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Review

Fire Impacts on Soil Properties and Implications for Sustainability in Rotational Shifting Cultivation: A Review

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Abstract: Fire, a prevalent land management tool in rotational shifting cultivation (RSC), has long been debated for its immediate disruption of surface soil, vegetation, and microbial communities. While low-intensity and short-duration slash-and-burn techniques are considered beneficial for overall soil function, the dual nature of fire's impact warrants a comprehensive exploration. This review examines both the beneficial and detrimental effects of fire on soil properties within the context of RSC. We highlight that research on soil microbial composition, carbon, and nitrogen dynamics following fire events in RSC is gaining momentum. After fires, soil typically shows decreases in porosity, clay content, aggregation, and cation exchange capacity, while sand content, pH, available phosphorus, and organic nitrogen tend to increase. There remains ongoing debate regarding the effects on bulk density, silt content, electrical conductivity, organic carbon, total nitrogen, and exchangeable ions (K^+, Ca^{2+}, Mg^{2+}). Certain bacterial diversity often increases, while fungal communities tend to decline during post-fire recovery, influenced by the soil chemical properties. Soil erosion is a major concern because fire-altered soil structures heighten erosion risks, underscoring the need for sustainable post-fire soil management strategies. Future research directions are proposed, including the use of advanced technologies like remote sensing, UAVs, and soil sensors to monitor fire impacts, as well as socio-economic studies to balance traditional practices with modern sustainability goals. This review aims to inform sustainable land management practices that balance agricultural productivity with ecological health in RSC systems.

Keywords: fire; slash-and-burn; prescribed burning; rotational shifting cultivation; soil property; soil microbial

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1. Introduction

Fire is a significant ecological disturbance that can profoundly affect terrestrial ecosystems. It plays a crucial role in shaping vegetation patterns [1,2], influencing nutrient cycling [3–5], and altering soil physicochemical properties [6–8]. In many regions, fire is also an integral component of traditional agricultural practices, such as rotational shifting cultivation (RSC) [9]. Fire plays a multifaceted role beyond nutrient release; it aids in controlling pests and diseases and shapes the landscape by influencing plant succession and diversity [10]. Over time, repeated applications of ash contribute to preserving or enhancing soil nutrient levels and organic matter content in agricultural systems that employ crop rotation [11,12]. When these substances are combined with topsoil layers through the process of rainfall, they become easily accessible for uptake by crops [13]. Additionally, burning makes the process of clearing land faster and easier for farmers compared to using their own hands. After numerous cycles of cultivation and burning, the soil's fertility declines, at which time farmers abandon that plot and shift to a new place, resuming the cycle.

RSC also referred to as slash-and-burn or swidden agriculture, is a traditional farming technique that has been practiced by indigenous and rural communities for millennia [14–17]. Historically, shifting agriculture has been prevalent in various tropical regions of South and Southeast Asia [18–20], as well as parts of Africa and South America [16,21–23]. This traditional practice is crucial for many communities, as it ensures food security, preserves cultural heritage, and supports biodiversity. However, population growth in many regions has altered fallow periods and led to the overexploitation of agricultural resources [24,25]. While shifting cultivation offers significant agricultural benefits, it also sparks debate over its ecological impact, particularly concerning soil sustainability and long-term environmental health [26–30]. RSC involves cyclically clearing land—primarily using fire—cultivating crops, and then allowing the land to lie fallow to recover. While fire can enhance soil fertility in the short term by releasing nutrients from burned vegetation, its repeated use can lead to long-term soil degradation, including the loss of organic matter, deterioration of soil structure, and disruption of essential microbial communities.

In the context of RSC, the use of fire has evolved significantly due to technological advancements and policy changes. Over time, technological progress has introduced new methods that reduce dependence on fire, such as the application of fertilizers, mulching, and incorporation [31,32], minimizing the need for extensive burning. Furthermore, policy changes and population pressures have increasingly influenced fire usage in RSC. Many countries have implemented regulations to control or limit slash-and-burn as well as prescribed burning, motivated by concerns over deforestation, soil degradation, and environmental pollution. However, fire still serves as a crucial tool for clearing vegetation and preparing the land for planting, a traditional agricultural method employed by some indigenous and rural communities [33–35]. In Thailand, for example, the government prohibited slash-and-burn in the 1960s [36], but enforcement of the ban was sporadic until the 1980s. Currently, open burning is banned for short periods as part of hazardous air pollution mitigation measures [37,38], particularly in Northern Thailand. However, burning in RSC fields still occurs in some areas [39–43]. These fields are managed in fallow cycles, where one plot is temporarily cultivated and then abandoned, while the cultivator moves on to another plot. The village remains a permanent settlement without relocating to new sites.

To achieve this, the impact of fire on soil physicochemical properties and soil microorganisms was discussed. For this review, existing peer-reviewed articles were searched using electronic databases such as ISI Web of Science, Scopus, and Google Scholar. Articles published up to May 2024 were collected, focusing on the impact of fire on soil properties and soil microorganisms. Keywords used for the search included ‘fire’, ‘burning’, ‘swidden cultivation’, ‘slash-and-burn’, ‘shifting cultivation’, ‘rotational shifting cultivation’, ‘prescribed fire’, ‘soil properties’, ‘microorganisms’, and ‘post-fire management’. We selected only articles written in English and included those reporting both field and laboratory studies. This review delineates the role of fire in RSC, its effects on soil properties, soil erosion, and soil microorganisms, as well as soil recovery post-fire and mitigation and management strategies. The aim of this review is to explore and discuss the dual nature of fire’s impact on soil within the context of RSC. By examining both the beneficial and detrimental effects, the review seeks to provide a comprehensive understanding of how fire influences soil properties and to highlight sustainable practices that can mitigate negative outcomes while leveraging positive effects.

Recent international research on the impact of fire on soil, particularly in the context of RSC system, distribution, and ecological effects, has significantly increased over the past two decades, as shown in Figure 1. The overall growth trend in publications reflects the evolving patterns in research findings over time. A total of 75 publications were analyzed, and Figure 1 illustrates the dynamics of publication numbers over the past 20 years. Between 1998 and 2005, the annual number of published papers remained below

10 papers. However, there was a notable increase from 2006 to 2010, with publications rising from 5 to 13 papers. From 2010 to 2024, the growth curve shows an exponential trend, with the number of publications increasing from 13 to 37 papers. This time series analysis provides insights into research trends and highlights specific phases of research, particularly in areas such as soil properties, microbial composition, soil carbon, and soil nitrogen. Notably, from 2006 to 2020, the majority of publications focused on soil properties. Since 2016, there has been a significant rise in research topics related to microbial composition, soil carbon, and soil nitrogen, indicating an emerging trend in these areas (Figure 2).

