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Essays and Perspectives

Turned to ashes: the environmental costs of using fire in slash-and-burn agriculture outweigh its benefits

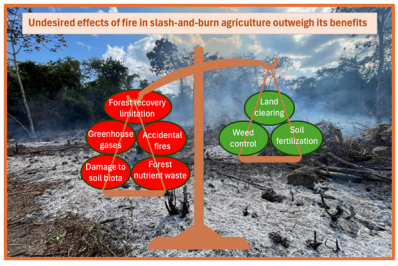
Jakelyne S. Bezerra [a,1], Víctor Arroyo-Rodríguez [b,1], Jorge A. Meave [a,*]

[a] Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México, Coyoacán 04510, Ciudad de México, Mexico
[b] Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Morelia 58190, Michoacán, Mexico

HIGHLIGHTS

- Fire in slash-and-burn agriculture clears land but wastes most forest nutrients.
- Ash increases soil nutrients but fertilization is short-term and surface-limited.
- Fire promotes weed control but also hinders succession and forest recovery.
- Fire-driven nutrient losses emit gases, fueling climate change.
- Slash-and-burn agriculture increases wildfire risk, biodiversity loss, and soil damage.

GRAPHICAL ABSTRACT



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ABSTRACT

Fire has been a fundamental tool for human evolution and well-being. In slash-and-burn agriculture (SBA), it has been used for millennia to eliminate field debris, accelerate the incorporation of nutrients into the soil, and control weeds. However, in addition to these desired outcomes, fire can have multiple undesired environmental impacts that threaten the sustainability of tropical forests and SBA itself. We hypothesized that the environmental costs of fire use in SBA can outweigh its agronomic benefits across tropical forests. To assess this hypothesis, we critically reviewed empirical evidence on both desired and undesired environmental effects of SBA-related fire across the tropics worldwide. We found that fire effectively facilitates land clearing and releases nutrient-rich ashes that temporarily fertilize the soil. However, this fertilization is short-lived and restricted to the topsoil, while a substantial fraction of forest nutrients is wasted through volatilization and post-fire erosion. SBA-related carbon emissions may also contribute to climate forcing at regional and global scales. Although fire can reduce weed pressure by damaging seeds and limiting seed bank viability, this recruitment limitation can delay or arrest secondary succession, thereby constraining forest recovery and its ability to offset fire damage in SBA-dominated landscapes. In addition, repeated burning increases the risk of accidental wildfires, amplifying forest loss and associated biodiversity loss and carbon emissions. Elevated soil temperatures during burning can negatively impact soil biota, disrupting their essential ecological functions. Overall, despite notable remaining knowledge gaps, our review suggests that the environmental costs of using fire in SBA outweigh its benefits.

* Corresponding author.
E-mail address: jorge.meave@ciencias.unam.mx (J.A. Meave).
[1] Current address: Escuela Nacional de Estudios Superiores, Universidad Nacional Autónoma de México, Mérida 97357, Yucatán, Mexico.

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Introduction

Fire has been a key factor in human evolution and remains widely used in modern societies (Gowlett, 2016; Myllyntaus et al., 2002). In tropical regions, it has been used for millennia in slash-and-burn agriculture (SBA) to clear land, release nutrients from biomass, and control weeds (Bezerra et al., 2024). These agronomic benefits, together with the rapid short-term returns often associated with SBA systems (Nhiuane et al., 2024), have supported the persistence of SBA as a widespread agroecosystem throughout the tropics (Curtis et al., 2018; Goldman et al., 2026). However, fire use in SBA can also generate multiple environmental impacts that may compromise both ecosystem functioning and long-term sustainability of the system itself (Arunrat et al., 2024a; Varma, 2003).

The ecological effects of SBA-related fire are highly context-dependent and thus highly heterogeneous across regions. They vary substantially with soil properties, fire severity and frequency, fallow duration, and landscape context (e.g., Arunrat et al., 2024a). Importantly, soil acts as a central mediator linking fire, vegetation dynamics, nutrient cycling, erosive processes, and long-term ecosystem recovery (Alegre and Cassel, 1996; Kukla et al., 2019; Serrani et al., 2023). Fire can directly alter soil temperature, nutrient availability, and biotic communities, while indirectly influencing vegetation regeneration, fuel accumulation, and erosion pathways (Bezerra et al., 2024). These effects may occur immediately after burning but also accumulate through repeated fire cycles and shortened fallow periods, potentially altering system trajectories over time (Fachin et al., 2021). Similarly, although SBA typically operates at small spatial scales (0.5 to 5 ha), its cumulative effects can extend to regional and global scales through landscape-level recurrence of burning and associated forest loss (Bezerra et al., 2024). Indeed, SBA has been estimated to contribute substantially to tropical deforestation worldwide (Curtis et al., 2018; Goldman et al., 2026), making fire use within this system a process of broader environmental relevance.

Despite the extensive literature on fire ecology and on land-use change in the tropics, the specific biotic and abiotic effects of fire induced by SBA remain comparatively understudied (Kobziar et al., 2024; Lambin et al., 2003; McLauchlan et al., 2020). Existing reviews often combine different fire types, ecosystems, or land-use trajectories (Arunrat et al., 2024a), or address SBA broadly without isolating the mechanistic effects of fire itself (Bezerra et al., 2024). Consequently, the empirical basis needed to evaluate the balance between agronomic benefits and environmental costs of SBA-related fire across tropical forest regions remains limited.

Given these ecological trade-offs and the lack of syntheses specifically focused on the mechanistic effects of SBA-related fire, we hypothesize that the environmental costs of fire may outweigh its agronomic benefits across tropical forests. To evaluate this hypothesis, we critically reviewed the desired and undesired environmental effects of fire induced by SBA across tropical forests worldwide. We compiled empirical evidence through a systematic literature assessment (Box 1) and synthesized the reported effects on key biotic and abiotic processes using a systematic approach (Fig. B1). Our review identified substantial geographic and thematic biases in the current evidence base: only 37 studies met our filtering criteria (Box 2). We then evaluated the empirical support for each reported effect of SBA-related fire, highlighting major knowledge gaps and research priorities. Finally, we discuss the implications of these findings for biodiversity conservation and the sustainable management of SBA systems across tropical forests.

