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Armed conflict and mining induced land-use transition in northern Nimba County, Liberia

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A R T I C L E   I N F O

A B S T R A C T

This study determined pre-conflict, conflict and post-conflict land use change and ana-lysed the impact of armed conflict on the intensity of land use change in northern Nimba County. Landsat images of 1986, 1990, 2002 and 2016 were classified into four dominant land use categories in the study area: cultivation, mine, forest and settlement using maximum likelihood classification algorithm. Land use change was determined by deriving pre-conflict, conflict and post-conflict transition matrix. Based on the transition matrix, gain, loss, persistence, total change, swap and absolute value of net change were computed. Intensity of land use change was determined using the intensity analysis approach. The results show that the intensity of land use change was slow during the conflict but increased sharply after the conflict. Pre-conflict, conflict and post-conflict mine occupied 0.63%, 0.78% and 17.68%, forest cover accounted for 71.08%, 69.26% and 56.42% and settlement was 1.99%, 1.96% and 25.63% respectively. Similarly, pre-conflict, conflict and post-conflict uniform intensity of land use change was 4.09%, 1.51% and 5.01% respectively. Recent forest cover loss is primarily driven by sustained settlement expan-sion. The implications of rapid post-conflict settlement increase and forest loss in northern Nimba County include threat to habitat in a globally important biodiversity hotspot, increasing pressure on available agricultural land because of increasing population and potential exposure of the population to pollution from increase in mining activities. Therefore, more effective forest management strategies need to be developed to mitigate the prevailing trend. The use of intensity analysis has provided insights on the patterns and processes of pre-conflict, conflict and post-conflict land use change in a biodiversity hotspot. This is important for defining effective conservation goals, planning sustainable conservation strategies and deploying relevant tools for forest conservation and gover-nance in conflict and conflict prone areas.

1. Introduction

Tropical rainforest degradation and loss have been of concern to scientists, environmental resources managers, and decision-makers because of the importance of the rainforest to human sustenance (Butsic et al., 2015; Kassa et al., 2017;

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Olanrewaju et al., 2018; Reddy et al., 2013). Studies have linked deforestation to the demand for ecosystem goods and services, agricultural expansion, urban sprawl and illegal timber extraction arising from rapid population increase (Bax et al., 2019; Enaruvbe and Atafo, 2019; Laurance et al., 2014). It is however likely that the increasing demand for food, raw materials, infrastructure and mineral resources may lead to scarcity of natural resources and limit the ability of the rainforest to provide ecosystem goods and services. The scarcity of resources, in the face of increasing demand, results in a scramble for available resources which could trigger, and in some instances, aggravate armed conflict and accelerate deforestation (Brown, 2010; Butsic et al., 2015; Downey et al., 2010; Machlis et al., 2008; Rustad et al., 2008; Sánchez-Cuervo and Aide, 2013; Swatuk, 2007; van Solinge, 2008). The competition for the control of scarce resources leads to socio-political changes that play important roles in shaping observed pattern and configuration of the natural environment (Austin et al., 2017; Hosonuma et al., 2012; Prokop, 2018; Rudel, 2013; Warren-Thomas et al., 2018) in many countries.

Historically, natural resources extraction is widespread in Africa (Elbadawi and Sambanis, 2000; Marais et al., 2018; Omotehinse and Ako, 2018). This is because many African societies depend on natural resources for their survival and wellbeing (Billon, 2001). Competition for access to the natural resources often leads to armed conflict. For instance, although studies suggest that the effects of armed conflicts on environmental resources could be positive or negative (Achour et al., 2018; Butsic et al., 2015; Lawrence et al., 2015), it is evident that armed conflicts have immense and far-reaching impacts on the social, economic conditions and the natural environment in many countries. This has prompted studies into the effects of armed conflicts on vegetation (Abdo, 2018; Black and Sessay, 1997; Leiterer et al., 2018), biodiversity (Bax et al., 2019; Brito et al., 2018; Hanson, 2018; Hanson et al., 2009; Lawrence et al., 2015), and socio-economic conditions (Black and Sessay, 1997; van Solinge, 2008) of affected regions. Unfortunately, armed conflicts have persisted in many African countries, including Liberia, Democratic Republic of Congo, Tunisia, Angola, South Sudan, Guinea and Cote d'Ivoire, in recent decades.

The Liberian civil war, which started as a social disturbance in the early 1980s, quickly snowballed into armed conflict in 1989 and lasted for fourteen years. The conflict consumed many lives and displaced about a million others (Black and Sessay, 1997). Studies suggest that proceeds from the sale of natural resources was used to sustain the conflict, not only in Liberia but in neighbouring Sierra Leone (Swatuk, 2007). Apart from its rich forest resources, Liberia is a mineral-rich country with large deposits of iron-ore, gold and diamond. In addition, the country hosts the biodiversity-rich transnational Nimba mountain range that is located in the northeastern part of Liberia, western part of Cote d'Iviore and southeastern Guinea. The mountain range is also popular for mineral extraction, hosting mining towns such as Yekepa and Camp Four on the Liberian side. The activities of mining companies and forced migration triggered by the armed conflict increased the pressure on the natural environment leading to substantial forest degradation and habitat loss. The pressure on the forest and the concomitant threat to wildlife and vegetation in the area prompted the creation of the Nimba Nature Reserve after the Liberian civil war. This was aimed at forest restoration and conservation.

