CONFLICT-INDUCED DEFORESTATION DETECTION IN AFRICAN CÔTE D'IVOIRE USING LANDSAT IMAGES AND RANDOM FOREST ALGORITHM: A CASE IN MOUNT PEKO NATIONAL PARK

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Abstract. African forests, especially in Côte d'Ivoire, have been lost during the past three decades. Worldwide, forests are being destroyed to make room for farmland. Deforestation depletes floral resources and fragments habitat. Cocoa growth threatens critical ecological zones, particularly in Côte d'Ivoire. The 2002–2007 conflict impacted Mount Peko National Park (PNMP). This issue has hastened the decline of endangered animal habitats (Colobus and Elephants). The classification approach based on Random Forest (RF) algorithm using the Mean Accuracy Decrease (MDA) has been applied for choosing a variable to select the best predictor variables in the model. A Spectral Index map and time series satellite images of the PNMP from 1985 to 2020 were used to identify land cover changes. RStudio and QGIS 3.4 software have been used to create training data. Among thirteen (13) variables studied, NIR (Near Infrared), Short-Wave Infrared 1 (SWIR 1) and SWIR bands had the increased importance of the variable for the performance of the classification prediction model. The NIR band was the greatest predictor. MDA predicted 75%. User accuracy (UA), Producer accuracy (PA), and Overall accuracy (OA) classifications were 98.75% ± 1.94, 99% ± 1.95, 97% ± 1.93. The park's dense forest remained unchanged, but nonforest was reforested and 12.22% was turned to forest. During the study period, extensive cocoa plantations were established in formerly forested regions.

Keywords: *change detection, cocoa plantation, satellite imagery, elephants, Colobus*

Introduction

Tropical forest ecosystems are valued for products and services all across the globe due to the resilience of these ecosystems and the sustainability of producing the products and services they offer (Malhi et al., 1999; Myers and Rocca, 2000; Pan et al., 2011; Poorter et al., 2015; Aubry-Kientz et al., 2015; Jhariya, 2017; O'Sullivan et al., 2017). Côte d'Ivoire forests provide many ecosystem services vital for maintaining the livelihoods and lifestyles of rural populations, such as firewood, fruits, fibers, medicinal plants, honey, game, and ecotourism (Aké-Assi, 1998; N'Guessan, 2004; Foley et al., 2005, 2007; Tadesse et al., 2014; O'Sullivan et al., 2017; Kassoum, 2018; Rowland et al., 2018;). According to Sangne (2009), protected areas of Côte d'Ivoire include 182 classed forests and eight national parks: the remaining remnants of the thick Ivorian forest, which covered approximately 10% of the country. Before the crisis, these woods were protected, preventing damage (Lauginie et al., 1995). The western Ivorian woods have an essential role in the protection of western chimps listed as Critically Endangered since 2016, forest elephants, and the uncommon pygmy hippopotamus (Chaléard, 1996; McGraw, 1998; Miller et al., 2007; Oates, 2011; Bitty et al., 2015). However, during the last decade, deforestation and forest degradation have become a significant issue in Africa, particularly in Côte d'Ivoire.

The Ivorian Forest massif is in decline and is now split into national parks and classified forests, reducing to less than 20% of its original size between 1960 and 1980 (Singh, 1993). Less than 10% between 1980 and 1990 (Menzies, 2000), and 7.5% between 1990 and 2000 (Chatelain et al., 2004). This makes Côte d'Ivoire the country with the highest deforestation rate in Sub-Saharan Africa, with a loss of 265,000 ha per year (Achard et al., 2002; Hansen et al., 2013) and an annual deforestation rate of 1% (Ibo and Léonard, 1994; Tutu and Akol, 2009; Ruf et al., 2015). Since 1977, Côte d'Ivoire has been the world's leading cocoa producer, accounting for more than 40% of global production and accounting for nearly 40% of total exports (Deheuvels et al., 2003; Konate et al., 2015). The changing worldwide prices of cocoa beans have pushed people to convert forest areas to cocoa plantations. This deforestation has encouraged the formation of pioneer fronts, which penetrate parks and designated forests. Cocoa farming is becoming a significant cause of deforestation and tropical forest degradation in Côte d'Ivoire (Aké-Assi, 1998; Bhagwat et al., 2008; Gnahoua et al., 2012; Konate et al., 2015). It is projected that forest clearance boosted cocoa-growing areas from 250.000 ha in 1961 to 4.000.000 ha in 2004 (Franzen and Mulder, 2007; Läderach et al., 2013; Konate et al., 2017). It is estimated that income produced by cocoa plantations following deforestation accounts for 10% of national GDP (Brou et al., 2004; Sonwa et al., 2007; Morris, 2010; Beucher and Bazin, 2012). According to the Ministry of Water and Forests of the Cote d'Ivoire land cover tree evolution was 17.000.000 ha of forests in 1960 which totaled 3.000.000 ha of forests in 2020 (http://www.eauxetforets.gouv.ci/ministere). Some authors believe that war is responsible for most of Africa's deforestation and forest degradation (Koning et al., 2007; Gorsevski et al., 2013; Nackoney et al., 2014; Ordway, 2015).

Côte d'Ivoire, like other West African nations such as Liberia and Sierra Leone, will face socio-political problems (Burgess et al., 2015).

Côte d'Ivoire suffered the most severe sociopolitical and economic turmoil in its history between 2002 and 2011. Several outbreaks of violence occurred over this lengthy period, the most significant being the breakout of an armed insurrection in 2002 and a violent post-election crisis between 2010 and 2011. Approximately 3000 individuals were

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killed. The conflict has resulted in many displaced people and refugees, the abandonment of park and reserve protection in rebel regions, exactions and rapes on civilians, looting, and fires. These crises exacerbated the worsening of environmental conditions in the west of the country. The preceding decades' violent conflicts hastened the unlawful takeover of existing protected areas.