Desired outcomes of fire

Although SBA is an ancestral agroecosystem, its modern practice has changed considerably across tropical regions over recent centuries and decades (Pedroso-Junior et al., 2009). In many areas, increased population density and its demand for new agricultural land, as well as market-oriented economies, have shortened fallow periods, leading to more frequent burning cycles and greater agricultural intensification (Osman, 2013; Tang and Yap, 2020). As discussed below, these shifts decrease biomass accumulation and soil recovery time, potentially limiting both the magnitude and duration of the agronomic benefits traditionally associated with fire (Bezerra et al., 2024). Therefore, to better understand the desired outcomes of fire, we need to consider these ongoing socio-ecological transformations.

Box 1
Literature Search.

To compile studies on the effects of fire induced by SBA in tropical forests, we conducted a systematic literature search in the Scopus and Web of Science databases on 29 November 2024 (Fig. B1). These search string combined three groups of terms related to fire, SBA practices, and tropical systems: (“burn*” OR “forest fire” OR “wildfire*” OR “human-induced fire” OR “human-caused fire”) AND TITLE-ABS-KEY (“slash-and-burn” OR “slash and burn” OR “agricultural fire” OR “shifting cultivation*” OR “swidden” OR “traditional agriculture”) AND TITLE-ABS-KEY (“tropic*” OR “tropical forest*” OR “tropical ecosystem*” OR “tropical biome*” OR “tropical rainforest”) AND NOT TITLE-ABS-KEY (“savan*” OR “peatland” OR “grassland”). We restricted this search to peer-reviewed articles published in English, Portuguese or Spanish, with no time period restrictions; we excluded books and book chapters, since the latter often do not undergo the strict peer review that journal articles do. After removing duplicates, titles and abstracts were screened to assess their relevance, resulting in 1,362 studies published between 1981 and 2024. Studies were then filtered using the following inclusion criteria: (i) conducted in lowland tropical regions (< 1100 m asl), avoid confounding effects of elevation-related variables (e.g., vegetation type, temperature); (ii) focused on fire associated with SBA systems, including subsistence annual or semi-permanent crops (e.g., beans, maize, squash, cassava, upland rice, banana); (iii) reporting at least one biotic (e.g., seed viability) or abiotic (e.g., soil temperature) response variable. We excluded studies conducted in commercial systems (e.g., oil palm, coconut, cashew) or mixed agro-pastoral systems, as well as those addressing only long-term post-fire effects (> 12 months), given our focus on short-term ecological responses. For studies including multiple land uses or treatments, only data corresponding to conditions that met these criteria were retained (e.g., forest plots before or immediately after burning, excluding post-conversion pasture systems [Hughes et al., 2000; Kauffman et al., 1995, 2003; Miller, 1999; Miller and Kauffman, 1998]). Following this screening process, 30 case studies were selected. An additional seven relevant studies were identified through complementary searches and reference checks, resulting in a total of 37 studies included in the analysis (Fig. B1). The full list of included studies and their extracted variables is provided in Table S1 (Supplementary Material), while the main patterns identified across studies are summarized in Fig. 2. The high heterogeneity in study designs and assessed variables precluded a formal meta-analysis. Therefore, these studies were used to develop a structured qualitative synthesis of the short-term ecological effects of SBA-related fire, allowing us to identify consistent patterns, sources of variability and key knowledge gaps across biotic and abiotic responses.