The impact of armed conflict on vegetation and other forest resources may be aggravated and accelerated in the presence of natural resources such as forest products and mineral resources because different factions in a conflict, may be fighting for different interests which may include control of resources (Downey et al., 2010; Lawrence et al., 2015). However, reports on the relationship between armed conflict and deforestation have been inconsistent. For instance, Butsic et al. (2015), analysed the relationship between armed conflict, mining and forest protection in Democratic Republic of Congo between 1990 and 2010 using instrumental variables approach. They reported that conflict and mining concession increased forest cover loss but forest protection reduced the rate of forest loss. Gorsevski et al. (2012), also showed that forest reserve slowed down the rate of forest loss during and after armed conflict in the eastern Afromontane forest region in the South Sudan-Ugandan border. Many studies however suggest that protected areas are vulnerable to migrants pressure as displaced persons may have to depend on the forest for their livelihood (Black and Sessay, 1997; Hassan et al., 2018; Leiterer et al., 2018; Ordway, 2015). Ordway et al. (2017), observed a concentration of forest loss in forest reserve in Rwanda resulting in more severe forest loss in the reserve than outside. They attributed the high forest loss in the protected area to the influx of migrants to communities around the reserve. In addition, Sánchez-Cuervo and Aide (2013), reported that although there was forest recovery in Columbia during a conflict period because of forced migration from conflict prone areas, forest loss increased in areas dominated by armed groups, gold mines and grazing fields.

In general, political instability tends to have negative impacts on social and economic conditions and may accelerate forest degradation and loss in many instances. This is because law enforcement mechanisms become dysfunctional during armed conflicts as migrants and displaced persons may depend more on the forest for food and other resources. However, although some studies have shown that forest reserves may reduce forest degradation and loss in some cases, limited attention has been paid to the processes that could lead to pre-conflict, conflict and post-conflict patterns of land use change in mineral-rich biodiversity hotspots.

Armed conflict and land use activities such as mining and conservation may interact to influence the processes of land use transition and the severity of forest conversion in conflict zones. Although different methods exist for analysing the relationship between armed conflicts and the environment, the processes influencing the nature of the relationship have not been adequately examined and are therefore poorly understood. The limited understanding of these processes of land use change in conflict zones is due to poor access and the difficulty of clearly determining the spatial or temporal boundaries of these zones during conflicts (Gorsevski et al., 2012). This limited understanding therefore leads to poorly defined post-conflict conservation goals, inadequate conservation planning and deployment of unsustainable conservation strategies.

Multi-temporal remote sensing data offers a way of analysing pre-conflict, conflict and post-conflict land use changes. However, rather than a mere comparison of maps to ascertain the changes, determining the processes that lead to observed patterns in biodiversity-rich conflict zones such as Nimba forest is crucial if deeper insight is desired. The method of Intensity Analysis (Aldwaik and Pontius, 2012) is widely accepted for analysing the patterns and processes of land use and ecological changes in different ecological zones (Akinyemi et al., 2017; Asubonteng et al., 2018; Villamor et al., 2014). The method provides critical insights into the processes driving the patterns of change in an area. It is therefore a reliable tool for the analysis of remote sensing data to gain insight into the patterns and processes of land use change in areas affected by armed conflicts. This study will determine pre-conflict, conflict and post-conflict land use change in northern Nimba County using remote sensing data, and analyse the influence of armed conflict on the Intensity of land use change in northern Nimba County. This will provide insight into the patterns and processes of land use change in conflict zones, which is important for scientist, forest managers, planners and decision-makers to adequately define conservation goals, plan and deploy sustainable conservation strategies in conflict and conflict prone areas.

2. Materials and methods

2.1. Study area

The study area (Fig. 1), comprising of three districts - Gbehlay-Geh, Yarmein and Sanniquellie-Mahn - in the northern part of Nimba County, covers an area of 1639.57 km^2. Rivers Khan and Dayea drain the area with many creeks that drain into St. John River. St. John River forms the boundary of the western and northern part of Nimba County with Guinea and the eastern part of the County is bounded by Cote d'Iviore. Apart from Sanniquellie, Yekepa, Camp Four and a few other towns, the area is largely rural with a total population of about 80,000 inhabitants according to the 2008 National Population and Housing Census (LISGIS, 2009). Similar to other parts of Liberia, more than 70% of the local population in northern Nimba is engaged in slash-and-burn subsistence farming practices and hunting activities (Bene et al., 2013; Kofron and Chapman, 1995).

Climate in Nimba County, like the whole of Liberia, is tropical rainforest. There are two seasons, the dry season starts in November and ends in April with March and September being the driest and wettest months respectively. Mean annual rainfall varies from the coast to the hinterland. Areas around the coast could have mean rainfall of over 4000 mm but rainfall in Yekepa is only about 1800 mm. However, because of the altitude in Mount Nimba area, rainfall could be above 3200 mm. Minimum and maximum mean monthly temperature is 23 °C and 27.5 °C respectively in northern Nimba. Biodiversity in northern Nimba is of global importance as it hosts a large number of endemic species including tree species such as *Fagara spp, Terminalia spp, Erythrophleum ivorense, Uapaca guineensis,* and *Strombosia glaucescens* (ArcelorMittal, 2010). Endemic wildlife species in northern Nimba County include the viviparous Nimba toad (*Nimbaphrynoides occidentalis*) and the rare and endangered Nimba otter shrew (*Micropotamogale lamottei*).

2.2. Data acquisition and pre-processing

This study determines pre-conflict, conflict and post-conflict land use change using remote sensing data, and analyse changes in the Intensity of land use change resulting from armed conflict and mineral extraction activities in a biodiversity important and mineral-rich area in northern Nimba County in Liberia. Therefore, in order to determine the impact of armed conflict on land use change, and at the same time avoid cloud cover, which usually limits the usefulness of optical remote sensing data for environmental analysis (Kuenzer et al., 2014), we acquired dry season images of the study area from the archives of the United States Geological Surveys. The data acquired are pre-conflict (Landsat TM images of 14 January 1986), conflict (27 December 1990 and ETM$^+$ image of 18 January 2002), and post-conflict (OLI_TIRS image of 2 February 2016) images. Pre-processing procedures, performed in ENVI 5.1 software, include radiometric calibration, atmospheric corrections and dark object subtraction to ensure that changes observed from image analyses is at the earth surface and not because of variation in atmospheric composition or differences in solar angle and illumination (Enaruvbe and Atafo, 2019; Munroe et al., 2007).

