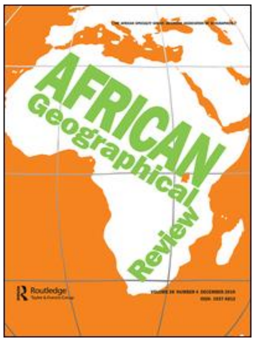

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Effects of anthropogenic activities on land-use dynamics in an upland tropical evergreen forest in Ghana

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ABSTRACT

The Atewa Range Forest Reserve (ARFR) in Ghanais threatened by anthropogenic activities. This study used geospatial techniques to assess the effects of human activities on land use and land cover (LULC) dynamics in ARFR using Landsat satellite images of 1986, 1991, 2006 and 2016. Estimated Normalized Differential Vegetation Index showed a continuous decline in LULC, signifying increasing stress on vegetation in ARFR. Between 1986 and 2016, the rainforest reduced from 345.83km^2 to 183.48km^2; logged land declined from 324.52km^2 to 186.21km^2; farmland increased from 328.43km^2 to 384.68km^2; and settlement expanded from 110.48km^2 to 354.91km^2, respectively.

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Land transition; deforestation; rainforest; anthropogenic activities; logging; NDVI

1. Introduction

Tropical forests occupy 12% of the world's land surface and play a crucial role in global biogeochemical cycles (Townsend et al., 2011). Tropical forests have a significant influence on weather patterns, freshwater, biodiversity, food, and human health in countries where they are found (Brandon, 2014). They serve as habitats for more than half of the world's species (Morris, 2010). Despite this, deforestation and degradation have reduced tropical forests to less than 5% of the total land surface of the Earth (Brandon, 2014). Harper et al. (2005) stated that nearly 80% reduction of primary forests between 1950 and 2000 is attributed to the intense pressure from habitat destruction and natural resource extraction. It has been suggested that deforestation and forest degradation by overexploitation are major reasons for the establishment of protected areas; however, only 11.5% of the world's natural vegetation is currently protected (Rodrigues et al., 2004).

Across West Africa, forest cover has seen a reduction of about 30% of its original extent (Bakarr et al., 2001). The remaining patches of forest are highly fragmented and continue to degrade at an alarming rate (McCullough et al., 2007). The Upper Guinea Forest being the 25th biologically richest and most endangered terrestrial eco-regions in the world is made up of remarkably diverse ecological communities providing refuge to copious endemic species (Allotey, 2007). Despite its importance to conservation and environmental sustainability, human activities within the forest have led to forest fragmentation which is threatening the variability of biodiversity over the years.

Ghana is losing its biodiversity to anthropogenic activities including mining, farming, and logging, among others. In recent times, mining activities in forest areas are on the rise, causing losses to the flora and fauna which in time past provided benefits including food, freshwater, and

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Supplemental data for this article can be accessed.

habitats for many organisms in the wild. Ghana has many densely forested hills with most of them occupying sections of the Upper Guinea forest ecosystem region of West Africa (Allotey, 2007). Although there are about 21 protected areas in Ghana, there is growing evidence of degradation in recent times (Janssen et al., 2018). It has been estimated that Ghana's high forest area of 8.2 million hectares at the turn of last century had dwindled to about 1.7 million hectares by the mid-1980s and about one million hectares by the mid-1990s (Forest Services Division, 1996). Over the years, the area of virgin forests has decreased to less than 25% of its original value in the early 1990s and with current fragmented pieces covering between 20 and 524 km^2 (Allotey, 2007).

Significant among existing forests in Ghana is the Atewa Range Forest Reserve (ARFR) which covers almost 75% of upland evergreen forests (McCullough et al., 2007). Apart from the highly degraded Tano-Offin Forest Reserve, the ARFR is the only upland evergreen forest reserve in Ghana (Abu-Juam et al., 2003). The reserve holds abundant, widespread, and rare species, owing to its unique floristic upland evergreen forest composition which is created by the misty conditions on top of the plateaus (Hall & Swaine, 2013). A total of 765 species of vascular plants including 106 Upper Guinea endemics have been recorded in the Atewa Forest (Abu-Juam et al., 2003).

Even though ARFR has been designated over the years as a protected area of international importance (Abu-Juam et al., 2003; Ntiamoa-Baidu et al., 2001), it has been subjected to massive degradation by anthropogenic activities (Ayivor et al., 2011; Hirons, 2015; McCullough et al., 2007). The major threats to the reserve are logging, mining, agricultural encroachment, high human population density, and settlement establishment (Ayivor et al., 2011). Although several studies have indicated significant destruction of the ARFR, little is known about the land-use dynamics of the reserve as a result of human activities, particularly with an approach that combines both spatial and temporal changes. Fewer studies have focused on understanding stressors because it is particularly challenging when their effect cannot be predicted based on evidence on site (Nakamura et al., 2017; Wood & Bhatnagar, 2014). Remote sensing is increasingly being employed by conservationists and policymakers to identify land-use/land-cover changes over large areas and conservation priorities. Geospatial technologies are becoming more useful, especially in important biodiversity areas where field data are limited and patchy and the landscapes are not easily accessible (Kusimi, 2015). One of the several benefits of using remote-sensing techniques is that it enables assessment of forest degradation and deforestation processes over large areas at much lower costs than the conventional in-situ methods (Mascaro et al., 2011; Olander et al., 2012). The present study sought to use remote-sensing techniques to estimate the effects of anthropogenic activities on land-use dynamics in ARFR from 1986 to 2016. The study has implications for forest conversation, management, theory, practice, and policy.

