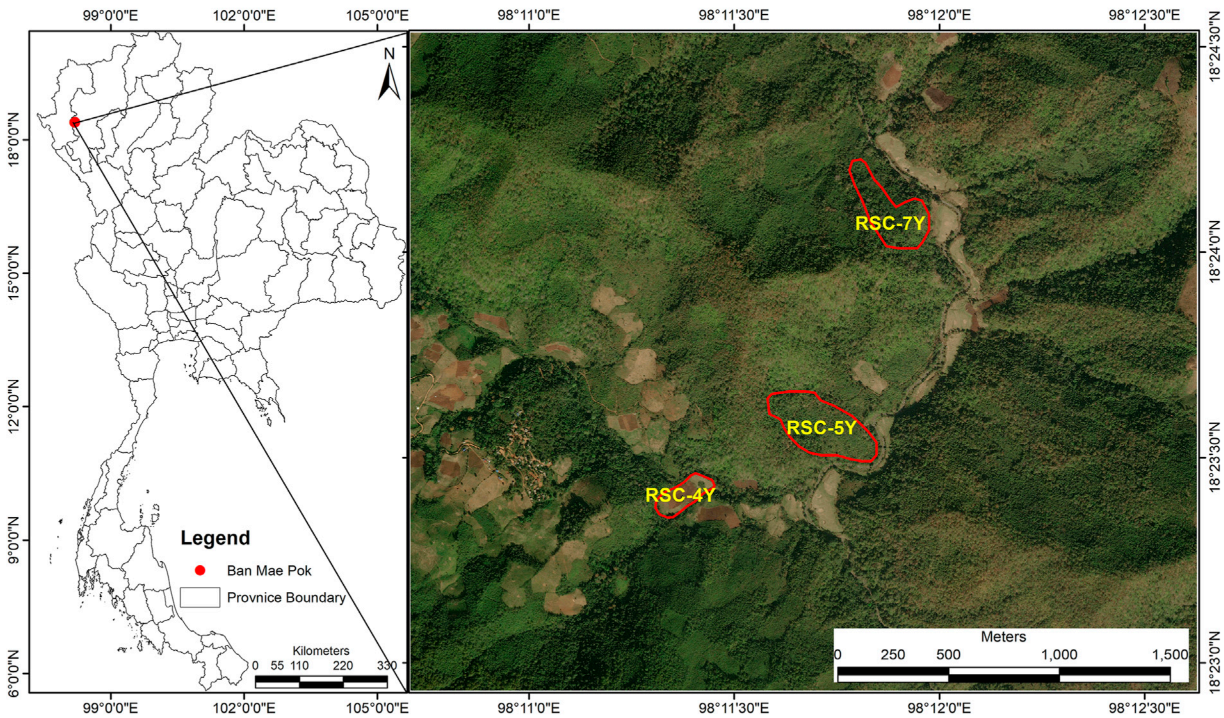

FIGURE 1
Study area; RSC-7Y = 7-year fallow (18° 24′ 6.57″N, 98° 11′ 53.68″E), RSC-5Y = 5-year fallow (18° 23′ 33.38″N, 98° 11′ 45.99″E), and RSC-4Y = 4-year fallow (18° 23′ 24.99″ N, 98° 11′ 22.73″ E); the aerial image was taken from Google Maps on 2 December 2022.

reddish-brown lateritic, with a sandy clay loam and a sandy clay texture based on USDA classification. The soil pH is acidic (5.0–5.8), and the organic matter level ranges from 2.60% to 3.86% (Mae Chaem Watershed Research Station, 2010).

Three RSC fields were selected based on a similar previous land use type (maize cultivation) before fallow to allow secondary succession. The RSC-4Y field refers to the 4-year fallow field after maize harvesting; it was cleared, burnt, and cultivated with upland rice in March 2020, at an elevation of 614 m a.s.l and a slope gradient of 21%. The RSC-5Y field was a 5-year fallow field after maize harvesting; it was cleared, burned, and cultivated with upland rice in March 2020, at an elevation of 643 m a.s.l and with a slope gradient of 25%. The RSC-7Y field was a 7-year fallow field after maize harvesting; it was cleared, burnt, and cultivated with upland rice in March 2020, at an elevation of 632 m a.s.l and with a slope gradient of 22%. All RSC fields were identified with the boundary and background history by the head of the community and field owners. At each field, a transect was designed, starting from the uppermost toposequence point to the lowermost toposequence point, and then the five replication plots were marked along the transect for soil sampling. The dominant tree species are *Pterocarpus macrocarpus* Kurz, *Xylia xylocarpa* (Roxb.) Taub, and *Lithocarpus ceriferus*. Moreover, *Tectona grandis Linn. f.*, *Bombax ceiba* Linn., *Pinus kesiya*, *Mangifera caloneura* Kurz, *Oroxylum indicum* (L.) Kurz, *Diospyros glandulosa* Lace, *Spondias pinnata* (L.f.) Kurz, and *Syzygium cumini* can also be found. The shrub and herbal vegetation are mostly *Chromolaena odorata* (L.) R.M.King & H. Rob, *Brainea insignis* (Hook.) J. Sm., and *Betula alnoides* Buch. Ham.

2.2 Fire measurements

In March 2020, all three experimental fields were cleared and burned for upland rice cultivation. During burning, the fire temperature at the surface layer at each plot of each field was measured using an infrared thermometer. Soil temperatures and soil moisture were measured at a soil depth of 1 cm before and 5 min after burning, using a thermocouple and moisture meter, respectively.

2.3 Soil and ash sampling and analysis

Topsoil samples were taken from all three fields at depths of 0–10 cm at four time points: before burning (March 2020), 5 min after burning (March 2020), 9 months after burning (harvest, December 2020), and 2 years after burning (March 2022). Topsoil was sampled because the effects of fire are best reflected at a depth of 0–10 cm, whereas soil erodibility is usually reflected at the soil surface.

Overall, 60 topsoil samples were obtained (three RSC fields × five plots × one depth × four time points). At each RSC field, topsoil samples were collected from the same five plots at each time point. At each plot (10 × 10 m), the topsoil samples were taken from five pits and thoroughly mixed to obtain one composite sample per plot. Grasses, stones, roots, and other residues were removed manually, and approximately 1 kg of soil was placed in a plastic bag. Ash colors were identified by the Munsell soil color charts 5 min after burning. Each color of ash was carefully determined for each sample plot. A steel soil corer (5.0 cm width × 5.5 cm length) was used to collect a soil sample for determining soil bulk density after oven-drying at 105°C for 24 h.

