Bruun *et al. Carbon Footprints* 2023;2:11
DOI: 10.20517/cf.2023.06

Carbon Footprints

Review

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Carbon footprint of shifting cultivation landscapes: current knowledge, assumptions and data gaps

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How to cite this article: Bruun TB, Hepp CM. Carbon footprint of shifting cultivation landscapes: current knowledge, assumptions and data gaps. *Carbon Footprints* 2023;2:11. https://dx.doi.org/10.20517/cf.2023.06

Received: 20 Mar 2023 **First Decision:** 4 May 2023 **Revised:** 17 May 2023 **Accepted:** 26 May 2023 **Published:** 7 Jun 2023

Academic Editor: Xiaogang Yin **Copy Editor:** Fangling Lan **Production Editor:** Fangling Lan

Abstract

Shifting cultivation, a rotational land use system widely practiced in tropical regions, is often blamed for contributing to climate change due to the perceived association with deforestation and resulting greenhouse gas (GHG) emissions from slash and burn activities. This concern is often used to justify the implementation of national land use policies aiming at restricting or eradicating shifting cultivation while encouraging alternative land use systems. However, the contribution of shifting cultivation to global climate change is questionable. This study summarizes the available - and unavailable - data and knowledge required to calculate the carbon footprint (CFP) of shifting cultivation and highlights the methodological challenges and problematic assumptions that lie therein. Data on carbon stocks of fallows are found to be incomplete with large unexplained variation in the relationship between fallow age and carbon stocks of above- and belowground vegetation, and studies from Africa are under-represented. Knowledge of GHG emissions during burning is limited and associated with unsubstantiated assumptions on combustion completeness and emissions factors that represent important sources of uncertainty. Data on the global extent of shifting cultivation is coarse, and spatially explicit data on the rotation intensity of these systems is unavailable, thus hindering any upscaling of CFP calculations. Finally, it is concluded that the contribution of shifting cultivation to deforestation remains unclear, with remote sensing-based studies likely overestimating the scale of this due to methodological flaws. This review calls for caution when interpreting data on GHG emissions from shifting cultivation and suggests ways of addressing the identified data gaps.

Keywords: Land use systems, greenhouse gas emissions, carbon stocks, soil organic carbon, above- and belowground biomass, carbon sequestration, fallow regrowth, subsistence agriculture

INTRODUCTION

Land use and land use change contribute around 23% of net anthropogenic greenhouse gas emissions (GHG)[1]. However, through sustainable management, land use systems can also act as GHG sinks through the enhancement of carbon (C) sequestration in soil and vegetation, leading to a reduced carbon footprint (CFP) (BOX 1)[1-4].

As climate change and its effects become more prevalent, land use systems are increasingly assessed, and compared, in relation to their CFP in a bid to find solutions or alternatives that would reduce global warming. However, land use systems should not only be evaluated based on their CFP, but also on their contribution to food security and local livelihoods[2]. This is especially relevant for the Global South, where food insecurity issues are prevalent (and likely to worsen due to the impacts of climate change)[5].

BOX 1: The Carbon Footprint concept:

Carbon footprint (CFP) is defined as the "*exclusive total amount of carbon dioxide emissions that are directly and indirectly caused by an activity or is accumulated over the life stages of a product*" (Wiedmann and Minx, 2008, p.3)[6]. A CFP includes the emissions of all greenhouse gasses (CO_2, CH_4, N_2O, N_2O_x), expressed in CO_2 equivalents (CO_{2eq})[6]. CFP is considered a sub-component of the ecological footprint concept that is defined as the total area of land and water ecosystems required to produce the resources for a population and assimilate the waste produced by that same population, regardless of the physical location[3,7].

Shifting cultivation is one of the oldest forms of agriculture and millions of people across the tropics depend fully or partly on the system for their livelihood and food security[8,9]. Due to the central practice of slashing and burning vegetation to prepare fields, the system is often portrayed as a source of GHG emissions and a driver of deforestation[10,11]. Critics, therefore, argue that to mitigate climate change and limit deforestation and forest degradation, shifting cultivation must be eradicated or reduced[10,12,13]. Accordingly, many countries in the Global South (particularly in Asia) have included eradication or "stabilization" of shifting cultivation in their strategies to reduce GHG emissions and adopted policies aimed at limiting the land area used for shifting cultivation or prohibiting the practice altogether while instead, promoting intensified agriculture or plantations (e.g., rubber, oil palm) that are perceived as sustainable alternatives[9,14,15]. However, empirical data on C emissions from shifting cultivation, and the promoted alternatives, are limited and much of the information that serves as the basis for such land use policies is inconsistent or has been misconstrued[16-18]. Land use policies are increasingly guided by desires to reduce the climate change impacts of land use systems, and should not uncritically be based on incorrect assumptions about shifting cultivation as a major source of GHG emissions. Therefore, efforts to accurately quantify the CFP of the system should be made.