2. Materials and methods

2.1. Study area

The ARFR is an ecologically unique site, which accommodates diverse fauna and flora resources in the Eastern Region of Ghana. It is located within 05° 58′ to 06° 20′ N and 0° 31′ to 0° 41′ W (see Figure 1) and occurs within the Moist Semi-Deciduous Forest Zone. The forest reserve covers an area of 258.3 km^2 and is made up of two forest blocks, namely, Atewa Range (237 km^2) and Atewa Range Extension. According to Mayaux et al. (2004), the Atewa Range represents approximately 33.5% of the closed forest in the Eastern Region. The ARFR was established as a National Forest Reserve in 1925. It has also been designated as an Important Bird Area based on its avian diversity, one of the 36 such areas in Ghana (Abu-Juam et al., 2003; Ntiamoa-Baidu et al., 2001). The area was classified as a Special Biological Protection Area in 1994, a Hill Sanctuary in 1995 and one of Ghana's 30 Globally Significant Biodiversity Areas in 1999 (Abu-Juam et al., 2003).

The ARFR forms part of an elongated mountainous range, varying between 200 and 750 m above sea level and a source of numerous rivers and streams (Hall & Swaine, 2013). The forest is characterized by high temperatures and bimodal rainy season with peak periods of April–July and September–October. The monthly temperature ranges between 24°C and 29°C and mean annual rainfall of between 1200 and 1600 mm (Asravor, 2018). The ARFR is underlain by Birimi rocks with derived soils mostly red clays, aggregated by humus to form light-textured soil, basic lithosols, and ochrosols (Hall & Swaine, 2013). The area is known to harbor mineralogical wealth including both gold and bauxite deposits (Kyereh et al., 2006) and diamond.

ARFR vegetation is an Upland Evergreen Forest and regarded as botanically important in terms of plant species richness and floral diversity (Abu-Juam et al., 2003). The forest reserve houses 656 species of vascular plants, comprising 323 tree species, 83 shrub species, 155 liane and climber species, 68 herbaceous species, 22 epiphytes, and 5 kinds of grass. It further forms the home for many endemic and rare species including black star plant species (Larsen, 2006) as well as seasonal marshy grasslands, swamps, and thicket species (Hall & Swaine, 2013). Common among woody epiphyte species in the area are *Anthocleista microphylla, Epistemma assianum, Medinilla mannii, Cyathea manniana* (Treefern), *Rubuspinnatus* var. *afrotropicus*, and *Hymenocoleus multinervis*, a group of plants rarely seen in most tropical West African forests. The area is also a home to shade-loving plants including *Alsodeiopsis staudtii, Buforrestia obovata, Cola boxiana, Dicranolepis persei, Diospyros chevalieri, Drypetes pellegrini, Mapania baldwinii, M. coriandrum, Nephthytis afzelii, Pauridiantha sylvicola, Combretum multinervium, Neolemonniera clitandrifolia, Newtonia duparquetiana, Strephonema pseudocola,* and *Strychnos icaja* (Bakarr et al., 2004).

2.2. Data collection and analysis

Landsat satellite images of the study area for 1986, 1991, 2006, and 2016 were used for the study. The Landsat satellite images were downloaded from the United States Geological Survey Department website

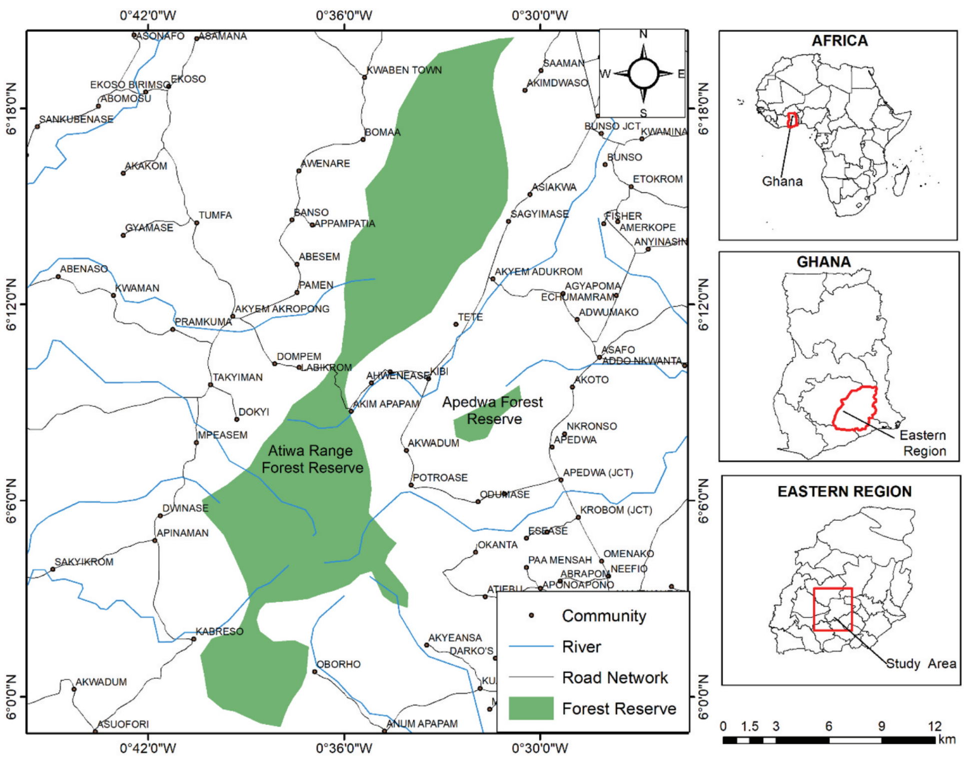

Figure 1. Location of the study area, Atewa Range Forest Reserve.

