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Extending the baseline of tropical dry forest loss in Ghana (1984–2015) reveals drivers of major deforestation inside a protected area

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ABSTRACT

Tropical dry forests experience the highest deforestation rates on Earth, with major implications for the biodiversity of these ecosystems, as well as for its human occupants. Global remote sensing based forest cover data (2000 – 2012) point to the rapid loss of tropical dry forest in South America and Africa, also, if not foremost, inside formally protected areas. Here, we significantly extend the baseline of tropical dry forest loss inside a protected area in Ghana using a generalizable change detection technique. The forest cover change detection is based on the normalized difference vegetation index (NDVI) derived from historical Landsat data (1984–2015). Field measurements were carried out in dry semi-deciduous forest and in the adjacent savanna and woodland. Estimates of the canopy area index and above ground woody biomass were related to NDVI derived from Landsat 8 data. The change detection indicated significant NDVI decrease in a large area initially covered by tropical dry forest, associated with deforestation. The peak in deforestation was found to have occurred between 1990 and 2002, hereafter, the conservation status of the area was improved. A combination of remote sensing data corroborated by secondary data sources provides evidence for the almost complete clearance of a tropical dry forest inside a strictly protected area, attributable to logging and land clearing for arable farming. The NDVI change detection also revealed NDVI increase in the adjacent woodlands from 2002 to 2015, demonstrating woody encroachment. Historical fire data from the MODIS burned area product indicate that the deforested area experienced a high frequency of anthropogenic burning since 2004, which may have caused further degradation and largely prevents forest regeneration. The results show the ongoing destruction of tropical ecosystems even within ostensibly protected areas and ask for the revision of protection and management strategies of such areas.

1. Introduction

Deforestation and forest degradation (DD) represent a global problem (e.g. Hansen et al., 2013). West Africa is no exception where DD has occurred for millennia, principally due to logging, charcoal production and slash and burn agriculture (Hawthorne and Abu-Juam, 1995; Lupo et al., 2015). However, agricultural expansion and increasing levels of illegal logging and fire disturbance have dramatically increased DD since the end of the 19th century (Hansen and Treue, 2008; Hawthorne and Abu-Juam, 1995; Hosonuma et al., 2012; Wardell et al., 2003). Since 1990, the forest area in Ghana has decreased on average by 2% every year (FRA, 2010). As a result, timber exports have dropped markedly over the past decade: from 2008 to 2013 the total volume of Ghana's timber exports declined by ~50% following decades of unsustainable exploitation (Hoare and Wellesley, 2014). The loss of natural forest in Ghana has significant socio-economic and ecological implications as these forests provide important ecosystem services and represent hotspots of biodiversity (Brooks et al., 2002; Norris et al., 2010).

In the forest savanna transition zone of West Africa, savanna and tropical dry forest occur in close proximity under similar climatic conditions. Tropical dry forests are particularly vulnerable to anthropogenic disturbances and experience high deforestation rates (Hansen et al., 2013). In contrast, woody encroachment of open ecosystems and

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Table 1
Description of the Landsat images used in the NDVI change detection.

Year	Date	Sensor	Cross-calibration formula
1984	21st of November	LS 5 TM	$NDVI_{calib1984} = 1.268(NDVI_{1984}) - 0.025$
1990	22nd of November	LS 5 TM	$NDVI_{calib1990} = 1.073(NDVI_{1990}) + 0.118$
2002	15th of November	LS 7 ETM +	$NDVI_{calib2002} = 1.158(NDVI_{2002}) - 0.089$
2015	27th of November	LS 8 OLI	

in particular the savanna and woodlands in large areas across sub-Saharan Africa is being reported (Eldridge et al., 2011; Mitchard and Flintrop, 2013). Rising atmospheric carbon dioxide and relief from anthropogenic pressure are cited as possible drivers of such encroachment (Lambin et al., 2001; Lloyd et al., 2008; Mitchard et al., 2009; Mitchard and Flintrop, 2013). In the forest-savanna transition zone, deforestation and woody encroachment can occur simultaneously due to the action of multiple anthropogenic and biophysical drivers. Dry forest and transitional forests harbour crucial resources of genetic diversity, increasingly important for climate change adaptation in the context of the predicted warming and drying trend for West Africa (Boko et al., 2007; Millar et al., 2007).

The Forestry Department of Ghana (FDG) formally recognised the importance of tropical dry forests in 1962 and established multi-function "barrier" reserves in the transitional zone between the Guinea savanna and the fringing dry semi-deciduous forest (Hagan, 1998; Hall and Swain, 1981; Hawthorne and Abu-Juam, 1995; Swaine, 1992). The aim was to maintain a high forest cover in order to protect natural water sources, to provide shelter to agricultural crops from dry season winds and to provide forest products for the surrounding human population (Hagan, 1998). Furthermore, the FDG aimed to preserve a dry forest belt as a fire break, to prevent the increasingly severe bushfires from northern Ghana spreading southward (Hagan, 1998). Yet due to illegal logging and the extreme El Niño drought of 1983, most of these barrier reserves were degraded by the mid-1990s and needed urgent protection (Hawthorne and Abu-Juam, 1995).

This paper focuses on one of these barrier reserves, the Kogyae Strict Nature Reserve (Figs. 1 & 2). Kogyae is the only designated strict nature reserve in Ghana, being "devoted solely to scientific research" with entry by humans for tourism or other uses prohibited (Hagan, 1998). The dry forest and savanna woodlands of Kogyae have received particular scientific interest recently, in the study of vegetation structure, fire ecology, plant physiology and carbon dynamics in the forest-savanna transition zone (Cardoso et al., 2016; Domingues et al., 2010; Moore et al., 2017; Torello-Raventos et al., 2013; Veenendaal et al., 2015). Kogyae is classified as category Ia protected area by the International Union for the Conservation of Nature (Ofori et al., 2014). The literature suggests that from 1984 to 1998 the population of communities inside and surrounding Kogyae tripled, mainly as a result of the new road access opened in 1984 (Awuku-bor, 1999; Hagan, 1998). In this period, illegal logging, agricultural expansion, charcoal production and widespread fire contributed to DD inside Kogyae (Awuku-bor, 1999; Hagan, 1998; Wildlife Department, 1994). According to a recent survey conducted by the authors among park rangers and local people, the local communities were removed from Kogyae by the Wildlife Department in 2002. While logging and farming have been limited since 2002, fires are now lit every year, both illegally by poachers as well as by wildlife officers to provide fresh grass for grazing wildlife (Ayivor and Ntiamoa-Baidu, 2015). The current reserve management may thus be in direct contradiction with the original aim, the conservation of tropical dry forest, for which the reserve was set up.

