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Dynamics of soil chemical properties in shifting cultivation systems in the tropics: a meta-analysis

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Abstract

The forest cultivation system (slash-and-burn or shifting cultivation) has contributed to the transformation of social systems since the early Neolithic period. Despite being considered by conservationists and public policymakers as a system of low productivity that generates environmental degradation and contributes to the maintenance of rural poverty, the shifting cultivation system (SCS) is being declared a practice that is highly ecologically and economically efficient. Such dichotomy of opinions is the consequence of the disparate results of studies assessing the effects of SCS on soil properties of rainforests throughout the last three decades. To circumvent this apparent inconsistency, we used a systematic quantitative review method (meta-analysis), with the objective of integrating and synthesizing the data published in the literature to assess the overall effects of SCS on soil chemical properties. Four variables traditionally assessed in primary studies were chosen for the meta-analyses: pH, cation exchange capacity (CEC), total carbon (Total C) and total nitrogen (Total N). Our results show that pH values increase under SCS conditions, while Total N and C content are significantly reduced under SCS. No significant impacts are observed on CEC. Our results on pH and CEC support the position from researchers who argue for the sustainability of SCS and highlight the importance of evaluating the soil system as a soil/vegetation complex. Also, our results indicate that soil chemical properties under SCS scenarios are better conserved and more readily recoverable, provided there is a rather longer fallow period than has been traditionally employed.

Keywords: Shifting cultivation, slash-and-burn, swidden, soil chemistry, meta-analysis

Introduction

The shifting cultivation system (SCS) has been considered by conservationists and policymakers as a system of low productivity that generates environmental degradation and contributes to the maintenance of rural poverty (Padoch & Pinedo-Vasquez, 2010). However, others consider it ecologically and economically efficient, as long as the conditions of low demographic pressure and a suitable fallow period are guaranteed (Nye & Greenland, 1960; Van Vliet *et al*., 2012). The sustainability of the SCS, under these conditions, is based on the balance between the input and output of nutrients from the soil/vegetation complex of the forest ecosystems. This dynamic is guaranteed by a cycle in which the conversion and cultivation stages responsible for a relative increase in the output of nutrients from the ecosystem are compensated for by an input during the fallow stage (Altieri, 1999; Ribeiro Filho *et al*., 2013).

The basic requirements to maintain a stable and productive soil system are as follows: (i) the re-establishment of the chemical nutrients removed by cultivation; (ii) the suitability of its physical conditions *vis-a-vis* the type of cultivation, which has to maintain or increase the quantity of humus; (iii) that it remains free from weed, disease and

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pest infestations; (iv) that its acidity conditions, or its toxic element concentrations, do not increase (e.g. aluminium); and (v) that the erosion be controlled (Greenland, 1975; Okigbo, 1981; Kang, 1993). These basic requirements are met in SCS when the ratio between the cultivation and fallow periods takes into consideration the use history of the area, the type of soil, the topography, the vegetation's successional stage (biomass and diversity), the biome and the climate (Kleinman *et al*., 1995; Szott *et al*., 1999), all of which are considered as independent variables of the system. For the majority of the biomes, the independent variables have a ratio of cultivation to fallow period of between 1:5 (Aweto, 1981) and 1:10 (Ribeiro Filho *et al*., 2013).

One of the issues raised by critics of the SCS refers to its tendency to degrade the soils (Rasul *et al*., 2004), although others disagree (Bruun *et al*., 2009; Mertz *et al*., 2009) and consider that the SCS has advantages over other cultivation systems by preventing erosive processes as well as safeguarding many of the environmental services provided by the forest ecosystems (Rerkasem *et al*., 2009).

This controversy regarding the impacts of SCS on chemical properties of tropical soils is revealed in numerous studies and reviews on the subject, published since the 1950s, 50% of which were written in the 21st century (Ribeiro Filho *et al*., 2013). This extensive literature divides the impacts of shifting cultivation on rainforest's soils between positive and negative, identifying and classifying them depending on the dynamics of the variables that comprise the physical, chemical and biological properties of the soil (Ribeiro Filho *et al*., 2013). These dynamics are usually evaluated by considering the three components of the SCS: conversion, cultivation and fallow (Ribeiro Filho *et al*., 2013).

According to the review by Ribeiro Filho *et al*. (2013), the most used variables in the literature to evaluate the effect of the SCS on the physical properties of the soil are as follows: texture, structure, density, colour, retention of humidity and the temperature of the soil. For the chemical properties, the most frequent ones are the pH, the dynamics of macronutrients in the soil, the cation exchange capacity (CEC), the soil organic matter (SOM), total carbon (Total C) and total nitrogen (Total N) (Yemefack *et al*., 2006; Ribeiro Filho *et al*., 2013). In regard to the biological properties, the most relevant are the micro- and macrofauna, and the seed bank (Ribeiro Filho *et al*., 2013).