The socio-political conflict in Côte d'Ivoire from 2002 to 2011 resulted in the nation being divided in two, with the rebel army controlling the north and part of the west (Bouquet and d'Ivoire, 2011; Bamba et al., 2018). The consequences were catastrophic for the natural environment and protected areas (Kadet, 2015; UNEP, 2015; Kouakou et al., 2017). This conflict emphasized illicit human activities like logging, mining, and poaching (Allnutt et al., 2013; Barima et al., 2016). For example, Mount Péko National Park was not spared. Large cocoa plantations have been built inside it violating protection regulations (Bredeloup, 2003; Woods, 2003; Kouakou et al., 2015; Bamba et al., 2018; Assalé et al., 2020), resulting in massive biodiversity losses (Kouamé, 1998; N'Guessan, 2004; Yao and Yves, 2005; Matsushita et al., 2006; Lauginie, 2007; N'Da, 2007; N'Da et al., 2008; Sangne, 2009). The Ivorian Office for the Protection of Parks and Reserves (OIPR) has conducted investigations that showed the installation of settlements inside the PNMP (Kassoum, 2018). The PNMP, like other classified forests and national parks, has lost biological value due to deforestation from cocoa production (Norris et al., 2010; Tano, 2012; Bitty et al., 2015). There have been few studies in Côte d'Ivoire on the effect of the crisis on forest resources. As a result, this study aims to identify forest cover change due to the Ivorian problem's impact on forest cover. For example, the PNMP, which has been under siege by armed fighters for a long time, has been the subject of many assaults. The insurgents have set up camps and communities in public schools, official health facilities, mosques, churches, shops, and cell phone towers. Large sections of the PNMP have been turned into cocoa producing zones. Before this research, it was unclear how a 10-year armed war affects deforestation and cocoa plantation growth in Côte d'Ivoire. As a result, in this research, we used the Random Forest (RF) (Breiman, 2001) classification method for Landsat data to identify forest cover change before and during the long-term PNMP crisis. The findings will help us understand the impact of previous instability on forest cover dynamics in western Côte d'Ivoire.

Literature review

History of cocoa and impact of the armed conflict in Côte d'Ivoire

The cocoa tree was brought to Côte d'Ivoire towards the end of the nineteenth century in the east part of the country (Ruf et al., 2015). Cote d'Ivoire is an agricultural country that produces 40% of the world's cocoa bean output, which is the foundation of its economy. As a result, the sector is critical for the macroeconomic balance and social stability of the country (Darie-Rousseaux and Brown, 2016). In 2018, its production and exports accounted for almost 40% of its goods exports and 14% of its GDP (Coulibaly and Erbao, 2019). Côte d'Ivoire is the global leader, with a market share of 29% and an export value of 2 to 3 billion euro (Hausmann and Hidalgo, 2011). Agriculture exports fuel its economic success (Esso, 2009). More than one million small-scale farmers work in cocoa production, mainly in the southern half of the country, generating 500-600 kg/ha on average (Deheuvels et al., 2003, 2009; Wessel and Quist-Wessel, 2015). About 6 million people are directly supported by cocoa earnings on a social level, which have increased in recent years (Tano, 2012). At the end of the 1970s, the cocoa, coffee, and

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wood industries accounted for 30% of GDP and 50% of Côte d'Ivoire's export profits (Ibo and Léonard, 1994). Côte d'Ivoire has been the world's top cocoa producer since 1977, accounting for more than 40% of global output. It accounts for approximately 40% of the country's exports (Ibo and Léonard, 1994; Akindès, 1994; Sanial, 2018). Côte d'Ivoire currently possesses the world's greatest crushing capacity, at 750,000 tonnes. It grinds around 20% of the world's coffee, some of which is exported. Côte d'Ivoire has implemented a policy of levying a tax on cocoa exports to maintain a level of equilibrium in the volatility of global cocoa prices (Deheuvels et al., 2003; Konate et al., 2015). Today, Côte d'Ivoire has the highest grinding capacity in the world, with 750,000 tons. It grinds about 20% of the world's beans, and a portion is exported. To increase revenues and stabilize its economy, Côte d'Ivoire has adopted a policy of imposing a tax on its cocoa exports to ensure a level of equilibrium in the fluctuation of world cocoa costs (McIntire and Varangis, 1999; Burger, 2008; Kireyev, 2010). These export tariffs provide substantial tax revenues for Côte d'Ivoire, amounting up to 10% of the state budget (Zamble, 2015). In 2010, this percentage was predicted to be 27% (Kireyev, 2010).

The changing worldwide prices of cocoa beans have pushed people to convert forest areas to cocoa plantations. This deforestation has encouraged the formation of pioneer fronts, which penetrate parks and designated forests. The decrease in cocoa prices has been directly linked to the rise in cocoa output throughout the years.

Cocoa output has increased dramatically in recent decades, mainly owing to establishing new plantations at the cost of natural forests. This trend can be attributed to the fact that some companies, such as Olam, Cargill, and Barry Callebaut, encourage farmers to establish large cocoa plantations within protected parks and classified forests (https://www.mightyearth.org), with little regard to the ecological impacts of providing cheap cocoa and authorities rarely enforce the rules governing cocoa production. Consequently, Côte d'Ivoire has become the world's biggest cocoa producer in less than 40 years, almost quadrupling its output from 550,000 tons per year in 1980 to over 2 million tons in 2018 (Fountain and HützAdams, 2018). This increase in cocoa output has depleted both natural and social capital (including child labor) in Côte d'Ivoire.