We assess the changes woody cover that has occurred inside Kogyae in the past three decades using Landsat-derived NDVI in a multi-decadal change analysis. Thereby, we add quantitative spatiotemporal data to the existing, mostly anecdotal, history of Kogyae from 1986 to 2015. In addition, the climate and fire record are used to provide insights into these drivers of woody cover change. We aim to answer the following research questions:

- What woody cover changes are observed and what was the extent of DD?
- How did the drivers of woody cover change develop over time?
- How did the legal protection status of Kogyae and management efforts contribute to the conservation of dry forest?

We use insights from the case study to understand the processes driving woody cover changes in the Zones of Transition in Africa and to evaluate conservation efforts in the past decades.

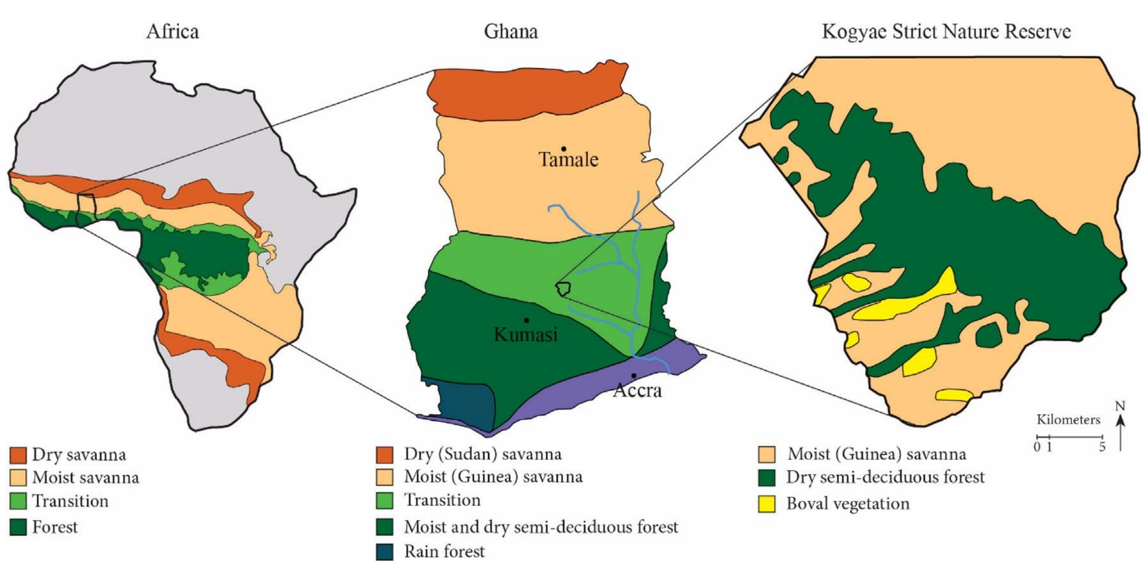

Fig. 1. The location of the Kogyae Strict Nature Reserve within the different vegetation zones of Africa and Ghana. Vegetation zonation of Africa and Ghana adapted from Aubreville et al. (1958) and Yengoh et al. (2010), respectively. The vegetation zonation within Kogyae is adapted from a vegetation map in the Kogyae Management Plan (Wildlife Department, 1994), which is based on in situ observations by Schmitt and Adu-Nsiah in April–June 1993 (K. Schmitt, pers. com. 27 August 2015).

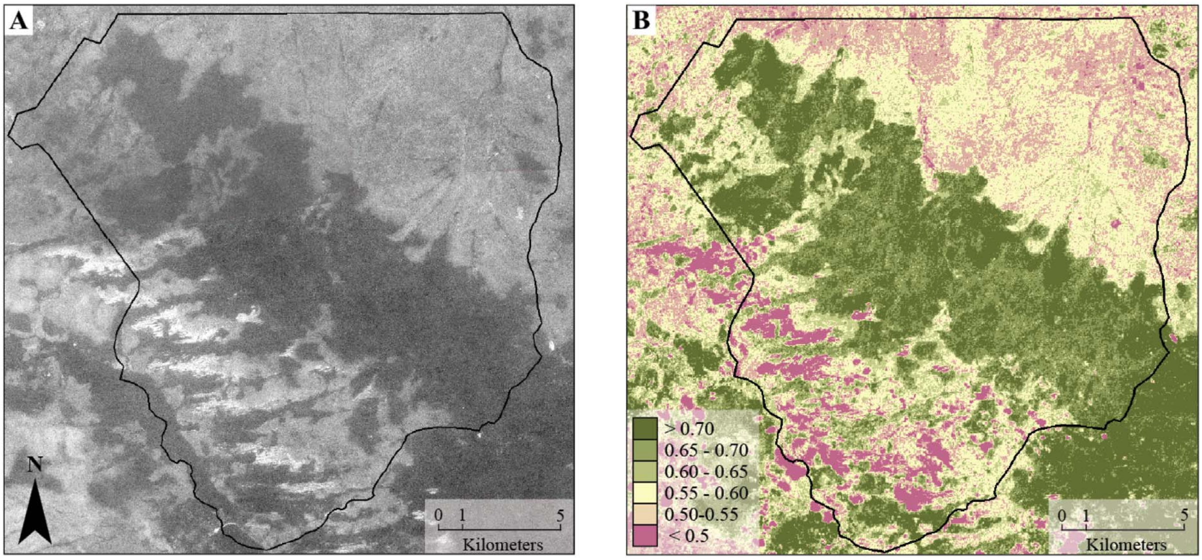

Fig. 2. A Corona satellite photograph captured in January 1966 (A) and a Landsat 5 NDVI image from November 1984 (B) provide an indication of the initial vegetation cover inside Kogyae. The dry semi-deciduous forest in Fig. 1 is visible as darker colours in the Corona photograph and as high NDVI (> 0.6) in the Landsat image. The bight white areas in the south west of the reserve (NDVI < 0.5) are sparsely vegetated rocky outcrops, known as Boval vegetation. The Guinea savanna is visible as greyish colours in the Corona photograph (NDVI 0.5–0.6). The boundary between the forest and savanna is abrupt, accentuated by annual fires that generally extinguish at the forest edge (Swaine, 1992).