Considering the stages of the SCS, the literature indicates that the conversion stage could potentiate the soil's fertility conditions, especially as it respects the first four basic requirements to maintain the stable cultivation system mentioned above (Greenland, 1975; Okigbo, 1981; Kang, 1993). It is in the cultivation stage that five basic requirements are potentially overlooked, which is why this stage is considered as the most critical for maintaining the stability of the SCS (Kleinman *et al*., 1995; Giardina *et al*., 2000). Fallow is the crucial stage for re-establishing the conditions that guarantee the stability of SCSs (Greenland, 1975; Okigbo, 1981; Kang, 1993), reverting the dynamics of the physical, chemical and biological variables of the soil to their initial conditions (Ribeiro Filho *et al*., 2013).

However, despite these general trends, research regarding the impact of SCS on soil chemical properties has shown disparate results, generating inconsistent conclusions in the literature about its sustainability (Kleinman *et al*., 1995; Van Vliet *et al*., 2012). A way to circumvent this inconsistency is to use a systematized quantitative review method, such as meta-analysis, that is capable of integrating and synthesizing the data published in the literature (Aguilar *et al*., 2008; Borenstein *et al*., 2009).

In this article, we report on a meta-analysis with the aim of evaluating the impacts of the SCS on soil chemical properties, in order to contribute to the discussion about its sustainability. The four variables most frequently cited in a recent literature reviews (Ribeiro Filho *et al*., 2013) regarding soil properties were chosen for the meta-analyses: pH, CEC, Total C and Total N. We specifically determined (i) the total magnitude and direction of SCSs' effects on these variables; (ii) whether the effects of SCSs vary in different soil depths, soil types, biomes, fallow age classes and stages of SCS; (iii) and whether the fallow stage re-establishes the initial conditions before the beginning of a new SCS cycle.

Material and methods

Literature search

The Web of Science, Scopus and Scielo databases were used to search the literature. The literature search was limited to the period between 1980 and 2013, using the following keyword combinations: 'shifting cultivation*' OR 'swidden*' OR 'slash-and-burn*' AND 'soil*'. We initially obtained over 1000 articles, which were screened for inclusion in the meta-analysis. To be included, an article had to: assess the impacts of the SCS on the soil; present primary numerical data; be conducted in tropical areas; evaluate the dynamics of the operating variables pH, Total C, Total N and CEC in the different stages of the SCS (conversion, cultivation, fallow); and compare the effects of the SCS with soils from forests on advanced successional stages (control), therefore evaluating the variation in pH, CEC, Total C and Total N between mature forest and areas subjected to SCS.

Meta-analysis

Meta-analysis is a quantitative review method that allows general conclusions to be reached about a certain problem or hypothesis from a set of individual studies with contradictory results (Borenstein *et al*., 2009). To determine the magnitude of the effect of the SCS on the operational variables (pH, Total C, Total N and CEC), we calculated the unbiased standardized mean difference (Hedge's *d*) between each of these soil property variables in control areas (forest) and under SCS conditions (see Aguilar *et al*., 2008 for details on Hedge's *d* calculations). Data were collected from texts, tables or graphs. The analyses were conducted using the Meta-Win 2.0 software, using the random effects model. We used the procedure described by Adams *et al*. (1997) for the calculation of confidence intervals around effect sizes. An effect of the SCS was considered significant when 95% of the bias-corrected confidence interval did not overlap zero (Borestein *et al*., 2009).

Positive values of the effect size (*d*) imply positive effects of SCS on the rainforest soil properties (specifically on Total C, Total N and CEC), while negative values indicate that SCS has negative effects on these variables. For soil pH, positive effect size (*d*) values indicate that the pH of soils subjected to SCS is altered to a less acidic state.

We also compared the relative effects of SCS on soil property variables at different soil depths (0–5, 0–10, 10–20 and >20 cm), soil types (oxisols, inceptisols, ultisols, spodosol, others, no data), biomes (tropical rain forest, dry tropical forest, deciduous dry forest savannah, no data), fallow age classes (0–5, 5–10, >10 yrs) and stages of SCS. Statistical comparisons among these categories were tested with $Q_{between}$ statistics (Borestein *et al*., 2009).