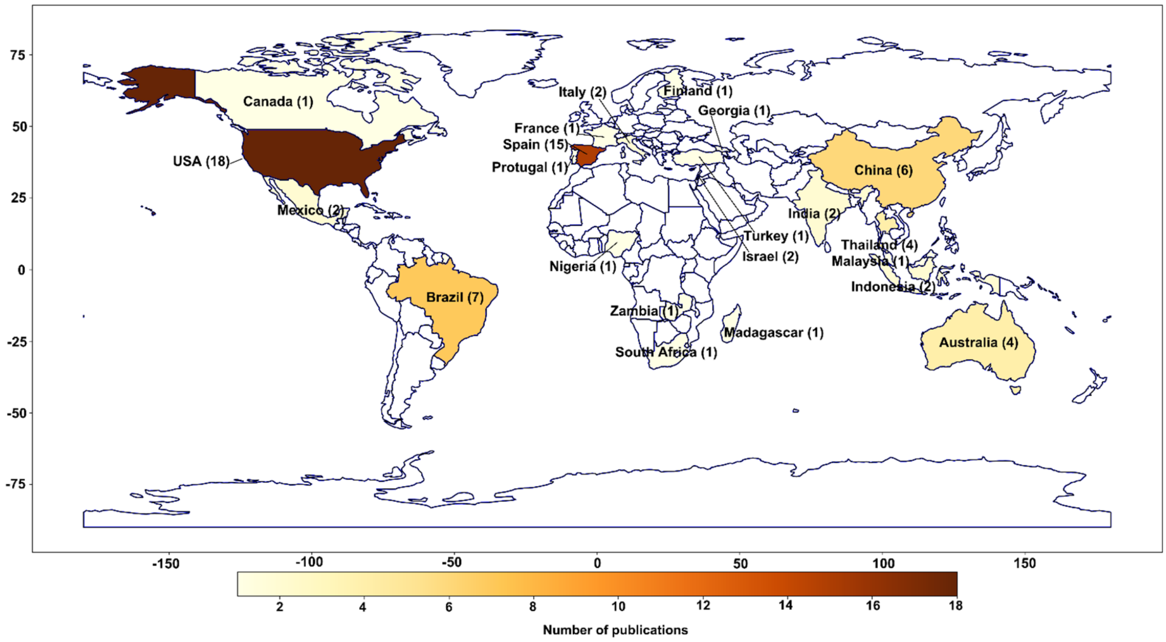

Figure 1. Global distribution of publications on the impact of fire in RSC across major countries (n = 75). The numbers in bracket represents the number of papers from each country.

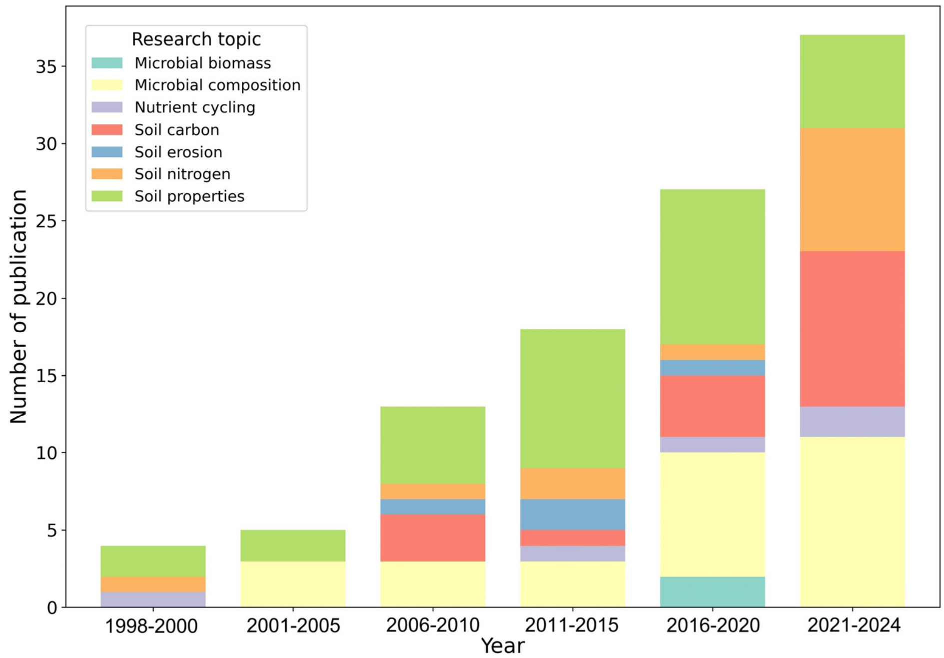

Figure 2. Number of publications on the impact of fire in RSC over 5-year intervals, color-coded by research topic (n = 75).

In our review, we identified a total of 422 keywords in the literature on this research field from 1998 to 2024. Figure 3 visualizes the 30 keywords with the highest co-occurrence and frequency. The most frequent keywords were 'microbial composition' (11 occurrences), 'soil nutrient' (10), 'wildfire' (9), 'carbon' (9), 'prescribed burning' (9), 'fire ecology' (8), 'soil properties' (7), 'nitrogen' (6), 'soil chemical' (5), and 'soil physical' (5). This analysis highlights that current research priorities and emerging topics are centered around soil microorganisms, feedback processes post-fire, and soil properties within the context of agricultural management ecosystems.