There is no standardized protocol for quantifying the CFP of land use systems, but the process requires a land cover classification allowing for the units of a given system to be mapped (without double-counting or gaps), and data on the C stocks and GHG emissions of the different units. This data serves as a basis for an area-based calculation of the time-averaged C stocks and GHG emissions of a given system[7]. However, the lack of methodological standardization leads to highly variable CFPs with no consensus on which reference system to use or how a system's boundary is defined[19]. While mapping the CFP of monocropping systems with clear boundaries and easily quantifiable inputs and outputs is relatively straightforward, the opposite is true for shifting cultivation systems that (among other things) are characterized by unclear boundaries and C stocks that are spatially heterogeneous and temporally dynamic.

Rather than attempting to quantify the CFP of shifting cultivation, this review summarizes the available - and unavailable - data and knowledge required for such a calculation and highlights the methodological challenges and problematic assumptions that lie therein. Moreover, it is hoped this review will raise awareness of not only the caution necessary when interpreting data on the CFP of shifting cultivation, but the need for more accurate data, and the development of methodological approaches.

Shifting cultivation

Shifting cultivation takes diverse forms, but it is essentially a rotational land use system that relies on the shifting of cultivation between different plots and extended fallow periods. Here we apply the definition suggested by Mertz *et al.*, which broadly captures most systems in Asia, Africa, Latin America, and the Pacific[20]:

"[Shifting cultivation is] a land use system that employs a natural or improved fallow phase, which is longer than the cultivation phase of annual crops, sufficiently long to be dominated by woody vegetation, and cleared by means of fire."

This rotational nature of shifting cultivation creates a mosaic landscape of patches of active plots (i.e., cultivated), fallows of varying age and - in many cases - areas of primary forest (e.g., forests on hilltops, community forests, and sacred forests)[21,22]. The management of traditional shifting cultivation systems is based on in-depth knowledge of the local environment (e.g., about soils, climate, plants, and fire management)[23,24]. Most shifting cultivation systems are focused on subsistence production, and the availability of products that can be harvested (or collected) both from the cultivated fields and the regrowing fallows throughout the year is important for the food security of local communities[25-27].

It is important to distinguish between the rotational clearing and burning of fallows used in shifting cultivation systems, and the permanent clearing of forests for pioneer agriculture which is also done by slashing and burning. The latter is often confused with shifting cultivation, although it is associated with fundamentally different land use systems and - as opposed to shifting cultivation - leads to net deforestation.

METHODOLOGY

As this review covers shifting cultivation and (i) carbon storage/stocks; and (ii) associated GHG emissions, two separate literature searches were conducted in the Web of Science Core Collection.

Shifting cultivation and carbon storage

For the identification of papers on shifting cultivation and carbon storage (i.e., biomass and soil), we took the point of departure in papers identified in a study on ecosystem services in secondary forests in shifting cultivation by Mertz *et al.* (please see this paper for a detailed description of the search strings and the methodology)[28]. Based on this collection of papers, we identified 78 papers reporting either on shifting cultivation and soil carbon storage/stocks or on shifting cultivation and carbon storage/stocks in above- or belowground biomass. We updated the search to identify recently published papers which only resulted in the identification of one additional paper.

Data were then extracted from the papers and aggregated according to region and rotation intensity or forest age to give an impression of the magnitude and range of values found in the current literature. The following categories for rotation intensities and forests were used: annual cultivation, fallows (1-5 years; 6-10 years; 11-15 years; 16-20 years; and 21-30 years), old growth forest (31-40 years; and 41-60 years), and primary forest (≥ 61 years). In regards to soil organic carbon (SOC) stocks, studies reporting values for depths of 0-20 cm and 0-30 cm were included. These are the most commonly sampled depth intervals, but there is a large variation in sampling depths and intervals between studies. Some of the identified studies were therefore not included, as the SOC stocks were reported according to different depth intervals. In studies that did not report SOC stocks directly, we calculated the stocks from the reported SOC% and bulk density measurements, when possible.

Shifting cultivation and GHG emissions

To identify papers on shifting cultivation and GHG emissions, we used the following search terms:

“Shifting cultivation” or “shifting agriculture” or swidden or “slash and burn” or “slash and burn” and “greenhouse gas emission*” or “emission factor*” or “biomass burning”

This search identified 111 papers that were screened at the abstract level, and the vast majority were found to be irrelevant as the search terms were only used in the general framing of the studies. We, therefore, used snowballing to identify more relevant papers.