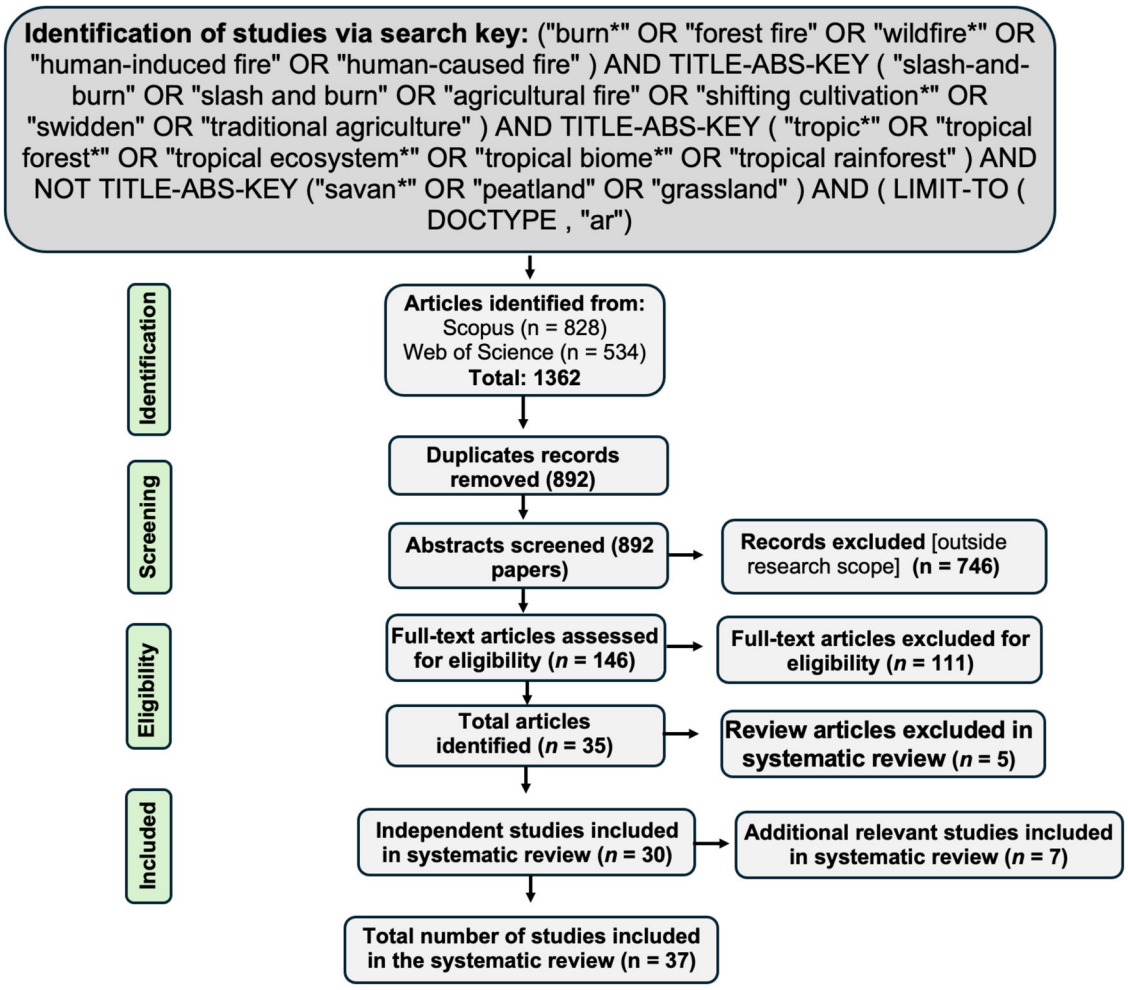

Fig. B1. PRISMA flow diagram of the stages of the systematic review, which included article identification, duplication removal, screening, exclusion, and final paper selection.

Box 2
Overview of reviewed studies

In our review (Box 1), only 37 studies met our filtering criteria. These studies are strongly biased to the Neotropical realm (n = 28 studies, 75.7%), with considerably less attention paid to Asian (n = 7, 18.9%) and African forests (n = 2, 5.4%) (Fig. B2). Notably, we did not find any study from Madagascar and Oceania, highlighting a significant geographic gap in the literature. Thus, considering that SBA is the primary cause of forest loss in Africa, Madagascar and Oceania (Curtis et al., 2018), additional studies on fire effects in these vast regions are needed to achieve a global understanding of SBA-related fire effects.

Regarding the type of response variables, most studies assess changes in abiotic variables (n = 24, 55.8%), especially to understand the effects of fire on physical and chemical soil properties (e.g., temperature, pH, organic carbon, and nutrient levels across the soil profile). In fact, there are some comprehensive reviews about this topic (Arunrat et al., 2024a), but they do not focus on SBA-related fires in tropical forests. Even fewer studies assess biotic responses (n = 19, 44.2%), especially soil fauna structure and composition (n = 5, 13.5%), and soil seed banks (n = 8, 21.6%), whereas a small proportion of studies evaluate both abiotic and biotic variables (n = 3, 8.1%). While this research has been key to understanding the abiotic and biotic consequences of fire, critical knowledge gaps remain, which we highlight below to guide future research on the topic.

Land clearing

Fire has traditionally been used as an easy (and cheap) method to clear land for agricultural purposes (D1 in Fig. 1; Fig. 2). This can be highly valuable to shifting cultivators, especially in developing tropical countries, where farmers are generally poor and often do not have access to heavy agricultural machinery (Bougma et al., 2025; Campos et al., 2025; Hauser and Norgrove, 2013). Therefore, the savings from avoiding more expensive mechanical methods to clear land can represent a significant economic benefit (Varma, 2003). However, as argued by Varma (2003), the economic costs of using fire can exceed the total economic benefits, so using fire for land clearing appears to be an inefficient method from a social perspective. These costs refer to the welfare loss caused by accidental fires (see below) and the negative

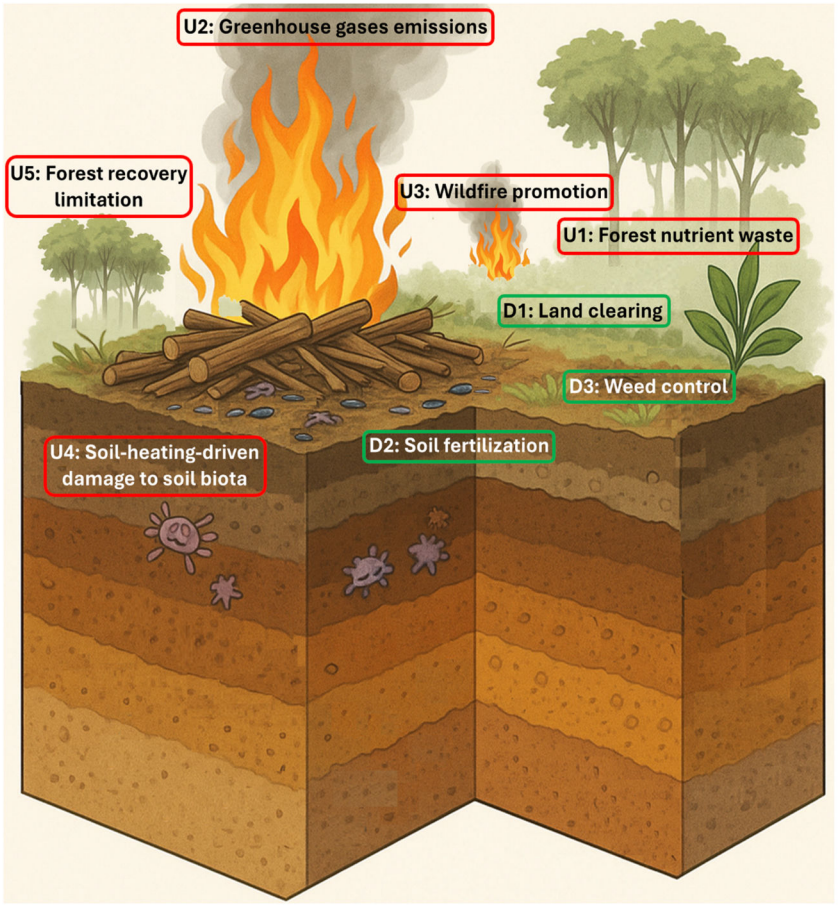

Fig. 1. Hypothetical desired (D, in green) and undesired (U, in red) effects of fire induced by slash-and-burn agriculture in the tropics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