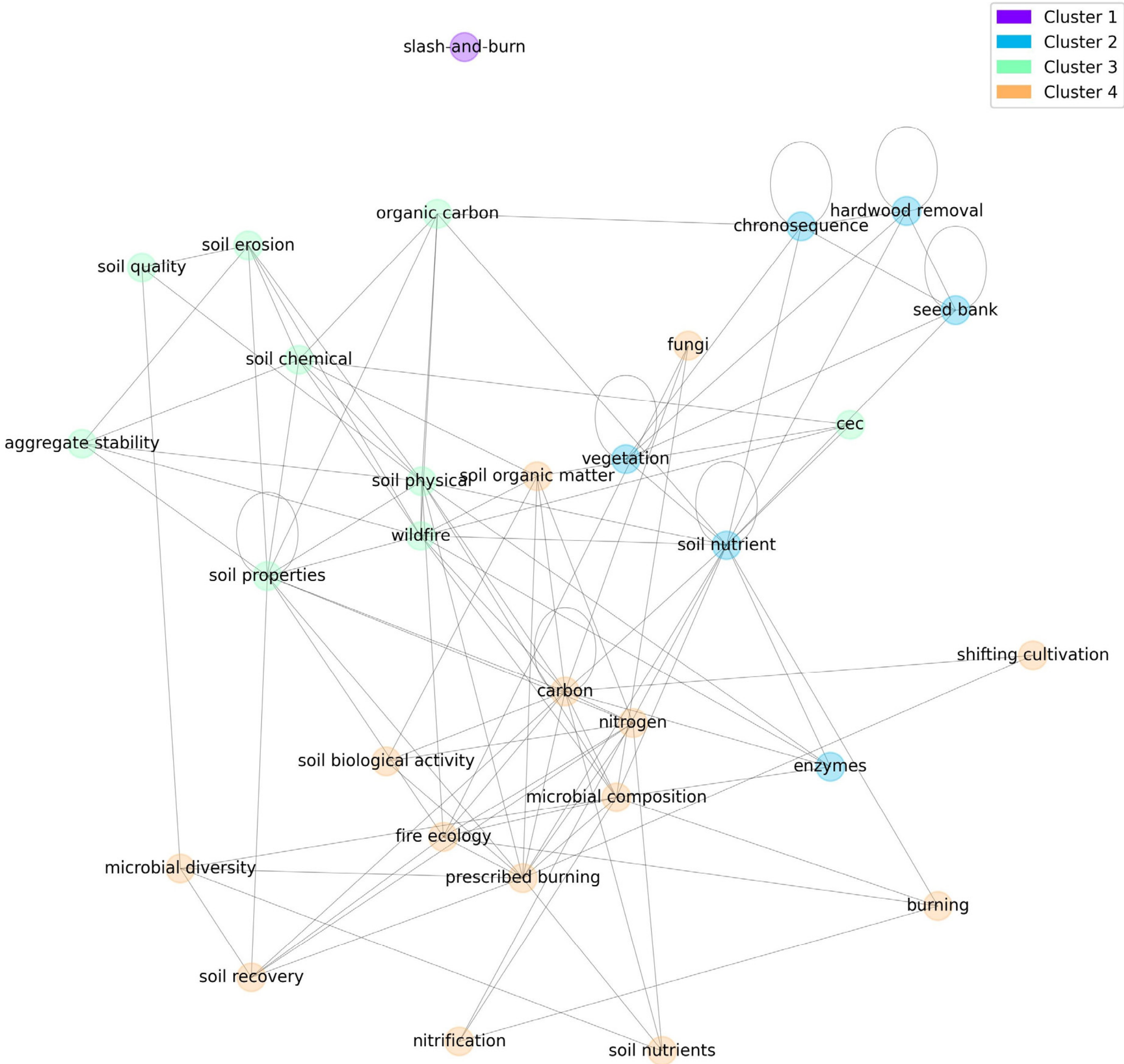

Figure 3. Network of keywords based on the co-occurrence method for the study of the impact of fire on soil in RSC (1998–2024).

The cycle of RSC begins with the selection of a suitable site in a previously fallow area. Initially, vegetation cover is cleared using tools such as axes, machetes, and chainsaws (Figure 4a). After clearing, the residues are left to dry for approximately one week to two months, followed by burning to eliminate the vegetation residues, weeds, and plant pathogens (Figure 4b). This burning process aims to release soil nutrients in the form of ash (Figure 4c,d), temporarily enhancing soil fertility and supporting crop growth. Subsequently, crops such as upland rice, tubers, vegetables, and flowers are planted and tended until harvest time. After the harvest, the land is left fallow to regenerate its fertility, with this period varying from a few months to several years. The cycle then repeats with the selection of a new site for cultivation.

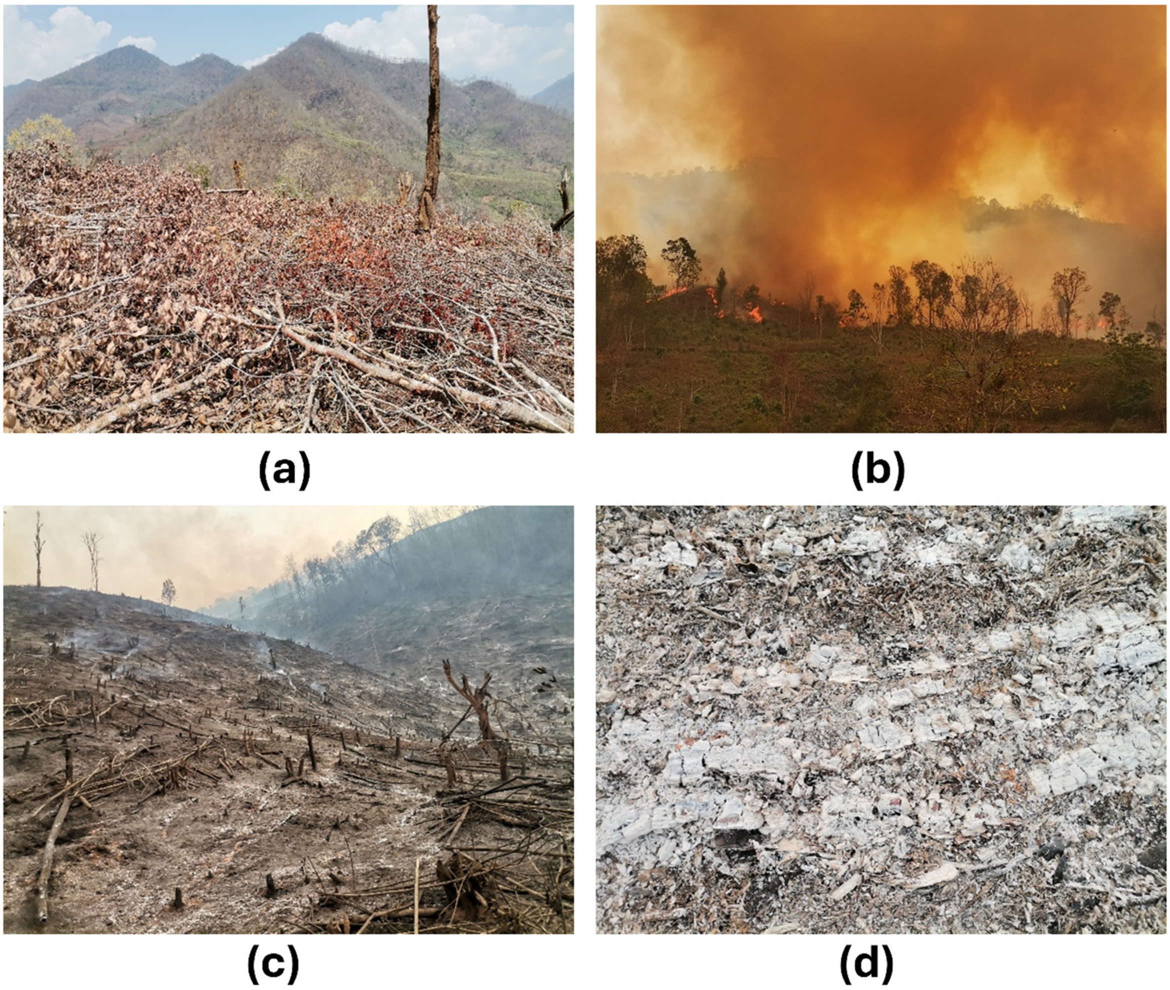

Figure 4. Land clearing of RSC in Northern Thailand. (**a**) cutting, (**b**) burning, (**c**) after burning, and (**d**) remaining ash and charcoal. Photos were taken by Noppol Arunrat.

2. Effects of Fire on Soil Properties

The impact of fire on soil texture, structure, and porosity can vary depending on the severity of the fire, resulting in both positive and negative effects [44]. Fire can profoundly alter soil structure by combusting organic matter [45] and directly affecting its physical, chemical, and biological characteristics through heating and combustion [5,46–48]. Indirect effects include modifications to biological, pedological, and hydrological processes [5,49,50].

In a fire, organic materials such as wood, soil, and leaves rapidly oxidize, releasing various gasses into the atmosphere, including carbon dioxide and water vapor. This process accelerates the conversion of carbon contained in organic matter into atmospheric carbon dioxide, surpassing the rate at which natural decomposition processes [51]. Here, we illustrate the physical changes in topsoil (0–30 cm) over various periods, from before burning to after burning, in an RSC field where ash covers the surface soil. The residual ash, visible as a black substrate, remained on the surface soil 6 months and 12 months post-burning (Figure 5). Intense fires can completely destroy the organic layer on the surface, while low-intensity fires may promote decomposition by releasing nutrients. However, large and intense fires frequently have the opposite effect [52]. Although fires can enhance nutrient availability for decomposition by releasing them from organic matter, uncontrolled and repeated burning can lead to nutrient loss through volatilization or leaching [53].