Data regarding the quantification of GHG emissions of shifting cultivation systems were extracted from the papers along with the associated assumptions that we compare and discuss.

THE CARBON FOOTPRINT OF SHIFTING CULTIVATION

Calculation of the CFP of shifting cultivation requires data on the sizes of the various carbon stocks of the systems and knowledge of the amount of GHGs released during burning. Furthermore, knowledge about the rotation intensity - i.e., the relation between the number of years under fallow and the number of years under cultivation - is needed along with data on the extent of the system. Finally, data on the contribution of shifting cultivation to net deforestation - along with knowledge of the C stocks of the affected forests - is required.

The following section provides an overview of the available data and knowledge required to calculate the CPF of shifting cultivation and discusses data gaps along with associated assumptions and challenges that lie therein.

Carbon stocks in shifting cultivation systems

In shifting cultivation systems, C is mainly stored in the above- and belowground biomass and in the soil, while smaller amounts may be stored in dead biomass (typically as unburned tree trunks). In this section, the factors controlling the C dynamics of these pools are described, and the range in C stocks (above- and belowground biomass, and soil C of shifting cultivation at various rotation intensities and of forests of various ages measured to date are summarized.

Above- and belowground biomass

On a broad scale, the growth rates of the fallow vegetation are controlled by climate - especially rainfall[29]. However, within a certain climatic regime, vegetation growth rates may be strongly affected by management practices. Clearing of large plots and intensive burns may reduce the quantities of seeds available for fallow recolonization, while repeated cultivation of the same plot may deplete soil fertility, resulting in reduced fallow growth rates, and a reduction of the amount of C stored in the aboveground biomass under a given rotation intensity[29,30]. Young fallows are dominated by pioneer species, many of which are woody N2-fixing leguminous species. In some systems, such species are actively promoted, which may speed up rates of biomass recovery and nutrient accumulation[31].

Fallows are often used as sources of wood (e.g., for construction, fuel, *etc*.), which will lead to a reduction of C in the aboveground biomass. Alternatively, in some cases, useful tree species are left standing and protected from fire, which will contribute to C storage[23,32].

Accordingly, the size of the aboveground C stocks of shifting cultivation systems is context-specific, and the variability is high - even within the same climatic zones[16]. This is also evident from the (non-exhaustive) overview of estimates of aboveground carbon reported by studies of shifting cultivation in Africa, Asia, and Latin America [Table 1].

Apart from the large variation in the aboveground biomass stocks within the relatively narrow ranges of fallow ages, it is worth noting the very limited number of studies from Africa which, to the best of our knowledge, represents the available studies from this continent.

The aboveground biomass values reported by the studies from Africa are low compared to values from the other continents which partly reflects that all the African studies are from areas with less than 900 mm of precipitation, while studies from Asia and Latin America are from areas with average precipitation of 1,400-4,000 mm and 900-2,200 mm, respectively [Table 1]. No studies from the humid parts of Africa where shifting cultivation represents an important land use type were identified.

Knowledge of the C storage in the belowground biomass (roots) of shifting cultivation systems is notoriously limited and very few studies provide direct measurements of this C pool[17,33]. In the absence of allometric equations developed for secondary vegetation (fallows), most estimates of belowground C stocks in shifting cultivation systems are based on root:shoot ratios derived from studies of undisturbed forests, and only two studies[33,34] are based on direct measurements. As in the case of aboveground biomass, the number of studies from Africa is very limited [Table 1].

Soil carbon

During the fallow period, the regenerating vegetation provides inputs of biomass (i.e., litterfall, root turnover, and root exudates) to the soil. A fraction of this biomass is incorporated as “new” C into the SOC pool, thereby replenishing the carbon lost during cultivation[35,36]. The degree to which the soil C pool is replenished is dependent on the biomass productivity of the fallow vegetation and if the soil carbon sequestration capacity has been reached[36-38]. The conversion from fallow to cultivation leads to a decline in SOC stocks due to the reduced biomass input and higher decomposition rates caused by topsoil exposure and disturbances[39,40].