DESIRED EFFECTS (D)			UNDESIRED EFFECTS (U)				
D1: Land clearing	D2: Soil fertilization	D3: Weed control	U1: Forest nutrient waste	U2: Greenhouse gases emissions	U3: Wildfire promotion	U4: Soil-heating driven damage to soil biota	U5: Forest recovery limitation
Fire makes clearing easier and cheaper*	**Fire releases nutrient-rich ashes, contributing to soil fertilization** Supporting refs.: 1-8 Rejecting refs.: 9-11 Non-conclusive: 12-15	**Fire decreases seed viability in the soil seed bank** Supporting refs.: 16-21 Non-conclusive: 22,23	**A large fraction of forest nutrients is volatilized and lost during burning** Supporting refs.: 9-10,24	**Fire causes the emission of greenhouse gases to the atmosphere, contributing to global climate change** Supporting refs.: 9,25-29	**Fire can get out of control and spread to nearby forests****	**Fire can decrease heat- and drought-sensitive organisms in the soil** Supporting refs.: 1,30-35	**By depleting the seed bank, fire makes forest recovery more dependent on plant resprouting and the seed rain, which can be limited in some SBA-dominated landscapes** Supporting refs.: 18,20, 34-37

*In the context of SBA, this is a basic and widely recognized function of fire (e.g., Varma, 2003), but none of the 37 reviewed studies explicitly demonstrate this benefit.
**None of the reviewed studies addresses this hypothesis.

Fig. 2. Synthetic overview of the desired (D1–D3) and undesired (U1–U5) effects of slash-and-burn agriculture (SBA) identified in the reviewed literature. For each hypothesis, the table summarizes the overall evidence as supporting, rejecting, or non-conclusive, based on the direction of the empirical findings reported by the studies included in the review (study IDs shown). The full database of reviewed studies, including study design, ecological response variables, and geographic context, is provided in Table S1 (Supplementary Material). Asterisks indicate hypotheses for which the effect is widely recognized in the SBA context but was not directly demonstrated by the reviewed studies.

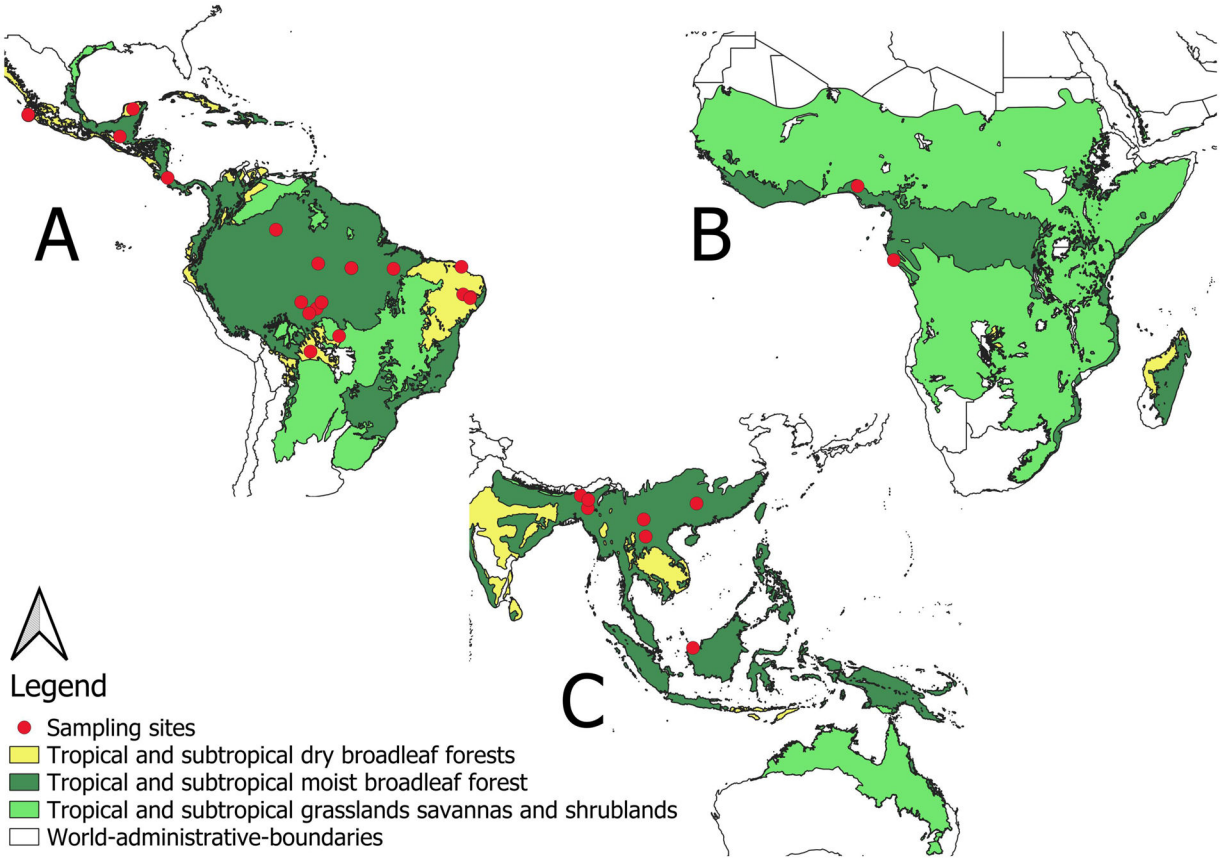

Fig. B2. Geographic distribution of 37 studies (red dots) on the desired and undesired effects of fire induced by slash-and-burn agriculture in the Neotropics (A), Africa (B), and Southeast Asia and Oceania (C). Ecoregions are based on the categorization proposed by Loidi et al. (2023).

externalities or social costs in the form of damage to valuable environmental services, such as air, water, and soil quality (Varma, 2003). We discuss these environmental costs more deeply in the "Undesired environmental impacts of fire" section.