Soil texture was measured using the hydrometer method. Soil and ash pH values were determined using a pH meter with a 1:1 and 1:10 suspension of solid-to-water ratio, respectively (National Soil Survey Center, 1996). Electrical conductivity (ECe) was measured using an EC meter in saturation paste extracts (Sparks et al., 1996). Total nitrogen (TN) was determined using the micro-Kjeldahl method. The available calcium (Ca), magnesium (Mg), and potassium (K) concentrations were analyzed by atomic absorption spectrometry (NH_4OAc pH 7.0 extraction) (Thomas, 1996). The available phosphorus (P) was measured using the molybdate blue method (Bray II extraction) (Bray and Kurtz, 1945), and the organic carbon (OC) content was analyzed following the method of Walkley and Black (1934).

2.4 Soil organic carbon and total nitrogen estimation

The SOC stock was estimated using the following equation:

$$SOC_{stock} = OC \times BD \times L \times 10,000, \tag{1}$$

where SOC_{stock} is the soil organic carbon stock (Mg C ha^{-1}), OC is the organic carbon content (%), BD is the soil bulk density (Mg m^{-3}), and L is the soil thickness (m).

The STN stock was calculated using the following equation:

$$STN_{stock} = TN \times BD \times L \times 10,000, \tag{2}$$

where STN_{stock} is the soil total nitrogen (Mg N ha^{-1}), TN is the total nitrogen content (%), BD is the soil bulk density (Mg m^{-3}), and L is the soil thickness (m).

Since soil bulk density varies over time, the soil thickness (cm) was adjusted based on a soil mass basis for eliminating the error in the SOC stock calculations. The following equations were used (Ellert and Bettany, 1995):

$$Soil\,mass = BD \times L, \tag{3}$$

where *Soil mass* is the mass of the soil sample (kg soil m^{-2}).

The additional soil thickness (m) for each field was calculated using the following equation (Arunrat et al., 2021):

$$\text{Additional soil thickness} = \frac{Mass_{initial} - Mass_{current}}{BD}, \tag{4}$$

where $Mass_{initial}$ is the soil mass at the initiation of the study (2020) and $Mass_{current}$ is the soil mass in the current study (2022).

2.5 Soil erodibility estimation

There are three widely used approaches for assessing soil erodibility (*k*-factor), namely, the nomograph (Wischmeier et al., 1971), the K-factor in the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1983), and a formula proposed by Shirazi and Boersma (1984). Among them, the *k*-factor in the EPIC model is calculated using the OC content and the soil particle distribution (the contents of sand, silt, and clay); this approach is widely used to predict soil erosion and indicate soil degradation (Wu et al., 2012; Chen et al., 2013; Zhang et al., 2018; Liu et al., 2020; Arunrat et al., 2022b; Arunrat et al., 2022c). Therefore, the *k*-factor in the EPIC model was used in this study, with the following equation:

$$K = \{0.2 + 0.3\,exp[-0.256SAN(1 - 0.01SAN)]\}\left(\frac{SIL}{SIL + CLA}\right)^{0.3} \times \left[1 - \frac{0.25OC}{OC + exp(3.72 - 2.95OC)}\right] \times \left\{1 - \frac{0.7\left(\frac{1-SAN}{100}\right)}{\left(\frac{1-SAN}{100}\right) + exp\left[-5.51 + 22.9\left(\frac{1-SAN}{100}\right)\right]}\right\} \times 0.1317, \tag{5}$$

where SAN is the fraction of sand (%), SIL is the fraction of silt (%), CLA is the fraction of clay (%), OC refers to the organic carbon concentration (%), and 0.1317 is the conversion factor for United States business units (t acre h/100 acre/ft/tanf/in) to the international system of units (t h MJ^{-1} mm^{-1}). A higher *k*-value indicates that the soil is easily eroded.

2.6 Statistical analysis

Significant differences in soil parameters along a fallow chronosequence were tested by analysis of variance (ANOVA). Tukey´s honestly significant difference (HSD) test was employed to perform the multiple *post hoc* mean comparisons when the ANOVA result was significant at $p \le 0.05$. Redundancy analysis (RDA) was used to investigate the multivariate response of soil properties to burning. The Hellinger transformation of values was applied to adjust the normality and homogeneity of the data. Variables with collinearity, variance inflation factor (VIF) > 10, and correlation coefficients $|r| > 0.7$ were eliminated. All statistical analyses and visualizations were performed using the R environment (v. 4.0.2).

3 Results

3.1 Fire temperature, soil temperature, and soil moisture after burning

The highest fire temperature of 579°C was detected for the RSC-5Y field, whereas the lowest temperature of 173°C was observed for the RSC-4Y field. At a soil depth of 1 cm, soil temperatures increased around 16.3°C–19.2°C at 5 min after burning in all RSC fields. Field RSC-7Y showed the highest soil temperature of 46.3°C, followed by the RSC-5Y (45.7°C) and RSC-4Y (43.5°C) fields, respectively. Soil moisture decreased by 0.4%–2.1% 5 min after burning due to the soil water content evaporating (Table 1). Fire temperatures in the surface layer and soil temperature mainly depended on the amount of dried fuel in each field.

3.2 Chemical properties of ash

The OM and TN contents were significantly different among dark reddish-brown, gray, and white ash colors (Table 2). The dark

TABLE 1 Fire temperature, soil temperature, and soil moisture after burning of RSC fields.

Field	Fire temperature (°C)	Soil temperature (°C)		Soil moisture (%)	
	(Minimum–maximum)	Before burning	5 min after burning	Before burning	5 min after burning
RSC-4Y	173–428	27.2	43.5	36.5	35.1
RSC-5Y	195–579	27.1	45.7	36.2	35.8
RSC-7Y	176–485	27.1	46.3	37.4	35.3

TABLE 2 Chemical properties of ash (mean ± SD).

Properties	Ash colors		
	Dark reddish-brown (5 YR 2.5/2)	Gray (7.5 YR 5/1)	White (5 YR 8/1)
pH (1:10)	11.21 ± 0.5[a]	10.04 ± 0.6[ab]	9.98 ± 0.5[b]
Organic matter (%)	6.18 ± 0.05[a]	3.11 ± 0.03[b]	2.01 ± 0.01[c]
ECe (1:5) (dS m^{-1})	5.12 ± 2.33[a]	4.88 ± 2.31[b]	4.65 ± 2.10[b]
Total nitrogen (%)	0.12 ± 0.03[a]	0.07 ± 0.01[b]	0.03 ± 0.01[c]
Available P (mg kg^{-1})	67.81 ± 22.10[a]	65.64 ± 19.12[a]	58.93 ± 20.21[a]
Available K (mg kg^{-1})	2,321.12 ± 1,467.5[a]	2,678.53 ± 1,205.1[a]	1,567.33 ± 654.3[b]
Available Ca (mg kg^{-1})	7,876.93 ± 1,612.5[a]	9,763.11 ± 1,700.3[a]	11,540.23 ± 1,948.3[b]
Available Mg (mg kg^{-1})	1,865.54 ± 854.34[a]	1,553.66 ± 587.55[a]	1,754.6 ± 600.8[a]

[a-c]Significant statistical differences ($p \leq 0.05$) among colors of ash.

