Revised manuscript (clean version) submitted to Environmental Research Letters, Sept. 25th, 2023.

Satellite data reveals a recent increase in shifting cultivation and associated carbon emissions in Laos

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Abstract

Although shifting cultivation is the major land use type in Laos, the spatial-temporal patterns and the associated carbon emissions of shifting cultivation in Laos are largely unknown. This study provides a nationwide analysis of the spatial-temporal patterns of shifting cultivation and estimations of the associated carbon emissions in Laos over the last three decades. This study found that shifting cultivation has been expanding and intensifying in Laos, especially in the last five years. The newly cultivated land from 2016-2020 accounted for 4.5% (±1.2%) of the total land area of Laos. Furthermore, the length of fallow periods has been continuously declining, indicating that shifting cultivation is becoming increasingly intensive. Combining biomass derived from GEDI (Global Ecosystem Dynamics Investigation) and shifting cultivation maps and area estimates, we found that the net carbon emissions from shifting cultivation declined in 2001-2015 but increased in 2016-2020. The largest carbon source is conversion from intact forests to shifting cultivation, which contributed to 89% of the total emissions from 2001 to 2020. In addition, there were increased emissions from intensified use of fallow lands. This research provides useful information for policymakers in Laos to understand the changes in shifting cultivation and improve land use management. This study not only supports REDD+ (Reducing Emissions from Deforestation and forest Degradation) reporting for Laos but also provides a methodology for tracking carbon emissions and removals of shifting cultivation.

Keywords: Shifting cultivation; Shifting agriculture; Slash and burn; Swidden agriculture; Disturbance; Forest degradation; Carbon emissions; REDD+; GEDI

1. **Introduction**

Shifting cultivation is an agricultural practice where farmers routinely move from one plot to another for cultivation. It begins with the practice of "slash-and-burn", where trees and woody plants are cut down and burnt to prepare an ash-fertilized plot for temporary cultivation. After short-term cultivation, the plot is abandoned, which allows the vegetation to recover. Shifting cultivation is the predominant land use and a major cause of forest degradation and deforestation in some tropical countries (Curtis et al., 2018; Jiang et al., 2022; Heinimann et al., 2017), such as Laos (Chen et al., 2023), and the Democratic Republic of Congo (Molinario et al., 2015). Monitoring shifting cultivation is complicated, because it is highly dynamic, and the area affected by each slash-and-burn event is small. Due to the difficulty of monitoring shifting cultivation, spatially and temporally explicit information on shifting cultivation is scarce.

Shifting cultivation has both short-term and long-term effects on carbon emissions (Ziegler et al., 2012). In the short term, the slash-and-burn activities cause immediate release of carbon. In the long term, encroachment of shifting cultivation into primary forest and intensified use of secondary forest both lead to long-term increases in net carbon emissions and degradation of ecosystems. Carbon emissions from shifting cultivation have not been well quantified, because of the lack of methodology for monitoring shifting cultivation and tracking the associated carbon dynamics. In contrast to deforestation (such as urbanization), which does not involve carbon sequestration, shifting cultivation involves both carbon emissions associated with slash-and-burn activities and carbon sequestration during the fallow period. Due to the complexity of monitoring shifting cultivation and tracking the associated carbon dynamics, estimates of carbon emissions or sequestration from shifting cultivation are usually unavailable in REDD+ (Reducing Emissions from Deforestation and forest Degradation) reporting.

In Laos, officially the Lao People's Democratic Republic (Lao PDR), shifting cultivation is an important agricultural system (Douangsavanh et al., 2006; Roder, 2000; Manivong and Cramb, 2020; Epprecht et al., 2018) and the major driver of forest dynamics (Curtis et al., 2018; Chen et al., 2023). It is estimated that shifting cultivation affected 32.9% ± 1.9% of Laos from 1991 to

2020, and the shifting cultivation activities increased in the most recent five years (Chen et al., 2023). Laos' population has been increasing steadily from 4.314 million in 1990 to 7.319 million in 2020 (World Bank, 2023), whereas upland rice yields did not distinctly improve between 1990 and 2020. Shifting cultivation activities are expected to increase due to the increasing demand for rice. Monitoring shifting cultivation and analyzing its patterns are important to understand the forest cover change in Laos and relevant to achieving Laos' goal of increasing forest cover to 70% (The current forest cover is 62%) (The Government of Lao PDR, 2005). Since there were few spatially and temporally explicit maps and estimates of shifting cultivation before Chen et al. (2023), carbon emissions from shifting cultivation have not been accurately estimated in the REDD+ reporting of Laos (Department of Forestry, 2018).

Spatially and temporally explicit information about shifting cultivation in Laos was unavailable until recently (Chen et al., 2023), and a comprehensive national-scale analysis of the spatial and temporal patterns of shifting cultivation has not been conducted to date. A traditional approach for mapping shifting cultivation is to create landscape mosaics based on a land cover map of a single year (Hett et al., 2012; Hurni et al., 2013a; Messerli et al., 2009; Silva et al., 2011). It is impossible to analyze the temporal patterns of shifting cultivation using this traditional approach. Another approach is to use multi-temporal land cover data to map shifting cultivation (Adhikary et al., 2019; Kurien et al., 2019; Leisz and Rasmussen, 2012; Molinario et al., 2015; Department of Forestry, 2018). In previous studies, the temporal resolution of the land cover maps was not high enough to support the analysis of temporal patterns (Heinimann et al., 2013). Recently, Chen et al. (2023) used satellite data to create shifting cultivation products for Laos with sufficient temporal frequency (annual) and spatial resolution (30 m) to support a national-scale spatial-temporal analysis. The recently launched GEDI (Global Ecosystem Dynamics Investigation) mission provides new opportunities for estimating biomass at a large scale (Tang et al., 2020).