Soil fertilization

In addition to land clearing, farmers use fire to accelerate the incorporation of nutrients into the soil (D2, Fig. 1). This is a valuable outcome in the tropics, where soils are generally thin and nutrient poor. By burning plant biomass, farmers expect to release solids (ash) rich in essential nutrients for plants (e.g., N, P, K) that were previously stored in plant biomass and organic matter. If fire contributes to soil fertilization, there should be a post-fire increase in soil nutrient concentrations. Despite considerable evidence supporting this prediction (8 out of 15 studies; Fig. 2), the effect of fire on soil nutrient concentration is highly variable among studies, depending on the evaluated nutrient, fire intensity, soil type and depth, as well as the timing of assessment (Arunrat et al., 2024a; Béliveau et al., 2009). For example, Kennard and Gholz (2001) and Williams et al. (1997) found significant increases in inorganic nitrogen (NH_4^+, NO_3^-) in soils shortly after fire, indicating that a portion of the nutrients contained in the aboveground biomass were transferred to the soil during burning (Montagnini and Buschbacher, 1989). Higher concentrations of P, Ca, K, and Mg have also been recorded after fire (Juárez-Orozco et al., 2024). However, Kauffman et al. (1993; 1995) found losses in N and P, probably because these nutrients volatilize at temperatures well below (e.g., N ≈ 200 °C; P ≈ 300 °C) those reached by fire (> 800 °C), suggesting that fire effects largely depend on fire intensity (Kennard and Gholz, 2001). The fertilizing effect of fire also depends on soil depth, as nutrient concentration increases are limited to the soil's surface layer (0–2.5 cm) where ash concentrates (Ando et al., 2014; Béliveau et al., 2015; Juárez-Orozco et al., 2024; Kauffman et al., 1995).

Although nutrient-rich ashes can fertilize the soil, this effect is only short-term, disappearing months after burning (Ellingson et al., 2000), when some nutrients may be depleted through leaching and surface runoff (Adeyolanu et al., 2013; Uhl and Jordan, 1984; Béliveau et al., 2017), or plant absorption (Arunachalam, 2002; Døckersmith et al., 1999). Rapid soil nutrient losses after fire due to leaching, erosion, and volatilization are well documented (Kauffman et al., 1995; Lungmuana et al., 2018; Wang et al., 2022); for example, more than 57% of the aboveground P present in the ash disappeared within just 17 days after burning, reflecting the high susceptibility of this nutrient pool to wind and water erosion in burned areas (Kauffman et al., 1993). Similarly, Giardina et al. (2000) observed that within the first month after fire, approximately 55% of P and 74% of N contained in the ash were removed from the site by wind. Therefore, the general trend is a transient nutrient enrichment followed by rapid losses. Post-fire nutrient losses can contribute to declining soil fertility in systems with shortened fallow periods, which in some regions lead farmers to burn field debris more frequently after each crop cycle and/or use chemical fertilizers. These fertilizers are often promoted by government programs, such as the "*Fertilizantes para el Bienestar*" (Fertilizers for Wellbeing) program in Mexico, and the "Subsidized Fertilizer Programme" in Ghana. In both countries, thousands of highly soluble chemical fertilizers are freely distributed each year, without correct monitoring of their impacts. For example, chemical fertilizers are known to pollute underground water bodies, negatively impacting aquatic ecosystems (Bijay-Singh and Craswell, 2021). However, to our knowledge, these potentially strong impacts have not yet been properly evaluated, so additional studies are needed to quantify them.

The effect of fire on soil fertilization and nutrient losses can also

depend on the amount of burned biomass. If fire releases essential nutrients stored in plant biomass and organic matter, the combustion of larger quantities of plant biomass should lead to the release of a proportionally higher amount of nutrients. Thus, the older the forest that was downed and burned, the greater the amount of ash and nutrients that should be transferred to the soil, since older forests accumulate more aboveground biomass than younger forests. However, empirical evidence for this relationship is scanty, as only one of five studies supported this prediction (Kennard and Gholz, 2001), whereas most (4 studies, 80%) did not detect higher soil nutrient concentrations after burning larger biomass stocks (Andriesse and Schelhaas, 1987; Døckersmith et al., 1999; Ellingson et al., 2000; Juárez-Orozco et al., 2024; Kauffman et al., 1995). One possible explanation is that larger biomass stocks may lead to more severe fires, increasing ash-derived nutrient inputs to the soil surface while simultaneously enhancing volatilization losses and soil organic matter combustion, partially offsetting potential gains (Ando et al., 2014; Kennard and Gholz, 2001). Evidence from a slash-and-burn chronosequence further shows that nutrient increases after fire are limited to the soil surface and that nutrient concentrations decline within a few years of fallow; therefore, repeated fire-fallow cycles over decades reduce soil nutrient retention and cation exchange capacity relative to forest soils (Fachin et al., 2021). Thus, even in those situations where substantial amounts of biomass are repeatedly burned, fertilization effects remain transient and do not prevent long-term soil nutrient depletion. Therefore, the influence of burned biomass on soil fertilization is context-dependent and difficult to predict across SBA systems (Andriesse and Schelhaas, 1987; Kauffman et al., 1995).

Weed control

Another important outcome of fire is the delay in the recovery of native and exotic plant species (D3, Fig. 1). Promoting such recruitment limitation is particularly valuable in the tropics, where hundreds of plant species can colonize the site and compete with crop plants for light and nutrients. However, fire effects on soil seed banks are not homogeneous and depend on fire regime characteristics (e.g., intensity and duration), soil properties and moisture, and species functional strategies (Bezerra et al., 2024). Because extreme heat can damage seed embryos and disrupt germination, fire may deplete the soil seed bank through direct seed incineration or reducing seed viability, particularly in the upper soil layers where heating is greatest. If this mechanism dominates, the number and diversity of viable seeds and/or the density of germinated seeds should be lower after fire and in burned areas compared to unburned areas, as observed in most studies that tested this prediction (Cao et al., 2000; Kennard et al., 2002; Mamede and Araújo, 2008; Miller, 1999; but see Bezerra et al., 2022; Ewel et al., 1981; Fig. 2).