Mighty Earth, a non-governmental organization, has previously condemned the role of chocolate industry in deforestation in Côte d'Ivoire, especially in the destruction of protected regions and national parks (Wessel and Quist-Wessel, 2015). The chocolate business encourages farmers to plant illegally manufactured cocoa beans in the PNMP, promoting deforestation in Côte d'Ivoire (Climate Chance, 2018). Cocoa farming is a significant cause of deforestation and tropical forest degradation and destruction of protected areas (*Fig. 1*) in Côte d'Ivoire (Bhagwat et al., 2008; Deheuvels, 2011; Gnahoua et al., 2012).

Materials and methods

Study area

Côte d'Ivoire has a land area of 322,462 km^2 and is located between 6° and 10° north latitudes, and 2° and 10° west longitudes. Cote d'Ivoire borders Liberia and Guinea to the west, Mali and Burkina Faso to the north, Ghana to the east, and a 550-km Atlantic Ocean coastline to the south (*Fig. 2*). Topographic features run north-east to south-west. The southern plateaus have several independent topographic features grouped into five main groups: the Guinean ridge, the northern plateaus, the transition zone, the interior lowlands, and the coastal fringe. The climatic conditions are ideal for agricultural growth.

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The forest zone of Côte d'Ivoire receives abundant rainfall, ranging from 1 600 to 2 000 mm per year. Mount Péko National Park, located in the western part of Cote d'Ivoire, has a study area of 34,000 ha. By Decree No 68-69 of 09/02/1968, this forest massif was designated as a national park to preserve the peaks of Mount Kahoué (1,125 m) (Lauginie, 2007); and Mount Péko (1,002 m). The PNMP is distinguished by its position in a zone of semi-deciduous montane woodland (Ibo, 2005). Its southern area is characterized by undulating plateaus 300 to 500 m above sea level, while the rockier northern region includes three distinct summits, including Mount Péko. The hydrographic network is mainly made up of tributaries of the Sassandra River, which runs through the park's southern boundary. Except for the inselbergs that appear in the north, the park is entirely covered with semi-deciduous rainforest. The top forest shares a border with the dry forest. Poaching has left its impact on wildlife, including big animals such as elephants and buffalo (Lauginie, 2007; Bi et al., 2013). The PNMP is rich in biodiversity, including unique species to the area and nation, and it represents a rare ecological treasure in the West African subregion (CEPF, 2000).

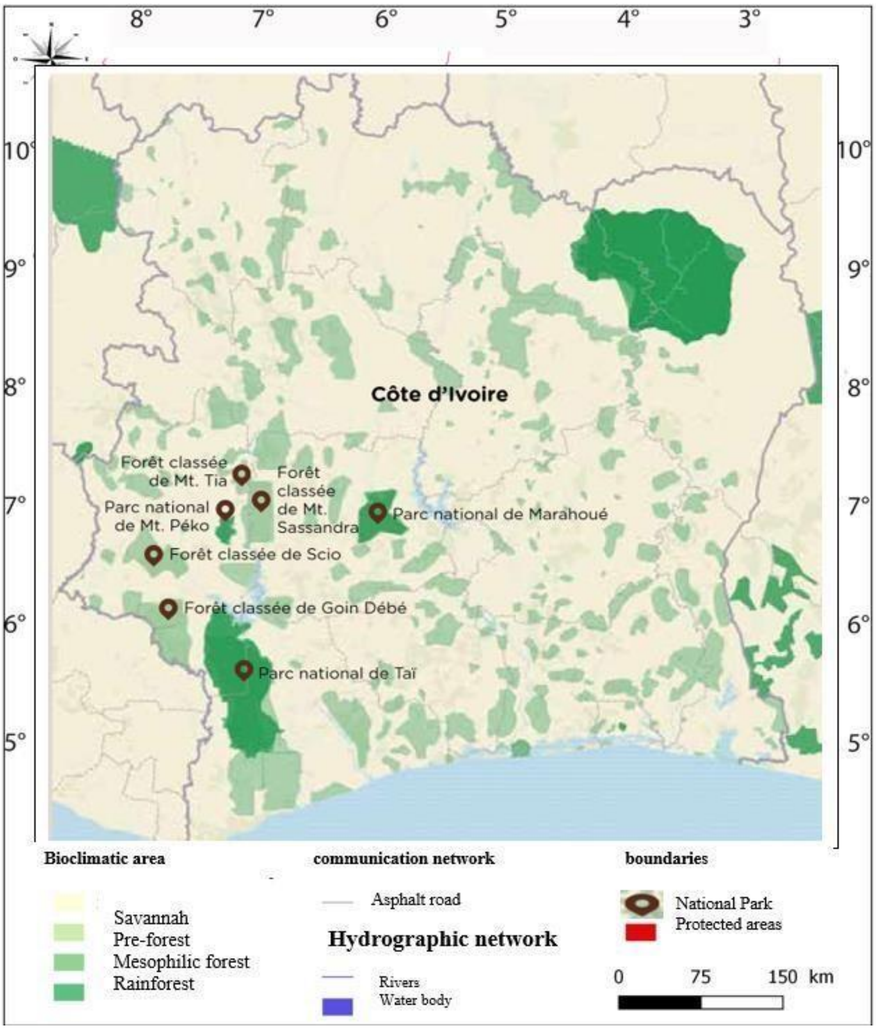

Figure 1. *Map showing the negative impacts of the crisis and development of cocoa plantations in protected areas source (https://www.protectedplanet.net/)*