This study used the map products and reference data in Chen et al. (2023), combined with GEDI, to conduct a national-scale analysis of the spatial and temporal patterns and carbon dynamics of shifting cultivation in Laos. The goal is to understand the spatial and temporal patterns of shifting cultivation and the associated carbon emissions, in support of decision-making to reduce carbon emissions and promote sustainable livelihoods depending on shifting cultivation.

2. **Method**

2.1. Mapping shifting cultivation

Shifting cultivation was mapped using Landsat data from 1987- 2020 on Google Earth Engine (Chen et al., 2023). CCDC-SMA (Continuous Change Detection and Classification - Spectral Mixture Analysis) (Chen et al., 2021; Zhu & Woodcock, 2014; Bullock et al., 2020) was used to detect forest disturbances in Laos. CCDC-SMA fits harmonic models to fractions of endmembers and NDFI (normalized difference fraction index) (Souza et al., 2005) to monitor forest disturbances (**Fig. 1**). Annual maps of *Shifting Cultivation* from 1991 to 2020 were created by combining time series analysis, object-based image analysis (OBIA), and post-disturbed land-cover classification. A total of 1000 sample units under simple random sampling were used as reference data for accuracy assessment and area estimation. For each sample unit, at least two interpreters interpreted the land change class and the year of each slash-and-burn event by examining high-resolution satellite imagery and Landsat time series (**Fig. 1 (a), Fig. 1 (c)** and **Fig. 2**). During 1991 - 2020, shifting cultivation was the main type of forest disturbance in Laos, affecting 32.9% ± 1.9% of Laos (Chen et al., 2023). Shifting cultivation was mapped with a producer's accuracy of 88% and a user's accuracy of 80% (Chen et al., 2023). Chen et al. (2023) describes more details of the monitoring method. Both the map products and the reference data from Chen et al. (2023) were used in this study.

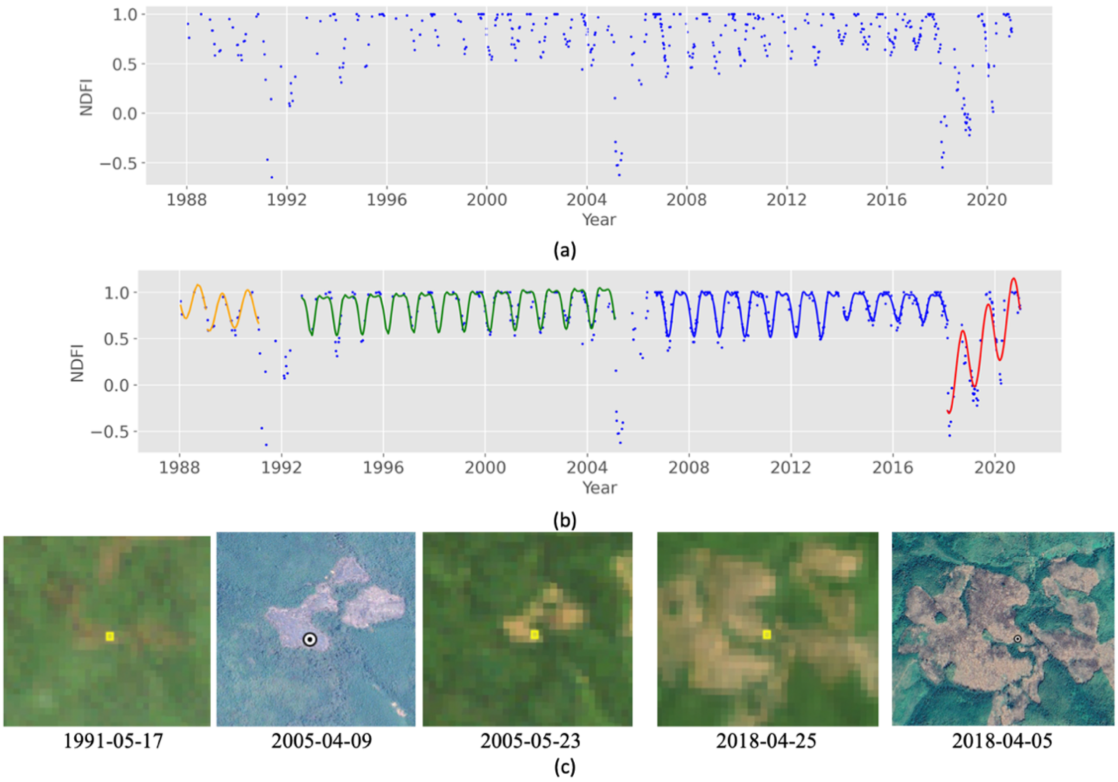

Fig. 1. An example of active shifting cultivation in previously cultivated land (location: 20° 7'13"N, 101° 6'59" E). The shifting cultivation events in 2005 and 2018 were categorized as *Previous Shifting Cultivation* because shifting cultivation first occurred in 1991. This place is also *Active Shifting Cultivation* because the latest shifting cultivation event occurred in 2018. (a) Landsat time series. (b) CCDC-SMA model fits (Different colours show different segments and the model breaks in 1991, 2005, and 2018 show slash and burn events). The coloured lines show the seasonality of the forest and the drops between lines show slash-and-burn events. (c) Landsat images and high-resolution images on Google Earth. In the Landsat images (Red-green-blue), the yellow squares show the pixel location. In the high-resolution image, the white point shows the pixel location.)