Theoretically, if the fallow length is sufficient to restore system productivity and the rotations are consistent, a dynamic equilibrium between soil C gains and losses will be reached[41]. This theoretical minimum fallow length, however, has been difficult to pinpoint because studies document inconsistent fallow length effects on soil C levels; positive, negative and neutral effects of fallow length on soil C levels have been found[36,42-48]. This is due to not only the high spatio-temporal variation found within shifting cultivation systems as previously discussed, but prior rotations and farmer preference also play an influential role. For example, Lawrence *et al*. found a positive correlation between the number of prior rotations (fallow-cultivation cycles) and SOC stocks[43]. This is likely attributed to the underestimated input of decaying roots from slashed fallow vegetation and the addition of incompletely combusted particles from the frequent slash and burn activity[47,49]. Farmers have also been known to preferentially select plots with more fertile soils,

Table 1. Above- and belowground carbon stocks (Mg C ha^{-1}) of shifting cultivation at different rotation intensities and of forests of various ages

Region	Land cover (years)	Carbon stock (Min-Max; Mg C ha^{-1})	
		Aboveground biomass	**Belowground biomass**
Latin America			
	Fallow (1-5)	5-70	3.3-11.5
	Fallow (6-10)	11.8-158	7.6
	Fallow (11-15)	15-152	15
	Fallow (16-20)	37.5-118.2	10.5
	Fallow (21-30)	46.5-196.6	No data
	Old growth (31-40)	60-304.9	14-17
	Old growth (41-60)	269.8-460.5	No data
	Primary forest	105-335.6	11-23.8
Africa			
	Fallow (1-5)	No data	No data
	Fallow (6-10)	No data	2.5-3.5
	Fallow (11-15)	7-11.5	5
	Fallow (16-20)	2.5-3.5	3.5
	Fallow (21-30)	13.5	No data
	Old growth (31-40)	5	No data
	Old growth (41-60)	15	No data
	Primary forest	3.5	9
Asia			
	Fallow (1-5)	2.1-33.5	0.5-11
	Fallow (6-10)	6.2-35.7	2.0-6.5
	Fallow (11-15)	25.0-43.3	6.2-10
	Fallow (16-20)	40.0-48.5	8.4-13
	Fallow (21-30)	41.6-59.5	No data
	Old growth (31-40)	134.1	No data
	Old growth (41-60)	No data	35-112
	Primary forest	No data	No data

Studies on aboveground biomass: Latin America (n = 8)[71-78]; Africa (n = 2)[79,80]; Asia (n = 6)[18,33,44,81-83]; Studies on belowground biomass: Latin America (n = 2)[34,75]; Africa (n = 1)[79]; Asia (n = 4)[18,33,44,81]; Average annual precipitation ranges at the study sites are 900-2,200 mm for Latin America (median = 1,450), 1,400-4,000 mm for Asia (median = 1,900), and 600-880 mm for Africa (median = 800).

cultivating them more intensively, which would have a similar effect as fertile soils are likely to have higher C content than less fertile soils[40,50]. A study by Bruun *et al*. accounted for farmers' preferential selection of plots in the sampling scheme and, nonetheless, found that fields cultivated more intensively (i.e., shorter fallows) have higher SOC stocks than extensively managed fields[47]. This finding was explained by the more frequent and recurrent additions of C from roots due to the shorter crop-fallow rotations.

Given such variation, it has been difficult to assign values to the soil C changes that occur within shifting cultivation and when it transitions to alternate land uses. A non-exhaustive overview of studies quantifying the soil C stocks (0-20 cm and 0-30 cm) in shifting cultivation systems in Latin America, Africa and Asia highlights the variable range that can be found [Table 2]. From the table, it is apparent that there is no consistent pattern in the effect of annual cultivation and fallow on soil C stocks [Table 2]. Furthermore, there is a lack of data for some fallow categories, especially from Africa, where shifting cultivation is an important land use system[22,51]. This is due to the limited number of studies from the region, inconsistencies in sampling methods (e.g., sampling depth) and in the way results are reported (e.g., soil C stocks vs soil C

Table 2. Soil carbon stocks (Mg C ha^{-1}) of shifting cultivation at different rotation intensities and of forests of various ages