Nutrient-poor conditions following a fire can reduce microbial activity and nutrient cycling within the ecosystem, ultimately impacting soil health and productivity. These dynamics highlight the complex interplay between fire intensity, nutrient cycling, and microbial activity in post-fire soil recovery.

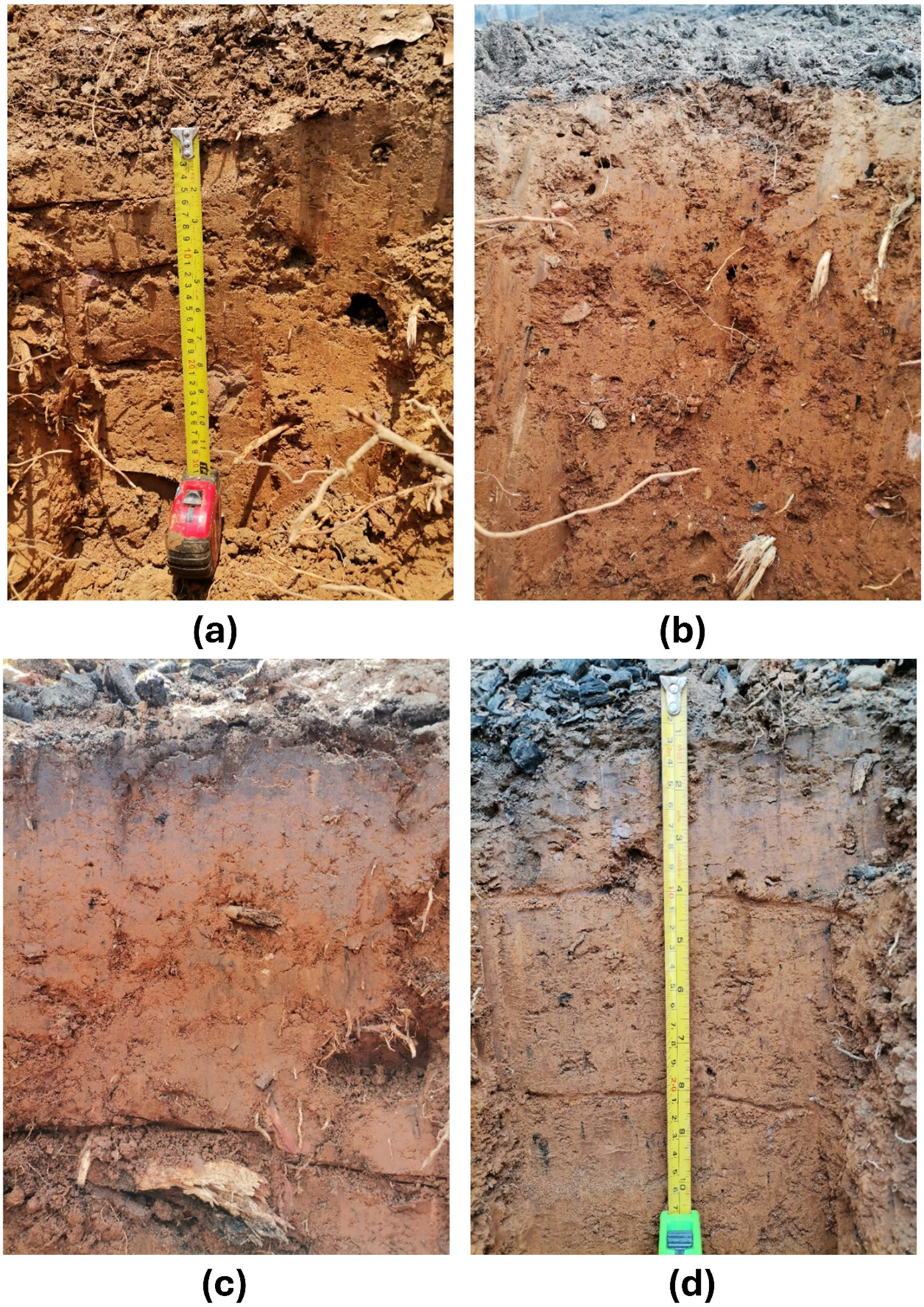

Figure 5. Soil profile (0–30 cm) at different periods of RSC in Northern Thailand. (**a**) before burning, (**b**) 5 min after burning, (**c**) 6 months after burning, and (**d**) 12 months after burning. Photos were taken by Noppol Arunrat.

Alcañiz et al. [54] reviewed the effects of prescribed fires on soil properties, highlighting that these fires have a less severe impact compared to wildfires due to lower soil heating and fire intensity. Intense heat from fires can also lead to the breakup of soil aggregates, which are groupings of soil particles contributing to its crumbly texture [49]. The combustion process leads to the collapse of organic-mineral aggregates and the destruction of organic matter, reducing both soil bulk density and porosity [55–59]. Despite this, bulk density may also increase due to soil compaction and the loss of organic matter, while porosity typically decreases as soil pores collapse [60]. Fire also affects soil structural stability, particularly altering the distribution and stability of soil aggregates $\geq$ 4 mm, described by Thomaz [61] as the formation of fire-hardened aggregates through rapid physical-chemical processes like mineral fusion and recrystallization. Moreover, prescribed burning conducted on moist soil significantly reduces heat penetration compared to dry soil conditions [62,63]. However, intermittent low-intensity fires can promote soil aggregation under specific conditions. The residual ash generated from combustion may contain oxides, such as aluminum and silica, which act as binding agents among mineral particles. This process facilitates the formation of soil aggregates, enhancing the cohesion and clumping of soil particles over time [64].

Post-fire, organic matter, and volatile substances burning alter soil composition, often increasing sand or silt content [65]. In general, fire tends to reduce the organic content of the soil and disturb its structure, temporarily giving the soil a sandier and less aggregated appearance. However, in specific ecosystems, long-term aggregation can be promoted by periodic low-intensity fires. The texture of the soil can be influenced by factors such as the frequency of fires, their intensity, and the characteristics of the surrounding environment [52]. Studies on slash-and-burn practices reveal varying impacts on soil texture: an increase in sand content due to aggregate breakdown and particle loss during combustion [33,55,56,66], fluctuating silt content influenced by fire severity and erosion processes [33,52,57,67], and a decrease in clay content attributable to physical and chemical transformations induced by fire [45,68].

Both RSC and prescribed burning significantly alter soil chemical properties, notably nutrient availability, pH levels, electric conductivity (EC), and cation exchange capacity (CEC). Fire can significantly affect soil EC due to the release of soluble ions from ash and burned organic matter. The combustion of organic materials releases nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium into the soil, temporarily increasing their availability [42,45,68–70]. While low-intensity and short-duration fires may not significantly alter some soil properties, they do result in notable increases in pH and EC [41]. The ash produced from burning is rich in alkaline elements [71], which raises soil pH and subsequently increases CEC [72]. The rise in pH is one of the most beneficial effects of prescribed burning, as it enhances the availability of essential nutrients, particularly in acidic soils [69]. The degree of pH alteration is contingent upon the severity of the fire, as more intense burns result in higher amounts of ash, hence leading to more substantial pH rises. The most significant elevations generally manifest in the upper layers of soil, where there is a buildup of ash [45]. The EC often rises in the medium to long term as soluble salts from ash accumulate, although there may be a short-term decrease as these salts leach away [73]. The formation of biochar is also observed in cases of extremely high temperatures, leading to the development of a more enduring alkaline nature compared to ash alone [44]. Moreover, the high-porosity physical structure of biochar can increase the soil's water content [74].