When assessing fire effects across plant groups, species responses are expected to vary with seed traits and post-fire regeneration strategies. Weaker fire damage has been predicted for species with small seeds and hard coats, as these traits may confer greater heat resistance or allow seeds to persist in deeper soil layers. Many small-seeded herbs or shrubs may also benefit from increased light and reduced competition in the months following fire (Tangney et al., 2020). If this is the case, the number of light-demanding and small-seeded species should be higher after fire and in burned areas compared to unburned areas. Most studies assessing this prediction (5 of 7 studies, 71%) supported it, showing increases in herbaceous and shrubby species (Cao et al., 2000; De Rouw et al., 2014; Kennard et al., 2002; Miller, 1999; Rico-Gray and García-Franco, 1992). However, contrasting responses occur across species and sites. For example, De Rouw et al. (2014) reported losses of some light-demanding species after fire, probably because seed survival depends strongly on soil-mediated thermal gradients and burial depth. Fire heat dissipates rapidly along the soil profile, so seeds near the surface experience lethal temperatures whereas deeper seeds may remain below mortality thresholds (Cao et al., 2000). Consequently, post-fire recruitment reflects the interaction between fire intensity, soil heating profile, burial depth, and seed traits, leading to context-dependent outcomes across species and environments (Pausas and Ribeiro, 2017). Empirical evidence on the role of seed size remains inconsistent. While deeper burial could allow smaller seeds to escape lethal temperatures, Bezerra et al. (2022) detected no significant effect of fire on seed size or seed mass, whereas Mamede and Araújo (2008) reported complete mortality for very small seeds (diameter $<$ 0.6 mm), especially monocot seeds. These contrasting results reinforce that fire effects on seed-bank structure and composition are highly contingent on local ecological conditions. Therefore, future studies should further investigate how soil properties, seed traits, and fire characteristics interact to shape the seed-bank structure and composition in SAB systems. Thus, while recruitment limitation may enhance short-term crop establishment, its cumulative effects under intensified management and shortened fallow cycles may involve ecological trade-offs, potentially constraining secondary succession and forest recovery (this undesired effect is discussed below).

Undesired environmental impacts of fire

Notwithstanding the importance of the desired outcomes described above, fire also has many undesired environmental impacts (Fig. 1), which can threaten the sustainability of tropical forests and SBA itself. Although many of these negative effects result from the same processes that bring about short-term agronomic benefits, their cumulative and long-term consequences can compromise essential ecosystem functions and feedback loops that sustain SBA over repeated cycles. Recurring fires can gradually reduce forest and soil resilience after cultivation, especially under shortened fallow periods and increased fire frequency (Arunrat et al., 2024a). As detailed below (U1-U5, Fig. 1), these impacts operate through multiple ecological pathways affecting nutrient pools, atmospheric processes, fire regimes, soil biota, and forest regeneration, ultimately compromising both ecosystem resilience and the long-term sustainability of SBA systems.

Forest nutrient waste

Although fire releases nutrient-rich ash, it is important to note that it represents only a small fraction of the nutrients previously contained in plant biomass and soil organic matter. In fact, a large fraction of forest nutrients is lost during burning (U1, Fig. 1), as high temperatures cause elements like N, P, S and K to volatilize from the biomass pool (Kauffman et al., 1995, 1993; Wang et al., 2022; Fig. 2). For instance, Kauffman et al. (1993) found that 96% of the pre-fire aboveground N and C pools and 56% of the pre-fire aboveground P pool were lost through combustion in a tropical dry forest. This likely occurs because, prior to burning, the highest concentrations of these nutrients are found in litter, leaves, and fine wood debris, which are almost completely burned by fire, promoting nutrient volatilization. In particular, N losses exceeded 500 kg/ha and P losses exceeded 20 kg/ha during severe fires (Kauffman et al., 1993). These values are even higher in tropical rainforests such as the Amazon, where N losses ranged from 817 to 1605 kg/ha, and S losses ranged from 92 to 122 kg/ha (Kauffman et al., 1995). However, fire behavior and severity can vary widely across slash-and-burn systems, depending on vegetation type, fuel structure, litter accumulation, atmospheric conditions, and burning practices (Fachin and Thomaz, 2023). In many smallholder agricultural plots, particularly those conducted under moist conditions or with discontinuous fuels, fires tend to be of low to moderate severity (Antoneli and Thomaz, 2025). Under these conditions, a fraction of the nutrients released from burned biomass is retained locally in ash and incorporated into upper mineral soil rather than being entirely exported from the system (Thomaz et al., 2025).

Experimental evidence indicates that soil chemical responses scale with fire severity. In low-severity burns typical of SBA, most soil

properties remain statistically similar to unburned controls, with only modest increases in some readily available nutrients (e.g., P and K), whereas larger increases in exchangeable base cations, particularly Ca and K, and in cation exchange capacity, occur mainly under moderate to high severity burns (Antoneli and Thomaz, 2025). Thus, although substantial nutrient losses occur from the biomass compartment, a fraction of immediate post-fire soil nutrients may be maintained or even temporarily enhanced depending on fire severity and ash retention. These apparently contrasting patterns reflect differences between biomass nutrient losses and soil-ash nutrient retention processes. Taken together, estimates of biomass nutrient losses through fire reported for tropical forests suggest that more than a century of fallow would be required for full nutrient reaccumulation, a period much longer than current average fallow times in tropical regions (< 20 yr; Schwartz et al., 2020). Consistent with this pattern, empirical evidence from African slash-and-burn systems indicates that shortening fallow periods reduces the recovery of soil nutrients and organic matter, with longer fallows showing higher soil organic carbon, total nitrogen, and exchangeable potassium contents (Kilawe et al., 2022). This indicates that once old-growth forests are converted to SBA, they are unlikely to fully regain their initial nutrient stocks under contemporary management regimes.

Greenhouse gases emissions

Related to the loss of forest nutrients, another major undesirable effect of fire is the emission of greenhouse gases (e.g., CO_2 and CH_4) responsible for global climate change (U2, Fig. 1). Again, the magnitude of these emissions varies considerably depending on fire intensity, biomass availability, and the land-use trajectory following cultivation. Although we could not find global estimates of SBA-related emissions, we found strong evidence supporting this undesired effect on a local scale (Fig. 2). For example, Kauffman et al. (1995) reported that in a single fire, carbon losses range from 58 to 112 Mg/ha in the Amazon, depending on the amount of aboveground biomass burned (also see Hughes et al., 2000; Kauffman et al., 2003 and Sampaio et al., 2003). Similarly, Guild et al. (1998) reported carbon losses of 79 to 102 Mg/ha, which were emitted into the atmosphere. More recent field-based measurements also show that greenhouse gas emissions increase significantly in recently burned areas, with carbon dioxide emissions being approximately twice those of unburned sites and post-fire methane emissions increasing (Dhandapani and Evers, 2020). Therefore, on a global scale, SBA-related carbon emissions may reach hundreds of megatons per year (Baccini et al., 2012). At broader spatial scales, remote sensing analyses indicate that SBA landscapes remain widespread across the humid tropics, covering hundreds of millions of hectares, highlighting the relevance of these land-use systems for regional and global carbon accounting (Heinimann et al., 2017). Although some of this carbon dioxide is captured by secondary forests once agricultural fields are abandoned (Chazdon et al., 2016; Heinrich et al., 2021), recent estimates for the Amazon, Central Africa, and Borneo suggest that the 107 megatons of CO_2 absorbed by secondary forests each year only represent 26% of the CO_2 emitted by the destruction of original forests (Heinrich et al., 2023). Clearly, such carbon uptake cannot fully offset the losses caused by increasing deforestation rates in the tropics (Sims et al., 2025), which in some regions may include SBA agriculture and other smallholder land-use transitions (Curtis et al., 2018).