2.3. Classification and error assessment

Supervised image classification technique was applied to generate the land use categories using maximum likelihood classification algorithm in ENVI 5.1 software. The study area was classified into four dominant categories - cultivation, mine, forest and settlement-based on a total of 973 randomly generated point data from a combination of Google Earth images, existing maps, the second author's knowledge of the study area and field survey conducted in February 2018. Table 1 shows the definition of land use classes in the study area.

In this study, assessment of classification error was based on 30% of the data obtained from a combination of field survey, existing maps, the second author's knowledge of the study area and Google Earth image of the study area. This same set of data was used for accuracy assessment of all the images because of the difficulty of obtaining reliable historical field data of each of the period (Enaruvbe and Pontius Jr., 2015).
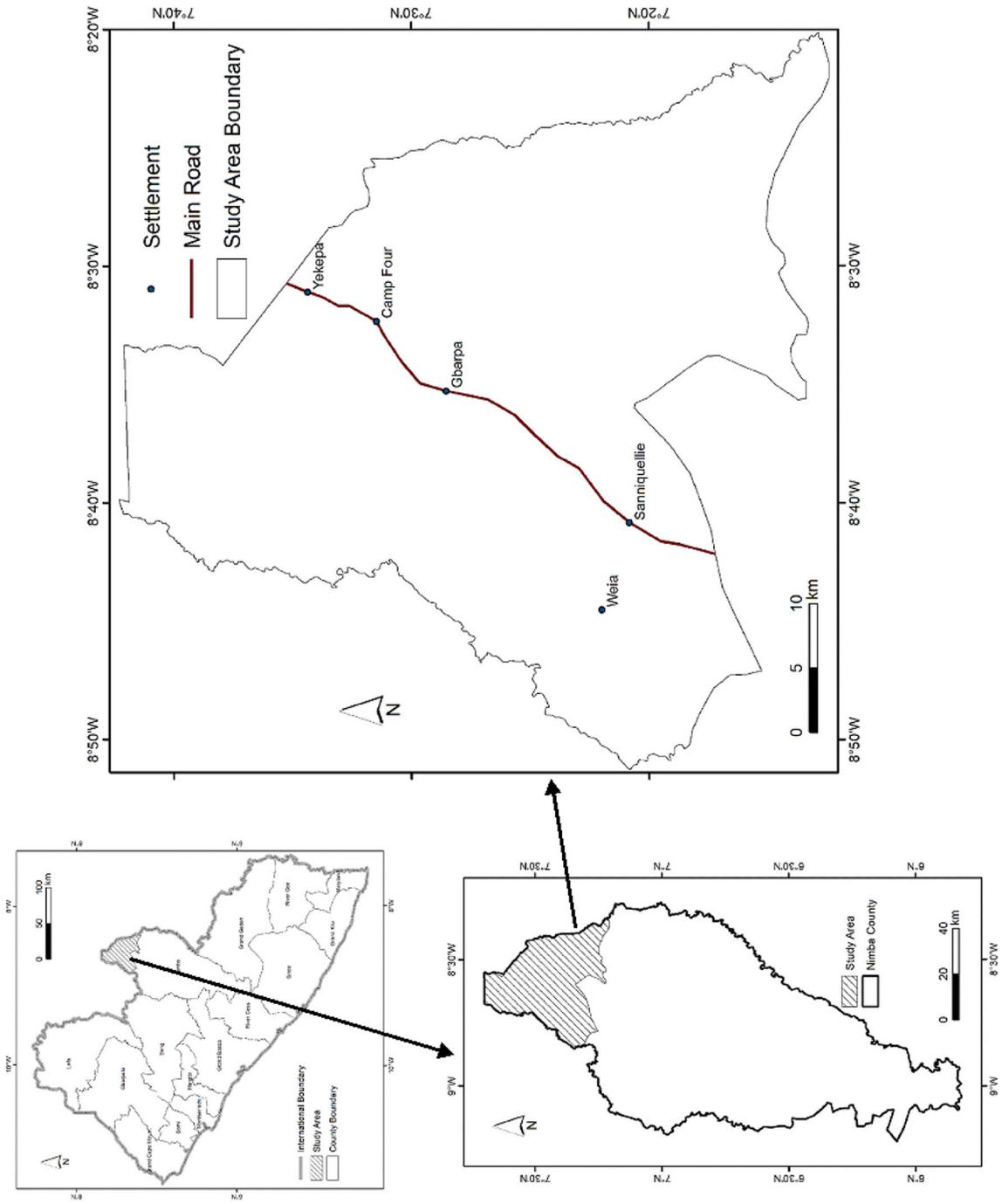
Fig. 1. The study area in Nimba County, Liberia.

Table 1
Definition of land use categories in northern Nimba County, Liberia.

Land use category	Definition
Mine	Areas dominated by mines. This includes active and abandoned iron ore, gold and diamond mines. It also includes bare surface around the mines
Forest	This includes forest reserve, other forest areas with dense crown cover and forest areas of not less than 20% canopy cover.
Settlement	This category includes built up areas such as roads, cities, towns and villages, bare surface within and around the settlement
Cultivation	This includes plantations such as rubber, oil palm and other tree plantations, areas dominated by subsistence farming, fallow land and abandoned farmlands (less than 20% canopy cover).

2.4. Change detection and intensity analysis

Change detection is an important part of environmental monitoring, analysis and management. There are many approaches for analysing change in the landscape which can be categorized as post-classification comparison and direct change detection methods (Gorsevski et al., 2012). However, post-classification comparison has become more common in the last few decades (Ayele et al., 2018; Mengistu and Salami, 2007; Peiman, 2011). In order to determine the pattern and processes of forest change in the study area, we overlaid successive image pairs (1986−1990, 1990−2002, 2002−2016), using CROSS-TAB module in Idrisi Selva software, to derive transition matrix of each period. The transition matrix is useful for the comparison of image pairs because it provides the areas of land use by categorical transition between two time points (Manandhar et al., 2010). The rows of the matrix display the proportion of each category at the initial time and the columns displays the proportion of the category at the final time. The on-diagonal values indicate persistence of each category during the period being examined while off-diagonal values show the amount of transition of a category to another category within the period. The row total at the right end of the matrix is the proportion of the landscape by category during the initial time point and the column total at the bottom of the matrix is the proportion at the final time point. Pontius Jr et al. (2004), has shown that extending the transition matrix by computing swap and net change could provide deeper insight about the nature of land use change in an area. On this basis, we computed gain, loss, total change, swap and absolute value of net change using the method described in Pontius et al. (2004).