Long-term impacts arise from the interactions between ash and carbonates, which facilitate the retention of pH and induce changes in the soil microbial community responsible for organic matter breakdown [75–77]. This enhanced cation exchange capacity improves the soil's ability to retain essential nutrients, making them more accessible to plants.

Fires can have dual effects on soil nutrients: initially causing losses through volatilization and combustion of organic matter or releasing nutrients like organic nitrogen from burned plant material, which becomes available to soil microorganisms and plants. The breakdown of organic matter post-fire can release organic nitrogen [58] and increase the availability of nitrogen, phosphorus, and potassium [12,33,54,55,58,67,78]. Generally, fire temperatures vary from moderate to very high at the soil surface but have a short residence time and rapidly decrease with soil depth [79]. Despite high temperatures, there is no depletion of carbon content in the topsoil [58]. While combustion may lead to the loss of some organic carbon, the charred residues left in the soil can contribute to long-term soil carbon pools [8,80,81]. Organic and total carbon levels initially increase with the addition of charred residues [41,55,80]. However, the volatilization of nutrients, which varies across regions, can result in the depletion of labile soil carbon, nitrogen, and potassium pools over time due to weathering processes [4,57,82]. Nitrogen dynamics are also significantly affected by fire. Organic nitrogen often experiences a temporary increase following events like fires [55,70,80], but total nitrogen tends to decline over time, largely due to processes such as volatilization and soil erosion. While available nitrogen may show short-term increases as fire releases nitrogen from organic matter, it typically declines in the long term [55,66,82–84]. Phosphorus and potassium levels usually increase after a fire as these nutrients are released from organic matter and minerals [12,33,56,67,78,84], although their availability can fluctuate over time [55,85]. This loss of key nutrients in specific areas can lead to decreased nutrient turnover in the long term, as observed in studies such as that by Wang et al. [35]. Table 1 provides an overview of the effects of fire on changes in soil physicochemical properties, as observed in studies of both slash-and-burn and prescribed burning systems.

Table 1. Effect of fire on soil physicochemical properties.

Soil Properties	Changes	Post-Fire Period	References
Bulk density	increase decrease	5–15 years 5–15 years	[56,60] [59,66]
Porosity	decrease	0–7 years	[55,59]
%Sand	increase	0–2 years	[33,66]
%Silt	increase decrease	10–12 years 5–15 years	[57] [66]
%Clay	decrease	0–15 years	[33,66]
Aggregation	decrease	0–1 year	[67,86]
pH	increase	0–15 years	[12,33,55,56,60,66,67,69,70,75,76,80,82,84–87]
EC	increase decrease	5–15 years 0–3 years	[33,55,56,66,67,69,80,84] [86]
CEC	decrease	12 h after fire	[67,88]
Organic carbon	increase decrease	0–1 year 0–15 years	[47,55,88] [33,56,89]
Total C	increase decrease	12 h after fire 0–15 years	[80,87] [12,66,69,75,82,86,90,91]
Organic nitrogen	increase	0–13 years	[83]
Total N	increase decrease	0–1 year 1–7 years	[55,70,80] [55,66,75,82–84,86]
Available N	increase decrease	0–7 years 0–15 years	[55,80] [33,56,57,82,89]
Available P	increase	0–15 years	[12,33,56,67,76,78,84,85,88,90]
Available K	increase decrease	0–20 years 0–7 years	[56] [55,85,92]
Exchangeable ion (K^+, Ca^{2+}, Mg^{2+})	increase decrease	12 h after fire 0–3 years	[66,67,69,80] [70,85]

Fire significantly influences microbial activities (Table 2) that play crucial roles in soil processes, including the decomposition of organic matter, nutrient mineralization, and enzyme production. The impacts of fire on microbial activity are complex and varied, with extreme temperatures and changes in nutrient availability substantially affecting microbial dynamics [93]. High temperatures from fire can directly damage microbial cells, leading to a significant decrease in overall microbial biomass immediately following the fire [94]. However, the extent of the impact varies depending on fire severity and subsequent environmental conditions [95,96]. Low-to-moderate severity fires often stimulate diverse microbial activities involved in decomposition, enzyme production, and nutrient mineralization. Small, low-intensity fires can stimulate microbial activity and facilitate nutrient mineralization by releasing organic nutrients such as nitrogen, phosphorus, and sulfur into mineralized forms that are more available for microbial and plant consumption [97,98]. However, in surface soils, microorganisms are often killed and organic matter is consumed by combustion during intense fire events. Following such events, nutrient mineralization rates slow down, and microbial activity is reduced [99]. Low-level fires may improve microbial enzyme production by making enzymes bound to soil particles easier to absorb. The heat from low-intensity fires causes structural alterations and increased mobility of enzymes such as cellulases, proteases, and chitinases, allowing them to interact with substrates and catalyze reactions vital for nutrient cycling [100]. Nevertheless, these benefits are limited as the intensity of the fire increases. Temperatures over 200 °C can eradicate enzyme activity within surface soils. Conversely, high-severity fires can temporarily inhibit several microbial processes until recovery [97]. Extreme burns not only eliminate the existing enzymes but also negatively impact the quantity, variety, and activity of soil microbial communities [101].

Fire also affects soil fungi and nitrogen-fixing bacteria. The intensity and duration of flames, along with the fire regime—frequency and return interval—determine the extent of this impact [102]. Arunrat et al. [103] found that bacteria exhibited greater sensitivity to fire compared to fungi. Bacterial richness and diversity increased significantly and recovered more rapidly than fungi one month after burning in RSC fields in Northern Thailand. Some fungi, such as pioneer fungi (*pyrophilous* fungi), are fire-adapted and can survive post-fire by colonizing and breaking down charred organic matter [104]. Mycorrhizal fungi, which form symbiotic relationships with plant roots, are also affected by fire, altering their diversity and abundance. Actinobacteria and Proteobacteria often become more widespread after a fire, while other bacterial species may decline due to competition or sensitivity to post-fire conditions [105]. High temperatures from fire can damage or reduce the population of nitrogen-fixing bacteria, which are vital for nitrogen cycling within ecosystems [106]. However, certain nitrogen-fixing bacteria adapted to fire conditions, such as those associated with fire-adapted plants or residing in fire-resistant structures, can persist or even increase in number following a fire event, including species like *Clostridium* and *Paenibacillus* [107]. These changes influence plant establishment and growth during post-fire recovery, ultimately altering the composition and dynamics of soil microbial communities [104].

Table 2. Effect of fire on soil bacteria and fungi.