2. Materials and methods

2.1. Study area

The Kogyae Strict Nature Reserve (7° 15′ 52″ N, 1° 04′ 47″ W) is a 330 km^2 protected area located in the north-eastern part of the Ashanti region in central Ghana. Kogyae experiences a bimodal annual rainfall distribution with high precipitation from March to July and from September to October corresponding to the passage of the Inter-Tropical Conversion Zone across the region (McSweeney et al., 2010). December and January are dry with 25.2 mm and 16.9 mm average accumulated precipitation respectively. The pronounced dry season from December to March is caused by prevailing dry and dusty 'Harmattan' winds from the north east (McSweeney et al., 2010). The mean annual rainfall is approximately 1350 mm and mean annual temperature is 28 °C with minimum variation in temperature over the year (McSweeney et al., 2010; Wildlife Department, 1994).

2.2. Woody cover change

2.2.1. Field data

Field estimates of aboveground woody biomass (AGB) and canopy area index (CAI) were used to evaluate the suitability of Landsat derived NDVI to detect changes in vegetation cover in the study area. Thirty nine rectangular vegetation plots of 20 × 20 m were established in the north-western corner of Kogyae in October 2014. The aim was to include the entire range of woody cover present in the study area, in order to evaluate the suitability of the NDVI in detecting gradual changes in woody cover. The field plots were located in vegetation types that are different in both their structural characteristics and floristic composition (Table S1), ranging from open, treeless grassland to tall forest with a high canopy cover and biomass (Torello-Raventos et al., 2013; Veenendaal et al., 2015). All trees with a diameter at breast height (DBH) of > 2.5 cm were tagged, measured and identified at species level. Tree height was estimated with a laser rangefinder (TruPulse® 200, Laser Technology Inc.). The projected crown dimension was estimated by measuring the diameter of the crown on two perpendicular axes with a measuring tape. The edge of the crown was visually determined by looking up at an angle of 180°. Geographic coordinates were determined at the centre of each plot using a hand held GPS device (Etrex Lengend HCx, Garmin Ltd., U.S.). For each plot the CAI (m^2 canopy area/m^2 ground area) was calculated as the sum of all crown dimensions divided by the plot area (400 m^2). AGB was calculated using the general dry forest equation from Chave et al. (2005). Tree DBH, tree height and species specific wood density retrieved from the Global wood density database (Chave et al., 2009; Zanne et al., 2009) were used to calculate the AGB of the individual trees.

2.2.2. Landsat based change detection

We chose to use the Normalized Difference Vegetation Index (NDVI) derived from images acquired by three Landsat satellites to detect changes in woody vegetation cover. Landsat satellites have continuously acquired multispectral images with a 30 m horizontal resolution since 1972. The NDVI was selected as it is a widely used and validated index of vegetation greenness. NDVI has been used to separate woody and grass vegetation in savannas (Archibald and Scholes, 2007) and to monitor woody vegetation changes in the Sahel (Horion et al., 2014) and in the forest savanna transition zone of Cameroon (Mitchard et al., 2009). Timing of image capture was chosen to maximise the contribution of woody vegetation to the NDVI signal and to omit the contribution of grasses. In a similar environment in Cameroon, Mitchard et al. (2009) found that the NDVI from images captured in the early dry season was most sensitive to woody vegetation greenness. We confirm this from regular in situ observations in Kogyae, as in the early dry season (mid-November) all tree species are still in full leaf while grasses have senesced. Unfortunately, cloud-free historical images from mid-November covering the study area are rare in the Landsat archive, making an annual assessment of changes in NDVI impossible. Therefore, we selected four usable (> 70% cloud-free) images for the change analysis that would approximate three periods in the recent management history of Kogyae: the pre-disturbance (1984–1990), the disturbance (1990–2002) and the recovery period (2002–2015).

Remaining clouds and cloud shadows were masked from the NDVI images using the Fmask automated cloud detection algorithm version 3.3 using default settings (Zhu et al., 2015; Zhu and Woodcock, 2012). The NDVI was calculated using the Landsat 8 image and values were extracted to derive plot averaged NDVI. To evaluate the suitability of NDVI to assess changes in woody vegetation cover in this environment, we performed an asymptotic regression to link plot-averaged NDVI to field estimates of CAI and AGB. Plots 32 and 34 were excluded as they

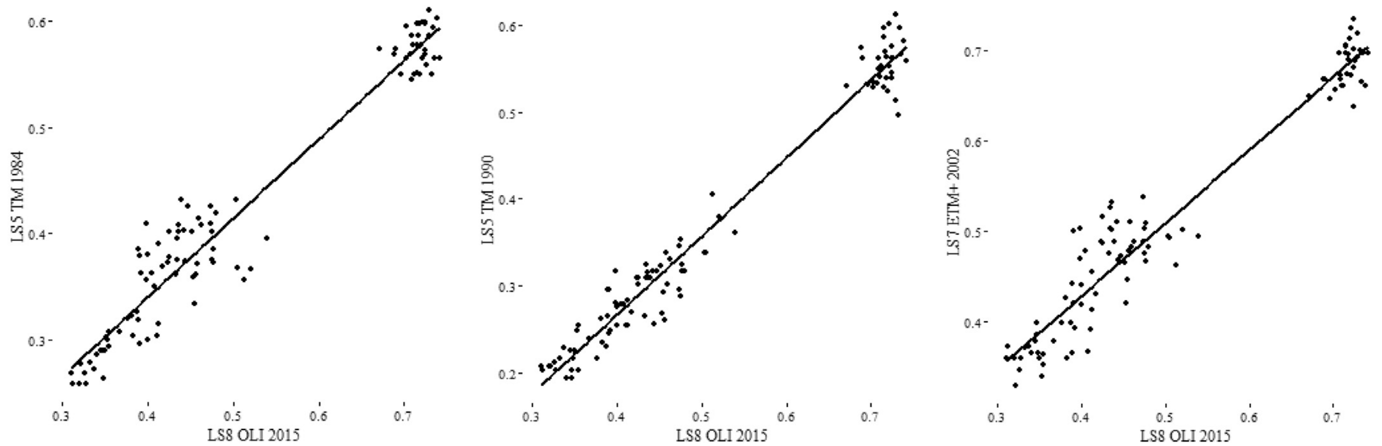

Fig. 3. The cross-calibration regression of 100 pseudo-invariant targets that expectedly did not change in vegetation cover between 1984 and 2015. From left to right: the regression of November 1984 NDVI against November 2015 NDVI ($R^2 = 0.94$, $p < 0.0001$), November 1990 against November 2015 ($R^2 = 0.97$, $p < 0.0001$, $n = 100$) and November 2002 against November 2015 ($R^2 = 0.94$, $p < 0.0001$). The cross-calibration equations are provided in Table 1.

were dominated by a few large trees resulting in unrealistically high AGB values for this environment of > 700 Mg ha^{-1} (see Table S1).