Region	Land cover (years)	Carbon stock (Min-Max; Mg C ha^{-1})	
		0-20 cm	0-30 cm
Latin America			
	Annual cultivation	37.1	48.6
	Fallow (1-5)	54.9	25.6
	Fallow (6-10)	35.0-53.3	15.1-18.6
	Fallow (11-15)	40.6	23.4-52.3
	Fallow (16-20)	27.0-50.3	20.6
	Fallow (21-30)	No data	22.9-23.3
	Old growth (31-40)	20.0-68.4	17.0-34.7
	Old growth (41-60)	No data	24.4-27.1
	Primary forest	27.8-67.0	20.4-25.7
Africa			
	Annual cultivation	35.3-46.0	9.0-40.3
	Fallow (1-5)	53.9-75.6	11.0-53.0
	Fallow (6-10)	53.5-72.5	9.5-81.5
	Fallow (11-15)	52.5-56.6	54.7
	Fallow (16-20)	60.6	56.5-59.4
	Fallow (21-30)	No data	14.5
	Old growth (31-40)	No data	53.0
	Old growth (41-60)	No data	No data
	Primary forest	53.3-62.0	16.9-67.5
Asia			
	Annual cultivation	58.0	No data
	Fallow (1-5)	42.1-85.2	50.6-119.7
	Fallow (6-10)	22.2-79.8	33.6-134.3
	Fallow (11-15)	39.5-92.0	50.7-65.9
	Fallow (16-20)	49.8	66.6-72.3
	Fallow (21-30)	39.7-42.0	55.7-56.4
	Old growth (31-40)	47.0-49.1	61.0-65.2
	Old growth (41-60)	34.4-35.9	46.4-48.0
	Primary forest	125.1	85.0-153.4

Studies reporting SOC stocks for the 0-20 cm layer: Latin America (n = 4)[75,84-86]; Africa (n = 3)[46,87,88]; Asia (n = 3)[44,50,89]; Studies reporting SOC stocks for the 0-30 cm layer: Latin America (n = 2)[74,86]; Africa (n = 2)[80,90]; Asia (n = 3)[44,48,91].

concentration) [Table 2]. Hence, it has proven to be extremely difficult to confidently characterize or quantify the soil C gains and losses from shifting cultivation; any such values should be used as guides and are not definitive.

Time-averaged carbon stocks

The C storage potential of rotational land use systems is not determined by the C stock at any point in time, but by the average amount of C stored in the system during its entire rotation - referred to as the "time-averaged C stock"[40,52]. In the case of shifting cultivation, the time-averaged C stock is dependent on the rotation intensity of the system and calculated as the sum of the C stocks in the biomass and soil each year of the rotation divided by the length of the rotation[18]. However, very few studies provide data allowing for a calculation of the time-averaged C stocks of shifting cultivation and most studies merely report a snapshot of C stocks of fallows of certain ages[28].

GHG emissions from shifting cultivation

The slash and burn activities associated with shifting cultivation are often categorized under the broader category of fires leading to "deforestation"; however, this classification is misleading as shifting cultivation does not lead to permanent deforestation.

The rotational nature of shifting cultivation means that a system with a stable rotation intensity will not be a net emitter of CO_2 over the long term[11,53] because the CO_2 released during the burning of fallows will be counterbalanced by the CO_2 captured by the regrowing fallows elsewhere in the system. This will change if the rotation intensity decreases (i.e., longer fallows), which will result in a net CO_2 uptake, while an increase in rotation intensity (i.e., shorter fallows) will lead to a net CO_2 emission.

GHG emissions from burning

Shifting cultivation systems are likely to be net emitters of non-CO_2 GHGs such as methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O) and nitrogen oxides (NO_x) due to the slashing and burning of biomass[53]. Quantifying the release of GHGs from the burning of fallow biomass relies on many assumptions related to: (i) the amount of biomass per area unit (a function of fallow length and biomass productivity); (ii) combustion completeness (influenced by biophysical factors such as vegetation type, moisture content and weather conditions during the time of the burn); (iii) emission factors (especially influenced by the type of biomass and temperature); and (iv) local management practices (e.g., protection of large trees or other desired woody species from fire, collection of biomass beforehand for fuel or building material, *etc.*)[53,54].

As discussed (and shown in Table 1), amounts of C in aboveground biomass of fallows are very variable and difficult to predict solely based on fallow age. The combustion completeness used in studies to calculate the emissions from shifting cultivation is also highly variable; Silva *et al.* show combustion completeness ranges from 20.1%-87.5%, with an average of 40.6%, while Lauk & Erb use an assumed value of 53.8%, based on Fearnside[11,53,55]. A literature review by van Leeuwen *et al.* found a combustion completeness average of 47% (range 30%-64%) for shifting cultivation, but this conclusion is based on only two studies (Zambia and India) and results are thus inconclusive[54]. Emission factors, defined as the amount of compounds released per unit of dry biomass consumed (g kg^{-1}), are a great source of uncertainty in model estimates of GHG emissions[53,54]. While ground measurements of species and biome-specific emission factors are available, the high spatial and temporal variability makes large-scale applications of GHG emission calculations challenging[56]. None of the identified studies of GHG emissions from shifting cultivation have included local management practices in estimations of the aboveground biomass burned, even though this is recognized as a potentially important factor[53].