(https://earthexplorer.usgs.gov). The detailed information about the satellite images is shown in Table 1. The images were preprocessed and bands stacked. The unsupervised classification was done using GIS Image Processing Module, Sub-Module Cluster. The unsupervised classification was carried out in order to generate possible clusters to give an idea of changes and their relative types in the study area. Supervised classification using maximum likelihood mode with training samples obtained from the field GPS data, Google Earth, and other topographic maps was carried out. An accuracy assessment was carried out after the image classification. This analysis offers the changing trends in land-use/land-cover patterns of the study area. In total, four land-use/land-cover classes were adopted for the study: rainforest, farmland, logged land, and settlement/bareland. The post-classification comparison approach was used to evaluate variations in land-cover maps obtained from satellite images.

2.2.1. Assessment of human-induced stress on the vegetation quality

Following anthropogenic activities in the reserve area, the quality of the vegetation over the years has been affected. Normalized Differential Vegetation Index (NDVI) was used to assess vegetation quality for the past three decades. The NDVI was adopted to map the effect of human-induced stress on the vegetation using the Landsat satellite images of 1986, 1991, 2006, and 2016. The NDVI of the study area was calculated from the visible and near-infrared (NIR) light reflected by vegetation. Healthy vegetation absorbs most of the incoming visible light and reflects a large portion (about 25%) of the NIR light but a low portion in the red band (RED). Unhealthy or sparse vegetation reflects more visible light and less NIR light. NDVI data provide an opportunity to assess quantitatively and qualitatively the vegetation cover status in the past and the present, to determine trends, and to predict the ecosystem processes (Herrmann et al., 2005). The NDVI was calculated using the formula:

Equation (1):

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

Calculation of NDVI for a given pixel always results in a number that ranges from −1 to +1: Bare soils give a value close to zero and very dense green vegetation has values close to +1 (0.8–0.9).

2.2.2. Intensity of induced anthropogenic activities on vegetation

Transition matrices in the study area for 1986–1991, 1991–2006, and 2006–2016 were analyzed quantitatively. The matrices were used to obtain both the stocks and flows of the land categories. Conventional matrix including the types of flows, i.e., gross losses and gross gains, were used as the basis for analysis. As percentage change in the landscape does not directly indicate the annual area change since differences were observed in the time interval, the rate of change was calculated in square kilometers per year between each interval. Total change at category level was calculated as the sum of the categories gross gain and gross loss (Huang et al., 2012).

The study employed Intensity Analysis to assess the impact of anthropogenic activities on ARFR. The Intensity Analysis was carried out at the interval and category levels. Intensity Analysis explains LULC change in two ways: the size of the spatial extent and the intensity of the change (Ekumah et al., 2020; Quan et al., 2019). At the interval level, the study compares the time intervals in terms of size and intensity of gross change in the study area. The annual area of change for each time interval

Table 1. Landsat satellite imagery data.

Data source	Acquisition date	Path/R
Landsat 5TM	22 December 1986	193/56
Landsat 4TM	10 January 1991	193/56
Landsat 7ETM	05 December 2006	193/56
Landsat 7ETM	31 January 2016	193/56

is computed and compared to a uniform rate of change that would occur if all the changes were equally distributed across the study period (Aldwaik & Pontius, 2012). A compressive account on notation and equations for Intensity Analysis has been reported in several studies (Aldwaik & Pontius, 2012; Huang et al., 2012; Quan et al., 2019). Regarding category-level analysis, the study compared the categories in terms of size and intensity of loss and gain by the land-use category in each time interval (Pontius et al., 2013). It examined how the intensity of change varied among categories. The annual gross losses and gains were calculated for each LULC category and then compared to the uniform intensity of change that would have occurred if the overall change was equally distributed across the study area. The equations given below were used to calculate the various parameters for assessing the changes and intensity during the study. Equation (2), for instance, is used to define the uniform annual rate of overall change, whereas Equation (3) is used to define a specific interval annual rate of the overall change. Equations (4) and (5) are used to define the intensity of a particular category's annual gross gain as percent of the size of the category at the end of the time interval and intensity of a particular category's annual gross loss as a percent of the size of the category at the beginning of the time interval (Huang et al., 2012).

$$U = 100\% \times \frac{\text{Changeareaduringallintervals}/\text{Areaofstudyregion}}{\text{Durationofallintervals}}$$

$$St = 100\% \times \frac{\text{Change area during interval } [Yt, Y1]/\text{Area of study region}}{\text{Duration of interval } [Yt, Y1]}$$

$$G = 100\% \times \frac{\text{Gross gain area of category } j \text{ during } [Yt, Y1]/\text{Duration of } [Yt, Y1]}{\text{Area of category } j \text{ at time interval } [Y1]}$$

$$L = 100\% \times \frac{\text{Gross loss area of category } i \text{ during } [Yt, Y1]/\text{Duration of } [Yt, Y1]}{\text{Area of category } i \text{ at time interval } [Yt]}$$

where U is the value of uniform line for time intensity analysis at $[Y_1, Y_t]$; St is the annual intensity of change for the interval $[Y_1, Y_t]$; G is the annual intensity of gross gain of category j for time interval $[Y_t, Y_1]$; L is the annual intensity of gross loss of category i for time interval $[Y_t, Y_1]$; i is the index for a category at an initial time; j is the index for a category at a subsequent time; t is the index for a time point which ranges from 1 to T − 1; and Y_t is the year at time point.