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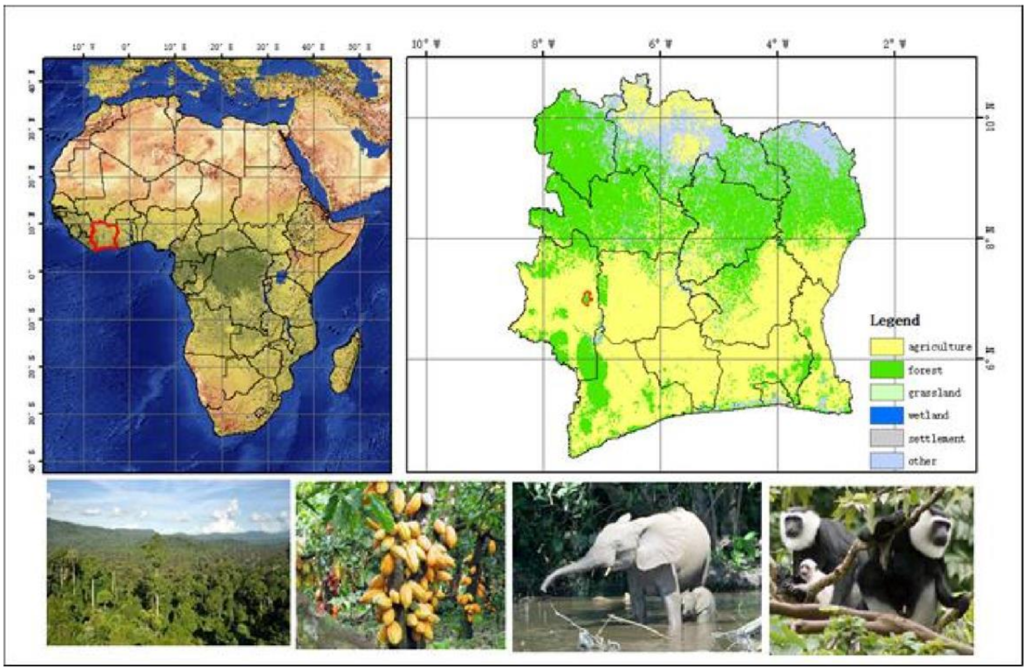

Figure 2. *Illustrated maps of the study area locations and exemplified plant and animal species. Côte d'Ivoire location (within red line) in African continent, (b) PNMP location (within red line) in Côte d'Ivoire, land cover map in background downloaded from the ESA-CCI site (http://maps.elie.ucl.ac.be/CCI/viewer/download.php). (c), (d), (e) and (f) is rainforest, cocoa plantation, elephants and colobus monkeys*

Data set

Landsat images have been downloaded from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/) for this research. We chose less than 10% cloud cover. We downloaded Landsat 4-5 Thematic Mapper (TM), and Landsat 8 Operational Land Imager (OLI), and Thermal Infrared Sensor (TIRS) collection 1 level 1 image from 1985 and 2020, respectively. The images that were downloaded had previously been radiometrically and geometrically adjusted. The Landsat sensor is often utilized in land cover mapping applications in the landscape sector (Hansen and Loveland, 2012; Sharma and Joshi, 2013) and forestry mapping (Hansen and Loveland, 2012; Sharma and Joshi, 2013; Cohen and Goward, 2004; Townshend et al., 2012). The images from January-February-March-April-May-December were chosen for the study to minimize cloud cover because the rainy season in the region lasts from June to November. Image characteristics are shown in *Table 1*.

Table 1. *Characteristics of the Landsat satellite images used in this study*

No	Acquisition date	Scenes ID	Sensors	Resolution (m)	Path	Row
1	12/11/2010	LT05-L1TP-198_19850120-20170219-01-T1	Landsat 4 and 5 (TM)	30	198	55
2	05/01/2020	LC08-L1TP-198055-20200512-2020526-01-T1	Landsat 8 (OLI) and (TIRS)	30	198	55

TM = Thematic Mapper; OLI = The Operational Land Imager; TIRS = Thermal Infrared Sensor

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Choice of the algorithm

The RF algorithm was chosen for its ability to forecast various land-use types (Gislason et al., 2006). It also discusses the significance of the factors utilized in the classification. We processed the NIR band for Landsat 4-5TM as band four (4) and the NIR band for Landsat 8OLI/TIRS as band 5. Once the changing image was acquired, it was utilized to identify the various locations on the resultant map where forest cover had grown, decreased, or stayed the same.

To produce an image with artificial colors and examine the vegetation in this color category, we layered the two multi-band images, namely date (1985) Landsat 4-5 TM (bands 1, 2, 3, 4, 5, 7) and date (2020) Landsat 8 OLI/TIRS (1, 2, 3, 4, 5, 6, 7). The color compositions were created using the near-infrared, mid-infrared, and red spectral bands from the 2020 Landsat 8 OLI/TIRS image (5/6/4) and (4/5/3) from the 1985 Landsat 4-5 TM images. We were able to see the images produced by combining false-color composite bands thanks to the categorization. We only utilized bands 12, 11, and 10 from the 2020 Landsat 8 images, corresponding to bands 6, 5, and 4. In reality, combining the two Landsat 4-5 TM and Landsat 8 OLI/TIRS images yielded 13 bands. We selected areas on the image where we knew the land use category and the change observed between 1985 and 2020 to establish training sites.

The establishment of training sites was spread across the park to identify areas with instability or no change. The training data was delineated in clusters, including gathering and defining multiple training plots in the same area. QGIS version 3.4.6 was used for processing. We used the near-infrared (NIR) band of each date to create a simple visualization of the change in Qgis. We created the training sites by generating a polygon shapefile before processing in the R program. The development of the training locations required the previous identification of places on the map where we understood the land use and the kind of change observed between 1985 and 2020. We then used and labeled the different type categories, as well as this identifying code (11: For-For), (12: For-NonFor), (21: NonFor-For), and (22: NonFor-NonFor).