We determined pre-conflict, conflict and post-conflict intensity of land use change in the study area using the intensity analysis approach described by Aldwaik and Pontius (2012). This method determines the intensity of land use change for one or more image pairs at three levels: interval, category and transition intensity using information contained in the transition matrix as input.

3. Results

3.1. Assessment of classification error

The level of error in a map derived from remote sensing data depends on several factors including the quality of the data and experience of the analyst. Map errors, if unreported, limit the reliability of decisions made on the basis of such maps (Shao and Wu, 2008). It is generally assumed that error level of not more than 15% is acceptable for maps used in environmental monitoring and management (Foody, 2002). In this study, commission error of cultivation is above the 15% acceptable standard (Table 2). However, in spite of the high error of commission in cultivation class, the overall error level in this study is adequate for analysis of the impact of armed conflict and mining activities on land use and forest resources. The overall error of the maps is 9.43% in 1986, 13.5% in 1990, 9.43% in 2002 and 4.83% in 2016.
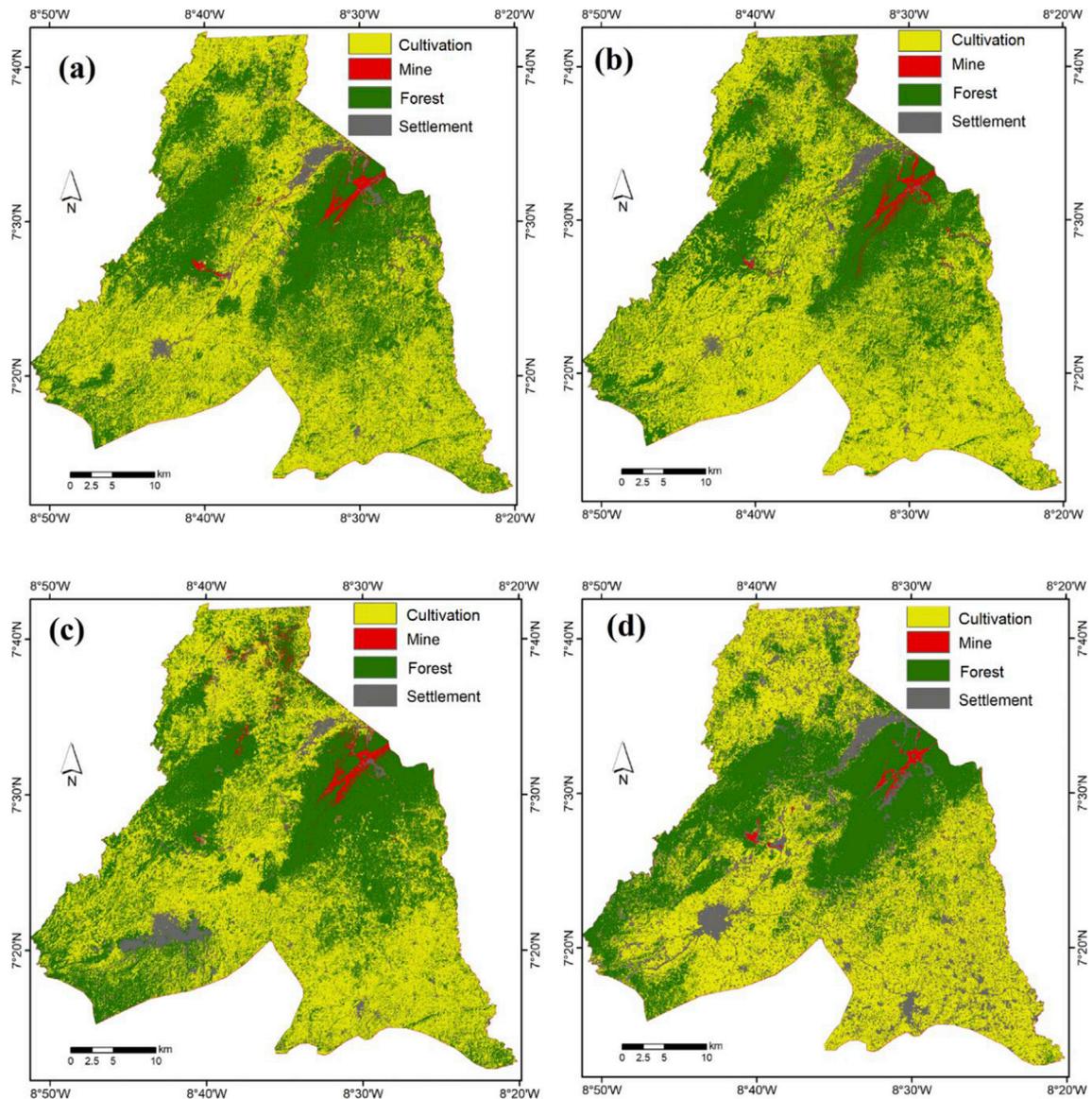
3.2. Land use change in northern Nimba County

In this study, we determined land use change by computing total area, gain, loss, total change, swap and absolute value of net change for each time-interval (1986−1990, 1990−2002 and 2002−2016) using data derived from the cross-tabulation of land use maps of the study area following the method described by Pontius et al. (2004). Fig. 2 shows the spatial pattern of

Table 2
Summary of land use classification error in maps of northern Nimba County, Liberia.