3. Results

3.1. LULC of ARFR

The study identified and classified four land uses in the ARFR between 1986 and 2016. These included rainforest, logged land, farmland, and settlement areas in three time intervals (i.e., 1986–1991, 1991–2006, and 2006–2016). The overall accuracy for LULC maps of 1986, 1991, 2006, and 2016 was 92.10%, 85.52%, 83.82%, and 74.17% with corresponding kappa coefficients of 0.86, 0.79, 0.78, and 0.66, respectively. The detailed results of the accuracy assessment are provided in the Supplementary material. Figure 2 shows the LULC maps of ARFR for the four time points (1986, 1991, 2006, and 2016). This study covered a total area of 1109.28 km^2 but reduced to 1057.64 km^2 in 1991 because the satellite image obtained for that year had some parts covered by clouds (see Figure 2).

Figure 3 provides information on the area covered by the various LULC types of the ARFR over the study period of 30 years (1986–2016). Rainforest was the largest LULC type covering 31.18% of the ARFR in 1986. In 1991, the settlement became the largest LULC type occupying 45.61% of the ARFR. Farmland became the largest LULC type in both 2006 and 2016 covering 38.05% and 34.68%, respectively.

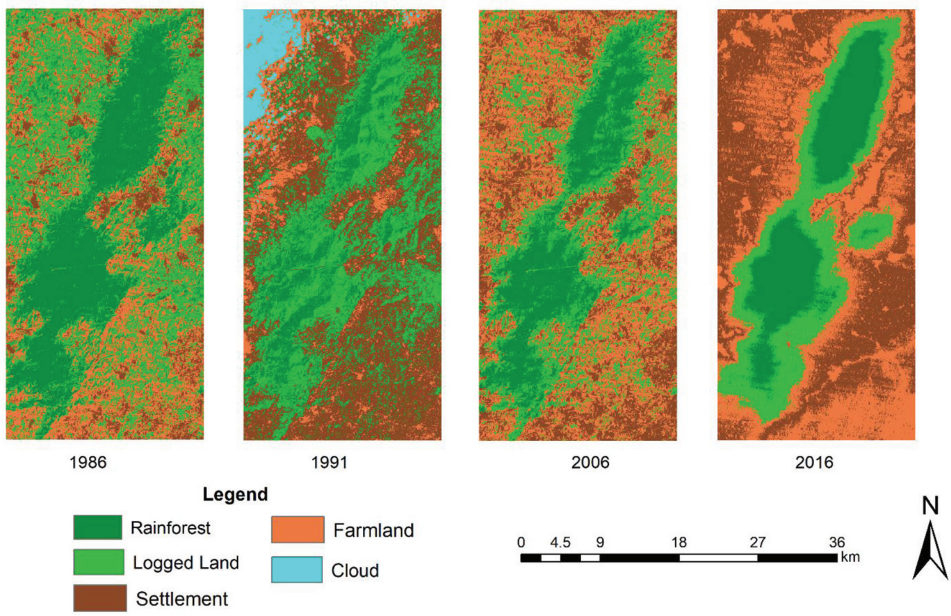

Figure 2. LULC maps of Atewa Range Forest Reserve for 1986, 1991, 2006, and 2016.

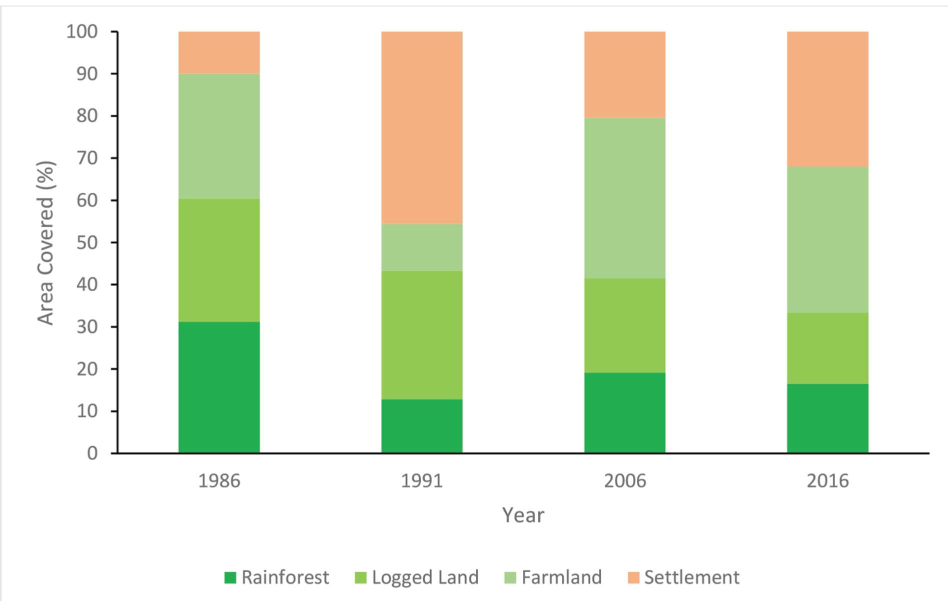

Figure 3. Area covered by the various LULC types of the Atewa Range Forest Reserve over 30 years (1986–2016).

3.2. Land-cover transition matrix for ARFR

Table 2 presents the land transition matrix for the ARFR. It gives information on the annual area of gross gain, gross loss, and net for each LULC and the overall change for the time intervals. The numbers on the diagonal (boldface) indicate persistence. The rainforest reduced from 345.83 km^2 in 1986 to 183.48 km^2 in 2016; similarly, logged land declined 324.52 km^2 in 1986 to 186.21 km^2 in

Table 2. Atewa Range Forest Reserve Land transition matrix from 1986 to 2016 (km^2).