Any quantitative review is subjected to potential publication bias. To test for such a possibility in our data set, we used graphical (funnel plots) and numerical tests (fail-safe numbers; see Aguilar *et al*., 2008 for details on each test). If no publication bias exists, the resulting plot is shaped like a funnel with the large opening at the smallest sample sizes. The fail-safe number estimates the number of non-significant, unpublished or missing studies that would need to be added to a meta-analysis to nullify its overall effect size (Rosenthal, 1979). If the fail-safe number is larger than $5n + 10$, where n is the number of studies, then publication biases (if they exist) may be safely ignored (i.e. the results are robust regardless of publication bias; Rosenthal, 1991).

Results

A total of 55 studies (Table S1) were compiled for the four meta-analyses conducted with the soil variables (pH, CEC, Total C and Total N). However, the estimator (average values that make up the calculation of Hedge's *d*) for each variable was higher than the number of reviewed studies as several studies provided more than one result: 44 studies for pH (216 estimators), 38 for Total C (206 estimators), 39 for Total N (185 estimators) and 22 for CEC (105 estimators). Among the meta-analysed studies, 28% of them assessed the variables pH, CEC, Total N and Total C in soil at the stage of conversion, 42% in the cultivation phase and 30% in the fallow phase. The mean time frame of fallow areas of the studies included in the meta-analysis was 28 yrs ± 9.6 yrs.

The overall weighted mean effect size for the pH variable was positive and significantly different from zero (Figure 1), implying a change towards less acidic soils after SCS (average pH values increased from 5.1 to 5.6). On the contrary, the overall weighted mean effect sizes for Total N and Total C were negative and significantly different from zero (Figure 1), showing that soils under SCS have a significant depletion of N and C contents. Although CEC also showed a negative overall weighted mean effect size, it was not significantly different from zero (Figure 1), implying that no changes occurred to CEC after SCS (average value was 28 cmolc/kg).

None of the four soil property variables showed publication bias. Each of the funnel plots of effect size versus sample size showed symmetric shapes (not shown), and each of the calculated weighted fail-safe numbers was always greater than $5n + 10$ (pH: 11,901 > 216; Total C: 5,582 > 206; Total N: 1,137 > 185; C, EC: 2,119 > 105), supporting the robustness of our results.

We also assessed the relative effects of SCS on the four different property soil variables, at different soil depths (Figure 2a). SCS has a significant effect on pH in the upper soil layers (0–20 cm), especially in the top layer (0–5 cm, Figure 2a; $Q_{between} = 22.87$; $P = 0.002$). At depths >20 cm, the effects of SCS were non-significant, implying no changes in pH levels Figure 2a. The effect size for pH on different soil types ($Q_{between} = 18.44$; $P = 0.319$) and fallow age classes ($Q_{between} = 6.18$; $P = 0.293$) was not significant, but among biomes comparison was significant ($Q_{between} = 36.24$, $P = 0.01$) (Figure 4b).

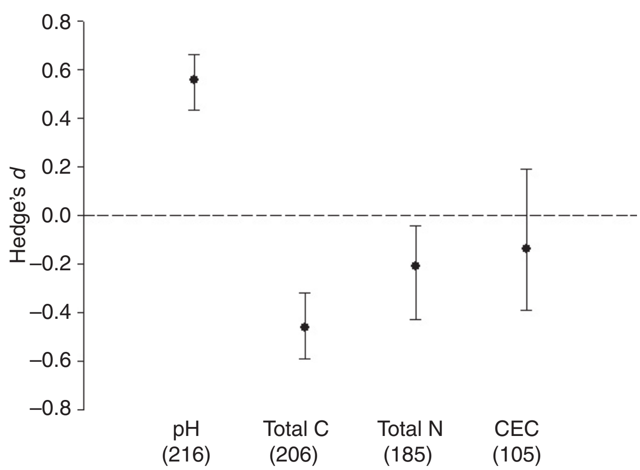

Figure 1 Overall weighted mean effect sizes and 95% bias-corrected confidence intervals of SCS on pH, Total C, Total N and CEC. Sample sizes for each meta-analysis are shown in parentheses. Dotted line shows Hedge's $d = 0$. When confidence intervals overlap zero, this implies the effect sizes are not significantly different from zero.