Wildfire promotion

The two major undesired effects described above can be further aggravated when fires used in SBA escape control and spread into surrounding forests (Bezerra et al., 2024; Varma, 2003; U3, Fig. 1). In fact, the Global Forest Watch platform reported that although tropical rainforest loss slowed in 2025, fire is a growing threat to forests worldwide (Goldman et al., 2026). This risk is particularly relevant in tropical regions, where burning of vegetation occurs in landscapes with high fuel load and where dry conditions may facilitate fire spread. As an example, during the 1997 dry season in Indonesia, fires associated with agricultural land clearing, coupled with the unusually dry weather linked to the ENSO climate phenomenon, ignited large forest fires that destroyed millions of hectares of land (Varma, 2003). As noted by Varma (2003), the cumulative environmental damage caused by these fires was enormous. Although there are no accurate global estimates of annual forest losses caused by accidental fires originating from SBA practices, these events can locally expand the spatial impact of agricultural burning beyond the intended cultivation area. For instance, in Yucatán, Mexico, we recorded two wildfires that spread over 200 ha that were caused by 1-ha SBA crops (J. S. Bezerra and V. Arroyo-Rodríguez, personal observation). These examples illustrate how escaped agricultural fires can amplify the impacts of slash-and-burn systems when burning is not properly controlled. However, additional studies are needed to quantify the impact of SBA on wildfires.

Soil-heating-driven damage to soil biota

An immediate consequence of fire is an increase in soil temperature. In slash-and-burn systems, soil heating is primarily determined by fire severity, which is generally low to moderate but spatially variable due to heterogeneity in fuel distribution and environmental conditions. The amount of heat released and retained in the soil largely depends on fuel availability, with greater vegetation biomass generally increasing combustion intensity and prolonging heat residence time (Døckersmith et al., 1999; Kauffman et al., 1993). Experimental evidence further indicates that burns involving larger biomass loads can generate higher and longer-lasting soil temperatures, with heating effects extending deeper into the soil profile (Ando et al., 2014). However, some studies suggest that the relationship between tree biomass and soil temperature is not straightforward (Andriesse and Schelhaas, 1987; Juárez-Orozco et al., 2024). For example, Andriesse and Schelhaas (1987) observed that burning different volumes of piled biomass resulted in highly variable soil temperatures, with no consistent pattern across fuel amount. These contrasting results highlight that soil temperature responses are not solely a function of fuel load, but also reflect variability in fire severity, which in turn depends on other factors such as substrate moisture and fuel spatial arrangement, both of which determine combustion efficacy (Andriesse and Schelhaas, 1987).

In any case, soil temperatures peak at the surface, where direct contact with the burning biomass occurs, and decrease rapidly with depth due to low thermal conductivity, especially in dry and unconsolidated substrates (Andriesse and Schelhaas, 1987; Kauffman et al., 1993). For example, maximum temperatures at the surface commonly exceed 500 °C and can reach over 900 °C in high-intensity burns (Døckersmith et al., 1999; Giardina et al., 2000; Kauffman et al., 1993; Kennard et al., 2002). However, soil heating declines sharply within the first few centimeters of depth (Ewel et al., 1981), indicating that direct thermal effects are largely confined to the uppermost soil layers.

However, even when confined to the topsoil, fire-induced heating can substantially alter soil physical and chemical properties, including pH, moisture, nutrient availability, and soil organic carbon (Certini, 2005; Certini et al., 2021; Pellegrini et al., 2020). These changes are driven not only by direct heat transfer but also by combustion of organic matter, ash deposition, and volatilization losses, which together reshape the abiotic environment where soil biota persists (U4, Fig. 1). For instance, soil pH often increases immediately after burning due to ash inputs rich in basic cations (Ca, Mg, K), temporarily reducing soil acidity. This shift can favor some bacterial groups (Arunrat et al., 2024b), while reducing fungal abundance, including beneficial arbuscular mycorrhizal fungi (AMF), by altering plant-soil interactions and reducing host plant availability, leading to more bacteria-dominated communities (Barraclough and Olsson, 2018; Sharmah and Jha, 2014). In addition, fire-induced pulses of inorganic nutrients (e.g., N

and P), followed by subsequent depletion, can further influence microbial activity and community composition (Arunrat et al., 2024b). As a consequence of these abiotic changes, fire can restructure soil microbial communities by favoring disturbance-tolerant taxa and reducing the abundance of groups with key ecological functions (Arunrat et al., 2024c). Nevertheless, many fire-induced changes in soil microbiota are likely to be transient, particularly under low-severity burns and in systems where fallow periods allow vegetation and soil to recover. Empirical evidence shows that the abundance and diversity of sensitive microbial groups are reduced in burned compared to unburned areas (Arunachalam, 2002; García-Oliva et al., 1999; Meyer et al., 2019; Navarrete et al., 2015; Sharmah and Jha, 2014; Fig. 2). These changes affect bacterial and fungal groups involved in key processes, such as nutrient cycling, organic matter decomposition, and soil structure maintenance. Therefore, although some microbial responses may diminish over time, recurrent burning and shortened fallow periods can impair microbial-mediated processes, potentially constraining soil recovery and vegetation regeneration in post-fire agroecosystems.