1991								
		Rainforest	Logged land	Farmland	Settlement	Initial total	Gross loss	Net
1986	Rainforest	**130.92**	176.26	5.97	29.02	345.83	211.25	−206.41
	Logged land	3.39	**102.00**	31.39	164.54	324.52	199.32	21.19
	Farmland	1.28	39.24	**41.63**	226.8	328.43	267.32	−191.99
	Settlement	0.17	5.01	37.97	**62.04**	110.48	43.15	377.21
	Final total	135.76	322.51	116.96[4]	482.4	1109.26	721.04	
	Gross gain	4.84	220.51	75.33	420.36	721.04		
2006								
1991	Rainforest	**119.50**	12.72	2.80	0.74	135.76	16.26	76.91
	Logged land	88.35	**133.08**	85.41	15.67	322.51	189.43	−82.21
	Farmland	0.87	10.83	**47.58**	57.69	116.97	69.39	274.20
	Settlement	3.95	83.67	255.38	**139.40**	482.40	343.00	−268.90
	Final total	212.68	240.29	391.17	213.50	1057.64	618.08	
	Gross gain	93.17	107.22	343.59	74.10	618.08		
2016								
2006	Rainforest	**149.19**	56.93	5.75	0.89	212.75	63.57	−29.28
	Logged land	31.83	**79.18**	77.88	58.87	247.76	168.58	−61.56
	Farmland	2.19	40.09	**174.11**	205.70	422.10	247.98	−37.41
	Settlement	0.27	10.00	126.94	**89.44**	226.66	137.21	128.25
	Final total	183.48	186.21	384.68	354.91	1109.27	617.34	
	Gross gain	34.29	107.02	210.57	265.46	617.34		

The bold figures present persistence

2016. On the contrary, farmland increased from 328.43 km^2 in 1986 to 384.68 km^2 in 2016; likewise, settlement expanded from 110.48 km^2 in 1986 to 354.91 km^2 in 2016. Rainforest experienced a net loss in all time intervals except for the 1991–2006 time interval. Rainforest recorded the biggest net change which was a loss of 206.41 km^2 in 1986–1991 period. Apart from the first time interval (1986–1991), logged land recorded net loss for the subsequent two time intervals. The biggest net change of logged land was a loss (82.21 km^2) which occurred in the 1991–2006 period. Farmland experienced a net loss in 1986–1991 and 2006–2016 time intervals but recorded a net gain in 1991–2006 time interval which was the greatest net change of 274.20 km^2. Settlement experienced a net gain in 1986–1991 and 2006–2016 time intervals but recorded a net loss in 1991–2006 time interval. The greatest net change for settlement which was a gain of 377.21 km^2 occurred in 1986–1991 time interval.

3.2.1. Vegetation quality assessment

In assessing the impacts of anthropogenic interference on the vegetation and its quality in the ARFR, the NDVI indicated a decreasing trend in general vegetation cover (see Figure 4) as indicated in the LULC results. The observed bands showed high concentration between 0.6 and 0.7 in the year 1986. In 1991, the concentration of the bands was in the region of 0.2–0.4, indicating a very drastic change between 1986 and 1991. The bands in 2006 showed slight decreases from the observed 0.2–0.4 to 0.2–3.5, and finally in the year 2016, the bands were observed in the region of 0.1–0.2 which showed a very substantial decrease in the vegetation cover.

3.2.2. Assessing the intensity of LULC change in ARFR

Figure 5 provides the results of the Intensity Analysis at the interval and category levels. At the interval level, the change in the first interval (1986–1991) was relatively rapid compared to the second (1991–2006) and third (2006–2016) time intervals. The uniform rate of change over the 30-year study period was 6.17%.

For the category Intensity Analysis, the results (see Figure 5) show that in the first time interval (1986–1991), logged land and settlement recorded active gains, while rainforest and farmland experienced dormant gains. Farmland was the only LULC type that recorded active losses in the first time interval. In the second time interval (1991–2006), farmland recorded active gains, while