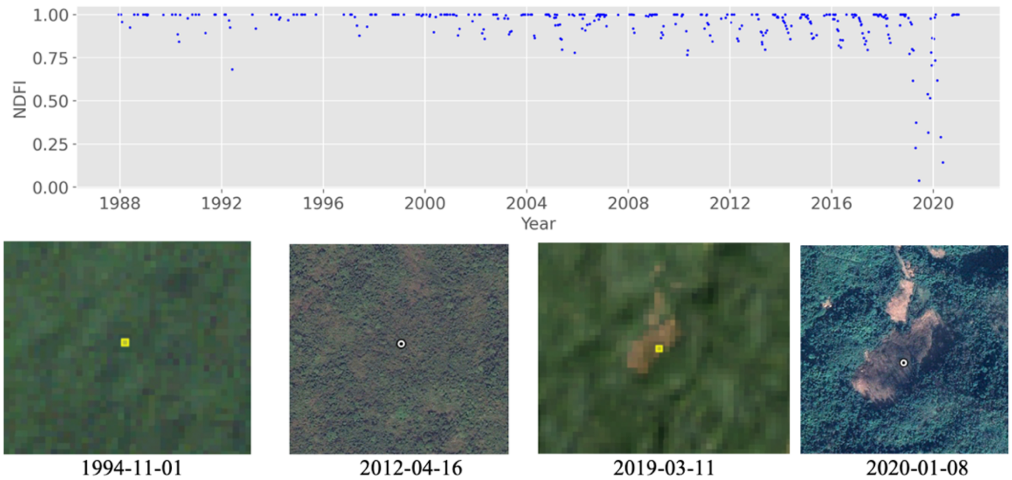

Fig. 2 An example of reference data (location: 20°15'8"N, 100°39'51"E). This shifting cultivation is *New Shifting Cultivation*. The time series shows that no shifting cultivation occurred before 2019. The new shifting cultivation occurred in 2019 and it can be verified by examining high-resolution images and Landsat images. (In the time series figure, the blue points are Landsat observations. In the Landsat images (Red-green-blue), the yellow squares show the pixel location. In the high-resolution image, the white point shows the pixel location.)

2.2. Spatial-temporal patterns of shifting cultivation

The annual maps of shifting cultivation (1991-2020) and the reference sample units interpreted as *Shifting Cultivation* were used to investigate the patterns of shifting cultivation. We estimated the area of shifting cultivation at different fallow and disturbance statuses. If a shifting cultivation place has been under fallow for at least seven years from now (2013-2020) (Department of Forestry, 2018), it is categorized as *Inactive Shifting Cultivation*; otherwise, it is *Active Shifting Cultivation*. Sampling-based area estimates of *Active Shifting Cultivation*, *Inactive Shifting Cultivation,* and *No Shifting Cultivation* were calculated. Moreover, to understand whether the extent of shifting cultivation is expanding, the newly and previously cultivated areas of shifting cultivation were estimated using reference sample units and maps in Chen et al. (2023) for every 5-year period from 2000-2020. In the reference sample points, whether a pixel is newly or previously cultivated is determined by the year of slash-and-burn recorded by the interpreters (e.g., **Fig. 1 (a), Fig. 1 (c),** and **Fig. 2**).

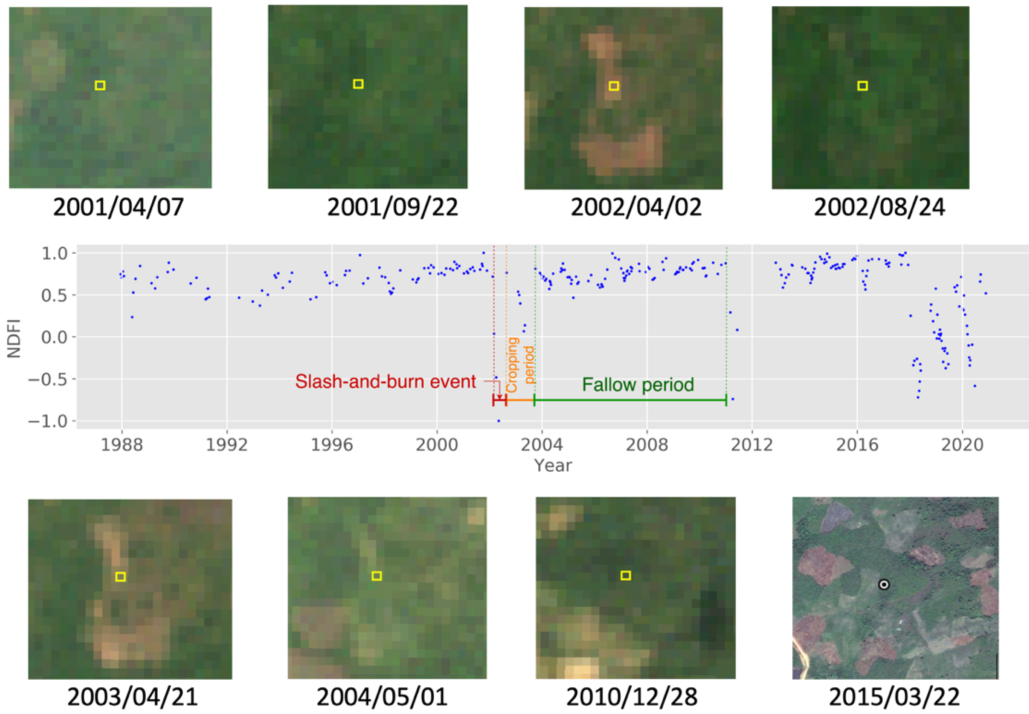

Fig. 3 Time series of shifting cultivation, labelled with different stages. (Example location: 16° 17' 6" N, 106° 55' 27" E. In the time series plot, the blue points are the Landsat observations. In the Landsat images (Red-green-blue), the yellow squares show the pixel location. In the high-resolution image, the white point shows the pixel location.)

Furthermore, to investigate the change patterns in fallow length and cultivation length (length of cropping period), we visually interpreted Landsat time series, Landsat imagery, and high-resolution images for 196 sample points (Fig. 3 as an example). These sample points are the points with at least two cultivation events in the aforementioned reference data with 1000 simple random sample points. For each point, the year of slash and burn (land clearing), cultivation length, and fallow length are recorded for every event.