Microbial Parameter	Post-Fire Recovery	Relate Factors	References
Bacterial diversity and richness	increase	higher C source	[88]
Actinobacteria	increase	higher N source	[108]
Acidobacteria	increase	higher soil pH	[75,77]
Proteobacteria	increase	higher P source	[75–77]
Firmicutes	increase	higher soil pH	[76]

Table 2. *Cont.*

Microbial Parameter	Post-Fire Recovery	Relate Factors	References
Fungal community composition	decrease	lower C source	[109]
Arbuscular Mycorrhizal Fungi (AMF)	decrease	Lower MBC	[110,111]
Ectomycorrhizal Fungi	decrease	lower C and N source	[91,109]
Cellulolytic Fungi	decrease	lower C source	[112]
Enzyme activities			
Urease	decrease	denatured/lower N source	[55,86,113]
Phosphatase	decrease	lower P source	[55,89,113,114]
β-glucosidase	decrease	denatured, lower MBC	[86,89,90,113,114]
Microbial C utilization	decrease	Lower labile C	[86,110,115]
Microbial Biomass Carbon (MBC)	increase decrease	higher DOC denatured/lower DOC	[47,89,110] [75,86,87]

DOC refers to soil dissolved organic carbon

3. Impacts of Fire on Soil Erosion

Fire disrupts soil structure by breaking down soil aggregates, resulting in a looser and more granular soil texture prone to erosion. This is compounded by the formation of water-repellent soil layers [7,116], which further exacerbates erosion by reducing water infiltration and increasing surface runoff [117]. Are et al. [118] documented significant reductions in structural stability, saturated hydraulic conductivity, sorptivity, and infiltration rate following slash-and-burn practices. In prescribed burning, fires influence soil natural density, bulk density, porosity, water repellency, and permeability, predominantly in the topsoil within a 5 cm depth [119]. Immediately following a fire, the soil's susceptibility to erosion increases dramatically due to the loss of vegetation and changes in soil properties [6]. Heating from fires can induce significant changes in water repellency and structural stability, influenced by fire intensity and initial soil characteristics [46,52,67,120,121]. Moreover, fire can increase the soil's susceptibility to wind erosion, which is associated with soil hydrophobicity. This is due to water-repellent compounds released by burning vegetation [122,123]. Over the long term, fire-induced changes in soil properties can have lasting effects on soil stability and landscape morphology [54,69,124]. The degree of this effect is influenced by various factors such as soil texture, slope grade, and rainfall intensity, with particles like clays and ashes being the most susceptible to loss. The absence of proper gaps for regeneration between repeated burns can accelerate erosion by inhibiting the complete restoration of root systems and ground cover, which are essential for absorbing and dispersing runoff energy [125]. Repeated fires can lead to persistent changes in soil structure and composition, making the soil more prone to erosion even years after the initial fire event. The loss of topsoil and nutrients can hinder vegetation regrowth, further perpetuating the cycle of erosion [116,126].

In agricultural areas with sloping topography, the absence of proper management practices can lead to uncontrollable runoff, causing erosion and the transport of both particulate and dissolved nutrients downslope. Arunrat et al. [33] reported that average soil surface loss ranged from 1.6 to 3.1 cm, with the highest loss observed during the rainy season on the upper slope in RSC in Northern Thailand. The implementation of RSC practices reduces fallow periods, limiting the time available for vegetation regeneration and the restoration of soil organic carbon levels before subsequent rotations. Consequently, erosion gradually reduces soil fertility by causing oxidation and the subsequent loss of topsoil over time within these dynamic smallholder systems [9].

4. Post-Fire Recovery, Successional Changes after Fire

Post-fire recovery and successional changes following agricultural burning are critical for understanding the resilience and long-term health of affected ecosystems. The soil recovery process after a fire is complex and varies based on several factors, including soil characteristics, fire intensity, microbial communities, and prevailing environmental conditions post-fire [105,127]. Creech et al. [128] found that after a fire with RSC, soil properties may take at least 6 years to return to pre-burn conditions, with changes in nutrient levels and soil pH persisting post-burn. Aboim et al. [129] observed that maintaining fallow plots for periods longer than 5 years can conserve soil quality in RSC in the Atlantic forest region of Rio de Janeiro. In highly vulnerable ecosystems, such as pine stands, the most significant changes in species composition and the lowest rates of post-fire plant recovery were observed [130,131]. However, in revegetated woodland communities in southeastern Australia, post-fire recovery has shown promising results. Pickup et al. [132] found high survival rates of revegetation plantings and substantial recovery of soil function to pre-fire levels within 5 years. Kutiel and Shaviv [133] observed that both bulk density and aggregate stability experienced long-lasting impairments exceeding 15 years due to the slow replenishment of organic matter. Similarly, Murdiyarso et al. [134] documented persistent issues with bulk density and compaction in Indonesian soils over a duration of 10–15 years, attributing these problems to the extended loss of organic matter caused by repeated fires in RSC areas. Piché and Kelting [135] observed that surface soils recover physical properties such as lower bulk density and higher macroporosity within 5–10 years. However, subsoils displayed a legacy effect of agricultural compaction even 55–60 years later. Arunrat et al. [43] reported that the total nitrogen stocks in soil under RSC in Northern Thailand significantly decreased after burning and had not returned to pre-burning levels even after 2 years.

Prescribed burning has minimal short-term effects on soil microbial community composition, likely due to limited soil heating and rapid post-fire vegetative recovery. Post-fire impacts on soil properties can induce short-term microbial responses and shift soil nutrient limitations [136–139]. Soil microbial activity plays a crucial role in nutrient recovery, highlighting its importance in post-fire ecosystem restoration. Studies have revealed diverse temporal recovery patterns in soil microbial communities following burns associated with RSC.

Leal et al. [51] observed that microbial biomass and activity in Amazon soils decreased for 10–15 years post-fire. Similarly, Kutiel and Shaviv [133] found microbial recovery in Israeli shifting plots extended beyond 15 years. In Thailand, Arunrat et al. [41] reported significant changes in certain bacterial phyla, specifically Proteobacteria and Acidobacteria, with soil bacterial communities beginning to recover during the rainy season despite declining nutrient availability. Alpha diversity decreased immediately after the fire but increased from the early rainy season until summer, with bacterial richness and community diversity returning to pre-fire levels within a year.

Some species, such as mycorrhizal fungi, exhibit resistance to surface fires and contribute to recovery [140]. Though severe burns can have long-lasting impacts, persisting for 10 years or more, Zhu et al. [141] found that burning led to relatively high bacterial diversity but low fungal diversity, while mowing increased the abundance of *Nitrospirae* bacteria. These findings underscore the complex and varied responses of soil microbial communities to fire, emphasizing the need for long-term monitoring and tailored management practices in different ecosystems.

Vegetation and plant communities play a crucial role in the soil recovery process after fire, significantly influencing soil structure, nutrient cycling, and microbial activity. Post-fire vegetation regrowth helps stabilize the soil, reducing erosion and promoting the retention of nutrients [142]. For instance, Qiu et al. [143] found that vegetation restoration, including the planting of trees and grasses, improved soil hydraulic properties and increased soil infiltration capacity on the Loess Plateau in China. Additionally, the presence of plant roots can enhance soil microbial activity by providing organic matter and root exudates, which serve as energy sources for soil microbes. Wang et al. [144] observed that coarse root biomass and soil organic matter were strong predictors of soil infiltration capacity, showing a significant positive correlation with infiltration rates after a severe forest fire in Daxing'anling, Northeast China. Different plant species contribute varying amounts and types of organic matter to the soil, influencing microbial community structure and function. Randriamalala et al. [145] studied the slow recovery of endangered xerophytic thicket vegetation after fire in Madagascar, highlighting the significant impact on soil as a driver of plant biodiversity and the key role of shrub species growth in influencing diversity and floristic composition along secondary succession stages. In RSC, the vegetation cover is primarily designed by the farmer. Therefore, the successional process of biodiversity in these areas is influenced by cropping practices and land management, as exemplified in Northern Thailand (Figures 6 and 7). Overall, the complex and prolonged nature of soil biological recovery after fire highlights the need for adequate fallow periods and targeted management strategies to facilitate the complete restoration of soil biota and maintain ecosystem functionality.