The different Landsat sensors exhibit differences in sensitivity and spectral band designation that can provide errors in the change detection. To minimize these errors we use a cross-calibration method to calibrate the three historical NDVI images to the NDVI image of November 2015 (Mitchard et al., 2009). For the cross-calibration procedure, 100 points were selected to represent pseudo-invariant target areas in undisturbed tropical forest fragments, on roads and rocky outcrops. A linear regression was then applied to obtain the calibration equation for the 1984, 1990 and 2002 images (Fig. 3). The calibrated NDVI images were compared pairwise (i.e. 1984–1990, 1990–2002, 2002–2015) to calculate the relative change in NDVI (ΔNDVI) in every time period, using the following equation:

$$\Delta NDVI = \frac{NDVI_n - NDVI_{n-1}}{NDVI_n + NDVI_{n-1}}$$

The magnitude and direction of change was established by scaling ΔNDVI in terms of standard deviations (SDs) away from no change (ΔNDVI = 0). We use the average SD (0.048) of change in the three examined periods obtained within the borders of the reserve. For more details about the change detection method, see Mitchard et al. (2009).

To examine how ΔNDVI differed between the initial land cover types in our study area, principally savanna and dry forest, we used the earliest Landsat image available from November 1984 to derive a land cover map. We used all seven spectral bands of the image in a random forest supervised classification (Breiman, 2001) with 50 randomly sampled training samples (100∗100 m). Because there is no field data available from 1984 to train the classification, we visually assigned the training samples to either forest, savanna or boval vegetation using the vegetation map and Corona satellite image in Fig. 1 and 2, respectively, as a reference.

2.3. Precipitation and fire

Monthly accumulated precipitation from January 2000 to January 2016 was retrieved from the tropical rainfall measuring mission (TRMM) (GIOVANNI, 2015). The monthly precipitation data was area averaged for a rectangular area around Kogyae (NE = 7° 43′, − 0° 83′; SW = 7° 0′, − 1° 24′). Fire data was collected from the Moderate Resolution Imaging Spectroradiometer (MODIS) Burned Area product (MCD45A1) which contains date of detected burning at a 500 m horizontal resolution. The data is acquired since the year 2000 by the MODIS sensor on-board the Terra and Aqua satellites. The separate monthly tiles were merged to derive one raster with the day of burning in the dry season (October – March) of every year. This resulted in 14 raster datasets containing the day of detected burning, from the dry season 2001–2002 to the dry season of 2014–2015. From these datasets the total area burned in every month of the dry season from 2000 to 2015 was calculated.

3. Results

3.1. Linking field data to the NDVI

Field estimated AGB was strongly related to field estimated CAI ($R^2 = 0.75$, $p < 0.0001$, $n = 37$, Fig. 4). AGB increased linearly with CAI, roughly 100 Mg ha^{-1} with every unit of CAI. Plot averaged NDVI was related to both field estimated CAI ($R^2 = 0.66$, $p < 0.0001$, $n = 37$) and AGB ($R^2 = 0.62$, $p < 0.0001$, $n = 37$, Fig. 5).

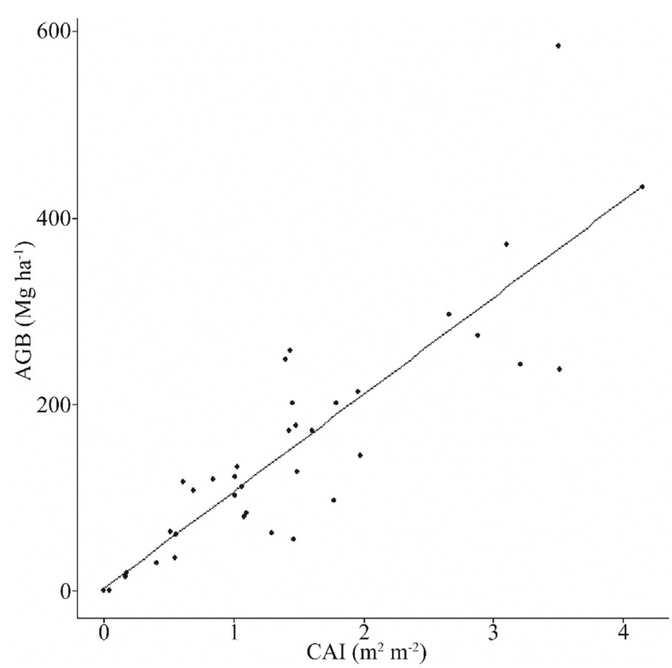

Fig. 4. Field estimated AGB regressed against the field estimated CAI. The correlation is particularly strong in open ecosystems with low AGB and CAI.