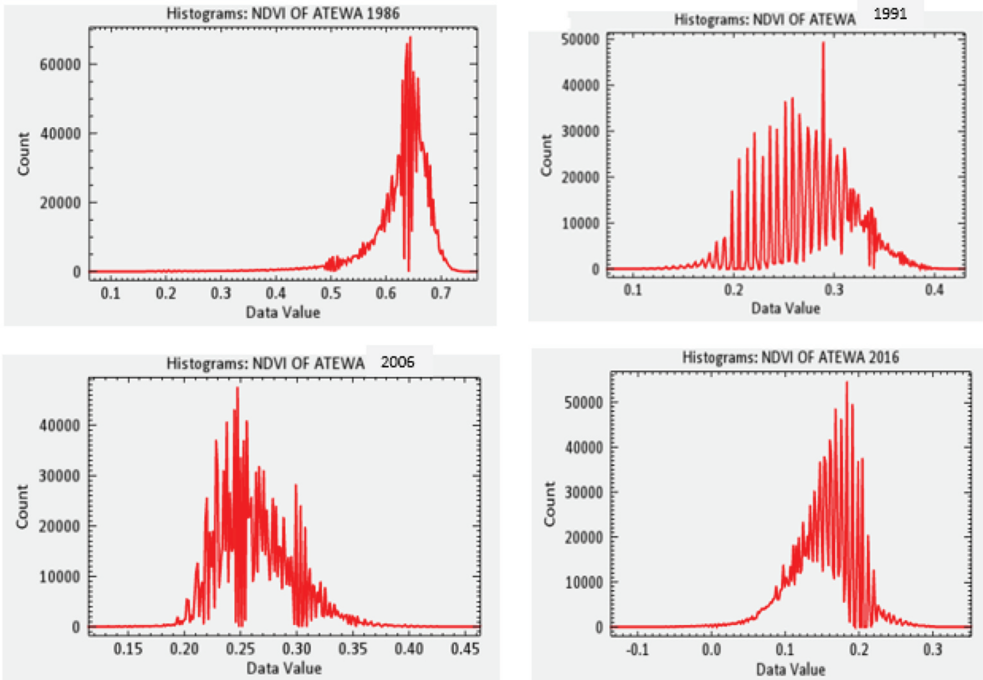

Figure 4. NDVI vegetation analysis of study area between 1986 and 2016.

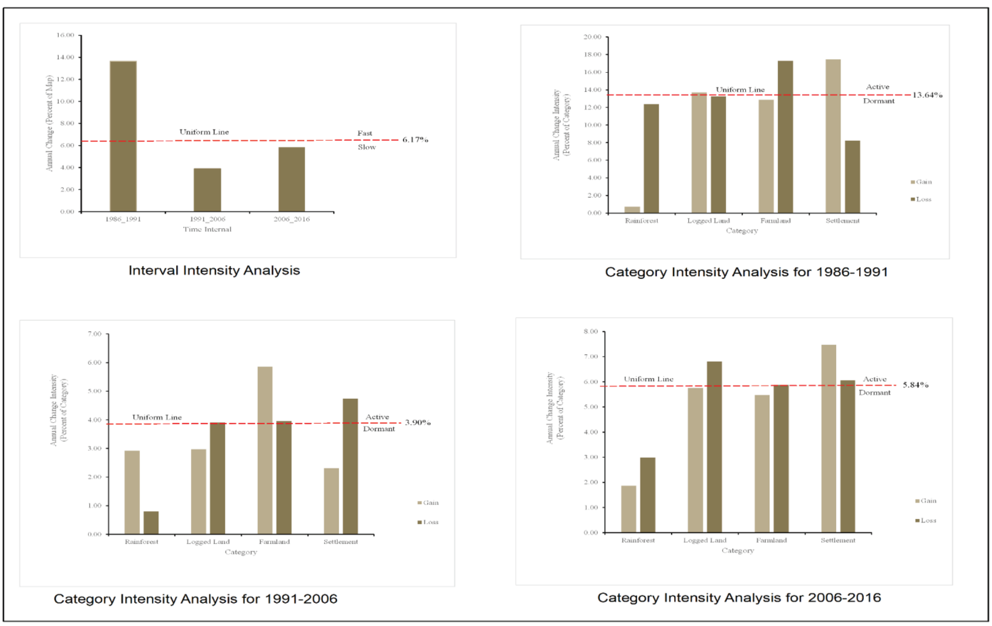

Figure 5. Intensity of land-use transformation between 1986 and 2016 in the study area.

rainforest, logged land, and settlement experienced dormant gains. Logged land, farmland, and settlement recorded active losses, but rainforest experienced dormant losses. In the third time interval (2006–2016), only settlement experienced active gains among the four LULC types, and the rest recorded dormant gains. Logged land, farmland, and settlement experienced active loss, while rainforest recorded dormant losses.

4. Discussion

4.1. Anthropogenic-induced stress on the vegetation quality

There are numerous indices for emphasizing vegetation-bearing areas using remote sensing. The most common and widely used index is the NDVI (Gao, 1996). This is frequently applied to the global environmental and climatic change research and used to assess the relationship between the changes in vegetation growth rate and spectral variability (Bhandari et al., 2012). Most researchers have recorded the use of NDVI for vegetation monitoring (Yang et al., 2010), assessing the crop cover (El-Shikha et al., 2007), and drought monitoring, among others (Kim et al., 2008).

Forest resource worldwide is continuously under pressure from anthropogenic activities to meet the needs of mankind, which eventually affects the quality of the resource including vegetation, soil, and water quality (Ayivor et al., 2011; Hirons, 2015; McCullough et al., 2007). In assessing the impacts of anthropogenic interference on the vegetation and its quality in the ARFR, the NDVI results showed a progressive decrease in the vegetation cover over the past three decades. The decline in vegetation cover observed in this study may be explained by the continuous increase in farmland and settlement. The rainforest in the ARFR was observed to have tremendously decreased over the past three decades (1986–2016), and logged land, which is a degraded forest, also decreased over the study period. However, farmland and settlement increased with time. In Ghana, gaps are created in forests as a result of competition among the three major economic sectors (agriculture, mining, and logging) (Hens & Boon, 1999). Ichii et al. (2002) found that a decrease in the NDVI in the equatorial regions was largely attributed to deforestation. Basommi et al. (2015) suggested that the increased conversion of forest into farmlands and bare lands between 1986 and 2007 could be attributed to the high rate of illegal mining recorded mostly in the reserved forests of Ghana. Many of the protected areas in Ghana have failed to fulfill the objective of conserving biodiversity for which they were established (World Rainforest Movement, 2002). Polyakov and Zhang (2008) have also indicated that growth in the human population is associated with the eventual expansion of the land area for housing, which affects the peripheries of forest reserves. The high rate of land-use change from forest to settlement may be attributed to the growing population coupled with the growing demand for shelter. The World Rainforest Movement (2002) estimates that between 1977 and 1997, Ghana lost 5.6 million ha of forest cover as a result of an increase in the human population. The study further showed a gradual transformation of the vegetation in the study area to bare lands. Guida-Johnson and Zuleta (2013) found that land-use changes are a major hazard to both forest conservation and biodiversity and are major sources of degradation.