The training areas were created on a computer by digitizing polygons on the multi-date (1985) and (2020) color composition for each specified spectral class (Forest to Non-Forest); (Forest to Forest); (Non-Forest to Non-Forest); and (Non-Forest to Non-Forest) (Non-Forest to Forest). Over the whole research site, 200 geometric polygons were developed, 50 for each land cover type. We assigned the value "100-100-100-500" respectively for (For-For), (For-NonFor), (NonFor-For), and (NonFor-NonFor) classes. The NonFor-NonFor class was given the number "500" since the training sites were lower in size than the other classes. These values enabled the classification algorithm to utilize the pixels in each class's formation polygons installation of the R packages "maptools", "sp", "randomForest", "raster", and "rgdal" was required prior to classification. RF classification was given to the whole collection of training areas. By combining the Landsat 4-5 TM (1985) and Landsat 8, OLI/TIRS (2020) bands utilized for the PNMP land cover categorization, thirteen (13) multi-temporal satellite imaging predictors were created. Throughout the categorization procedure, about 500 trees were mobilized to stabilize the classification.

Qgis has been used to apply the post-classification classifier majority filter (Pixel size 3×3) to the final PNMP map to improve our actual classification. This majority filter aims to remove pixel occurrences to prevent pixelated "salt and pepper" effects.

Statistical evaluation of classification accuracy

Calculations of accuracy: user's accuracy ($\widehat{U}$i) (*Eq. 1*), (Story and Congalton, 1986) producers' accuracy ($\widehat{P}$) (*Eq. 2*) and overall map accuracy ($\widehat{O}$) (*Eq. 3*) (Congalton and Green, 2019), allowed to estimate the accuracy of the classification. *Equations 2, 3,* and *4* are derived from Olofsson et al. (2014).

$$\widehat{U_i} = \frac{\hat{p}_{ii}}{\hat{p}_{i}} \quad \text{(Eq.1)}$$

$$\widehat{P_j} = \frac{\hat{p}_{jj}}{\hat{p}_{.j}} \quad \text{(Eq.2)}$$

$$\hat{O} = \sum_{j=1}^{n} \breve{y}_{jj} \quad \text{(Eq.3)}$$

where $\widehat{P_j}$ is the estimated proportion of area in cell, *j* of the error matrix *i* and *j* are the rows and columns of the confusion matrix.

In addition to the calculations of ($\widehat{U_i}$) and ($\widehat{P_j}$), we calculated estimates of the accuracy of final change map by combining *Equations 1* and *2* to the estimated error matrix as reported in *Table 2*. We evaluated the standard error of each class using *Equation 4:*

$$\hat{P}_{ij} = \theta_{i} \frac{n_{ij}}{n_{i.}} \quad \text{(Eq.4)}$$

where θ is the class error *''i''*, and *''j''* are the rows and columns of the confusion matrix.

The "*freq*" function in the Raster package enables us to calculate how many pixels exist in each class. It is a function that displays weighted or unweighted frequencies, including counts and proportions < NA > in the computation of pixels for area estimate. Areas were calculated by multiplying the total number of pixels by the size of each image pixel (900 m^2).

-In terms of surface area (m^2):

Each class's pixel count has been doubled by 900.

-In (ha), for the surface:

The surface area in (m^2) has been divided by 10000.

To calculate the percentage the quotient of the area in (ha) and the total area in (ha), was multiplied by 100.

$$\text{ClassArea (Ha)} = \frac{[\text{Count} \times 900]}{10000} \quad \text{(Eq.5)}$$

$$\text{ClassSurface } (m^2) = \text{Count} \times 900 \quad \text{(Eq.6)}$$

Results

Tree cover change

This descriptive study was performed on the whole territory from 1975 to 2013 (*Fig. 3*), focusing on our expanded region, the PNMP, and the Random Forest algorithm.

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We chose to investigate the condition of the land cover prior to the time of this research in order to identify the pattern of changes that have happened. It enabled us to observe what happened before, during, and after the crisis.