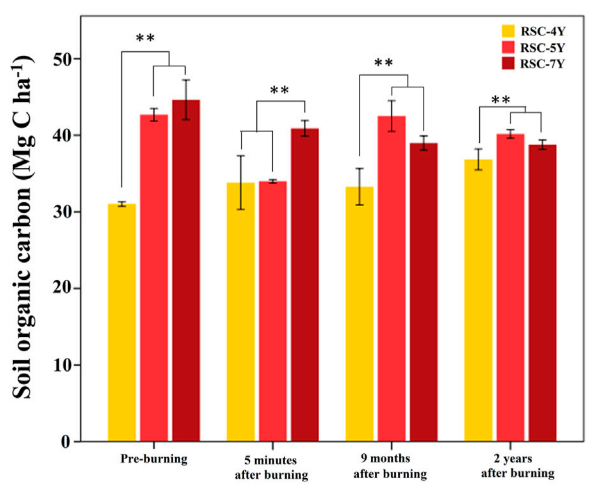

FIGURE 2
Soil organic carbon levels (Mg C ha^{-1}) in the topsoil (0–10 cm) before burning and at 5 min, 9 months, and 2 years after burning in three fallow fields.

reddish-brown ash showed high values of pH, ECe, OM, and TN compared with gray and white ash (Table 2). White ash contained the lowest levels of OM (2.01%), TN (0.03%), and available K (1,567.33 mg kg^{-1}), whereas available Ca was the highest (11,540.23 mg kg^{-1}) (Table 2). The ashes were produced under different heating temperatures, which changed their color. Black ash is produced at low temperatures (<300°C) and is the product of incomplete combustion of the litter (Úbeda et al., 2009; Kuzyakov et al., 2018), which contains a high proportion of carbon (Khanna et al., 1994). The reddish color is due to the oxidation of iron minerals at low temperatures (Markl et al., 2006). At > 500°C, the ash became gray and white in color, which indicated that fire severity was high and litter underwent more complete combustion (Úbeda et al., 2009; Kuzyakov et al., 2018).

3.3 Soil organic carbon

The highest soil organic carbon (SOC) stock in the topsoil (0–10 cm) was found before burning in the RSC-7Y field, with 44.6 Mg C ha^{-1}, whereas the SOC stock was decreased after burning in all fields. Before burning, the RSC-5Y and RSC-7Y fields showed similar SOC levels, significantly differing from that of the RSC-4Y field. No remarkable variation in the SOC stock was found when comparing the soils of the RSC-4Y and RSC-5Y fields at 5 min after burning. At 9 months after burning, the SOC stock had reached the highest level of 42.51 Mg C ha^{-1} in the RSC-5Y field. There was no significant difference in the SOC stock between the RSC-5Y and RSC-7Y fields at 2 years after burning, whereas the SOC stock was significantly lower in the RSC-4Y field (Figure 2).

At 2 years after burning, the SOC stock was higher than before burning in the RSC-4Y field, with an increase from 31.03 to

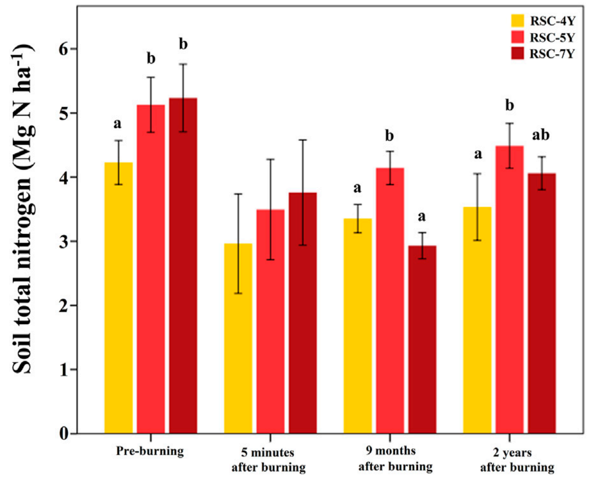

FIGURE 3
Soil total nitrogen (Mg N ha^{-1}) in the topsoil (0–10 cm) before burning and at 5 min, 9 months, and 2 years after burning in three fallow fields.

36.83 Mg C ha^{-1} (18.7%). On the other hand, the SOC stocks in RSC-5Y (5.9% decrease) and RSC-7Y (13.1% decrease) could not reach pre-fire levels (Figure 2).

3.4 Soil total nitrogen

Before burning, the highest stock of soil total nitrogen (STN) in the topsoil (0–10 cm) was found in the RSC-7Y field, with 5.23 Mg N ha^{-1}, whereas the STN level was significantly lower in RSC-4Y. A similar trend was observed at 5 min after burning in all fields. Notably, the STN stock was significantly higher in the RSC-5Y field, with 4.14 Mg N ha^{-1}, at 9 months after burning compared to the other fields. All three fallow fields showed significant differences in STN stock levels at 2 years after burning (Figure 3).

In all fields, the STN stocks were significantly lower after burning (with an average decrease of 30.0%) and higher at 9 months after burning, although after 2 years, the initial levels were not reached (with an average decrease of 17.1%; Figure 3).

3.5 Soil chemical properties

The variations in soil chemical properties among the RSC-4Y, RSC-5Y, and RSC-7Y fields after maize harvesting under different conditions at the four time points are shown in Table 3.

In the RSC-4Y field, the pH level was 5.72 before burning. However, it increased to 8.80 5 min after burning and decreased to 6.27 and 6.07 at 9 months and 2 years after burning, respectively. There was no significant difference in the pH value between 9 months and 2 years after burning in the RSC-5Y and RSC-7Y fields. When comparing the overall pH levels of the three fields, notable differences were observed between the RSC-4Y and RSC-5Y fields. The soil pH was significantly increased after burning at all fallow fields. At 2 years after burning, the soil pH levels were still high compared with pre-burning levels (Table 3).