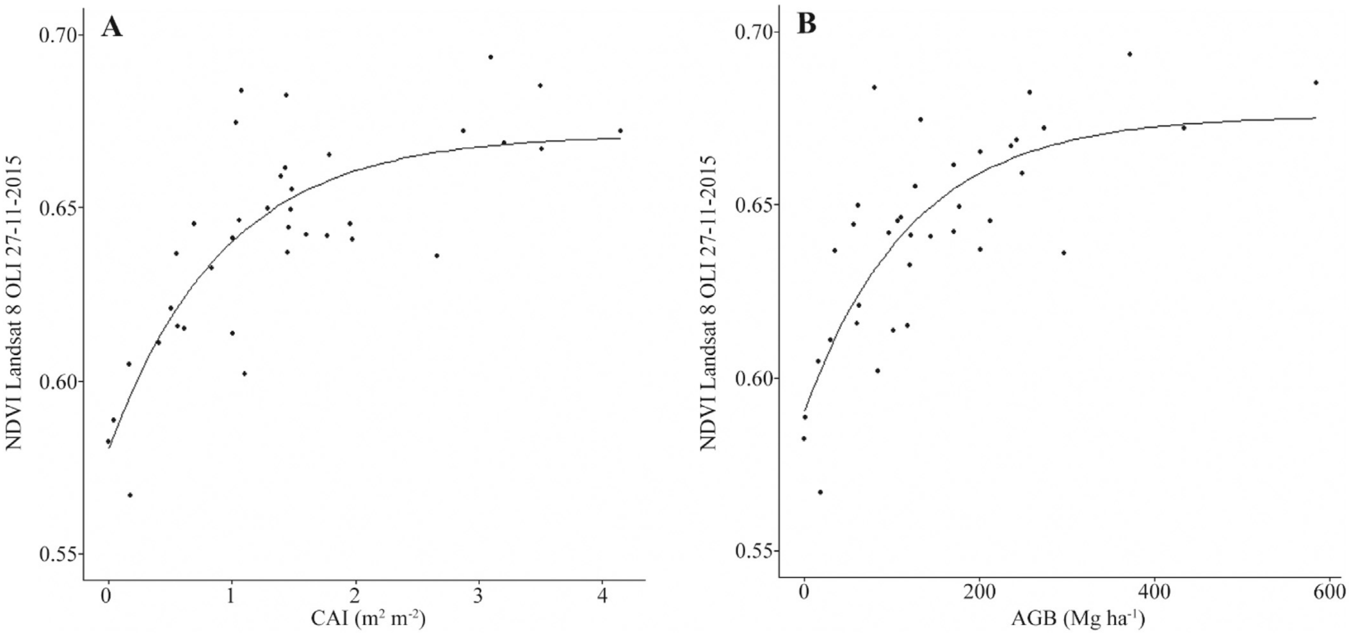

Fig. 5. Landsat 8 NDVI captured on the 27th of November 2015 regressed against field estimated CAI (A) and AGB (B). CAI and AGB showed an asymptotic relationship with NDVI with the response of NDVI to woody cover saturating around CAI = 2 $m^2 m^{-2}$ and around AGB = 200 Mg ha^{-1}.

3.2. Changes in NDVI

The change detection procedure showed both NDVI increase and decrease between 1984 and 2015 (Fig. 6, Table S2). The detected decrease in NDVI occurred almost exclusively in areas that were covered by dry forest in 1984. Between 1984 and 1990, 10.2% of this forest area experienced a detectable decrease in NDVI. More than half of this area (64.7%) decreased in NDVI between 1990 and 2002. In the period 2002–2015 there was a loss of NDVI in 28.3% of the dry forest area. NDVI increase occurred mainly in the savanna, with 4.4%, 4.8% and 37.6% of this area showing detectable increases in NDVI in the periods 1984–1990, 1990–2002 and 2002–2015, respectively.

The rate of significant NDVI loss in the area covered by dry forest increased from 1.7% $yr.^{-1}$ in the first 6 years (1984–1990) to 5.4% $yr.^{-1}$ in the following 12 years (1990–2002). Hereafter, from 2002 to 2015, the rate of NDVI loss in the forest area decreased again to 2.2 $yr.^{-1}$, cancelled out by a detectable increase of 2.4% $yr.^{-1}$. Based on the observation that the decrease in NDVI occurred almost exclusively in the central dry forest belt (Figs. 6 & 7) we can conclude that this NDVI decrease is indicating DD inside Kogyae. The NDVI increase from 2002 to 2015 in the area initially covered by forest points to a possible post-disturbance recovery of the vegetation. The area covered by savanna showed a 2.9% $yr.^{-1}$ increase of NDVI in the period 2002–2015. Branching patterns of positive NDVI change were visible in the NDVI change map of 2002–2015 that closely match the branching patterns of small streams that flow to the north into the Sene river (Fig. 7). This suggests that water availability is possibly driving the rate of woody encroachment in the savanna of Kogyae.

3.3. Interactions of fire and climate

The MODIS burned area product showed that fires were very frequent inside Kogyae (Fig. 7). In 52.3% of the reserves surface area (180.7 km^2) a fire was recorded every 1 to 2 years, while in another 24.1% of the area (83.3 km^2) a fire was recorded at an interval of 2 to 3 years. The remaining 23.6% of the area (81.8 km^2) experienced a fire return interval of 3 to 14 years. The area inside the reserve that burned annually varied significantly over the years (Fig. 8). The first four years of the record show relatively small burned areas. However, in the dry season of 2004–2005, 56.3% of the reserve area (194.6 km^2) burned. Thereafter, the area that burned annually remained large, with the exception of 2010–2011 (51.2 km^2) and 2013–2014 (35.2 km^2). There was a significant linear correlation between the extent of area burned in January and February and the accumulated precipitation in January ($R^2 = 0.45$, $p < 0.001$, $n = 14$).

4. Discussion

We observed a number of changes in the study area that are important for the long term resource exploitation and future management of the area and offer insights into long term dynamics of protected areas. The NDVI change detection procedure reveals the previously unidentified and complete clearance of a dry forest inside Ghana's IUCN Category Ia Kogyae Strict Nature Reserve between 1984 and 2015. The Landsat archive offered us the possibility to detect woody cover changes in three time periods that correspond to changes in land use, resource management and human pressure inside the reserve (Fig. 9). The estimated rate of deforestation more than doubled from 1.7% yr^{-1} in the pre-disturbance period to 5.4% yr^{-1} in the disturbance period (1990–2002). From 2002 to 2015, referred to as the recovery period, the deforestation rate declined again to 2.2% yr^{-1}, somewhat higher than the national deforestation rate of 2% yr^{-1} in Ghana in the same period (FRA, 2010).

Three different procedures were performed to reduce uncertainties and prevent errors of commission in the NDVI change detection analysis. First, by selecting images captured on similar times in the different years intra-annual or seasonal variation in NDVI is largely excluded from the NDVI change detection. Secondly, the cross-calibration of the NDVI images from the different years ensures that distortions due to sensor differences are excluded while the cross-calibration procedure also reduces some of the remaining seasonal variation. Finally, by measuring NDVI change in terms of standard deviations of change within Kogyae, only areas that show a significant magnitude of change are detected. The observed changes in tree cover were found to coincide with a number of historical events in the region. (Fig. 9). The opening of road access in 1984 contributed to the influx of migrant farmers into Kogyae, engaged in arable farming (Mertens and Lambin, 2000; Wildlife Department, 1994). Low initial population density and land