	1986		1990		2002		2016	
	Ec (%)	Eo (%)	Ec (%)	Eo (%)	Ec (%)	Eo (%)	Ec (%)	Eo (%)
Cultivation	36.7	11.8	41.2	6.2	36.9	5.1	25.4	1.1
Mine	5.7	2.5	19.4	3.3	4.4	8.3	0.0	0.0
Forest	2.9	11.0	1.6	17.4	0.5	11.0	0.2	8.2
Settlement	2.0	6.5	8.4	11.9	6.3	8.5	0.8	0.0

Ec = Commission error; Eo = Omission error. Overall error: 1986 = 9.43%; 1990 = 13.5%; 2002 = 9.43%; 2016 = 4.83%.

Fig. 2. Land use pattern at Northern Nimba County, Liberia in (a) 1986; (b) 1990; (c) 2002; and (d) 2016.

land use and Fig. 3 shows the spatial pattern of land use gain, loss and persistence in pre-conflict (1986—1990), conflict (1990—2002) post-conflict (2002-2016) period in northern Nimba County. Table 3 is a summary of the land use change (%) in the study area. The table indicates that forest loss was reversed in northern Nimba during the armed conflict. However, there has been a substantial loss of forest since the end of the conflict in 2002. Between 2002 and 2016, forest accounted for 27% of total change, 13% swap and 15% of net change in the landscape. In addition, mineral extraction activities and settlement expansion rate have increased sharply since the end of the conflict. For instance, although absolute value of net change in mine accounted for barely 0.16% in 1986—1990 period and 0.03% in the 990—2002 period, it increased more than 100-folds to 17% during 2002—2016. Settlement shows a similar pattern in the area. This pattern indicates an improvement in economic activities which also increases pressure on forest cover, forest resources and biodiversity. Lambin et al. (2003), argued that changing opportunities created by markets, outside policy interventions and changes in social organization and attitude increases pressure on land cover. The increasing pressure on forest cover in northern Nimba County may be attributed to changes in political organization and increasing population pressure following the return of peace in Liberia. However, the changes in cultivation appear unrealistic because of the high error margin observed in the maps (Table 2). Shao and Wu (2008), noted the importance of considering inherent errors in remote sensing derived map before they are used in decision-making process.
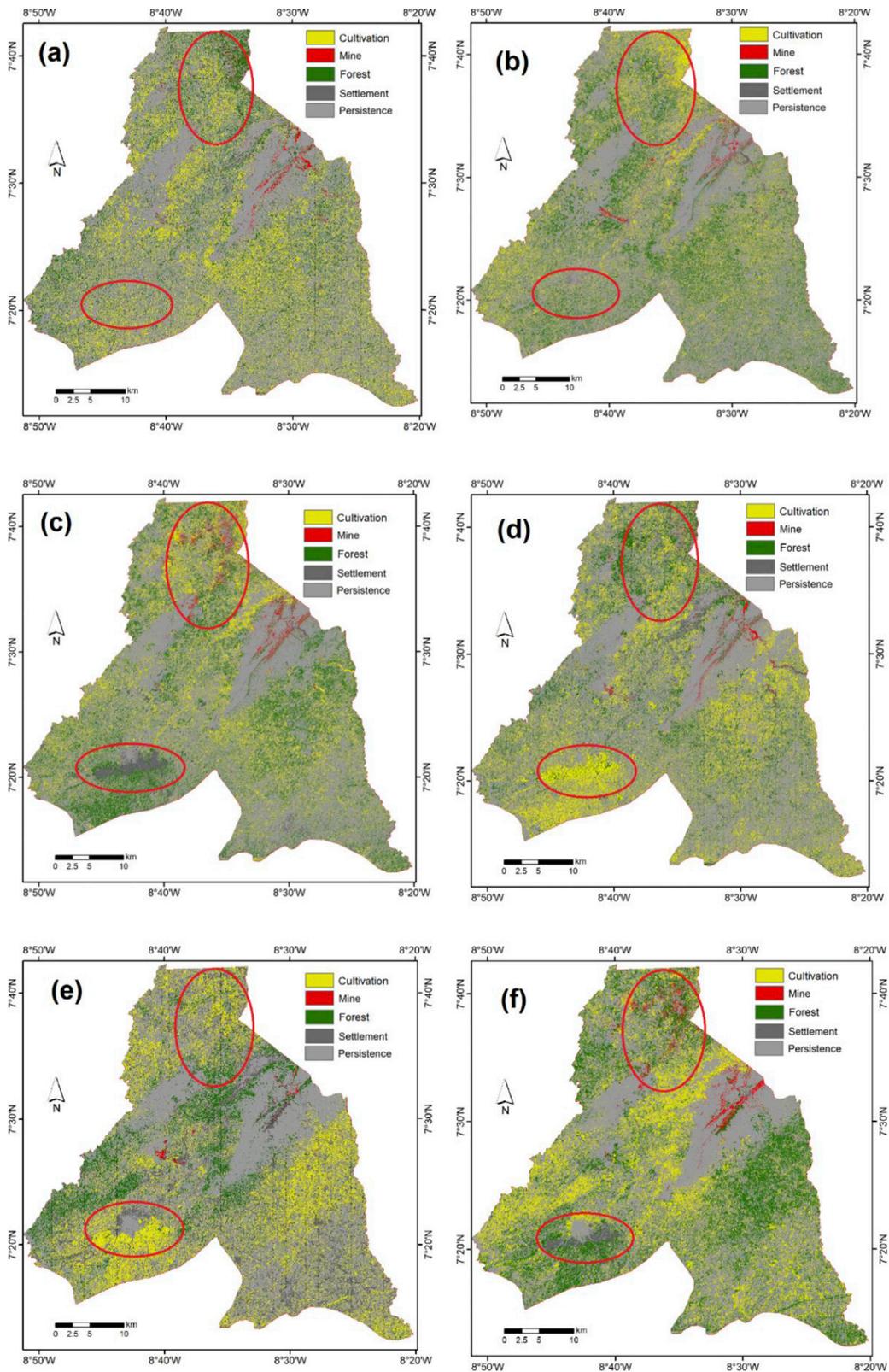
Fig. 3. Pattern of land use change in northern Nimba County, Liberia: (a) gains and persistence, 1986–1990, (b) losses and persistence, 1986–1990 (c) gains and persistence, 1990–2002 (d) losses and persistence, 1990–2002 (e) gains and persistence, 2002–2016; (f) losses and persistence, 2002–2016.