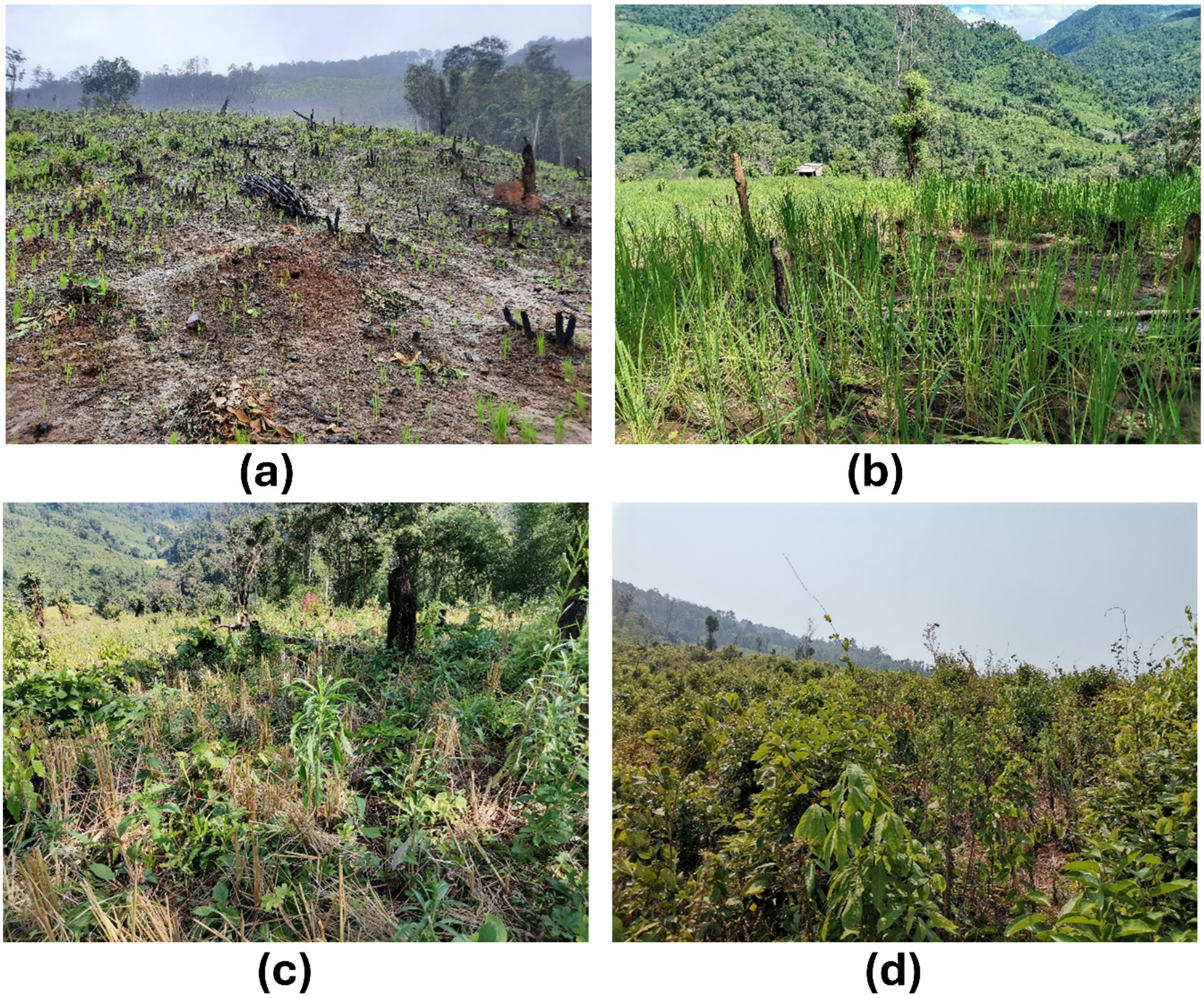

Figure 6. Post-fire rotational plots of RSC in Northern Thailand. (**a**) 3 months after burning, (**b**) 6 months after burning, (**c**) 9 months after burning, and (**d**) 12 months after burning. Photos were taken by Noppol Arunrat.

Figure 7. Examples of vegetables and flowers in RSC in Northern Thailand. Photos were taken by Noppol Arunrat.

5. Implications for Sustainability: Mitigation and Management Strategies

Effective mitigation and management strategies are crucial to minimizing the negative impacts on soil health, biodiversity, and carbon emissions while promoting sustainable agricultural practices. The practice of burning in RSC presents significant challenges and opportunities for sustainability. This method involves clearing land by systematically cutting down vegetation, followed by the controlled use of fire. Implementing careful burn management strategies, such as regulated application and maintenance of buffer zones, can help mitigate the risks of erosion caused by fires. The loss of vegetation that protects soils from fire creates at least a short-term window of increased erosion risk, which can alter long-term soil quality and productivity until cover is restored [146]. Arunrat et al. [43] recommended three approaches for post-fire management in RSC: (1) leaving weeds and grasses on the soil surface during vegetation cutting, (2) conducting burns in late winter or early summer to reduce the complete combustion, and (3) constructing contour-felled log erosion barriers using the trunks left after the fire to trap sediment and slow surface runoff.

Controlled burns in RSC fields are intentional and planned fires set by farmers as part of their agricultural practices. Land zoning and establishing protected areas are crucial for conserving valuable ecosystems and mitigating fire risks. Allocating distinct zones for agriculture, forestry, and conservation helps prevent the expansion of RSC into ecologically vulnerable areas. Protected areas act as buffer zones, mitigating fire spread and safeguarding biodiversity. This methodology necessitates a thorough understanding of the appropriate location, limited area, and vegetation cover to prepare the land for cultivation. Additionally, conducting controlled burns in a sustainable manner requires taking into account weather conditions and implementing safety procedures [147,148]. While burning practices in RSC pose significant environmental risks, they also offer potential benefits if managed with sustainable strategies [149,150]. Key measures include careful planning of burn locations, maintaining buffer zones, monitoring weather conditions, and following safety protocols.

Rapid recovery, genetic adaptation, nutrient cycling, and organic matter decomposition are essential for restoring and functioning fire-affected ecosystems [151]. Some soil microorganisms can quickly recolonize burned areas from less impacted or unburned nearby regions [103,152]. Dispersal mechanisms like wind, water, or animal vectors aid in moving microbes to fire-affected areas. This rapid rehabilitation preserves vital ecosystem functions, facilitating plant regeneration. In post-fire pasture, soil organic matter is primarily contributed by *Brachiaria*. At depths of 40–50 cm, alkyl and hydroaromatic compounds accumulate in the pasture post-fire, while unspecific aromatic compounds (UACs) accumulate in the pasture after burning. UACs and polycyclic aromatic hydrocarbons (PAHs) are abundant in RSC practices, likely air-transported from the burn sites [48]. Over time, soil microorganisms can genetically adapt to fire disturbances. Through natural selection, some microorganisms develop traits that confer resistance or tolerance to fire, such as heat resistance or the ability to metabolize fire-altered compounds. These genetic adaptations enhance their survival and recovery in fire-affected soils, contributing to ecosystem resilience [153].