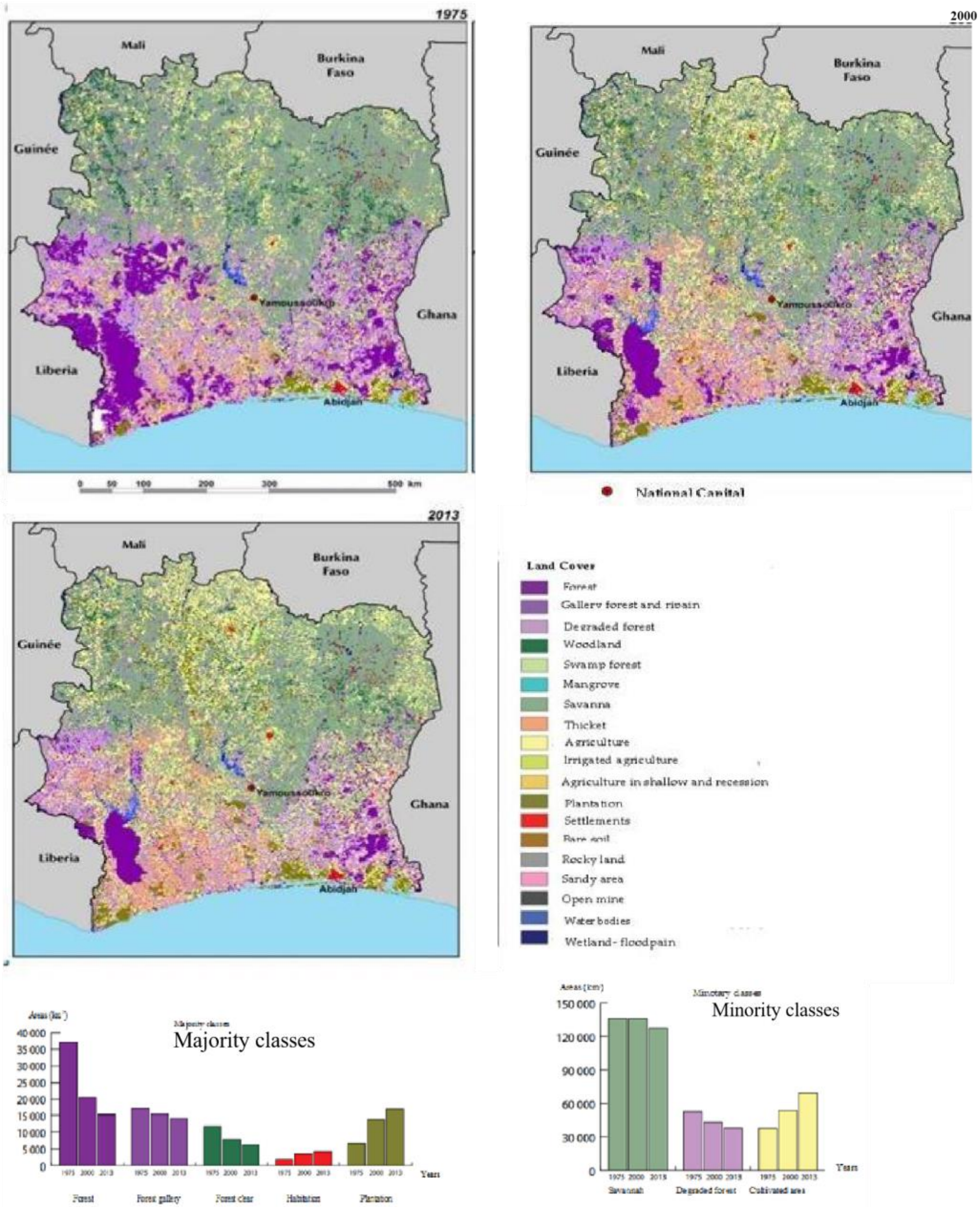

Figure 3. *Statistic Côte d'Ivoire land use and land cover class from 1975 to 2013 (CILSS, 2016)*

According to Hansen et al. (2013), the overall loss of trees is six times more than the total increase across the whole area in one year (2000). When we attempt to simulate the yearly loss from the beginning of the war in 2002 to the conclusion of the conflict in 2012, we see that the PNMP has lost a significant portion of its forest cover over these ten years (Hansen et al., 2013). The increase of cultivated land has had an impact on the woodland landscape. Indeed, deforestation caused by the expansion of agricultural land is one of the most significant and unquestionably permanent changes in Côte d'Ivoire. Historically,

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most logging occurred inside the reserves and classed forests that surrounded about 40% of the Ivorian forest in 1975 (approximately 14,500 km^2) (CILSS, 2016). Dense forests, as well as open forests outside of protected zones, were severely damaged. Côte d'Ivoire lost almost 60% of the 37,300 km^2 of thick tropical forest in 1975 by 2013 (CILSS, 2016) (*Fig. 3*).

Similarly, the degraded forest has reduced by 28%, while open forest has dropped by 48%. Gallery forest is another significant forest type in Côte d'Ivoire. Gallery woods covered 17,100 km^2 in 1975. In 2013, this number was decreased to 14,130 km^2.

According to *Figure 4*, the park suffered its most significant loss in forest cover over the 10-year crisis period in 2012, with an estimated loss of 344590.88 Mg, which corresponds to an area of 1930.42 ha. Aside from this day, this region suffered a comparable loss in the year 2020 as it did in 2012. This is because the area was the site of violence and conflicts, and the warring parties and the people were concerned with fighting and escaping. After a few years of quiet, the warring armies entered the park to establish plantations. The park's tree loss has been a significant trend throughout the research period. The graph depicts the loss of primary forest and tree cover in the PNMP between 2001 and 2020 (https://www.globalforestwatch.org/). Over the whole time, we see a pattern of a substantial decline in tree cover across the park.

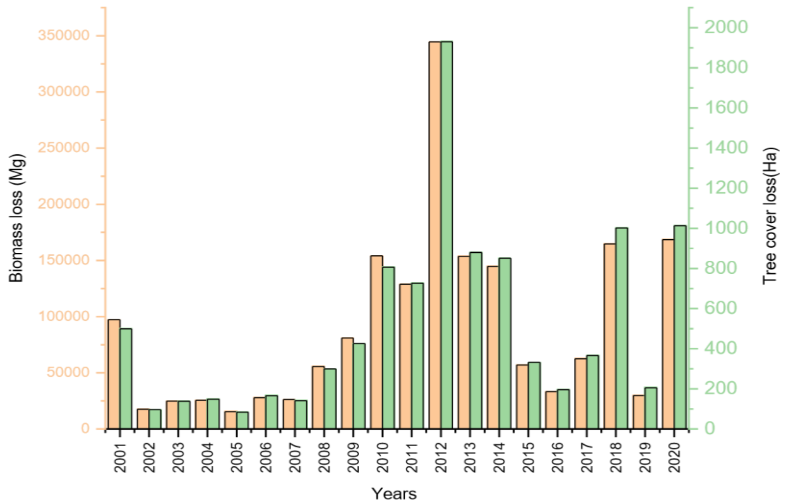

Figure 4. *PNMP Biomass and tree cover lost from 2001 to 2020*

Cocoa production increase

Figure 5 shows world cocoa prices from 1952 to 2017. The prices were high in the first ten years of the crisis, varying from 2000$ to 3000$. The world cocoa price from 2002 to 2007 increased above the trendline as the Côte d'Ivoire, the leading supplier of more than half of world production, could no longer supply the international market due to the crisis.

Vegetation index (NDVI)

Figure 6 shows the evolution of the vegetation index of the PNMP over the two periods 1985 and 2020. The figure illustrates a decrease in the NDVI pixels. The graph shows a reduction in the NDVI pixels performed in Qgis using Landsat 4-5 TM and Landsat 8

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OLI/TIRS data. *Figure 6a* and *b* illustrate the drop in NDVI frequency values from 1400 to 1200 and in pixel values from 0.42 to -0.28 between 1985 and 2020.