2.3. Carbon emission/removal

The Global Ecosystem Dynamics Investigation (GEDI) mission provides space-borne LiDAR data to estimate aboveground biomass (Healey et al., 2020). GEDI's L4A Footprint Level Aboveground Biomass Density (Version 2.1) 25-meter data (Beck et al., 2020; Dubayah et al., 2022) were used to explore the effect of shifting cultivation on biomass. GEDI data collected in 2020 was used because it was the only year of data with good spatial coverage when the study was conducted. To overlay the GEDI footprint and Landsat, for each GEDI footprint, we extracted the value of the 30-meter pixel in the Landsat-based map that has the largest overlap with the 25-m footprint. Only lidar observations with good quality (using the "*quality_flag*" band and the "*degrade_flag*" band) and collected at places with a slope less than 20 degrees and in the interior of shifting cultivation sites (excluding a 2-pixel edge) were used, to eliminate the effect of terrain and possible misregistration at the edges of slash-and-burn events. The reason why we excluded lidar points with slopes larger than 20 degrees is that GEDI-based biomass estimates tend to be overestimated at steep terrain. Aboveground biomass density (AGBD) was calculated for *Active Shifting Cultivation*, *Inactive Shifting Cultivation*, *Intact Forest,* and *Others*. *Intact Forest* here is defined as forests without significant anthropogenic disturbances. The relationship between AGBD and years of regrowth since the latest slash-and-burn events was analyzed. The hypothesis was that AGBD has a positive relationship with years of regrowth since the latest slash-and-burn activity. From this relationship, a country-level growth curve of AGBD can be developed and used to estimate the biomass of fallow lands.

Carbon emissions from shifting cultivation were estimated for every five-year period from 2001-2020. **Table 1** shows the activity classes, definitions, and emission factors. *New shifting cultivation* area was estimated from a sampling-based method and other activity classes in **Table 1** were estimated from the maps. This is because the sampling-based area estimates of *New shifting cultivation* adjusted errors in mapping and are more accurate than pixel-counting from the maps (Olofsson et al., 2013; Olofsson et al., 2014). The area estimates of *New shifting cultivation* were calculated by 5-year periods with low uncertainty. For other activity classes, it is difficult to get area estimates from the reference data while including the dynamics of biomass of fallow land, and thus we used a spatially explicit method. In Table 1, the biomass of the forest before disturbance was the biomass of *Intact Forest* estimated from GEDI. The biomass of fallow land was estimated from the growth curve developed from GEDI based on years since disturbance. Years since disturbance for each pixel was obtained from the annual maps of shifting cultivation. The cleared land biomass was estimated as the biomass of non-forest by the Department of Forestry (2020) based on field surveys. The emission factor of *New shifting cultivation* is 75.95 Mg C/ha. The emission factor of *Cleared land -> Cleared land* is zero.

The emission factors for other activities are spatially explicit and were determined by the map of the latest year of slash and burn and the growth curve. **Fig. 8** shows an example of the spatially explicit emission factors for different activities. Specifically, this was how the carbon emissions and removals of *Fallow land -> Fallow land*, *Fallow land -> Cleared land,* and *Cleared land -> Fallow land* were calculated: The latest year of disturbance of *Fallow land* was determined using the annual shifting cultivation maps. Then, the AGBD of fallow lands was calculated using equation (1). Using AGBD of fallow land in the end year minus AGBD in the start year of each period, the differences in AGBD were obtained. Multiply the differences in AGBD by the area of different activities and then multiply it by the conversion factor (0.5), and the carbon emissions and removals of each activity were calculated. The average emission/removal factors were calculated using the emissions and removals divided by the total area of activities in different categories.

Table 1 Activity classes, definitions, and carbon emission/removal factors for each 5-year period (CF: Conversion factor to convert biomass to carbon equivalents, CF=0.5)

Activity Class	**Definition**	**Emission/Removal factors**
Intact forest -> shifting cultivation (*New shifting cultivation*)	No shifting cultivation before. Previous intact forests began to be used for new shifting cultivation.	Biomass of forest before new shifting cultivation × CF (75.95 Mg C/ha)
Fallow land -> Fallow land	Shifting cultivation occurred before. The start and end land cover were both fallow lands.	(Fallow land biomass in the start - Fallow land biomass in the end) × CF
Fallow land -> Cleared land	In previously cultivated land, fallow land became cleared land.	(Fallow land biomass - Cleared land biomass) × CF

Cleared land -> Fallow land	In previously cultivated land, cleared land became fallow land.	(Cleared land biomass-Fallow land biomass) × CF
Cleared land -> Cleared land	In previously cultivated land, cleared land became cleared land.	Zero

3. **Results**

3.1. Spatial-temporal patterns of shifting cultivation

A large proportion of the land used for shifting cultivation in Laos remains in use. During our study period, the estimated area of *Active Shifting Cultivation* (19.1% ± 1.6%) exceeded the area of *Inactive Shifting Cultivation* (13.7% ± 1.8%). In the future, there is a possibility of reusing *Inactive Shifting Cultivation* and further increasing the area of *Active Shifting Cultivation*, given the increasing demand for crops. *New Shifting Cultivation*, defined as shifting cultivation that first occurred in each period, was estimated from 2001 to 2020 by period (**Fig. 4**). The area estimates were aggregated into 5-year periods instead of calculating annual to reduce uncertainties of the area estimates. From 1991 to 2000, it is difficult to tell whether the shifting cultivation areas were new or old, and thus this analysis started in 2001. In all five-year periods, the area of *New Shifting Cultivation* is higher than 3% of Laos, implying that on average, over 0.6% of Laos' land area is converted from intact forest to shifting cultivation each year. Our results indicate that the extent of shifting cultivation has been expanding.