Table 3
Land use change (%) pattern in northern Nimba County.

| 1986−1990		Total 1986	Total 1990	Gain	Loss	Total change	Swap	Absolute value of net change
(a)	Cultivation	26.30	28.00	8.40	6.70	15.10	13.40	1.70
	Mine	0.63	0.78	0.53	0.37	0.90	0.74	0.16
	Forest	71.08	69.26	6.48	8.31	14.79	12.96	1.83
	Settlement	1.99	1.96	0.95	0.99	1.94	1.90	0.04
	Total	100.00	100.00	16.36	16.37	16.37	29.00	3.73
1990−2002		Total 1990	Total 2002	Gain	Loss	Total change	Swap	Absolute value of net change
(b)	Cultivation	28.00	25.32	6.88	9.58	16.46	13.76	2.70
	Mine	0.78	0.80	0.53	0.50	1.03	1.00	0.03
	Forest	69.26	71.02	8.67	6.90	15.57	13.80	1.77
	Settlement	1.96	2.86	2.03	1.13	3.16	2.26	0.90
	Total	100.00	100.00	18.11	18.11	18.11	30.82	5.40
2002−2016		Total 2002	Total 2016	Gain	Loss	Total change	Swap	Absolute value of net change
(c)	Cultivation	25.32	0.27	0.25	25.30	25.55	0.50	25.05
	Mine	0.80	17.68	17.36	0.48	17.84	0.96	16.88
	Forest	71.02	56.42	6.30	20.90	27.20	12.60	14.60
	Settlement	2.86	25.63	24.55	1.78	26.33	3.56	22.77
	Total	100.00	100.00	48.46	48.46	48.46	17.62	79.30

3.3. Intensity of pre-conflict, conflict and post-conflict land use change in northern Nimba County

In this study, we analysed the influence of armed conflict on intensity of land use change using the widely used (Akinyemi et al., 2017; Asubonteng et al., 2018; Enaruvbe and Pontius Jr., 2015) method of intensity analysis proposed by Aldwaik and Pontius (2012). The method uses the transition matrix as input for detailed analysis of land cover change. We computed intensity analysis at three levels: interval, category and transition using the transition matrix as input in the intensity analysis programme developed by Aldwaik and Pontius (2012). Figs. 4−6 show pre-conflict, conflict and post-conflict intensity of land use change at interval, category and transition levels respectively in northern Nimba County.
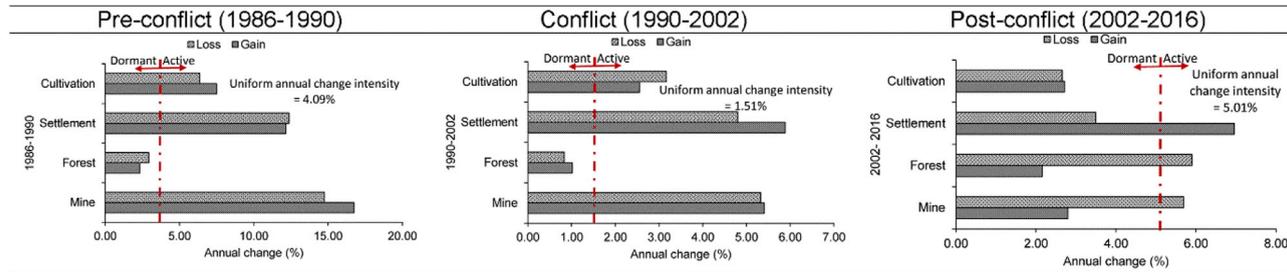
The intensity of land use change in northern Nimba County is generally increasing. The sharp increase in settlement between 2002 and 2016 (Table 3) suggests that the general increase in intensity of land use change is being driven by a sustained high intensity of settlement gain (Fig. 6). This sustained settlement increase may be related to the presence of large-scale mining concession companies that provide employment opportunities for local inhabitants and migrants alike.

Fig. 4 indicates that although pre-conflict annual intensity of land use change was fast, it slowed during the conflict period (1990−2002). However, post-conflict intensity has accelerated beyond the pre-conflict annual intensity of land use change in the study area. Intensity of land use change in northern Nimba County increased from about 4% in 1990 to over 5% in 2016 with a uniform intensity of 3.49%. Similar pattern is observed at the category level where uniform intensity reduced from 4% before the conflict to less than 2% during the conflict and increased to 5% after the conflict.

Fig. 6 shows the transition intensity of land use change in northern Nimba County. The figure indicates that although the overall pattern of transition of cultivation and forest is unaffected by armed conflict, the intensity of land use change has decreased considerable over the years. Similarly, although the intensity of mine reduced overtime, mine gain targeted forest during the conflict. This indicates that mining activities may have increased in forested areas while the conflict lasted. In contrast, however, the intensity of settlement change slowed slightly during the conflict, reducing from 0.24% pre-conflict to 0.17% during the conflict. Post-conflict intensity of settlement change however soared to over 4% and targeted forest. The
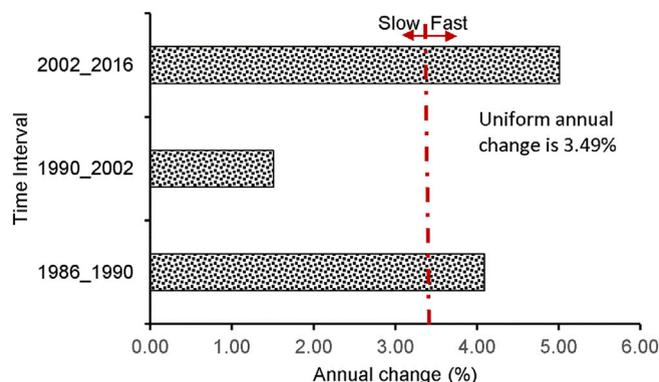
Fig. 4. Pre-conflict, conflict and post-conflict interval intensity of land use change in northern Nimba County, Liberia.