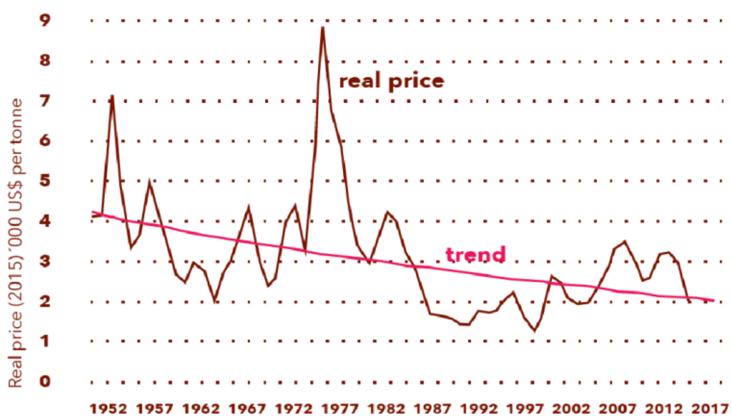
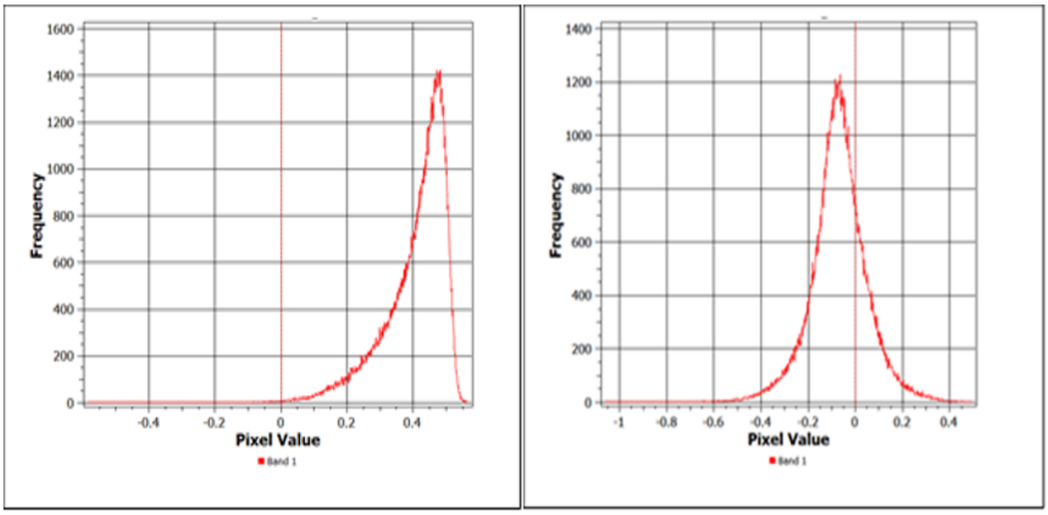


Figure 5. *Evolution of the world cocoa price trend (LMC, 2018)*



(a) 1985 (b) 2020

Figure 6. *Vegetation index NDVI (a: 1985), NDVI (b: 2020)*

As seen in *Figure 6*, there was an overall reduction in NDVI between 1985 and 2020, suggesting that the PNMP zone lost forest cover, supported by the findings (Ousmane et al., 2020).

The RF method allows to evaluate the significance of specific predictors in the model. The Random Forest model's variable importance graph (*Fig. 7*) shows the reduction in model accuracy (i.e., the percentage rise in the OOB error rate) caused by the permutation of each predictor variable. A decrease in accuracy indicates the variables increased significance for model performance.

Mean Decrease Accuracy (MDA) has been chosen because it allows quantifying the significance of variables (Genuer, 2010). MDA assesses the OOB error both before and after random permutation of the variable's values. If there is a significant reduction in OOB accuracy, the variable is deemed necessary.

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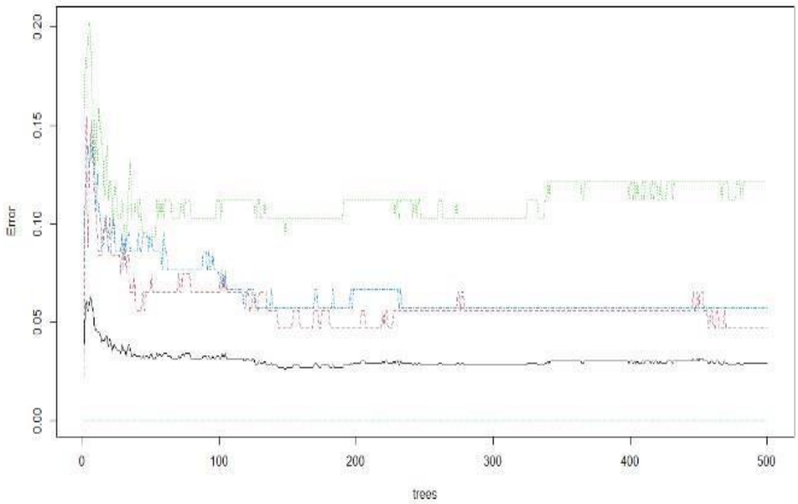

Figure 7. *Out-of-bag error rate plot. OOB error plotted against the number of trees included in the model. The error rate stabilizes after 500 trees to the point where any variations are accounted for by statistical noise*

Bands 12, 11, and 10 of the Landsat 4-5 TM and Landsat 8 OLI/TIRS image correspond to bands 6, 5, and 4 of the 2020 Landsat 8 image. We have six bands from Landsat 4-5TM image stacked on top of the 7 Landsat 8 OLI/TIRS bands. This is the same composite colour presentation as before.