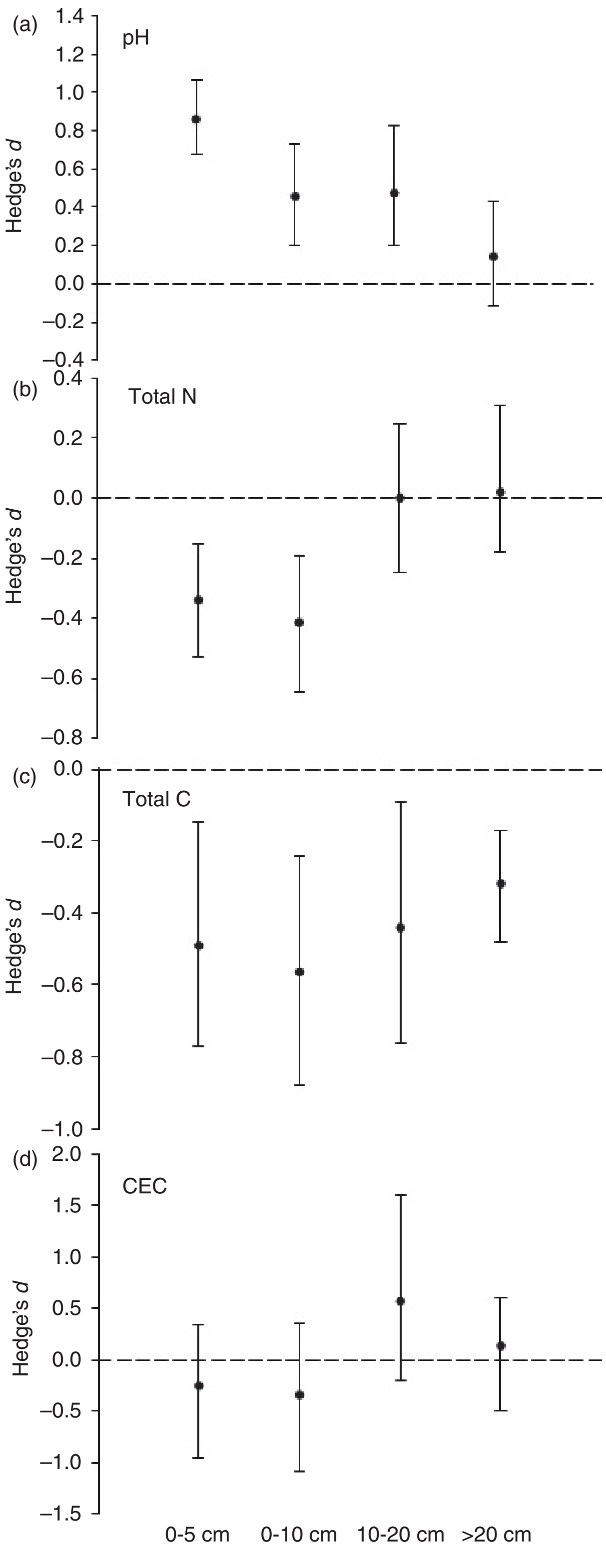

Figure 2 Overall weighted mean effect sizes and 95% bias-corrected confidence intervals of SCS at different soil depth on (a) pH, (b) C total, (c) N total and (d) CTC. Dotted lines shows Hedge's $d = 0$. When confidence intervals overlap zero imply the effect sizes are not significantly different from zero.

Our results also show that Total N significantly decreases in the upper soil layers (0–10 cm) as a consequence of SCS (0–10 cm, Figure 2b; $Q_{between} = 12.33$; $P = 0.02$), whereas no effects are observed at deeper layers (>10 cm, Figure 2b). The effect size for Total N was significant among soil types ($Q_{between} = 28.92$; $P = 0.03$) (Figure 3d), but not among biomes ($Q_{between} = 17.10$; $P = 0.108$) and fallow age classes ($Q_{between} = 0.63$; $P = 0.75$).

Total C was negatively affected by SCS at all the investigated depths. Comparison of effect sizes among biomes was not significant ($Q_{between} = 9.82$; $P = 0.78$), but was significant among soil types ($Q_{between} = 160.31$; $P = 0.001$) (Figure 3a) and fallow age classes ($Q_{between} = 21.99$; $P = 0.05$) (Figure 3b). The result patterns observed for CEC are similar to those of Total N (i.e. decreases in the upper layers and increases in the lower layers); however, none of the effects were significantly different from zero. The effect size of CEC among biomes ($Q_{between} = 1.11$; $P = 0.867$) and class fallow ($Q_{between} = 7.61$; $P = 0.381$) was not significant, but was significant for soil types ($Q_{between} = 124.48$, $P < 0.001$) (Figure 3c).

The comparison of effect sizes among the stages of the SCS was marginally significant ($Q_{between} = 4.26$; $P < 0.08$), only for pH (Figure 4a). The pH increased by nearly 0.8 units on average in the conversion phase, when the slashing and burning of the vegetation occurs. However, this effect shows a decreasing trend through the cycle, to the extent that in the fallow stage the pH of the soil is nearly 0.4 units lower than the original level.