Studies have attempted to estimate the emissions of GHGs from shifting cultivation with variable results. Silva *et al.* used spatial information derived from satellite imagery to estimate global CO_2 emissions from shifting cultivation to be 741 Tg yr^{-1}, with the largest GHG emissions coming from America, followed by Asia and then Africa [Table 3][53]. Previous estimates of the global CO_2 emissions from shifting cultivation range from 950 Tg CO_2 yr^{-1}[11] to 2,764 Tg CO_2 yr^{-1}[57], highlighting the high degree of variability in the approach to quantifying emissions and the importance of the associated assumptions. These include assumptions about the geographical extent of shifting cultivation, rotation intensity, combustion completeness and emission factors, and local management practices. Hence, the reported GHG emissions should be considered as place-based scenarios that bring awareness to the sources and magnitude of uncertainty (as described above).

Table 3. Regional GHG emission estimates from shifting cultivation in America, Africa, and Asia. Mean values (and standard deviations) are based on the Global Land Cover 2000 Map and adapted from Silva *et al.*[53]

	CO_2 (Tg yr^{-1})	CO (Tg yr^{-1})	CH_4 (Gg yr^{-1})	NO_x (Gg yr^{-1})	N_2O (Gg yr^{-1})
America	295 (197)	18 (13)	1,197 (892)	410 (389)	36 (33)
Africa	205 (139)	13 (9)	832 (626)	285 (272)	25 (23)
Asia	241 (132)	15 (9)	979 (618)	335 (282)	30 (24)

The geographical extent of shifting cultivation

The spatio-temporal diversity and dynamic nature of shifting cultivation make it notoriously challenging to map, and the mosaic landscapes produced by shifting cultivation are often not captured by remote sensing-based land cover and land use classifications[22]. Moreover, as shifting cultivation falls between conventional agricultural and forestry land cover categories, the system is often not included in national land cover assessments, but rather referred to as “idle” or “degraded” land[28,58]. These methodological and political challenges mean that shifting cultivation is normally absent from land cover maps and that the knowledge of the extent of the system remains limited.

Efforts have been made to obtain a broad estimation of the global extent, but to date, the global area under shifting cultivation is based on few and varying estimates, with the most recent, and likely most accurate, being 280 Mha[22]. This study relied on a combination of expert information and visual inspection of very high-resolution satellite imagery to detect the specific spatio-temporal pattern of shifting cultivation at a one-degree cell resolution worldwide[22]. The study found signs of shifting cultivation in 62% of the investigated one-degree cells in the humid and sub-humid tropics[22]. The majority of these cells were found in Latin America (41%), followed by Africa (37%)[22].

Moreover, it was found that the area under shifting cultivation in Southeast Asia has declined since the early 2000s[22] - a finding that is corroborated by results of a case-study-based meta-analysis[59]. Trends in the extent of the system in Africa and Latin America vary by region and are both positive and negative but much more subtle than in the case of Southeast Asia[22,59].

Rotation intensity and system boundaries

There is no spatially explicit data on the rotation intensity of shifting cultivation systems at the global (or regional) scale, but a meta-analysis of land cover transformations observed reductions of fallow lengths in the majority of the reviewed cases[59]. It should also be noted that there are often large differences in the rotation intensities within the same area (at the village level) as this (among other things) is influenced by biophysical factors and household characteristics, such as soil types, availability of land, labor and other assets[47,60]. Hett *et al.* developed a land use intensity map for a 26 × 26 km area of Northern Laos with promising results, but the methodology used in their study is difficult to upscale and no attempts to do so have been made[21].

Another challenge related to the spatial complexity of shifting cultivation systems is the fact that the system is rarely found in isolation, but rather as a component of a landscape that also contains other land use types that may (or may not) be considered a part of the shifting cultivation system. Such landscapes are, for example, common in Borneo (Sarawak and Kalimantan), where rubber plots, pepper gardens and stands of fruit trees are often integrated into the shifting cultivation cycle[61-64] [Figure 1]. This implies that it is often notoriously difficult to draw meaningful boundaries around a shifting cultivation area.