Fig. 5. Pre-conflict, conflict and post-conflict category change intensity of land use in northern Nimba County, Liberia.
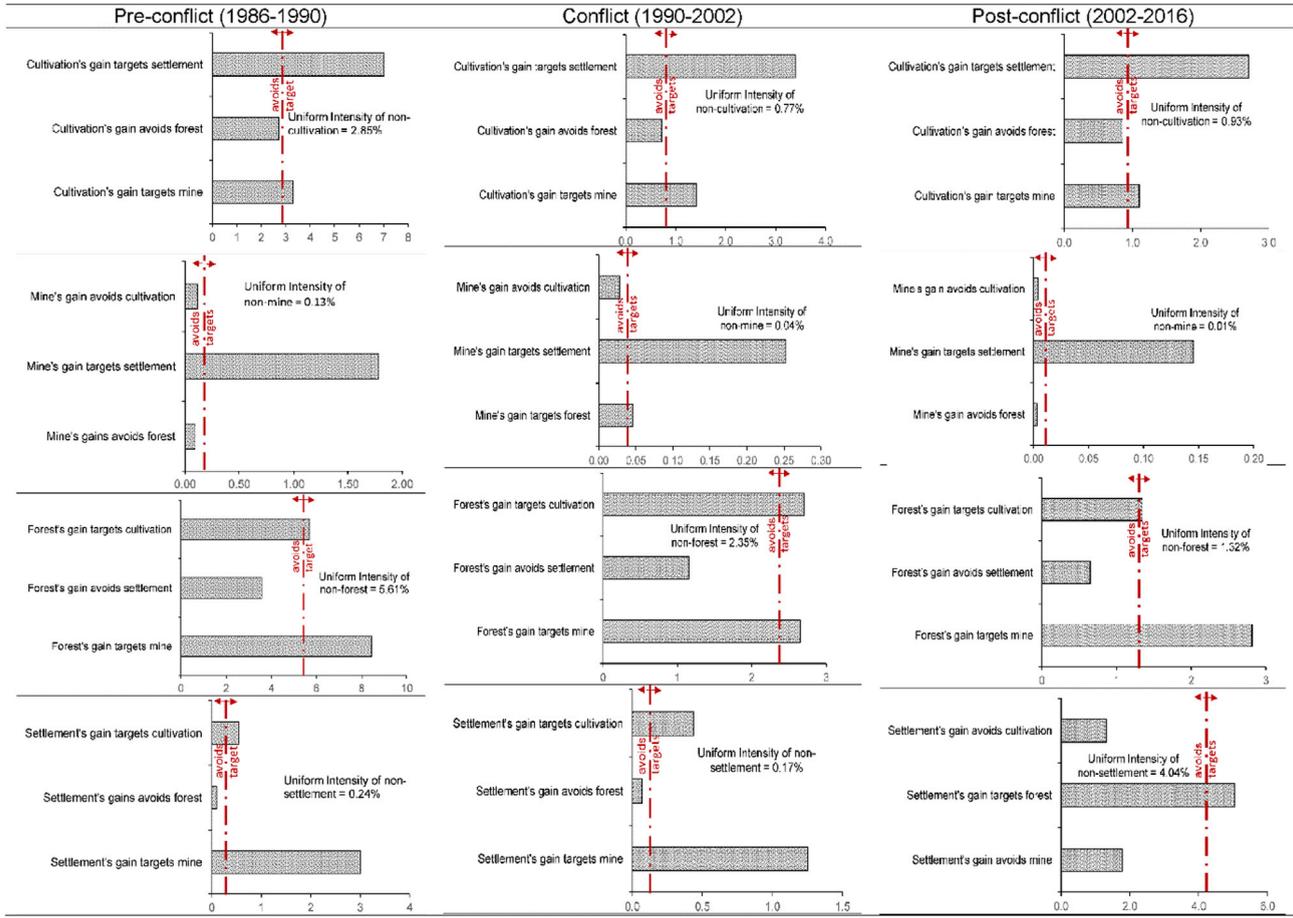
Fig. 6. Pre-conflict, conflict and post-conflict intensity of land use transition in northern Nimba County, Liberia.

rapid post-conflict settlement growth may be because of returnees, changing opportunities created by markets and enhanced post-conflict economic potentials.

4. Discussion

4.1. Error assessment

The use of remote sensing and geographic information system (GIS) for the analysis and monitoring of the impacts of conflicts on environmental resources such as forest resources (Achour et al., 2018; Hassan et al., 2018), mineral extraction and mining (Bax et al., 2019; Butsic et al., 2015; van Solinge, 2008), plant and wildlife conservation (Mucova et al., 2018; Ordway, 2015) and soil degradation (Berhe, 2007) is gaining increasing level of importance. This trend may be related to the difficulty of accessing active conflict zones and the lack of defined spatial and temporal boundaries during conflicts (Gorsevski et al., 2012). Moreover, the impact of armed conflicts on society and the natural environment persist long after it is declared over. However, in spite of the increasing importance of remote sensing and GIS for environmental monitoring in conflict zones, all classification of remote sensing data is subject to various types of error.

The result of this study shows a consistently high commission error in cultivation category. This high commission error implies overestimation of cultivation in the study area. Land use classification errors may be because of difficulty in separating classes that exhibit similar spectral signatures such as matured plantation agriculture and forest (Enaruvbe and Atafo, 2019). In addition, there are evidence that accuracy may be influenced by the characteristics of the terrain in an area. Areas with mountainous and rugged terrains appear to be more prone to classification errors than relatively more even terrains. For instance, Gorsevski et al. (2012), reported omission error of 42.86% and Achour et al. (2018), reported omission error of between 26.2% and 29.7% in mountainous areas of South Sudan-Ugandan border and in Tunisia respectively. Similarly, Sánchez-Cuervo and Aide (2013), reported omission error of 63.7% and commission error of 27.5% in areas of remarkable elevation difference in Columbia.