Discussion

Response of soil pH to SCSs

Soil pH is considered one of the most important indicators to evaluate the fertility of tropical soil subjected to SCSs (Kleinman *et al.*, 1995), and our results corroborated its importance.

The overall positive effect size of SCS on soil pH (Figure 1) indicates that the impact of the slashing and burning of the vegetation biomass reduces soil acidity. This reduction occurs mainly due to the demobilization of the base cations (K, Ca, Mg) in burnt vegetation and their incorporation into the soil with the ashes (Nye & Greenland, 1960) and, to a lesser degree, due to the heating of the superficial layer of the soil caused by the use of fire (De Rouw, 1994).

The reduction of soil acidity also changes the dynamics of other variables connected to soil properties. Of interest to this review, the alkalinization of the soil generated during the conversion phase promotes increased base saturation, releasing the pH-dependent negative charges contained in the SOM and in the available clays (Hölscher *et al.*, 1997). Moreover, the increase in pH causes a

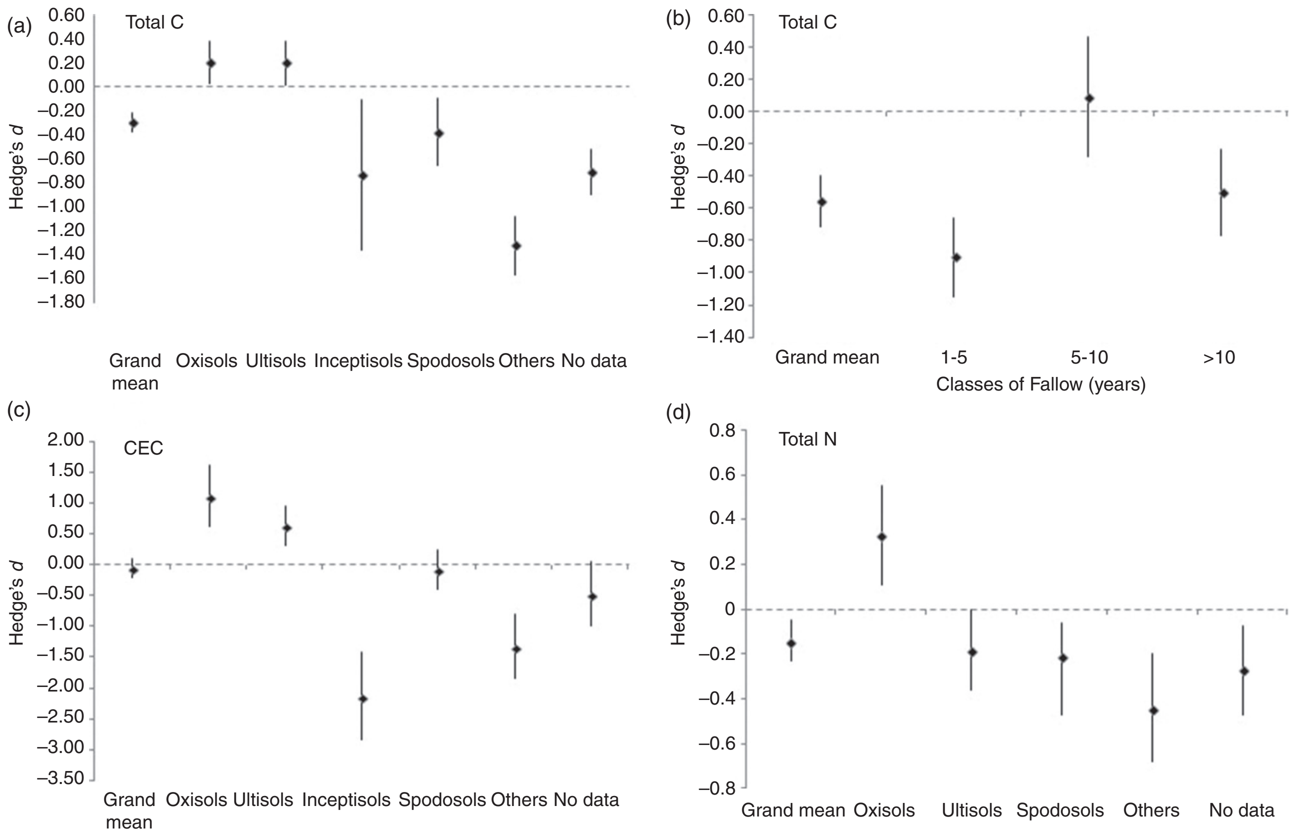

Figure 3 Overall weighted mean effect sizes and 95% bias-corrected confidence intervals at different categories on (a, b) Total C, (c) CEC and (d) Total N of SCS. Dotted lines shows Hedge's $d = 0$. When confidence intervals overlap zero, this implies that the effect sizes are not significantly different from zero.