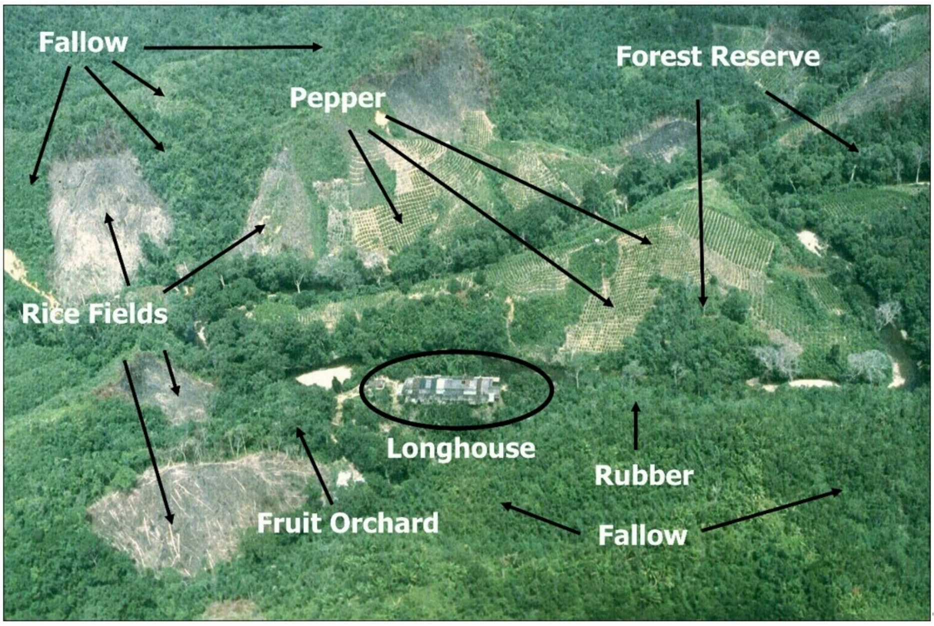

Figure 1. Shifting cultivation area of the longhouse, Nanga Tapih, Betong Division, Sarawak, Malaysia. From a livelihood perspective, all the specified land uses are considered part of the shifting cultivation system. The pepper fields are likely to eventually be left fallow and included in the shifting cultivation rotation system, and the plots that are currently used for rubber or fruit trees are likely to eventually be slashed and burned and used for rice at the end of the life cycle of the trees (or if other factors encourage this conversion). Photo: Rob Cramb.

Shifting cultivation *vs*. deforestation

Shifting cultivation is often blamed for causing deforestation, but it is important to note that rotational shifting cultivation - meaning cycling between plots within the same landscape - does not constitute deforestation[16,65,66]. Deforestation only occurs when plots are established in forest areas that have not been cultivated before. Shifting cultivation systems under intensification, meaning increased frequency of cropping under shorter fallows, will experience a net tree cover loss that translates into reduced C storage at the landscape level.

In a widely cited global assessment of drivers of deforestation, Curtis *et al*. identify shifting cultivation as the dominant driver of observed forest loss in Africa, causing 93% ± 3% of this loss[67]. In comparison, 20% ± 10% of the forest loss observed in Southeast Asia was attributed to shifting cultivation[67]. However, the authors acknowledge, albeit briefly, that the model accuracy for Africa was low and that much of the commodity-driven deforestation was misclassified as shifting cultivation due to the similar regional spatial patterns of the two land uses.

Interestingly, using the data derived from Curtis *et al*., a global study on C fluxes concludes that shifting cultivation is a net C sink[67,68]. This conclusion is based on several assumptions: (i) all shifting cultivation systems are managed under shortened fallows whereby the vegetation does not fully recover; (ii) the calculation of emission factors is based on a total loss of C in the above- and belowground, deadwood and litter pools, and a soil C loss determined by the soil type and ecological zone; and (iii) removal factors are calculated by linking available - and often limited - data on growth rates to the ecological zone, forest type, and age. Furthermore, any forest C sink within the same 10 km grid cell as a forest disturbance event attributed to shifting cultivation by Curtis *et al*. was attributed to shifting cultivation[67]. The fact that shifting cultivation can be seen both as a dominant driver of forest loss and a C net sink reflects the methodological challenges and the problematic assumptions made in remote-sensing-based GHG flux estimations or land use change that involves shifting cultivation.

CONCLUSION AND PERSPECTIVES

As discussed in this paper, quantification of the CFP of shifting cultivation is hindered by limited data availability and methodological challenges related to measuring the extent and intensity of shifting cultivation. This research documents that:

(1) Data on C stocks is incomplete

There are gaps in our understanding of C storage in belowground biomass of fallows and of C transfer from this pool to the soil when fallow vegetation is slashed. There are also large unexplained variations in the relationships between fallow age and C stocks of above- and belowground biomass of fallows within similar climate conditions. This could indicate large differences in local management practices, gaps in our understanding of C accumulation in fallows, or may be a sign of methodological inconsistencies between studies. Empirical data on C stocks of African shifting cultivation systems are particularly scarce and data allowing for calculation of time-averaged C stocks of the system are generally missing.