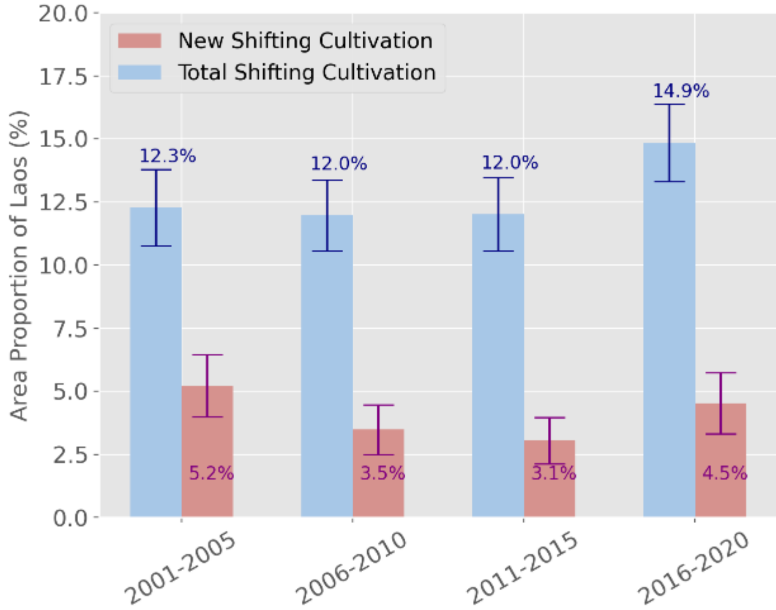

Fig. 4 Area estimates and uncertainties of *New Shifting Cultivation* and total (new and previous) shifting cultivation by five-year intervals. The y-axis is the area proportions of the total area of Laos (230,405 km^2). Any pixel that was newly cultivated at any time within a specified 5-year period would be counted and added to the total height of the corresponding pink bars.

During 2001 - 2015, there was a decrease in the area of *New Shifting Cultivation*. However, both the area of *New Shifting Cultivation* and the total area of *Shifting Cultivation* have increased significantly in 2016-2020. The proportion of previously and newly cultivated to the total area of shifting cultivation was calculated for every year using the annual maps (**Fig. 5**). Before 2007, the newly cultivated areas were larger than the previously cultivated, and the trend reversed after 2007. There was a general decreasing trend in the proportion of *New Shifting Cultivation,* but increases were observed in 2019 and 2020. We suppose that the general decreasing trend is because intact forests available for cultivation decreased over time and previously cultivated land is easier to clear for future cultivation.

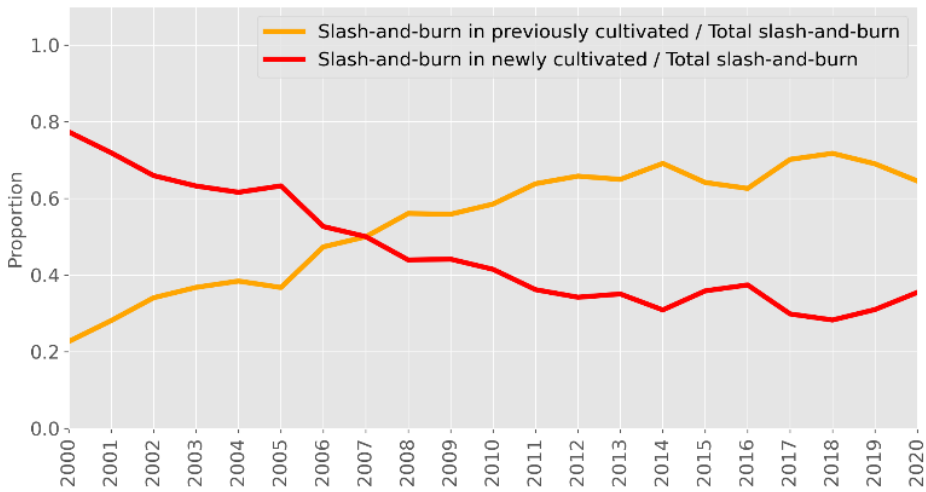

Fig. 5 Annual proportion of slash-and-burn areas in previously and newly cultivated regions.

Based on the sample interpretation results, most cultivation lengths are either one year or two years. Although there are variations across the years, we have not seen major changes in average cultivation length (Figure S1 and S2). The mean length of the fallow periods of shifting cultivation in Laos is 6.5 years, which is close to the length of fallow periods reported in the literature (7 years) (Department of Forestry, 2018). The fallow length has been continuously declining **(Fig. 6).** The reduction in the length of fallow periods indicates that shifting cultivation has intensified.