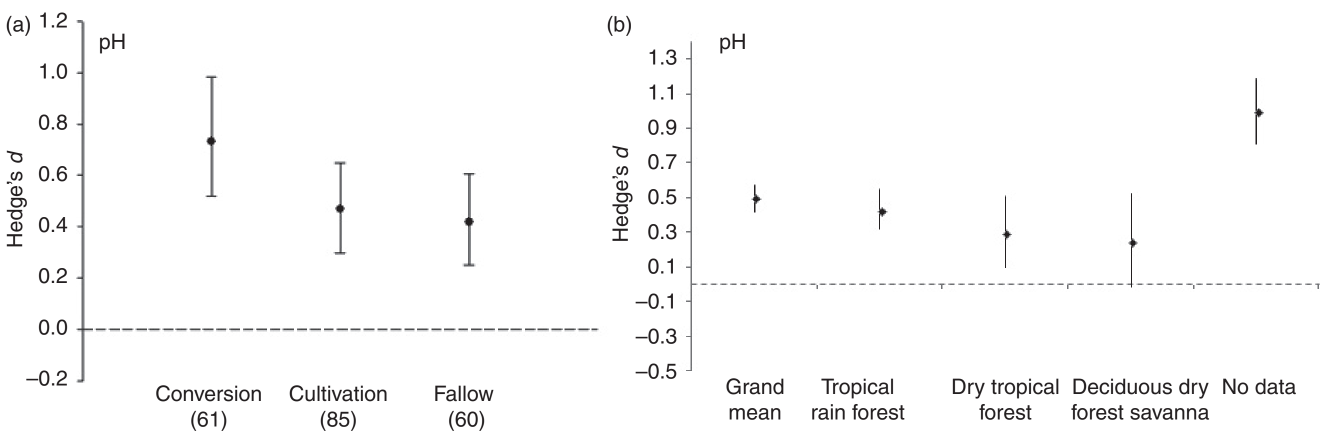

Figure 4 Overall weighted mean effect sizes and 95% bias-corrected confidence intervals of (a) different phases of SCS and (b) biomes on pH. Dotted lines shows Hedge's $d = 0$. When confidence intervals overlap zero, this implies that the effect sizes are not significantly different from zero.

decrease of the hydrolysis of aluminium and manganese, reducing the saturation of the soil by these elements and consequently reducing their toxicity to crops (Juo & Manu, 1996).

There was a significant increase in pH in the top soil layer (0–5 cm, Figure 2a; $Q_{between} = 22.87$; $P = 0.002$), where the highest concentration of nutrients will be available for the crops, as well as the major portion of the SOM, enhancing soil fertility and its resilience (Ribeiro Filho *et al.*, 2013).

Figure 4a shows that the initial impact of change in soil acidity is mitigated throughout the SCS cycle and that there is a tendency for prior conditions to be re-established in the fallow stage. Although pH Hedge's *d* did not reach the no-impact line (i.e. effect size zero), one has to consider that from the 216 estimators evaluated for this operational variable, only 24.1% were collected at the late fallow stage (>10 yrs) and that the mean late fallow age was 28.4 ± 9.6 yrs. This probably explains why the comparison among fallow age classes showed no significant differences (Figure 3) and indicates that most fallow stages evaluated were are not lengthy enough to guarantee the nutrient balance of the system (Szott *et al*., 1999; Vadez *et al*., 2004). The return of soil acidity to the condition prior to the conversion and cultivation stages is considered as fundamental for ecological succession, which will allow biomass recovery and diversification of secondary vegetation (Juo & Manu, 1996; Szott *et al*., 1999). Our results also show that pH did not change significantly among soil types and different biomes (Figure 4b), confirming findings from a previous literature review (Ribeiro Filho *et al*., 2013).

Response of CEC to SCSs

The fact that CEC is unaltered by SCS (Figure 1) means that soils maintain their ability to retain exchangeable bases. Maintenance of the CEC during the cycle could be explained by the changes observed in the pH during the SCS, which would maintain the soils in less acidic conditions promoting the stability of the soil properties.