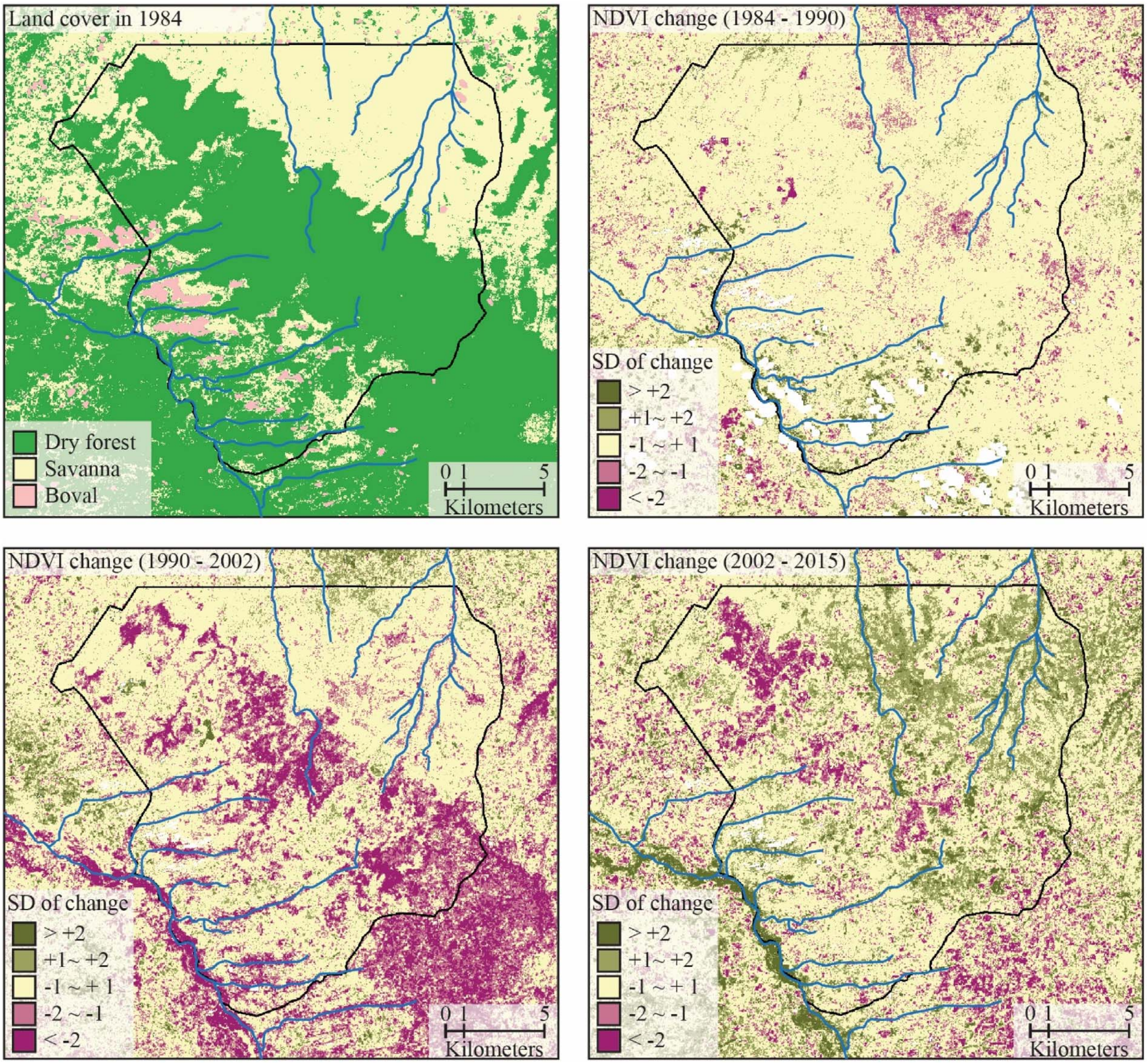

Fig. 6. Map showing the 1984 land cover in Kogyae derived from the random forest classification (top left). Major rivers and streams in the study area are depicted in blue: the Afram river tributaries in the south-west and the Sene river tributaries in the north-east. Negative change in NDVI occurred mainly in the dry forest belt in the centre of the reserve, particularly in 1990–2002. Large areas of the savanna in the north-east of the reserve show a significant increase in NDVI in 2002–2015 associated with woody encroachment. The increase of NDVI in this period shows branching patterns, following the course of multiple streams that intersect the savanna. Clouds were masked and shown in white. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

availability in protected areas have been found to act as pull factors to migrants in Ghana and elsewhere in Africa (Awuku-bor, 1999; Hartter et al., 2014; Zommers and Macdonald, 2012). The rate of forest clearing for arable farming accelerated in the early 1990s (Fig. 9) (Awuku-bor, 1999; Hagan, 1998; Wildlife Department, 1994).

Two factors have been contributed to the failing of the reserve management in protecting the dry forest of Kogyae. First, a lack of definite policies and management guidelines led to a situation in which the local wildlife officers were responsible for setting out their own management priorities (Wildlife Department, 1994). Secondly, the community of settlers used to see the reserve as potential farmland that was to be released to them and therefore they did not recognise the status of Kogyae as a protected area (Awuku-bor, 1999; Hagan, 1998; Wildlife Department, 1994). The history of Kogyae provides a textbook example of how imposing protected areas on local communities without strong enforcement rarely leads to successful conservation (e.g. Infield, 2001). The extensive deforestation observed is in line with the general trend of DD in Ghana's barrier reserves in the 1990s. Another documented example is the Tain II tributaries barrier reserve (Hawthorne and Abu-Juam, 1995; Kyereh et al., 2007). Kogyae's watershed protection function is now lost with the effects felt by local communities. Streams dry up completely during the dry season (Hagan, 1998) and the water supply from boreholes is reduced, resulting in water shortages (Ofori et al., 2014). Furthermore, dry forest tree species constitute an essential part of rural livelihoods as many species are used for charcoal and household fuel, fodder, construction wood, medicine and food (Paré, 2008). The effects of DD on biodiversity inside the reserve are expected to be substantial (Barlow et al., 2007; Green et al., 2013; Koh and Sodhi, 2010; Norris et al., 2010).