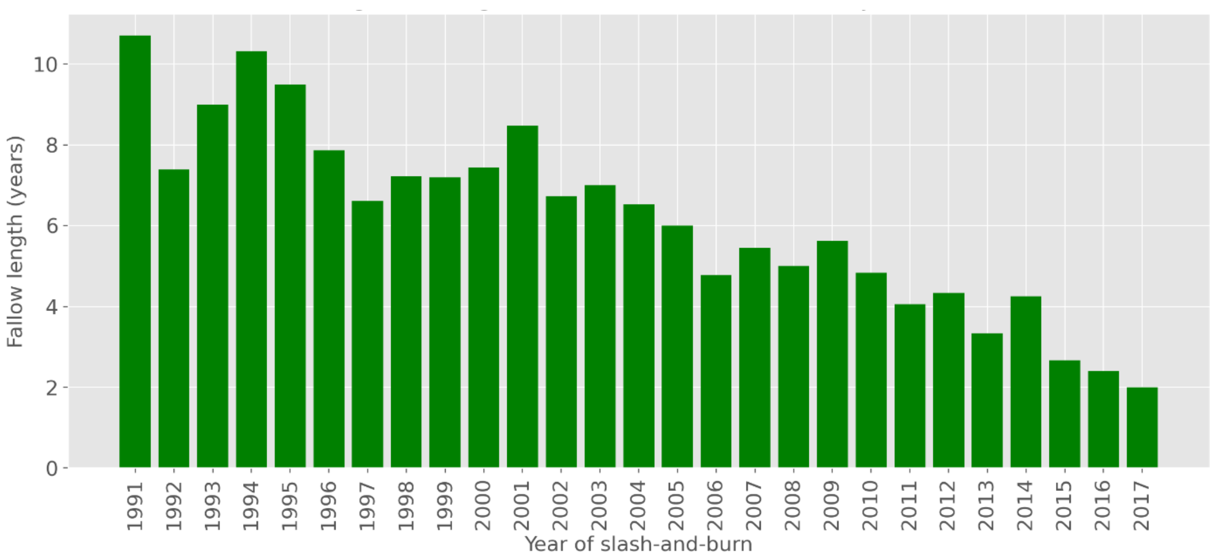

Fig. 6 Average fallow length by year calculated from sample interpretation.

3.2. Growth curve of fallow lands

The aboveground biomass density was lower in shifting cultivation regions than in the intact forests**.** The median AGBD of *Intact Forest*, *Inactive Shifting Cultivation*, *Active Shifting Cultivation,* and *Others* are 151.9 Mg/ha, 87.9 Mg/ha, 39.5 Mg/ha, and 22.8 Mg/ha, respectively. The biomass of *Inactive Shifting Cultivation* only reached about 60% of that of the intact forest. In the literature (Department of Forestry, 2018), the regions of *Inactive Shifting Cultivation* were considered to be "recovered", whereas our results show that the aboveground biomass density is not recovered even if these regions have been left for fallow for at least seven years.

To investigate the relationship between median AGBD and disturbance history, a logarithmic regression was conducted on years of regrowth since the latest slash-and-burn events and median AGBD of GEDI footprints (**Fig. 7**). The logarithmic model of years of regrowth (x) and AGBD (y) is (R square is 0.93):

$$y = 29.129\, ln(x) + 9.907 \qquad (1)$$

Aboveground biomass density was strongly correlated with years of regrowth. Equation (1) and the maps of years of regrowth were used to calculate the biomass of fallow lands and spatially explicit emission/removal factors **(Fig. 8)**.

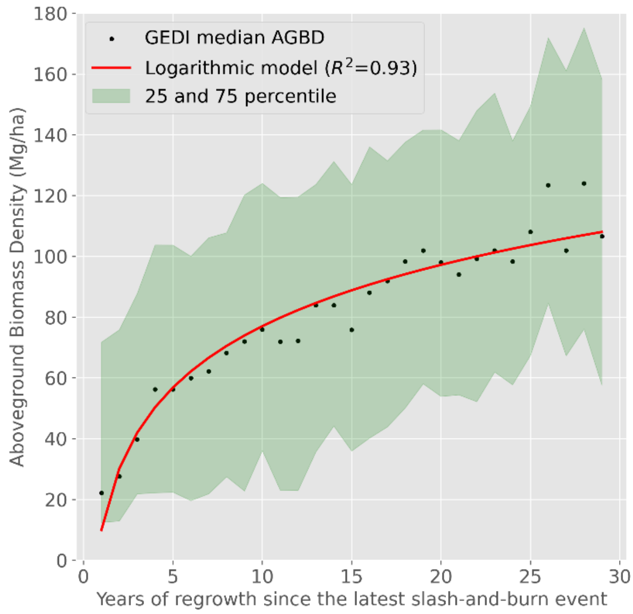

Fig. 7 Growth curve of aboveground biomass density.

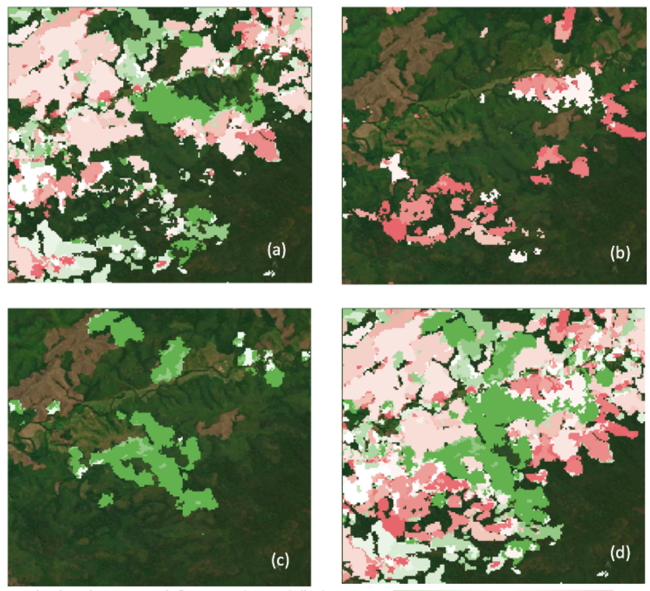

Fig. 8 Spatially explicit emission (+)/removal (-) factors for different activities in a region (the background image is the high-resolution image): (a) *Fallow land -> Fallow land;* (b) *Fallow land -> cleared land*; (c) *Cleared land -> fallow land*; (d) Total of (a), (b) and (c).