The release of the pH-dependent negative charge usually promotes increased soil CEC (Sanchez & Logan, 1992). The CEC of tropical soils mainly consists of clay with low activity and organic matter, and the latter may determine more than 50% of its value (Nye & Greenland, 1960). An increase in pH-dependent negative charges could be offset by the loss of organic matter, which was indirectly verified in this study by the reduction in Total C and Total N during the cycle. In addition, 50% of meta-analysed studies were undertaken in oxisols and ultisols (relatively fertile) that showed an increase in CEC, while the remaining were in less structured soil types, which had a decrease (Figure 3c).

The unaltered CEC and less acidic pH are two synergistic results that contribute to enhance the effects of SOM, even if it has been partially reduced, contributing to the maintenance of soil resilience (Sanchez *et al*., 1989; Lemenih *et al*., 2005). The high CEC mean value found in the topsoil in this review (28 cmolc/kg) agrees with those found in most tropical soils (Sanchez & Logan, 1992).

Responses of Total C and Total N to SCSs

Total C and Total N showed significant overall reductions with SCS (Figure 1), which was expected due to the exposure of soil surface to irradiation and direct rainfall during the cultivation phase, increasing the rate of mineralization, in addition to the removal of crops at the end of this phase (Brand & Pfund, 1998).

The overall significant reduction of Total N implies that soil N is lost during SCS cycle, when compared to the soil of a mature forest. The loss of soil Total N in the SCS cycle occurs due to the volatilization caused by the use of fire, the increased rate of mineralization of SOM during cultivation, and to leaching, runoff and erosion (Ribeiro Filho *et al*., 2013).

However, N has a complex dynamic in the soil, quickly moving from one form to another (mineral, organic, different ionic forms, gas forms). The dynamics of Total N are determined mainly by the kinetics of SOM, as the largest part of soil N is found in the organic form (Szott *et al*., 1999). The increase in the rate of mineralization of SOM observed after the clearing and burning of vegetation enhances the nitrification rate, which elevates the concentration of nitrate (Ilstedt *et al*., 2003; Bruun *et al*., 2006). Higher concentrations of nitrate favour crop growth, while increasing the loss of N by leaching. In more structured and fertile soils, this loss can be mitigated, as seen in Figure 3d (Topoliantz *et al*., 2006).

The same process seems to be happening with Total C in relation to different types of soils (Figure 3a). Losses of soil C under regular cultivation are well established in the literature, and usually occur within a few years of starting cultivation (Murty *et al*., 2002).

SCS: a sustainable system for tropical soils?

Most of the studies, included in this meta-analysis (72%), evaluated the impacts of SCS on pH, Total N, Total C and CEC during the cultivation and fallow stages. During these stages, the flows of matter (nutrients, especially the base cations and N) and energy are accumulating in the vegetation biomass (Kleinman *et al*., 1995, 1996). Therefore, a deficit in Total C and Total N should be expected when comparing their levels in mature forests (or the reference stage) where the accumulation process is slower (Szott *et al*., 1999; Béliveau, 2008).

Total N stocks in the soil/vegetation complex, are located largely in the soil compartment (Johnson *et al*., 2001), which is not much affected during the cultivation stage of the SCS (reviewed by Murty *et al*., 2002). However, in the fallow stage, with the linear increase in biomass through time, especially in the first 5–10 yrs, there is a removal of the stock of Total N from the soil to the vegetation, which will be later compensated by the fixation of N_2 from the air into the soil (Johnson *et al*., 2001; Béliveau, 2008).

Much like other cultivation systems, SCS also promotes a decrease of soil Total C stocks, however, in markedly lower quantities when compared with intensive cultivation systems that are not based on natural ecological processes (Kleinman *et al*., 1996).

The mean time frame of the fallow areas of the studies included in the meta-analysis was 28 yrs. Our results indicate that this time period might not be long enough to attain complete soil recovery. Therefore, we stress the need to improve the knowledge of soil chemical properties in older fallow areas, to confirm the importance of longer fallow periods in maintaining the sustainability of SCS. Moreover, our results are limited to the chemical properties of the soil, and a comprehensive discussion about the sustainability of SCS should also include physical and biological properties (Figure 5).

The sustainability of SCS can change when the ratio of cultivation/fallow periods increases, a common situation following the transition towards more intensive land uses (Van Vliet *et al*., 2012), increasing acidification and the loss of C and N, and compromising the CEC. So, in many locations, it may prove necessary to improve the system or even replace it with other systems. Moving towards more actively managed fallows as a result of changes in the biophysical, social, economic and political environment has been one of the paths followed by shifting-cultivators (Burgers *et al*., 2005), and different strategies of fallow management have been proposed (Burgers *et al*., 2005; Robiglio & Sinclair, 2011).