Forest recovery limitation

As discussed above, farmers benefit from fire in the short term by limiting unwanted plant recruitment. Nevertheless, when repeated over long time periods or combined with shortened fallow cycles, such fire-related recruitment limitation may constrain secondary succession and slow down forest recovery in abandoned lands (Arroyo-Rodríguez et al., 2017; Barraclough and Olsson, 2018; Meyer et al., 2019; Tabarelli et al., 2025; U5 in Fig. 1; Fig. 2). Contemporary SBA systems in some regions operate with fallow periods of approximately 3–5 years, and reductions in fallow length have been widely reported (Thomaz and Rosell, 2020), potentially limiting the system capacity for full ecological recovery. Under intensified management, this may compromise the long-term sustainability of both tropical forests and the SBA itself, which depends on forest regeneration to offset the environmental degradation caused during the stages of vegetation slashing, vegetation burning, and farming (Bezerra et al., 2024; Hauser and Norgrove, 2013).

Because fire can reduce viable propagule pools (see Weed control section), forest recovery in SBA-dominated landscapes becomes increasingly dependent on seed rain and resprouting strategies (Arroyo-Rodríguez et al., 2017; Poorter et al., 2024). In tropical dry forests, however, a large proportion of seeds arriving via seed rain may be non-viable due to harsh conditions that damage embryos, especially in small, recalcitrant, and animal-dispersed seeds lacking dormancy (Bezerra et al., 2023a, b). Therefore, regeneration tends to be dominated by disturbance-adapted plant species, especially those with abiotic dispersal syndromes, hard-coated seeds, or high resprouting ability (Miller and Kauffman, 1998; Rico-Gray and García-Franco, 1992; Vanderlei et al., 2024). Similar patterns have been reported in African SBA systems, where shortened fallow periods were associated with reduced tree species richness and recovery, as well as increased dominance of shrubs and disturbance-adapted vegetation during succession (Kilawe et al., 2022). Fire-induced topkill often stimulates the activation of dormant buds, increasing resprouting incidence and altering forest structure and composition during secondary succession (Barros et al., 2021; Vanderlei et al., 2024). However, resprouting ability varies among species and may depend on fire severity and pre-disturbance carbohydrate reserves stored in stems and roots (Baião et al., 2024; Kennard et al., 2002; Miller and Kauffman, 1998). Under recurrent burning and shortened fallow cycles, these trait-mediated filters may progressively simplify forest structure and redirect successional trajectories. Further research is needed to clarify how fire severity, propagule limitation, carbohydrate storage, and species-specific traits interact to shape long-term regeneration success and successional pathways across heterogeneous SBA systems.

Conclusions and applied implications

This review represents the first attempt to summarize the available information on the desired and undesired effects of SBA-related fire across tropical forests. We found that much of the available evidence comes from case studies in specific regions (Box 2), and therefore, it cannot be generalized to every region where SBA is practiced. For instance, in tropical dry forests, such as the Caatinga in Brazil, where forests are exposed not only to SBA but also to resource overexploitation and overgrazing, the environmental impact of fire can be particularly negative (Tabarelli et al., 2025). However, in humid tropical regions with low population density and extensive old-growth forests, forest regeneration may be faster and fallow periods much longer, enabling the compensation of many of the environmental impacts discussed here (Bezerra et al., 2024). Importantly, SBA systems vary widely in their ecological, social, and historical contexts, including differences in management intensity and fallow duration. Nevertheless, given the expansion of SBA in the tropics and existing studies on the costs and benefits of using fire in this ancient agroecosystem, the available evidence suggests that, in many contemporary contexts, the environmental costs of fire use appear to outweigh its benefits.

Undoubtedly, important knowledge gaps remain. For instance, there is a clear geographic bias in the literature, indicating the scarcity of information on fire effects across vast regions, such as Africa, Madagascar, and Oceania (Box 2), where SBA is the main cause of forest loss (Curtis et al., 2018; Goldman et al., 2026). Although important studies have been conducted in other tropical regions, including Asia and parts of Africa (Are et al., 2009; Yemefack et al., 2006; Laskar et al., 2021; Rodenburg et al., 2003), large geographic gaps in empirical evidence remain. Moreover, some topics have not yet been addressed. For example, we do not know how SBA-related fires affect animals that live or seek shelter underground, such as many insects, amphibians, reptiles and small mammals. Furthermore, because research has mainly been conducted at the local scale, the landscape-scale abiotic and biotic effects of fire are largely unknown, limiting our ability to design spatial scenarios that promote the sustainability of tropical forests and SBA itself (Bezerra et al., 2024).

Despite these and other knowledge gaps, our synthesis highlights several potential pathways for reducing the environmental impacts associated with fire use in agricultural systems. In this regard, permaculture, syntropic agriculture, and agroforestry are growing fields that propose fire-free alternatives for plant-food production (Andrade et al., 2020; O'Donoghue et al., 2022; Tremblay et al., 2015). For example, adding ashes and organic matter to the soil can increase crop yields and lengthen the fallow period, as these applications help preserve soil nutrient levels and organic matter content in agricultural systems that use crop rotation (Ebel, 2018; Gay-des-Combes et al., 2017). Since charcoal is produced in most regions where SBA is practiced, these ashes can be obtained from the waste from these coal pits. Likewise, biological management strategies, including the inoculation of beneficial microorganisms such as rhizobia and mycorrhizal fungi, have shown potential to increase crop productivity in SBA systems while reducing dependence on inorganic fertilizers (Nwaga et al., 2010). Alternative (but non-mutually exclusive) options to the previous ones are the combination of annual and perennial crops, and the use of nitrogen-fixing plants to foster soil health, increase biodiversity, and enhance landscape moisture (Comte et al., 2012; Silva-Galicia et al., 2023), all of which make the land more resilient to fires. In fact, perennial crops are a key element, as they create a year-round living root system that stabilizes soil and adds organic matter (Silva-Galicia et al., 2023). Implementing these and other fire-free agricultural strategies in tropical forests is imperative to prevent unintended but adverse fire effects.

CRediT authorship contribution statement

Jakelyne S. Bezerra: Conceptualization, Formal analysis,

Investigation, Writing – original draft, Writing – review & editing, Visualization. Víctor Arroyo-Rodríguez: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization. Jorge A. Meave: Conceptualization, Supervision; Investigation, Writing—original draft, Writing—review and editing, Visualization. All authors have read and agreed on this manuscript.

Data availability

The data that has been used is confidential.
Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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