(2) Knowledge of GHG emissions during burning is limited

The number of studies of GHG emissions associated with burning in shifting cultivation is very limited and the few available studies employ numerous assumptions. Important sources of uncertainty are related to unsubstantiated assumptions regarding combustion completeness and emissions factors.

(3) Knowledge of the intensity and extent of shifting cultivation systems is limited

Spatially explicit data on the rotation intensity of shifting cultivation systems are unavailable, and data on the extent of the system (regardless of the intensity with which it is practiced) is prohibitively coarse, which hinders any upscaling of CFP calculations.

(4) The contribution of shifting cultivation to deforestation remains unclear

Rotational shifting cultivation does not lead to deforestation; however, systems undergoing intensification (i.e., an increased frequency of cropping under shorter fallows) do result in a net loss of tree cover. The methodological challenges and numerous assumptions in GHG flux measurements are obvious, considering that shifting cultivation has been identified simultaneously as a cause of forest loss and a net C sink.

Recommendations

Given these large gaps in data, we did not attempt to calculate the CFP of shifting cultivation, but based on the identified shortcomings, we advocate for comprehensive research focused at the local level to advance our understanding of the complex dynamics occurring within shifting cultivation systems to reduce the uncertainties that currently exist due to data scarcity and the associated assumptions.

This research should focus on the C dynamics of shifting cultivation as more data on these are clearly needed - especially from Africa. We also encourage the development of coupled biomass-soil C models for well-studied shifting cultivation systems. Such models would make it possible to assess the time-averaged C stocks of systems at various rotation intensities, which is an important input for assessing the CFP.

It was beyond the scope of this study to review the methodologies and context-specific characteristics of the identified studies of C pools of shifting cultivation, but such an analysis is called for to improve our understanding of the large differences observed in the dataset.

The lack of data on GHG emissions during burning remains a challenge and is probably best addressed through field experimental studies at the plot level integrated with model simulations and ground-airborne-satellite observations[69].

To address the lack of data on the extent and rotation intensity of shifting cultivation, efforts should be made to develop remote sensing methods that are able to capture the dynamic nature of shifting cultivation at the landscape level. Such methods are currently under development, and with recent advances in Earth observation systems providing images at both high spatial and temporal resolution coupled with the emergence of deep learning approaches in artificial intelligence, there is a large potential for improvements.

Perspectives

It was beyond the scope of this paper to discuss the CFP of the land use types that are currently replacing shifting cultivation in many areas - often with the encouragement of land use policies claiming to reduce the climate change impacts of land use systems. A recent pan-tropical meta-study concluded that shifting cultivation is mainly replaced by monocrop tree plantations, annual crops, permanent agroforestry systems and regrowing secondary vegetation[66], and while positive environmental outcomes prevail for transitions to permanent agroforestry and regrowing secondary vegetation, most of the transitions resulted in negative outcomes for the environment (including a decrease in carbon storage)[9,28,59,66,70].

Moreover, this review calls for caution when comparing CFPs of land use systems with no (or very limited) use of external inputs like shifting cultivation. Land use systems with a high reliance on external inputs to maintain production will have additional attributable GHG emissions such as from the production of fertilizers, pesticides, or transport - emissions which are not included in calculations of their CFPs[7]. Hence, comparing the CFPs of shifting cultivation and most alternative production systems (perhaps with the exception of permanent agroforestry) is inherently problematic. Furthermore, the smallholder farming communities practicing shifting cultivation often have low CFPs as practitioners produce the majority of their own food, live in relatively isolated areas lacking electricity, and have a low level of consumption of material goods.

A valid calculation of the CFP of shifting cultivation is not possible at this time for reasons discussed in this paper. Nonetheless, there is evidence to suggest that the C dynamics in shifting cultivation systems result in lower emissions compared to other, far more dominant systems. This, alone, is grounds for advancing shifting cultivation onto scientific and political agendas for sustainable land use. Any communication about the climate change impacts of the system should be done carefully, as such can have real repercussions on the livelihoods of its often resource-poor and socially vulnerable practitioners.

DECLARATIONS

Acknowledgements

The graphical abstract was made by Louise Hedegaard Madsen.

Authors' contributions

Conceived the study: Bruun TB

Contributed equally to the development of the methodology, the data analysis and interpretation, and the writing and reviewing of the manuscript: Bruun TB, Hepp CM

Availability of data and materials

Not applicable.

Financial support and sponsorship

Hepp CM is funded by the Research Institute for Humanity and Nature (FairFrontiers, Project Number 14200149).

Conflicts of interest

Both authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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