Finally, to put the soil sustainability discussion into perspective, impacts of SCS should also be discussed *vis-a-vis* modern agroecosystems. Our results indicate that soil chemical properties under SCS scenarios are better conserved than under currently extensive agricultural practices and are more readily recoverable, provided a reasonable fallow period is maintained (Padoch & Pinedo-Vasquez, 2010; Van Vliet *et al*., 2013).

Conclusions

The objective of this meta-analysis was to evaluate the impacts of SCS on selected soil chemical properties and to discuss its sustainability. Our results, obtained from the evaluation of four system variables (pH, CEC, Total C and Total N), showed that the SCS cycle can meet the basic requirements for the maintenance of a sustainable cultivation system, as advocated by Greenland (1975), Okigbo (1981) and Kang (1993), provided that the fallow period is not too short.

The overall positive effect size obtained for pH, and unaltered CEC, showed that the SCS stabilizes pedologic conditions, contributing to the maintenance of the soil/vegetation complex in rainforests. While Total C and Total N significantly decreased following SCS, these parameters did not refute the conclusions reached from the pH and CEC analysis. However, more fertile soils have greater potential to maintain the soil/vegetation complex. When different soil depths were taken into consideration, our

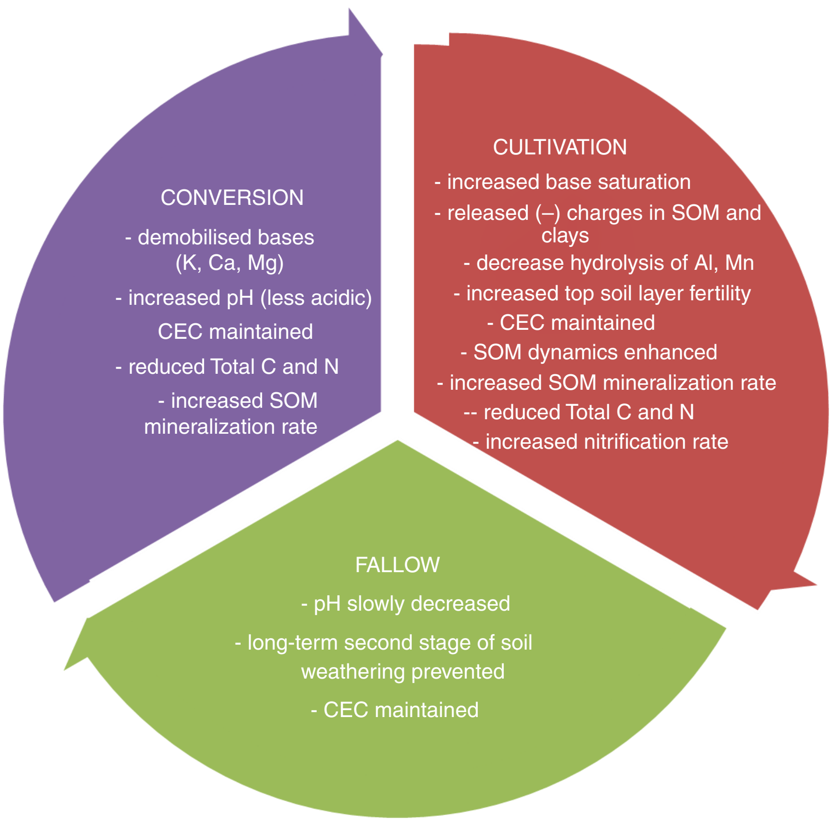

Figure 5 Shifting cultivation system cycle and changes in operational variables (pH, CEC, Total N and Total C).

results showed that SCS has a more significant effect on pH in the top layer (0–5 cm), on Total N and CEC at the 0–10 cm layer, and on Total C at all depths (0–20 and >20 cm). The comparison of effect sizes among the stages of the SCS was marginally significant ($Q_{between} = 4.26$; $P < 0.08$), only for the pH variable. For this study, other categories of independents variables (biomes, fallow class) did not show the effect size for the meta-analysed variables. We stress the need to improve the knowledge of soil chemical properties in older fallow areas, for a better evaluation of the impacts of SCS on tropical soils.

Our results call for the need to evaluate SCS from the point of view of the soil/vegetation complex. Furthermore, our meta-analysis was limited to the chemical properties of the soil, and physical and biological properties should also be evaluated. Lastly, as suggested by Kleinman *et al.* (1995), social and economic parameters should also be included along ecological ones in a comprehensive evaluation of the sustainability of SCS.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. List of articles included for the four meta-analyzed variables.