In the RSC-4Y field, before burning, the percentage of OM was 4.79%, whereas the RSC-5Y and RSC-7Y fields showed OM percentages of 5.92% and 5.92%, respectively. Notably, in the RSC-7Y field, there were no significant differences in OM among the three time points after burning. However, the overall OM amount significantly differed among the three fields. A decrease in OM was detected at 5 min after burning in all fallow fields. At 2 years after burning, in the RSC-4Y field, the OM had recovered, with levels above those measured before burning, whereas in the RSC-5Y and RSC-7Y fields, the OM levels did not return to the initial levels (Table 3).

In the RSC-5Y and RSC-7Y fields, the amount of organic carbon (OC) was lower at all time points after burning, whereas in the RSC-4Y field, at 2 years after burning, the OC had recovered. Similar to OM, there was no significant variation in OC at all time points after burning in the RSC-7Y field. The overall OC percentage of the RSC-5Y field was not significantly different from that of the RSC-4Y field (Table 3).

In the RSC-4Y and RSC-5Y fields, before burning, the electrical conductivity (ECe) was around 0.26 dS m^{-1}. Significantly different values of ECe were observed at all time points in the RSC-4Y and RSC-5Y fields, whereas the changes in ECe were not remarkable at 5 min and 2 years after burning in the RSC-7Y field. Regarding the overall ECe, the RSC-5Y and RSC-7Y fields did not differ considerably. The ECe values were significantly increased after burning and then slightly declined. After 2 years, the ECe levels were still above the pre-burning values (Table 3).

The differences in the content of available phosphorus (available P) at the time points after burning in the RSC-4Y and RSC-5Y fields were not significant, whereas the overall available P levels in the RSC-5Y and RSC-7Y fields were similar. The largest increase in available potassium (available K) was observed at 9 months after burning in the RSC-4Y and RSC-5Y fields, whereas the available K had reached the highest level of 520.50 mg kg^{-1} in the RSC-7Y field 5 min after burning. The highest overall available calcium (available Ca) and magnesium (available Mg) levels were found in the RSC-4Y and RSC-7Y fields, with 1,774.34 and 364.42 mg kg^{-1}, respectively. The levels of soil nutrients (available P, available K, and available Ca) tended to be higher at 5 min after burning for three fallow fields, except for available Mg, which remained at similar levels in the RSC-7Y field. At 2 years after burning, the levels of available P, K, and Ca were higher than before burning (Table 3).

Before burning, the TN contents did not significantly differ among the three fields and ranged from 0.38% to 0.41%. However, a significant decrease in TN was detected 5 min after burning. Although the contents of TN were increased at 2 years after burning, they did not reach the pre-burning levels (Table 3).

3.6 Soil physical properties

Only in the RSC-4Y field was there a decrease in bulk density 5 min after burning. The highest bulk density levels were observed in the RSC-4Y and RSC-5Y fields at 9 months after burning, whereas in the RSC-7Y field, bulk density was not significantly different 5 min after burning. Overall, bulk density differed significantly among the

TABLE 3 Variations in soil chemical properties: pH; organic matter (%); organic carbon (%), EC_e ($dS\ m^{-1}$); available P, K, Ca, and Mg ($mg\ kg^{-1}$); and total nitrogen (%) along the fallow chronosequence.

Field	Period	pH (1:1)	OM (%)	OC (%)	EC_e ($dS\ m^{-1}$)	Avail. P ($mg\ kg^{-1}$)	Avail. K ($mg\ kg^{-1}$)	Avail. Ca ($mg\ kg^{-1}$)	Avail. Mg ($mg\ kg^{-1}$)	Total N (%)
RSC-4Y	Pre-burning	$5.72^{ab} \pm 0.04$	$4.79^{b} \pm 0.05$	$2.79^{b} \pm 0.03$	$0.26^{a} \pm 0.02$	$6.25^{a} \pm 1.31$	280.78 ± 39.82	$1,706.64 \pm 41.60$	301.33 ± 78.74	$0.38^{b} \pm 0.03$
	5 min after burning	$8.80^{c} \pm 0.29$	$4.72^{b} \pm 0.09$	$2.74^{b} \pm 0.05$	$0.54^{c} \pm 0.05$	$11.03^{b} \pm 1.98$	363.33 ± 66.33	$1,858.21 \pm 98.10$	298.34 ± 49.14	$0.24^{a} \pm 0.07$
	9 months after burning	$6.27^{b} \pm 0.15$	$4.38^{a} \pm 0.19$	$2.55^{a} \pm 0.11$	$0.33^{b} \pm 0.02$	$11.45^{b} \pm 1.11$	392.13 ± 30.79	$1,694.38 \pm 140.29$	273.18 ± 48.58	$0.26^{a} \pm 0.01$
	2 years after burning	$6.07^{b} \pm 0.06$	$5.32^{c} \pm 0.11$	$3.09^{c} \pm 0.06$	$0.29^{ab} \pm 0.02$	$9.36^{b} \pm 0.72$	390.36 ± 62.34	$1,838.11 \pm 97.73$	251.54 ± 60.45	$0.30^{ab} \pm 0.04$
	Average	$6.72^{iii} \pm 1.28$	$4.80^{i} \pm 0.37$	$2.79^{ii} \pm 0.21$	$0.35^{ii} \pm 0.12$	$9.53^{i} \pm 2.43$	356.65 ± 64.83	$1,774.34^{iii} \pm 115.76$	$281.10^{i} \pm 55.75$	0.29 ± 0.07
RSC-5Y	Pre-burning	$5.18^{a} \pm 0.03$	$5.92^{c} \pm 0.07$	$3.44^{c} \pm 0.04$	$0.26^{a} \pm 0.03$	$2.71^{a} \pm 0.39$	294.03 ± 73.03	$1,343.67 \pm 117.90$	401.13 ± 81.94	$0.41^{b} \pm 0.03$
	5 min after burning	$7.83^{c} \pm 0.25$	$4.51^{a} \pm 0.03$	$2.62^{a} \pm 0.02$	$0.35^{bc} \pm 0.04$	$12.20^{b} \pm 4.16$	359.06 ± 64.37	$1,477.26 \pm 261.16$	350.64 ± 76.28	$0.27^{a} \pm 0.06$
	9 months after burning	$5.87^{b} \pm 0.14$	$5.24^{b} \pm 0.27$	$3.04^{b} \pm 0.15$	$0.37^{c} \pm 0.02$	$10.65^{b} \pm 1.62$	404.51 ± 19.96	$1,268.64 \pm 110.40$	261.81 ± 37.90	$0.30^{a} \pm 0.02$
	2 years after burning	$5.84^{b} \pm 0.18$	$5.34^{b} \pm 0.08$	$3.11^{b} \pm 0.05$	$0.29^{b} \pm 0.03$	$8.91^{b} \pm 2.53$	357.06 ± 61.06	$1,131.85 \pm 140.02$	263.91 ± 65.31	$0.35^{ab} \pm 0.02$
	Average	$6.18^{i} \pm 1.05$	$5.25^{ii} \pm 0.54$	$3.05^{ii} \pm 0.31$	$0.32^{i} \pm 0.05$	$8.62^{ii} \pm 4.36$	359.09 ± 60.45	$1305.35^{i} \pm 194.28$	$319.37^{i} \pm 84.54$	0.33 ± 0.06
RSC-7Y	Pre-burning	$5.40^{a} \pm 0.02$	$5.92^{b} \pm 0.30$	$3.44^{b} \pm 0.18$	$0.21^{a} \pm 0.02$	21.16 ± 2.53	$375.36^{ab} \pm 49.46$	$728.64^{a} \pm 144.60$	$210.47^{a} \pm 18.65$	$0.40^{b} \pm 0.03$
	5 min after burning	$8.44^{c} \pm 0.31$	$5.41^{a} \pm 0.02$	$3.15^{a} \pm 0.01$	$0.34^{b} \pm 0.03$	23.11 ± 3.28	$520.50^{b} \pm 109.58$	$1,073.15^{a} \pm 196.29$	$315.62^{ab} \pm 101.55$	$0.29^{ab} \pm 0.06$
	9 months After burning	$6.16^{b} \pm 0.06$	$5.18^{a} \pm 0.03$	$3.01^{a} \pm 0.01$	$0.44^{c} \pm 0.02$	22.03 ± 3.35	$408.66^{ab} \pm 46.91$	$2,388.58^{b} \pm 247.5$	$523.52^{c} \pm 47.38$	$0.23^{a} \pm 0.02$
	2 years after burning	$5.77^{ab} \pm 0.35$	$5.36^{a} \pm 0.04$	$3.12^{a} \pm 0.02$	$0.30^{b} \pm 0.06$	21.50 ± 2.60	$306.76^{a} \pm 61.98$	$2,298.77^{b} \pm 106.03$	$408.07^{bc} \pm 59.59$	$0.33^{b} \pm 0.02$
	Average	$6.44^{ii} \pm 1.26$	$5.47^{iii} \pm 0.31$	$3.18^{iii} \pm 0.18$	$0.32^{i} \pm 0.09$	$21.95^{ii} \pm 2.64$	402.82 ± 101.17	$1,622.29^{ii} \pm 780.38$	$364.42^{ii} \pm 132.39$	0.31 ± 0.07