4.2. Land use change in northern Nimba County

The dependence of many African societies on the extraction of natural resources have often triggered armed conflict as rival groups compete for control of dwindling resources. Studies (Butsic et al., 2015; Gorsevski et al., 2012; Swatuk, 2007) have therefore examined the relationship between armed conflict, mineral extraction and deforestation in the tropical rainforest. However, there have been inconsistent reports about the nature of the relationship leading to poor understanding of the issues. In this study, we determined pre-conflict, conflict and post-conflict land use change and the influence of armed conflict on the Intensity of land use change in northern Nimba County. Our results showed that although settlement growth and forest loss reduced during the conflict, there was a sharp increase in mining activities, rapid post-conflict settlement expansion and increasing forest loss (Table 3). This findings confirm that reported by Wilson et al. (2017), who found that recent growth in the mining sector in Liberia is leading to environmental degradation. Our results imply that armed conflict may limit access to natural resources such as forest resources thereby leading to some forest recovery but negatively impact social and economic conditions of societies. Although Solomon et al. (2018), reported that armed conflict hinders economic growth and social development, the results of this study indicate that armed conflict may promote forest and habitat recovery. This is because in spite of recent efforts of the Liberian government to conserve forest in Nimba County by the creation of Nimba nature reserve, deforestation has been on the rise since the end of the conflict in 2002. The rapid increase in post-conflict forest loss may be because of poorly defined forest policies and deployment of unsustainable forest management and conservation strategies. Achour et al. (2018), argued that post-conflict deforestation appears to be higher because forest laws are widely violated during conflict period. They reported a three-fold increase in post-conflict forest loss in Tunisia. In addition, increase in opportunities created by market and enhanced economy resulting from political stability could increase demand for goods and services leading to more pressure on natural resources. However, mining activities has been shown to complicate forest loss in conflict zones (Sánchez-Cuervo and Aide, 2013). Butsic et al. (2015), observed that deforestation was higher in areas with high mining potential than in areas with low potential. Our results showed that mine gain targeted forest during the conflict (Fig. 6). This finding suggests that some mining activities were on-going in the forest during the conflict (Fig. 3(c)). The competition for access to mining resources may have contributed to the conflict in the first instance (Swatuk, 2007). Alternatively, mining activities during the conflict may have been a survival strategy by those who were economically displaced by the conflict as they have to depend on available natural resources for survival.

4.3. Intensity of pre-conflict, conflict and post-conflict land use change

Our results showed that intensity of land use change in the study area is generally increasing. The increase in the intensity of land use change could be attributed to sustained settlement gain in the study area during the period of this study (Fig. 6). Intensity of settlement gain and loss were active in pre-conflict and conflict period. Pre-conflict gain intensity of settlement was active at about 13%. However, the loss intensity reduced to 5% and gain intensity dropped to 6% during the conflict. Pre-conflict uniform intensity of land use change was 4% but it reduced to 1.5% during the conflict. This suggests a large-scale forced migration during the conflict. This is evident in Fig. 3(c) where settlement gained a large area and a simultaneous

loss of cultivation during the conflict (Fig. 3(d)). This finding is similar to that reported by Hassan et al. (2018), who noted a rapid increase in refugee camps in Bangladesh following the Rohingya refugee crisis. They showed that the rapid expansion of the camps resulted in forest loss and degradation around the camps. In addition, Black and Sessay (1997), reported that the influx of refugees into the forest region of Guinea resulted in the shortening of fallow period and apparent shortage of farmland in the area. This perceived scarcity of agricultural land could threaten existing forest as it increases the pressure on land for agricultural purposes in the area. This implies that conflict-induced forced migration could complicate the stress on forest resources and may lead to forest loss. The increasing intensity of land use change in northern Nimba County is a threat to plants and animal species as it could lead to habitat fragmentation, degradation and loss. Studies indicate that settlement growth around forest and protected areas generally pose threats to biodiversity (Enaruvbe and Atafo, 2019; Mucova et al., 2018). The implications of rapid post-conflict settlement increase and forest loss in northern Nimba County include threat to habitat in a globally important biodiversity hotspot, increasing pressure on available agricultural land because of increasing population, and pollution from increase in mining activities in northern Nimba County. The results of this study have provided better insight into pre-conflict, conflict and post-conflict land use change patterns and processes in northern Nimba County which could also apply in other biodiversity-rich conflict zones. This insight is important if scientist, forest resources managers, planners and decision-makers hope to adequately define conservation goals, plan sustainable conservation strategies and deploy adequate tools for conservation of endemic plants and animal species in conflict and conflict prone areas.

In spite of the insight gained from this study however, post-conflict land use change may be influenced by other deep-rooted socio-cultural factors that may promote deforestation and biodiversity loss in northern Nimba which this study has not highlighted. Therefore, further studies should focus on the social and cultural practices that may contribute to post-conflict forest loss and their implications on biodiversity in conflict and conflict prone zones.

5. Conclusion

In this study, we determined pre-conflict, conflict and post-conflict land use change and examined intensity of land use change in northern Nimba County. Our results showed that although, settlement growth and forest loss reduced during the conflict, there was a sharp post-conflict increase in mining activities, rapid settlement expansion and increasing forest loss. We observed that armed conflict might promote forest recovery. However, post-conflict intensity of land use change increased rapidly because of a sustained settlement gain. The implications of rapid post-conflict settlement increase and forest loss in northern Nimba County include threat to habitat in a globally important biodiversity hotspot, increasing pressure on available agricultural land because of increasing population, and potential exposure of the population to pollution from increase in mining activities. Therefore, strategies for a more effective forest management need to be developed to mitigate the prevailing trend.

The use of remote sensing data and intensity analysis approach have provided a clear understanding of pre-conflict, conflict and post-conflict patterns and processes of land use change in a globally important biodiversity hotspot. This is important for adequately defining conservation goals, planning sustainable conservation strategies and deploying adequate tools for conservation of endemic plants and animal species in conflict and conflict prone areas. However, further work is required to examine the social and cultural practices that may promote deforestation and biodiversity loss in conflict and conflict prone areas.

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