Some of the larger mammal species previously common inside the reserve, for example Elephant (Loxodonta africana) and Black-and-white Colobus (Colobus polykomos) have become locally rare or extinct (Ayivor and Ntiamoa-Baidu, 2015). Tree species that occur in the dry semi-deciduous forest inside Kogyae are growing at the very limit of their ecological distribution. Economically important transitional tree species in Kogyae include Afzelia africana and Khaya senegalensis, both classified as vulnerable in The IUCN Red List of Threatened Species. Genotypes found in these populations are expected to represent

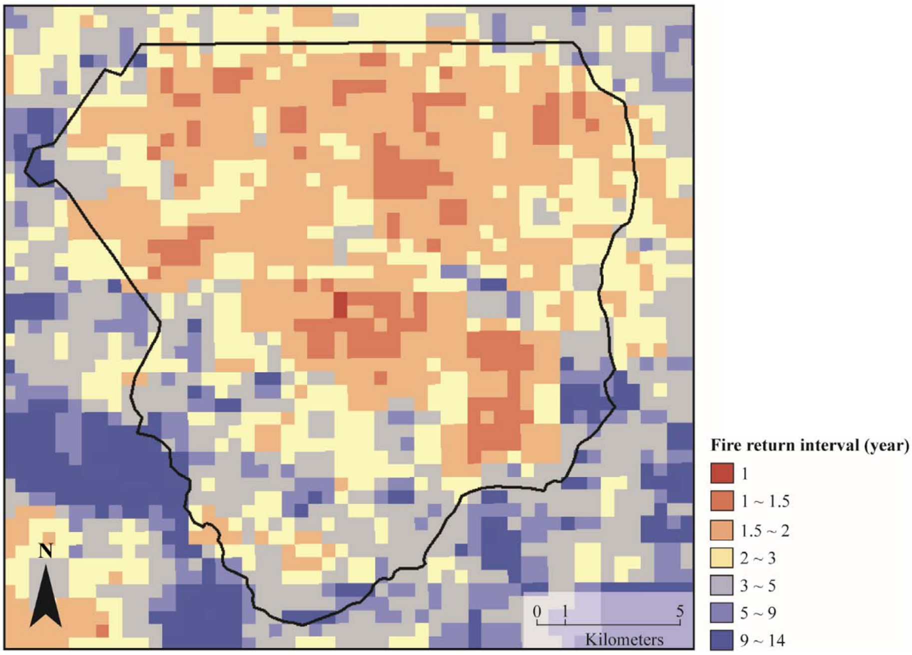

Fig. 7. Fire return interval from 2000 to 2015 derived from the MODIS burned area product. The deforested area shows frequent burning as this area experiences at least one fire every two years. Also the savanna in the north experiences a high fire frequency. Areas in the south-west are characterised by a longer fire return interval of 3 to 5 years. Note that the fire return interval inside Kogyae is significantly shorter compared to the fire return interval in the direct surroundings.

valuable genetic resources, especially in the context of climate change adaptation (Gonzalez, 2001; Millar et al., 2007). It would be a tremendous loss for the biodiversity, rural livelihoods and the forestry sector of Ghana if these genotypes would disappear completely.

A recent survey among (retired) wildlife officers and people from local communities (results not shown) confirmed that in 2002, all the farming communities residing within the reserve were expelled by the Wildlife Department. This is confirmed by the interpretation of aerial images (Google Earth™), as the area that was deforested within the reserve is presently not cultivated and has been clearly abandoned. The decline of forest loss observed after 2002 (Fig. 6) can therefore be attributed with confidence to a tighter control on arable farming within

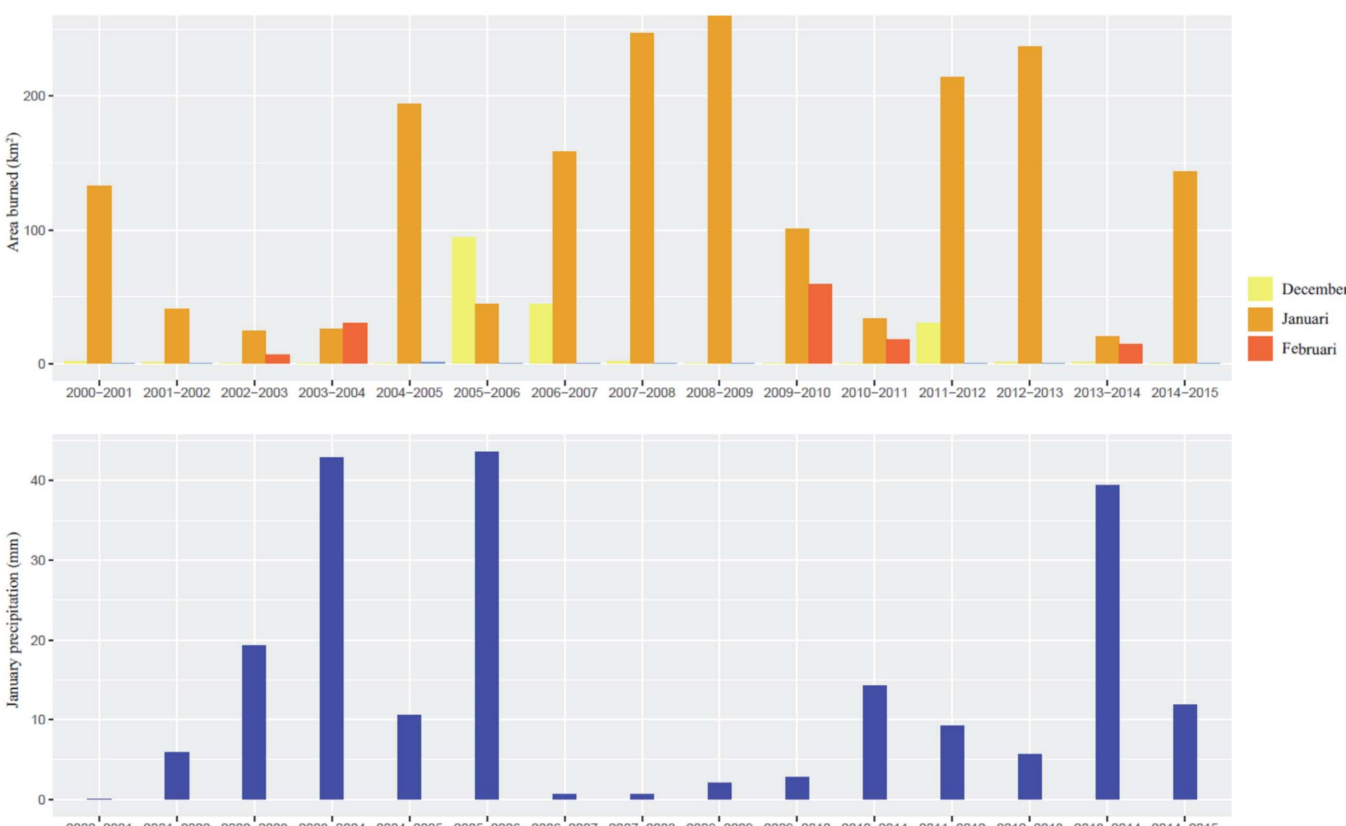

Fig. 8. The extent of area burned in the three dry season months (above) and the accumulated precipitation in January (below). Associations are observable between the detected burned area and January precipitation. In 2004, 2006 and 2014 the accumulated precipitation in January peaks above 35 mm. In these years the recorded burned area in the dry season was also relatively low. From 2007 to 2010, January was dry and these years also show a large area burned in January.