[a-c]Significant statistical differences ($p \leq 0.05$) among periods of each field.
[i-iii]Significant statistical differences ($p \leq 0.05$) among fields.

three fields. The most significant difference in bulk density between pre-burning and 5 min after burning was observed in the RSC-5Y field (Table 4) due to the significant loss of OM.

The proportion of sand in the soil of the RSC-4Y field was 62.27% and 62.75% higher at 5 min and 9 months after burning, respectively, whereas it was 56.00% lower at 2 years after burning. In the RSC-5Y field, the content of sand was lower at all time points after burning. On the other hand, sand was most prevalent in the RSC-7Y field, with 63.93% at 9 months after burning, although it had decreased by 52.23% 5 min after burning (Table 4). Although there was no significant change in the proportion of silt in the RSC-4Y field 5 min after burning, we observed remarkable changes in the RSC-5Y and RSC-7Y fields. The highest overall proportion of silt was observed in the RSC-4Y field, with 23.38%. Notably, the overall proportion of silt in the soil of all three fields varied significantly (Table 4). The contents of clay in the soil of the RSC-4Y and RSC-5Y fields were highest at 2 years after burning, whereas the amount of clay in the soil of the RSC-7Y field decreased at all time points after burning compared to pre-burning. There was no significant difference in the overall clay content between the RSC-4Y and RSC-5Y fields. The effect of fire on soil texture was detected 5 min after burning. The clay content significantly decreased from 18.0% to 14.43% in the RSC-4Y field, while the sand content significantly decreased from 59.43% to 52.23% in the RSC-7Y field. In the RSC-5Y and RSC-7Y fields, the proportion of silt was significantly increased (Table 4).

3.7 Soil erodibility

The overall soil erodibility (*k*-value) differed significantly among the three fields. The largest overall *k*-value was found in RSC-4Y, with $0.143\ t\ h\ MJ^{-1}\ mm^{-1}$, whereas the *k*-value in the RSC-7Y field was lowest at $0.126\ t\ h\ MJ^{-1}\ mm^{-1}$ (Table 4). This indicates that the soil in the RSC-4Y field was more susceptible to erosion than that in the other fields.

There were no significant differences in the *k*-value among the different time points within the same field. In the RSC-5Y field, the

TABLE 4 Variations in soil physical properties: bulk density (Mg m^{-3}), proportions of sand, silt, and clay (%), and *k*-value (t h MJ^{-1} mm^{-1}) along the fallow chronosequence.