4.2. Gross patterns and land-use transformation in the ARFR

The pattern of land-use depends on several factors including demand for food, shelter, and social values by humans (Basommi et al. 2015), and this demand increases with human population growth. In the first year (1986), the rainforest was the largest LULC type, but in the subsequent three years, human-induced LULC types, settlement (1991), and farmland (2006 and 2016) expanded to become the largest LULC types. This indicates the growing dominance of anthropogenic activities in ARFR over time. The study area is rich in timber species of high economic value, and this accounts for the increase in logging activities. The geospatial analysis of the satellite images shows that rainforest and logged land in ARFR have decreased, while farmland and settlement have increased within the past three decades. This agrees with an assertion by Antwi-Agyei et al. (2014), who reported a deforestation rate in Ghana. The high deforestation rate in Ghana is as a result of the increasing human population and the associated pressures on natural resources. The conversion of rainforest into farmlands and settlement is consistent with the findings of Sala et al. (2000). Alo and Pontius (2008) pointed to the fact that the transition from forest to the other land-use forms could be considered systematic because it increased with population growth. The increased land-use change is largely associated with agriculture intensification, infrastructure expansion, and mining (Guida-Johnson & Zuleta, 2013). This has largely resulted in deforestation, degradation, and the loss of biological diversity in rainforest areas (Van Gemerden et al., 2003).

4.2.1. Study limitations

Some important LULC categories such as built-up and bareland were classified together as one because the resolution of the satellite images (30 m) was not high enough to enable the separation of these two LULC categories. Even though Landsat satellite images have been available since 1972, not all images met the inclusion criteria set for this study. Distorted images were not considered. High-resolution satellite images could have improved the accuracy of the image classification, but such images of the study area were not available for all the years considered in this study. The available high-resolution images were captured recently. The time intervals between the study years were also not equal; nonetheless, it is important to note that the unequal time interval does not affect Intensity Analysis.

5. Conclusion

The study sought to assess the effects of human activities on land-use dynamics in ARFR over the past 30 years (1986–2016) using geospatial techniques. The indicators examined were vegetation quality and LULC changes for four main LULC types: rainforest, logged land, farmland, and settlement. NDVI which was used to estimate vegetation quality showed a continuous decline over the study period, indicating increasing stress on vegetation in ARFR. The decline in the NDVI values can be attributed to forest deforestation and degradation activities such as logging, farming, and encroachment for settlement. The findings of the present study also indicated that the LULC change pattern in ARFR was largely driven by anthropogenic activities. The rainforest reduced from 345.83 km^2 in 1986 to 183.48 km^2 in 2016; similarly, logged land declined 324.52 km^2 in 1986 to 186.21 km^2 in 2016. However, farmland increased from 328.43 km^2 in 1986 to 384.68 km^2 in 2016; likewise, settlement expanded from 110.48 km^2 in 1986 to 354.91 km^2 in 2016.

Expansion of human-induced LULC types is a clear indication of the growing dominance of anthropogenic activities in ARFR. One major activity which might have indirectly contributed to settlement increase is the indiscriminate illegal mining activities in the area, and the excavated lands in the satellite images might have been classified as the settlement by the software because settlement and bare land have similar spectral reflectance. ARFR is a gazetted forest reserve managed by the Forestry Commission which is not expected to be degrading at this alarming pace. It is fair to state that strategies and plans put in place to manage the reserve are not working and need to be revised by the Forestry Commission. There is also a need to implement succession inventory service which requires formalizing and enforcing land rights for forest dwellers, alongside payments for ecosystem services to those living near the ARFR.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

Class Confusion Matrix

File

Confusion Matrix: C:\Users\oliver\Documents\RS\RS WORK\felicity\class\2006class

Overall Accuracy = (21423/25559) 83.8178%
Kappa Coefficient = 0.7824

Class	Ground Truth (Pixels) RAINFOREST	LOGGED LANDS	FARMLAND	SETTLEMENT	Total
Unclassified	0	0	0	0	0
RAINFOREST	6974	595	12	0	7581
LOGGED LANDS	1513	3432	189	112	5246
FARMLANDS	111	647	5263	658	6679
SETTLEMENT	6	121	172	5754	6053
Total	8604	4795	5636	6524	25559

Class	Ground Truth (Percent) RAINFOREST	LOGGED LANDS	FARMLAND	SETTLEMENT	Total
Unclassified	0.00	0.00	0.00	0.00	0.00
RAINFOREST	81.06	12.41	0.21	0.00	29.66
LOGGED LANDS	17.58	71.57	3.35	1.72	20.53
FARMLANDS	1.29	13.49	93.38	10.09	26.13
SETTLEMENT	0.07	2.52	3.05	88.20	23.68
Total	100.00	100.00	100.00	100.00	100.00

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
RAINFOREST	8.01	18.94	607/7581	1630/8604
LOGGED LANDS	34.58	28.43	1814/5246	1363/4795
FARMLANDS	21.20	6.62	1416/6679	373/5636
SETTLEMENT	4.94	11.80	299/6053	770/6524