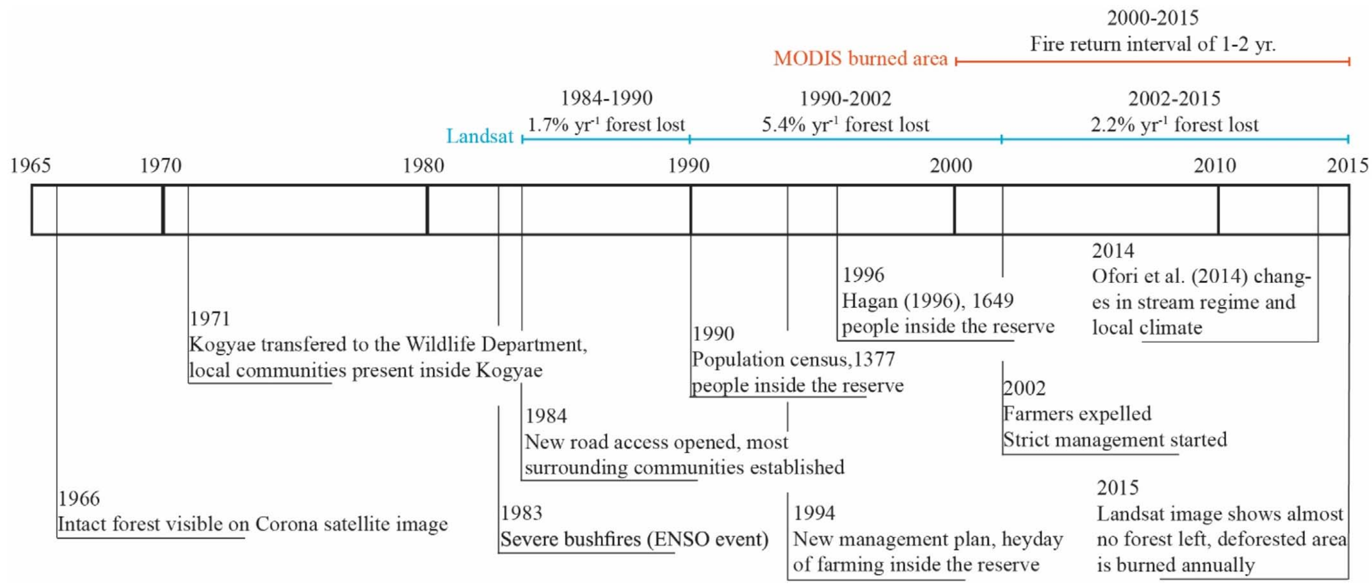

Fig. 9. History of Kogyae, as described in the literature (Awuku-bor, 1999; Hagan, 1998; Ofori et al., 2014; Wildlife Department, 1994) and from the interpretation of the NDVI change detection and MODIS fire record results.

Kogyae by the reserve management. Yet the rate of woody cover loss in the north of the reserve remained high until 2015 (Fig. 6). This can be attributed to the damage caused by recurrent annual fires, as fire is known to accelerate forest degradation in areas where forest cover has been previously reduced and a high fire frequency is maintained (Hawthorne, 1994; Hosonuma et al., 2012; Swaine, 1992).

While fires are lit every dry season at the edges of the reserve (Ayivor and Ntiamoa-Baidu, 2015), the fire record shows that a relatively high precipitation in January (> 35 mm) can prevent the fires from burning a large area of the reserve (Fig. 8). This effect of dry season precipitation via fuel moisture on the annual variability of fire extent is well described on larger spatial scales for the African continent (Andela and van der Werf, 2014), Amazonia (Aragão et al., 2008) and equatorial Asia (van der Werf et al., 2008). The MODIS fire record suggests that the area burned inside the reserve has increased since 2004, this is confirmed by observations by the reserve management (Ayivor and Ntiamoa-Baidu, 2015). The fragmentation of dry forest, the opened canopy and the increase of savanna grasses in open areas have increased fire fuel loads with poaching and park management sustaining a high fire frequency. Logged and burned forests are found to be susceptible to renewed burning due to a substantial and dry fuel load (Kyereh et al., 2007) and a similar effect is found when analysing long term fire experiments(Veenendaal et al., in press). Eventually, much of the original forest changed into the treeless tall grasslands and Chromolaena odorata thickets existing there today. The annual early burning management likely prevents or slows down the return of tropical dry forest previously present.

NDVI increase was widespread in the savanna and woodland inside Kogyae from 2002 to 2015. Our results suggest that regular fires were not able to prevent woody encroachment in the savanna as the NDVI increase occurred in the north eastern savanna zone that experienced a relatively short fire return time of 1 to 2 years in the period 2000–2015 (Fig. 7). Finding woody encroachment along streams and in the savanna ads to the increasing amount of evidence reporting woody encroachment in the woodlands and savanna of sub-Saharan Africa (Mitchard and Flintrop, 2013) and in the western Sahel (Horion et al., 2014).

Deforestation of tropical dry forests is a major global issue. From 2000 to 2012 tropical dry forests in Latin America, Africa and Eurasia experienced the highest deforestation rates of all forest ecosystems (Hansen et al., 2013). Forest clearing for agriculture is recognised as the main driver of DD in the tropics (Hosonuma et al., 2012). We show how dry forests are extremely susceptible to DD even if they are located in a protected area in the strictest sense. Formal de jure protection can be totally disconnected from de facto status, leading to creation of so-called 'paper parks' (Figueiredo, 2007; Joppa et al., 2008). Dry forest patches are still present in Kogyae and the areas surrounding these patches are showing signs of forest recovery. However, annual fires are hindering forest recovery. This suggests that Kogyae's management should re-assess the current practice of deliberate burning. International mechanisms that will provide funding for reforestation activities in the context of climate change (REDD +), and biodiversity conservation schemes may provide an avenue for the restoration of Kogyae's forest. Most broadly, this study contributes to the ongoing debate about the effectiveness of protected areas (Di Minin and Toivonen, 2015; Joppa et al., 2008; Symes et al., 2016). We have demonstrated the application of remote sensing techniques to provide robust change detection using freely-available data, and have revealed a hitherto undocumented and near-complete loss of Ghana's most strictly protected forest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: https://doi.org/10.1016/j.biocon.2017.12.004.

These data include the Google maps of the most important areas described in this article.

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