Field	Period	Bulk density (Mg m^{-3})	Sand (%)	Silt (%)	Clay (%)	k-value (t h MJ^{-1} mm^{-1})
RSC-4Y	Pre-burning	1.11 ± 0.01	$58.70^{ab} \pm 2.44$	23.30 ± 2.00	$18.00^{b} \pm 0.60$	0.143 ± 0.004
	5 min after burning	1.23 ± 0.12	$62.27^{b} \pm 1.45$	23.30 ± 2.62	$14.43^{a} \pm 2.00$	0.143 ± 0.005
	9 months after burning	1.31 ± 0.13	$62.75^{b} \pm 2.47$	22.71 ± 2.44	$14.55^{a} \pm 0.97$	0.142 ± 0.004
	2 years after burning	1.19 ± 0.02	$56.00^{a} \pm 1.40$	24.20 ± 2.43	$19.80^{b} \pm 1.08$	0.145 ± 0.005
	Average	$1.21^{i} \pm 0.11$	$59.93^{i} \pm 3.35$	$23.38^{iii} \pm 2.10$	$16.70^{i} \pm 2.63$	$0.143^{iii} \pm 0.004$
RSC-5Y	Pre-burning	$1.24^{a} \pm 0.02$	$69.77^{b} \pm 3.67$	$17.20^{a} \pm 2.01$	$13.03^{a} \pm 2.34$	$0.129^{a} \pm 0.006$
	5 min after burning	$1.30^{b} \pm 0.02$	$66.40^{b} \pm 1.11$	$22.30^{b} \pm 1.11$	$11.30^{a} \pm 0.80$	$0.141^{b} \pm 0.002$
	9 months after burning	$1.40^{c} \pm 0.02$	$58.85^{a} \pm 1.03$	$17.64^{a} \pm 1.87$	$23.51^{b} \pm 0.98$	$0.131^{a} \pm 0.004$
	2 years after burning	$1.29^{b} \pm 0.03$	$60.27^{a} \pm 1.68$	$15.40^{a} \pm 0.17$	$24.33^{b} \pm 1.61$	$0.126^{a} \pm 0.000$
	Average	$1.31^{iii} \pm 0.06$	$63.82^{ii} \pm 5.00$	$18.14^{ii} \pm 2.94$	$18.05^{i} \pm 6.32$	$0.132^{ii} \pm 0.007$
RSC-7Y	Pre-burning	1.30 ± 0.02	$59.43^{b} \pm 1.90$	$13.30^{a} \pm 2.01$	$27.27^{b} \pm 2.05$	$0.121^{a} \pm 0.006$
	5 min after burning	1.30 ± 0.03	$52.23^{a} \pm 4.90$	$22.13^{b} \pm 1.65$	$25.63^{ab} \pm 3.31$	$0.142^{b} \pm 0.004$
	9 months after burning	1.29 ± 0.03	$63.93^{b} \pm 2.00$	$14.59^{a} \pm 1.66$	$21.48^{a} \pm 1.00$	$0.124^{a} \pm 0.004$
	2 years after burning	1.24 ± 0.01	$62.30^{b} \pm 0.17$	$11.93^{a} \pm 0.74$	$25.77^{ab} \pm 0.81$	$0.117^{a} \pm 0.002$
	Average	$1.28^{ii} \pm 0.03$	$59.47^{i} \pm 5.26$	$15.49^{i} \pm 4.34$	$25.04^{ii} \pm 2.85$	$0.126^{i} \pm 0.01$

[a-c]Significant statistical differences ($p \le 0.05$) among periods of each field.
[i-iii]Significant statistical differences ($p \le 0.05$) among fields.

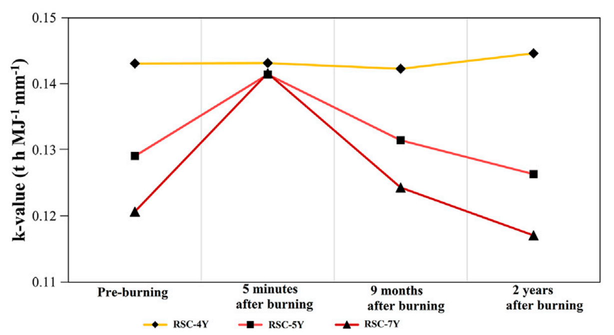

FIGURE 4
k-values (t h MJ^{-1} mm^{-1}) before burning and at 5 min, 9 months, and 2 years after burning in three fallow fields.

k-value was significantly higher at 5 min after burning, with 0.143 t h MJ^{-1} mm^{-1}, followed by a gradual decrease. Likewise, a similar trend of the variation in the *k*-value was observed for the RSC-7Y field (Figure 4). This indicates that the soils were more susceptible to erosion after than before burning.

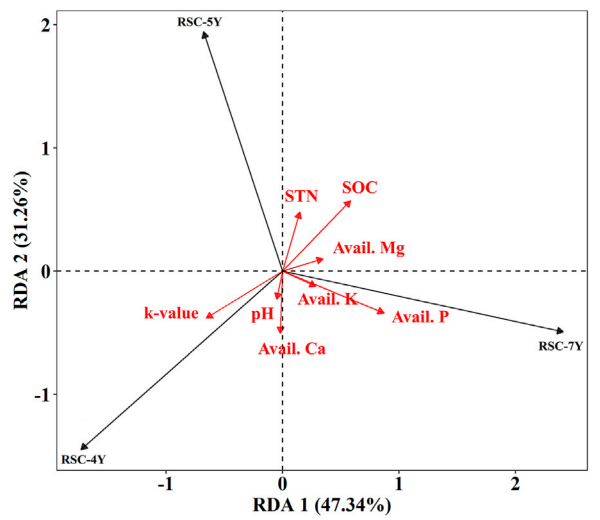

FIGURE 5
Redundancy analysis (RDA) of soil properties response variables and quantitative explanatory variables under rotational shifting cultivation for three fallow fields.

3.8 Soil property response to fallow years and burning time

The RDA plot shows the relationships between soil variables and the different time points (Figures 5, 6). Since a significant correlation was found for EC_e vs. N (r = –0.72, $p < 0.05$) and %silt vs. *k*-value (r = 1.00, $p < 0.05$), EC_e and %silt were eliminated from the RDA. Soil variables with VIF >10, %clay, %sand, and bulk density were also eliminated.

As seen in Figure 5, two groups of samples are separated along the first axis (47.34%, $p = 0.001$), whereas the second axis (31.26%, $p = 0.001$) separates the samples according to the fallow chronosequence (adjusted $R^2 = 0.73$). The RSC-4Y has a high

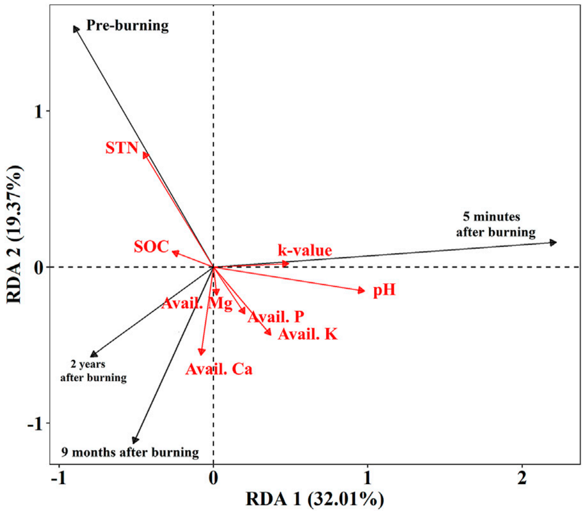

FIGURE 6
Redundancy analysis (RDA) of soil properties response variables and quantitative explanatory variables under rotational shifting cultivation before burning and at 5 min, 9 months, and 2 years after burning for three fallow fields.

positive correlation to *k*-value, pH, and available Ca; whereas STN and SOC show their higher effect in the RSC-5Y field. The available P, available K, and available Mg have a positive correlation to the RSC-7Y field.