Improperly managed RSC areas can lead to significant deforestation and biodiversity loss. However, when executed with sustainable principles, these practices can enhance soil fertility and biodiversity conservation. Conservation agriculture techniques, such as no-tillage, cover cropping and mulching, and soil erosion protection, can reduce the need for chemical substances. No-tillage reduces soil disturbance and improves moisture retention, while cover cropping enhances soil fertility, decreases weed spread, and increases organic matter content, promoting sustainable land management [154]. Extending the fallow periods between agricultural cycles allows for the restoration and recovery of soil. Longer fallow periods promote vegetation regeneration, replenishing organic matter and nutrient levels, and enhancing microbial activity [150,155–157].

Alternative land management strategies can effectively minimize the adverse effects of fire in these systems. A pivotal strategy involves transitioning from traditional practices to agroforestry systems, integrating tree maintenance with crop production. Agroforestry, integrating trees with crops, not only provides shade and mitigates soil erosion but also contributes to biodiversity conservation and carbon sequestration, aligning with climate action goals. Chowdhury et al. [158] demonstrated that agroforestry holds greater potential for soil restoration after RSC compared to reforestation, showing significantly higher concentrations of soil organic matter, available phosphorus, and exchangeable potassium in agroforestry plots. Moreover, agroforestry extends the rotation period, thereby reducing the frequency of land clearing and burning, and enhances carbon sequestration [149,159].

In conjunction with agroforestry, intercropping and crop rotation are effective agricultural practices that contribute to soil conservation, nutrient cycling, and overall soil health. These techniques have been extensively studied, revealing numerous ecological benefits. Intercropping, the practice of growing multiple crop species in the same field, offers significant advantages. It enhances soil carbon and nitrogen content, leading to increased soil organic carbon and nitrogen levels compared to sole crops, thereby promoting soil conservation through enhanced belowground productivity and root litter input [160] Additionally, intercropping systems have been shown to improve soil fertility and microbial activity essential for sustainable agriculture [161,162].

Crop rotation, which involves changing the types of crops grown in an area each season, disrupts pest and disease cycles and improves soil quality. This practice helps avoid the buildup of pathogens and pests while enhancing soil structure and fertility by alternating deep-rooted and shallow-rooted plants [163]. Furthermore, crop rotations with legumes, such as alfalfa and clover, significantly enhance soil organic carbon sequestration and soil physicochemical properties, contributing to long-term soil sustainability [164]. Implementing these practices can help maintain soil productivity, promote soil improvement, and ensure sustainable agricultural productivity, ultimately contributing to ecological and economic benefits [165].

Education and awareness programs are essential for promoting sustainable land management practices among farmers, especially in the face of climate change. While RSC is traditionally used by indigenous groups and has been inherently conservative, there is a growing need to ensure these practices are sustainable in the long term. These programs can equip farmers with the knowledge and tools necessary to adopt more sustainable techniques, thereby enhancing the benefits of traditional methods and addressing climate resilience. Engaging with indigenous communities in these programs ensures that traditional knowledge is respected and integrated with sustainable practices. This collaborative approach fosters a sense of ownership and empowerment among local farmers, promoting practices that benefit both the environment and local livelihoods. By aligning traditional methods with modern sustainable practices and climate action strategies, education and awareness programs can play a pivotal role in achieving long-term sustainability and resilience in agricultural landscapes.

6. Future Research Directions

Future research in sustainable land management should focus on several key areas to enhance our understanding and implementation of effective practices. A crucial avenue is the development of technology and methodologies to investigate the interaction of fire, soil characteristics, and soil microorganisms. Large-scale analysis using spatial techniques such as remote sensing, unmanned aerial vehicles (UAVs), geographic information systems (GIS), and field measurements can provide valuable insights into the interplay between fire occurrences, land management, and soil degradation across extensive geographical areas [166–168].

Monitoring and understanding soil properties in RSC can be significantly enhanced with real-time information provided by soil sensor technology [169,170]. These sensors can offer crucial insights into how fire and other land management methods affect soil properties, facilitating informed decision-making for sustainable land management. In-depth studies on the dynamics of soil microorganisms and nutrient cycles can be advanced using techniques such as stable isotope probing (SIP) and high-throughput DNA sequencing. SIP allows researchers to trace nutrient flow through microbial communities by incorporating isotopically labeled compounds into the DNA or RNA of active microorganisms [171]. High-throughput DNA sequencing enables comprehensive analysis of microbial diversity and function by rapidly sequencing large volumes of genetic material from soil samples [141]. By integrating these advanced technologies and methodologies, researchers can develop more effective and sustainable land management practices that address the complex interactions between fire, soil characteristics, and soil microorganisms.

Last but not least, the socio-economic aspects of fire management in RSC should focus on understanding the intricate balance between traditional practices, community livelihoods, and sustainable land use. Investigations should delve into the socio-economic drivers behind the use of fire in shifting cultivation, assessing how these practices affect local economies, food security, and cultural heritage. Furthermore, research should explore the effectiveness of community-based fire management strategies and their potential to enhance resilience against environmental and economic pressures. By integrating socio-economic analysis with ecological data, researchers can develop holistic fire management policies that support sustainable development, improve the well-being of local communities, and preserve essential ecosystem services. Furthermore, the economic trade-offs and challenges faced by communities in adopting sustainable fire management practices should be thoroughly investigated. These multi-disciplinary approaches will provide valuable insights into the long-term viability of RSC in the face of changing environmental and socio-economic conditions.

7. Conclusions

This review underscores the intricate effects of low to medium-severity burning, including slash-and-burn and prescribed burning, on soil properties and microbial communities in RSC systems. These fire practices have dual impacts: while they initially cause nutrient losses through volatilization and combustion, they also release essential nutrients such as nitrogen, phosphorus, and potassium from burned vegetation, enhancing their availability to soil microorganisms and plants. The breakdown of organic matter post-fire further increases nutrient availability. Although high surface temperatures during burning may affect soil carbon content, charred residues contribute to long-term soil carbon pools. Recovery of soil properties and microbial communities post-fire is influenced by fire intensity, soil characteristics, and environmental conditions. Fire affects soil microbial diversity and activity, with low-severity burns generally causing minimal short-term changes due to rapid vegetative recovery, while severe burns can lead to long-lasting alterations in microbial community structure. For instance, some microbial species, such as fire-adapted fungi and nitrogen-fixing bacteria, may show resilience or even increased numbers post-fire, whereas others may decline. Understanding these dynamics is crucial for ecosystem restoration and function.

Effective management strategies, including controlled burns, proper land zoning, and sustainable practices such as agroforestry, cover cropping, and crop rotation, are essential for mitigating negative impacts on soil health and microbial communities. Future research should prioritize advancements in technology, such as remote sensing, UAVs, GIS, and soil sensors, to better understand fire interactions with soil and microbial dynamics. Techniques like stable isotope probing and high-throughput DNA sequencing can provide deeper insights into microbial diversity and nutrient cycles. Additionally, exploring the socio-economic dimensions of fire management can help balance traditional practices with sustainable land use, enhancing community resilience and preserving ecosystem services. This holistic approach is vital for achieving long-term sustainability and resilience in fire-affected agricultural systems.

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