3.3 Carbon emissions from shifting cultivation

Carbon emissions from shifting cultivation were estimated by period from 2001-2020 (**Table 2, 3, and 4, and Fig. 9**). The net carbon emissions of shifting cultivation declined during 2001-2015, but significantly increased during 2016 - 2020. The decline in net carbon emissions during 2001-2015 is mostly because the area of new shifting cultivation decreased in this period. The increase during 2016-2020 is mostly due to the increase in new shifting cultivation activities in this period (**Fig. 5**) and the decrease in carbon sink of fallow lands in this period. For every period, *New Shifting Cultivation* is the largest carbon source, contributing to more than 80% of the total emissions. From 2001 to 2020, *New Shifting Cultivation* contributed to 89% of the total emissions. Fallow lands are important carbon sinks and sequestered about 70% of the total emissions during 2006-2015. However, carbon sequestration of fallow lands also decreased in recent years because of the intensified use of fallow land. To summarize, the increase in emissions from shifting cultivation encroachment to intact forests (*New Shifting Cultivation*) and intensified use of secondary forests both led to the recent increase in net emissions from shifting cultivation.

Table 2. Area of difference land use activities for each period (5 years).

Area (ha)	2001-2005	2006-2010	2011-2015	2016 - 2020
Fallow land -> fallow land	2,379,847	3,809,008	5,213,561	6,009,880
Fallow land -> cleared land	226,240	361,992	397,236	630,467
Cleared land ->fallow land	441,757	768,342	748,692	696,501
New shifting cultivation	1,198,106	806,418	714,256	1,036,823

Table 3. The country-average emissions or removal factors for each period (5 years). The original emission or removal factors except for new shifting cultivation are spatially explicit. This table shows the country averages of the spatial explicit emission or removal factors.

Average Emission/Removal factors (Mg C/ha)	2001-2005	2006-2010	2011-2015	2016 - 2020
Fallow land -> fallow land	-8.06	-7.57	-5.65	-1.56
Fallow land -> cleared land	18.70	19.26	23.58	26.10
Cleared land -> fallow land	-23.14	-24.28	-23.67	-21.36
New shifting cultivation	75.95	75.95	75.95	75.95

Table 4. Carbon emissions (+) and removals (-) of different activities for each period (5 years).

Carbon emission/removal (Mg C)	2001-2005	2006-2010	2011-2015	2016 - 2020
Fallow land -> fallow land	-19,175,009	-28,833,216	-29,440,602	-9,348,118

Fallow land -> cleared land	4,230,290	6,970,956	9,366,236	16,452,893
Cleared land -> fallow land	-10,222,046	-18,657,539	-17,717,827	-14,879,752
New shifting cultivation	90,996,151	61,247,409	54,247,705	78,746,669
Period total (Net emission/removal)	65,829,387	20,727,610	16,455,512	70,971,692
Annual average	13,165,877	4,145,522	3,291,103	14,194,339

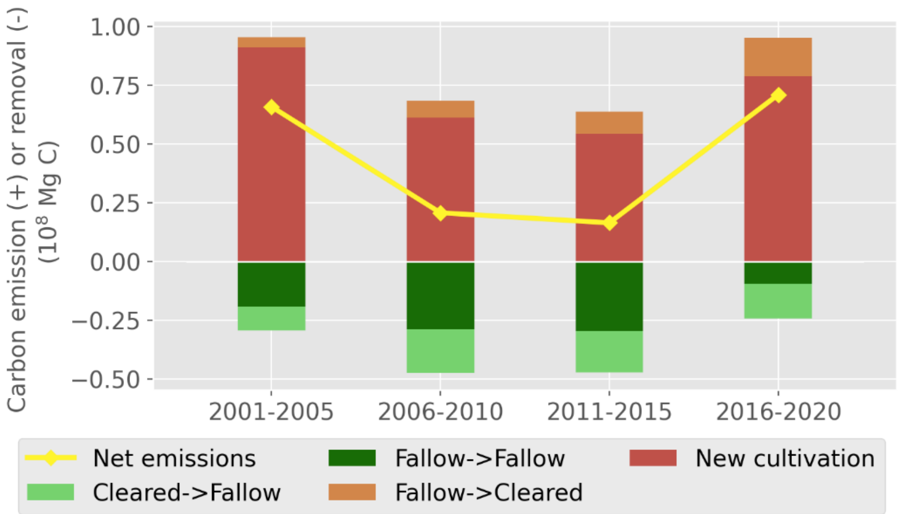

Fig. 9 Carbon dynamics by period.

4. Discussion

In this study, the spatial-temporal patterns and the carbon dynamics of shifting cultivation in Laos were analyzed. The results showed that shifting cultivation has been expanding and intensifying. The area of shifting cultivation has increased significantly over the last five years. The fallow length has been declining continuously, which indicates the intensification of shifting cultivation. Our finding of a reduction of fallow length is consistent with previous local studies (Rasul and Thapa, 2003; Saphangthong and Kono, 2009; Van Vliet et al., 2012). We found that aboveground biomass density was strongly correlated with years of regrowth since the latest year of slash-and-burn activities, which can be expressed by logarithmic models. The carbon estimates by period show that the net carbon emissions of shifting cultivation increased in recent years.

Chen et al. (2023) provided more accurate maps at a higher temporal frequency and finer spatial resolution than existing products related to shifting cultivation or forest disturbance in Laos, such as the global map of forest drivers (Curtis et al., 2018). The global map misclassified a large proportion of *Shifting cultivation* into *Forestry* or *Commodity driven Deforestation* in Laos. Although Curtis et al. (2018)'s map is valuable for global analyses, Chen et al. (2023)'s shifting cultivation map is more appropriate for this study in Laos. The only previous national-level estimate of shifting cultivation in Laos was Messerli et al. (2009), which used landscape mosaics and the resulting map was at 5km and without pixel-level accuracy assessment. Chen et al. (2023)'s area estimates of shifting cultivation (32.9% ± 1.9%) are close to the estimate from Messerli et al. (2009) (29%). Other forest disturbance products, such as the map of global forest change (Hansen et al., 2013) and forest canopy cover map (Potapov et al., 2019), do not attribute the forest loss; however, since most forest disturbances in Laos are shifting cultivation, we compared the area of forest disturbance from these products to our estimates. Based on pixel counting, the area of forest loss during 2000-2020 in the global forest change map is 17% and the "forest rotation" class during 2000-2017 in Potapov et al. (2019) is 22%, both of which are lower than our sampling-based area estimation for 2000-2020 (30.08% ± 1.9%). The underestimation of shifting cultivation in Hansen et al. (2013) and Potapov et al. (2019) is understandable since their major focus is forest loss instead of shifting cultivation. This comparison is not a criticism of the aforementioned studies. Instead, it highlights the benefits of using shifting cultivation maps and reference samples with better spatial resolution and high temporal frequency for the analysis of spatial-temporal patterns.