In Figure 6, the RDA plot separates the first axis (32.01%, p = 0.001) and the second axis (19.37%, p = 0.012) into different time points (adjusted R^2 = 0.44). STN and SOC show a significant relationship to pre-burning soils, while *k*-value and pH have a higher effect on the 5 min after burning soil. At 9 months after burning, the soils were more characterized by available C and available Mg and had a smaller relationship with available P and available K. At 2 years after burning, both available Ca and SOC have a higher positive relationship with the soils, among other properties.

4 Discussion

4.1 Recovery of SOC, STN, and soil nutrients after fire in rotational shifting cultivation

Fire alters soil properties due to heat and the formation of ashes. In the present study, the soil pH and ECe values were significantly increased after burning, followed by a slight decline until 2 years; the levels remained above the pre-burning values due to the incorporation of ashes and chars into the soil (Table 3). Previous studies (Ulery et al., 1993; Mataix-Solera et al., 2002; Muñoz-Rojas et al., 2016) also stated that the increases in soil pH and ECe after a fire are due to the burning of vegetation residues in the litter layer, generating ashes and resulting in the accumulation of ions, minerals, carbon, and other nutrients. However, the values of soil pH and ECe could be gradually decreased and returned to the pre-burning values due to soil leaching and runoff (Mataix- Solera et al., 2002; Lucas-Borja et al., 2020). Studies also detected high pH levels after burning for up to 6 months, followed by a return to the initial values after 36 months (Fonseca et al., 2017) or 25 months in a Mediterranean forest in southwestern Spain (Jiménez-González et al., 2016). In a study in the Sonoran Desert creosote bush scrub, at 21 years after burning, the pH was still considerably higher compared to pre-burning (Allen et al., 2011).

Soil texture is not easily affected by fire because sand, silt, and clay have high-temperature thresholds (Alcañiz et al., 2016). Sand and silt (1,414°C) have a higher temperature threshold than clay (400°C–800°C) (Neary et al., 2005). Thus, clay particles are more affected by fire when compared to sand and silt particles. As shown in Table 4, the increase in sand and silt particles after a fire is due to the collapse of clay particles, which is consistent with the study of Granged et al. (2011).

The OM levels in the RSC-5Y and RSC-7Y fields were higher than that in the RSC-4Y field before burning, which is due to the long fallow period. However, a decrease in OM was detected after burning at all fallow fields (Table 3). Neary et al. (1999) reported that the OM is mainly accumulated at the surface layer, where it is exposed to heat during burning, resulting in its combustion. Fire temperatures of 200°C–315°C can cause OM loss (Knicker, 2007). As shown in Table 3, OM recovery was observed in the RSC-4Y field, with higher levels after than before burning, whereas the OM in the RSC-5Y and RSC-7Y fields had not returned to the initial levels at 2 years after burning. This can be explained by the presence of grasses covering the surface soil in the RSC-4Y field, compared to the RSC-5Y and RSC-7Y fields, where trees were more common. After the fire, some shoots and roots of grasses in the RSC-4Y field showed rapid regrowth due to the available nutrients (available P, available K, available Ca, and available Mg) from ashes, which increased the OM inputs.

Before burning, the highest SOC and STN stocks were found in the RSC-7Y field (Figures 2, 3), indicating that the long fallow period can accumulate OM inputs from litter and roots, which is consistent with previous findings (Sarkar et al., 2015; Arunrat et al., 2021). Fire can alter soil carbon and nitrogen dynamics by changing carbon and nitrogen inputs and outputs, consequently altering SOC and STN stocks. During fires, some parts of aboveground biomass are incompletely combusted and transformed into pyrogenic carbon, which is resistant to degradation, whereas the aliphatic components are lost (Czimczik et al., 2002; Kasin et al., 2013). The SOC and STN stocks significantly declined at 5 min after burning in all fallow fields (Figures 2, 3) due to losses *via* volatilization by converting OM into mineral carbon and nitrogen (Nigussie and Kissi, 2011; Zavala et al., 2014). Unlike other soil nutrients (P, K, Ca, and Mg), carbon and nitrogen can be volatilized at lower temperatures (Knicker, 2007) and are thus dramatically lower after fire. For example, Neary et al. (1999) reported that nitrogen can be volatilized at 200°C, whereas Ca volatilization starts at 1,240°C. However, the accumulation of ashes in soil pore spaces can restrict water infiltration and increase surface runoff, leading to the leaching out of soil nutrients, which can explain the observed losses.

Changes in soil chemical and physical properties after fire alter the soil microbial community, thereby influencing the recovery of soil properties and the regrowth of vegetation. In the present study, the native successional and surviving plant species in the RSC fields were mostly grasses rather than woody shrubs, and their root systems may contribute to the recovery of ecosystem processes. Brockway and Lewis (1997) and Rasse et al. (2005) reported that early successional native grasses can facilitate the recovery of SOC after a fire and contribute to STN recovery by native nitrogen-fixing plants (Newland and DeLuca, 2000). Moreover, Johnson et al. (2004) reported that nitrogen can rapidly return to pre-fire levels when nitrogen-fixing plants appear. As presented in Figures 1, 2, 2 years of recovery in RSC fields were not long enough to restore the SOC and STN stocks. This is consistent with the study of Santorufo et al. (2021), who found a similar result in Mediterranean Andosol properties 2 years after fire. Moreover, the OM level was not recovered even 10 years after a wildfire in the semi-arid Zagros woodlands (Sadeghifar et al., 2020) and 6 years after a fire in the Mediterranean shrubland (Girona-García et al., 2019). In another study, the total carbon and nitrogen levels in a pine plantation (*Pinus halepensis* Miller) in Catalonia, Spain, could not be restored to the initial levels 9 years after the prescribed fire (Alcañiz et al., 2016), most likely because the recovery of SOC, STN, and soil nutrients (available P, K, Ca, and Mg) starts with vegetation restoration, especially grass species. The results of the redundancy analysis (Figure 6) also evidenced higher pH, available K, available P, and available Mg levels 5 min after burning. This was the case for the RSC-4Y field, where the SOC stock was slightly increased after the fire (Figure 2) due to the survival of weeds and grasses and because of the increased nutrient levels from ashes and charcoal. Quintero-Gradilla et al. (2015) reported the rapid recovery of carbon, nitrogen, and phosphorus in a *Pinus douglasiana* stand in central-western Mexico after severe fires. The authors explained this by the impact of climate and soil conditions on vegetation growth, resulting in considerable OM inputs and accumulation. Post and Kwon (2000) also reported that the recovery of SOC and STN stocks after a fire depends on the OM input, climate, soil type, plant species, nutrients available, and plant species.