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
RAINFOREST	81.06	91.99	6974/8604	6974/7581
LOGGED LANDS	71.57	65.42	3432/4795	3432/5246
FARMLANDS	93.38	78.80	5263/5636	5263/6679
SETTLEMENT	88.20	95.06	5754/6524	5754/6053

Class Confusion Matrix

File

Confusion Matrix: C:\Users\oliver\Documents\RS\RS WORK\felicity\class\1991class

Overall Accuracy = (13101/15319) 85.5212%
Kappa Coefficient = 0.7882

Class	Ground Truth (Pixels)				
	RAINFOREST	LOGGED LANDS	FARMLAND	SETTLEMENT	Total
Unclassified	0	0	0	0	0
RAINFOREST	5698	155	14	1	5868
LOGGED LANDS	984	4308	98	31	5421
FARMLANDS	324	251	1498	109	2182
SETTLEMENT	62	35	154	1597	1848
Total	7068	4749	1764	1738	15319

Class	Ground Truth (Percent)				
	RAINFOREST	LOGGED LANDS	FARMLAND	SETTLEMENT	Total
Unclassified	0.00	0.00	0.00	0.00	0.00
RAINFOREST	80.62	3.26	0.79	0.06	38.31
LOGGED LANDS	13.92	90.71	5.56	1.78	35.39
FARMLANDS	4.58	5.29	84.92	6.27	14.24
SETTLEMENT	0.88	0.74	8.73	91.89	12.06
Total	100.00	100.00	100.00	100.00	100.00

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
RAINFOREST	2.90	19.38	170/5868	1370/7068
LOGGED LANDS	20.53	9.29	1113/5421	441/4749
FARMLANDS	31.35	15.08	684/2182	266/1764
SETTLEMENT	13.58	8.11	251/1848	141/1738

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
RAINFOREST	80.62	97.10	5698/7068	5698/5868
LOGGED LANDS	90.71	79.47	4308/4749	4308/5421
FARMLANDS	84.92	68.65	1498/1764	1498/2182
SETTLEMENT	91.89	86.42	1597/1738	1597/1848

Class Confusion Matrix

File

Confusion Matrix: C:\Users\oliver\Documents\RS\RS WORK\felicity\class\1986class

Overall Accuracy = (10164/11036) 92.0986%
Kappa Coefficient = 0.8636

Class	Ground Truth (Pixels) RAINFOREST	LOGGED LAND	FARMLAND	SETTLEMENT	Total
Unclassified	0	0	0	0	0
RAINFOREST	6269	103	0	0	6372
LOGGED LAND	167	2513	0	1	2681
FARMLAND	21	193	21	62	297
SETTLEMENT	4	9	312	1361	1686
Total	6461	2818	333	1424	11036

Class	Ground Truth (Percent) RAINFOREST	LOGGED LAND	FARMLAND	SETTLEMENT	Total
Unclassified	0.00	0.00	0.00	0.00	0.00
RAINFOREST	97.03	3.66	0.00	0.00	57.74
LOGGED LAND	2.58	89.18	0.00	0.07	24.29
FARMLAND	0.33	6.85	6.31	4.35	2.69
SETTLEMENT	0.06	0.32	93.69	95.58	15.28
Total	100.00	100.00	100.00	100.00	100.00

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
RAINFOREST	1.62	2.97	103/6372	192/6461
LOGGED LAND	6.27	10.82	168/2681	305/2818
FARMLAND	92.93	93.69	276/297	312/333
SETTLEMENT	19.28	4.42	325/1686	63/1424

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
RAINFOREST	97.03	98.38	6269/6461	6269/6372
LOGGED LAND	89.18	93.73	2513/2818	2513/2681
FARMLAND	6.31	7.07	21/333	21/297
SETTLEMENT	95.58	80.72	1361/1424	1361/1686

Class Confusion Matrix

File

Confusion Matrix: C:\Users\oliver\Documents\RS\RS WORK\felicity\class\2016class

Overall Accuracy = (35840/48319) 74.1737%
Kappa Coefficient = 0.6576

	Ground Truth (Pixels)				
Class	RAINFOREST	LOGGED LANDS	FARMLAND	SETTLEMENT	Total
Unclassified	0	0	0	0	0
RAINFOREST	8164	177	169	125	8635
LOGGED LANDS	2941	9961	200	581	13683
FARMLANDS	780	591	6466	6093	13930
SETTELEMENT	68	67	687	11249	12071
Total	11953	10796	7522	18048	48319

	Ground Truth (Percent)				
Class	RAINFOREST	LOGGED LANDS	FARMLAND	SETTLEMENT	Total
Unclassified	0.00	0.00	0.00	0.00	0.00
RAINFOREST	68.30	1.64	2.25	0.69	17.87
LOGGED LANDS	24.60	92.27	2.66	3.22	28.32
FARMLANDS	6.53	5.47	85.96	33.76	28.83
SETTELEMENT	0.57	0.62	9.13	62.33	24.98
Total	100.00	100.00	100.00	100.00	100.00

Class	Commission (Percent)	Omission (Percent)	Commission (Pixels)	Omission (Pixels)
RAINFOREST	5.45	31.70	471/8635	3789/11953
LOGGED LANDS	27.20	7.73	3722/13683	835/10796
FARMLANDS	53.58	14.04	7464/13930	1056/7522
SETTELEMENT	6.81	37.67	822/12071	6799/18048

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
RAINFOREST	68.30	94.55	8164/11953	8164/8635
LOGGED LANDS	92.27	72.80	9961/10796	9961/13683
FARMLANDS	85.96	46.42	6466/7522	6466/13930
SETTELEMENT	62.33	93.19	11249/18048	11249/12071