We compared our area estimates of *New Shifting Cultivation* with the official forest change statistics from Laos (**Table S1**). The Laos official forest change maps (https://nfms.maf.gov.la/)

are created from the land cover classification maps from the start year and end year for each period (See the periods in **Table S1**). Since shifting cultivation is the major driver of forest degradation and deforestation in Laos, we expect that there are some consistencies between the areas of *New Shifting cultivation* and the areas of forest degradation and deforestation. There are consistencies in the period 2006-2010 and 2011-2015, with the differences between our estimates and the official statistics both less than 1% of Laos. Our estimates of *New Shifting Cultivation* are generally higher than the Laos official estimates of deforestation and forest degradation, except for 2006-2010. This was partly due to the different monitoring approaches. Without using dense time series, the shifting cultivation events that occurred over five years may be difficult to detect using two classification maps from the start and the end. In the period 2001-2005 and 2016-2020, our estimates are about 2 - 3% higher than the official estimates. For 2016-2020, the discrepancy is partly because the 2019 and 2020 changes are included in our estimates but not in the official statistics. Overall, our results and area estimates provide valuable information regarding the forest dynamics of Laos.

Furthermore, we compared the shifting cultivation map with the field survey data in the Laos National Forest Monitoring System https://nfms.maf.gov.la/. The shifting cultivation map was compared with 39 field points identified as "*Regenerating Vegetation*" or "*Upland crop*" in 2010, 2011, 2012, or 2019, since these two land cover classes are generally considered to have an association with shifting cultivation practices (Department of Forestry, 2020). 31 out of 39 (80%) points are correctly mapped as shifting cultivation.

As a national-level analysis of spatial-temporal patterns and estimation of carbon dynamics of shifting cultivation in Laos, our research is valuable to sustainable land resource management. The sustainability of the land is negatively impacted by the recent expansion and intensification of shifting cultivation, indicated by an increase in newly cultivated areas in 2016-2020 and a reduction of fallow length in 1991-2020. Moreover, our research provides a quantitative analysis of carbon emissions of shifting cultivation, which is crucial for REDD+ reporting in Laos. Our research indicates that carbon emissions from shifting cultivation can be quantified by combining GEDI data with shifting cultivation maps and area estimates. The fallow land sequestrated a significant amount of carbon in the past, but this carbon sink declined in recent years. The recent increase in new shifting cultivation events also led to an increase in net carbon emissions. This highlights the importance of protecting the primary forest from the encroachment of new shifting cultivation and the restoration of old fallow lands.

Our study has several limitations and future research can make improvements by using more sophisticated models and integration with other data. The first limitation is the usage of GEDI data. Our research only used GEDI in one year (2020), because GEDI is a new mission and 2020 was the only year with good coverage data when the study was conducted. Future studies can use GEDI for multiple years as more data will be collected. In addition, we excluded GEDI points where the slope is larger than 20 degrees to avoid overestimation of biomass in steep terrain. This would introduce regional bias on the growth curve and emission factors. Based on our map, 69% of the shifting cultivation area is in places with slopes less than 20 degrees (Chen, 2022). Future research should improve GEDI biomass estimates in steep terrain. Second, although we compared our map with some field survey data in Laos, the field data information for each location is limited. Future studies should collect more detailed information on shifting cultivation in field surveys, especially biomass in shifting cultivation landscapes (e.g., Borah et al., 2018, Gogoi et al., 2020 and Salinas-Melgoza et al., 2017). Third, the carbon estimation only considered aboveground biomass change and no other carbon pools due to a lack of field survey data on those carbon pools. Future research can conduct field surveys on belowground biomass and include the belowground carbon pools in carbon emission estimation. Fourth, future research should investigate the causes of the recent increase in shifting cultivation, which requires field surveys.

5. Conclusion

Our research provides a national-level analysis of spatial-temporal patterns and estimation of carbon dynamics of shifting cultivation in Laos. Our analysis shows that shifting cultivation in Laos has been expanding and intensifying, particularly in the recent five years. The practice of shifting cultivation has become increasingly intensive as the length of the fallow periods has been continuously shortening. Combining GEDI data with shifting cultivation maps and area estimates, carbon emissions from shifting cultivation can be quantified. The net carbon emissions from shifting cultivation declined in the past but increased recently. This study not only supports REDD+ reporting for Laos but also demonstrates a method of tracking carbon dynamics in shifting cultivation landscapes.

Data availability

The datasets are publicly available and can be downloaded from:
https://doi.org/10.5281/zenodo.7782782

Google Earth Engine applications to visualize the datasets: https://github.com/shijuanchen/shift_cult

Map products visualization: https://sites.google.com/view/shijuanchen/research/shift_cult

Acknowledgment

This research was funded by the NASA Land-Cover and Land-Use Change Program (grant number: 80NSSC18K0315), the NASA Carbon Monitoring System (grant number: 80NSSC20K0022), and USGS Landsat Science Team Program for Better Use of the Landsat Temporal Domain: Monitoring Land Cover Type, Condition and Change (grant number: G12PC00070). The authors are grateful to the editors and two anonymous reviewers for their insightful and constructive comments, which greatly helped to improve this paper.

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