4.2 Post-fire soil erodibility changes in rotational shifting cultivation

Since the vegetation is cut and burnt in the RSC field, soil degradation, erosion, and nutrient leaching frequently occur. Soil erodibility is widely used to describe the sensitivity of soil particles to detachment and transport by heavy rainfall and runoff (Wischmeier and Smith, 1978). According to Zhu et al. (2010), soil organic matter can influence the *k*-value due to its ability to absorb water and increase soil infiltration. As shown in Figure 4, the topsoil of the RSC-4Y field before burning was most susceptible to erosion because of the lower organic carbon (Table 3) and higher silt content (Table 4) compared with the RSC-5Y and RSC-7Y fields. At 5 min after burning, the *k*-values in the RSC-5Y and RSC-7Y fields were remarkably higher than before burning. This indicates an increase in erosive processes through the reduction of organic carbon (Table 3) and inputs from vegetation and an increase in silt contents after a fire (Table 4). According to Ostovari et al. (2016), fine soil particles lack adhesion properties and are easily broken and transported, whereas soil with coarse particles has a high permeability, impeding soil erosion. On the other hand, the *k*-value in the RSC-4Y field was unchanged, as the fire did not alter the organic carbon (Table 3) and silt contents (Table 3). We hypothesized that weeds and grasses may protect the OM in the surface layer from fire and that they regrow after a fire, in contrast to the trees. This was observed at 9 months and 2 years after burning; in the RSC-4Y field, the *k*-values were unchanged, most likely because of the survival and regrowth of weeds and grasses, slowing down runoff and leaching. In contrast, the RSC-5Y and RSC-7Y fields showed a slight increase in soil erosion resistance (reduced *k*-values) after burning compared to the pre-burning values, which can be explained by the increase in the clay content *via* the decomposition of new litter inputs and the reduction of the silt content through surface runoff. This is consistent with the study by Zhang et al. (2004), who also found a significant negative correlation between clay content and *k*-value when using the RUSLE model. Zhang et al. (2011) mentioned that the lack of grasses and litter under the canopy results in low water retention capacity, whereas the roots of grasses can potentially enhance the carbon input and reduce land-surface erodibility (Fu et al., 2011; Arunrat et al., 2022b). Garcia-Ruiz et al. (2015), in their meta-analysis, showed that agricultural lands have the highest erosion rates, whereas the lowest rates are found in forests and shrublands.

Ash and charcoal play important roles in post-fire soil. It is a consequence of the solubilization components that not only alter soil physio-chemical properties but also increase or decrease soil erosion and deposition. In the RSC fields, the ashes were reddish-brown, gray, and white (Table 2). Gray and white ashes are produced under complete combustion at temperatures of 500–1,400°C (Goforth et al., 2005) and are usually on top of black ash, whereas dark brown ash is produced through the oxidation and dehydration of Fe (Bodí et al., 2014). In contrast, combustion under low temperatures produces ash with a higher OC content and a dark color (Kuhlbusch and Crutzen, 1995). Before the first rain, the colors of ash can affect the soil's thermal properties. Bodí et al. (2014) reported that darkened ash may increase soil temperatures by decreasing soil albedo. After the rain, the soil pores can be sealed by ash, charcoal, and clay minerals and become clogged (Mills and Fey, 2004), leading to changes in runoff and erosion (Onda et al., 2008; Woods and Balfour, 2010). Dark ash acts as a mulch cover by protecting the topsoil from raindrops, detachment, and increasing water infiltration, whereas white and gray ashes may increase overland flow due to the clogging of soil pores (Thomaz, 2018).

4.3 Implications for post-fire land management

Ash plays a crucial role in the altering and recovery of soil physio-chemical properties, whereas soil erodibility controls soil properties after a fire (Figure 6). Based on the present study, three possible effective practices for post-fire land management in the RSC fields are recommended. The first is allowing weed and grass growth before burning to reduce soil heat; the survival of shoots and roots of grasses and weeds can facilitate rapid regrowth, supporting soil recovery (Kirchmann et al., 2013; Arunrat et al., 2022c) (as seen in the RSC-4Y field; Table 3; Figures 1, 2). The second is burning while fuels contain high moisture levels, namely, in late winter or early summer (November–February), to impede the complete combustion of the topsoil layer; incomplete combustion produces dark ash and charcoal, which may reduce soil detachment and increase soil pyrogenic carbon. It should be noted that smoldering fires burn for longer periods, resulting in more smog compared with flaming fires (Rein et al., 2008; Arunrat et al., 2022a). Therefore, the burning schedule and cultivation calendar should be well planned based on weather conditions, especially precipitation. Finally, the trunks remaining after a fire can be used as contour-felled log erosion barriers to slow down surface runoff and trap the sediment, ash, charcoal, and nutrients (Robichaud et al., 2008) that can promote crop growth and soil recovery. However, it is necessary to develop appropriate post-fire land management practices and to study the effect of ash characteristics on soil erosion in RSC fields.

5 Conclusion

Soil pH, ECe, and soil nutrients (available P, available K, and available Ca) were increased after burning and were above the pre-burning levels at 2 years after burning, mostly because of the incorporation of ash and charcoal into the soil. The SOC stock decreased after burning in all fallow fields. At 2 years after burning, in the RSC-4Y field, the SOC stock was higher than before burning, whereas in the RSC-5Y and RSC-7Y fields, the levels were 5.9% and 13.1% lower than the pre-burning levels. Weeds and grasses were more prominent in the RSC-4Y field, and their regrowth after fire promoted OM inputs. The STN stocks of all studied fields were significantly decreased after burning (30.0%, on average), followed by an increase up to 9 months; however, at 2 years after burning, they were still lower than the pre-burning stocks (17.1% decrease, on average). These losses may be due to the sealing of soil pores by ash, charcoal, and clay minerals, impeding water infiltration and increasing surface runoff. Although before burning, the topsoil of the RSC-4Y field was most susceptible to erosion because of the lower organic carbon and higher silt contents compared with the RSC-5Y and RSC-7Y fields, the *k*-value in the RSC-4Y field was unchanged at 2 years after burning. This suggests that weeds and grasses protect the surface soil from fire and their regrowth after burning decreases runoff and leaching.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

NA: conceptualization, methodology, investigation, writing—original draft, and writing—review and editing. SS: conceptualization, methodology, investigation, and writing—original draft. PK: methodology, investigation, and writing—original draft. CI and MY: supervision. RH: conceptualization, methodology, and supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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