This band combination combines bands from both dates to highlight changes in the shortwave infrared (SWIR) bands 13 (or the equivalent band 7 from the 2020 Landsat 8 image) and 5 (from the 1985 Landsat 4-5TM image).

The RF approach was used to assess the significance of specific variables in the classification model that was chosen. The random forest model's variable importance graph (*Fig. 8*) shows the reduction in model accuracy (i.e., the percentage rise in the OOB error rate) caused by the permutation of each predictor variable. A decrease in accuracy indicates the variables increased significance for model performance.

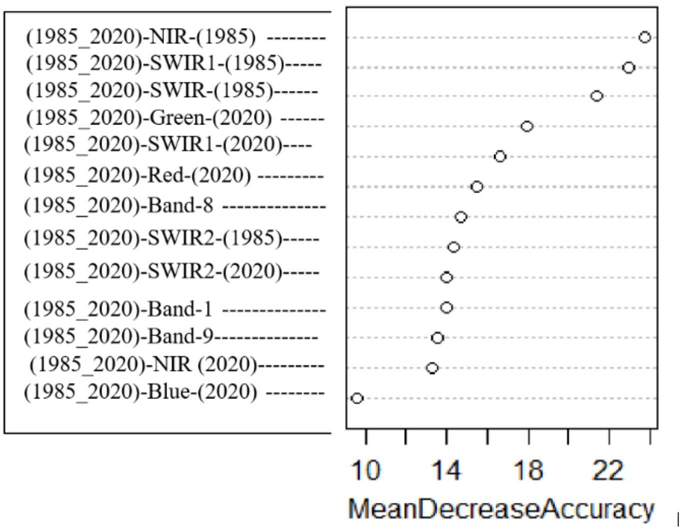

Figure 8. *Variable importance plot for random forest model, showing the mean decrease in accuracy for each predictor variable*

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Table 2 shows the categorization findings in the form of a confusion matrix. This coefficient has a confidence interval of 0.95. The confidence interval was determined by multiplying the square root of the variance (User's accuracy ($\widehat{U}$i), Producer's accuracy ($\widehat{P}$), Overall accuracy ($\widehat{O}$), by 1.96 (Olofsson et al., 2014)).

Table 2. *The confusion matrix of the classification generated by Random Forest Landsat 4-5TM (1985) combined with Landsat 8 OLI/TIRS (2020)*

Class	**For-For**	**For-NonFor**	**NonForFor**	**NonFor-NonFor**	**Total**	**Class.error (θ)**	**User's**	**Producer's**	**Overall**	**SE**
For-For	**100**	0	2	0	102	0.0196	0.980±1.92	0.980±1.92		0.009
For-NonFor	0	**100**	0	0	100	0	1±1.96	1±1.96	0.972	0.123
NonFor-For	2	0	**100**	0	102	0.0196	0.980±1.92	0.970±1.93		0.064
NonFor-NonFor	0	0	1	**502**	503	0.0019	0.99±1.95	1±1.96		0
Total	102	100	103	502	807	0.04118	-	-		

OOB error rate estimate 0.0069%. Bold values in the diagonals indicate the number of samples (pixels) correctly classified Column totals are the total number of reference pixels in each class, and row totals are the total number of classified pixels in each class. Off diagonal numbers represent errors in the classification. SE: Standard Error

User's accuracy:

$$\widehat{U_i} = \frac{\hat{P}_{ii}}{\hat{P}_{i}} \times 100 \quad \text{(Eq.7)}$$

Of the 102 pixels classified as (For-For), 100 were identified as For-For in the reference data; 2 NonFor-For were included in the For-For classification.

Of the 100 pixels all were identified as (For-NonFor).

Of 102 pixels classified as (NonFor-For), 100 were identified as NonFor-For in the reference data; 2 For-For were included in the (NonFor-For) classification.

Of the 503 pixels classified as (NonFor-NonFor), 502 were identified as NonFor-NonFor in the reference data, 1 NonFor-For were included in the NonFor-NonFor.

Producer's accuracy:

$$\widehat{P_j} = \frac{\hat{p}_{jj}}{P_{.j}} \times \mathbf{100} \quad \text{(Eq.8)}$$

Of the 102 pixels that were referenced as (For-For), 100 were correctly classified as For-For; 2 were classified as NonFor-For.

Of the 100 pixels that referenced as (For-NonFor), all were correctly classified as ForNonFor.

Of 103 pixels that referenced as (NonFor-For), 100 were correctly classified as NonFor-For; 2 were classified as For-For and 1 was classified as NonFor-NonFor. All of the 502 pixels were correctly classified as NonFor-NonFor.

Change detection analysis

Table 3 shows how much space each class takes up. The dominating class is the regular forest class (For-For) (43.16%). This class is located in the park's north-central area. The

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map's visual analysis reveals a significant decrease in forest cover (ForNonFor) from 1985 to 2020, including the pre-and post-conflict eras. The findings indicate an alarming deforestation trend in the PNMP, with about 27.95% or 8455 ha of forest converted to nonforest. This reduction is due to cocoa farming. The For-NonFor class dominates the center area of the park. The replanting class (NonFor-For) encompasses 16.65% of the park. This type includes crops, fallow ground, and occasionally rocky outcrops that have been reforested. Finally, the regular nonforest class (NonFor-NonFor) area is 12.22% and it is located in the park's northern region.

Table 3. *National Mount Peko Park surface in 2020*

Class	Counts	Class area (m^2)	Class area (ha)	Percentage (%)
For-For	145013	1305511700	13051.17	43.16
For-NonFor	93941	84546900	8454.69	16.65
NonFor-For	5545	50350500	499.05	12.22
NonFor-NonFor	41087	36978300	3697.83	27.95

Figures 9 and *10* show the PNMP's final forest cover change map and statistic cover map. This map's visual evaluation reveals a substantial decrease in forest cover.

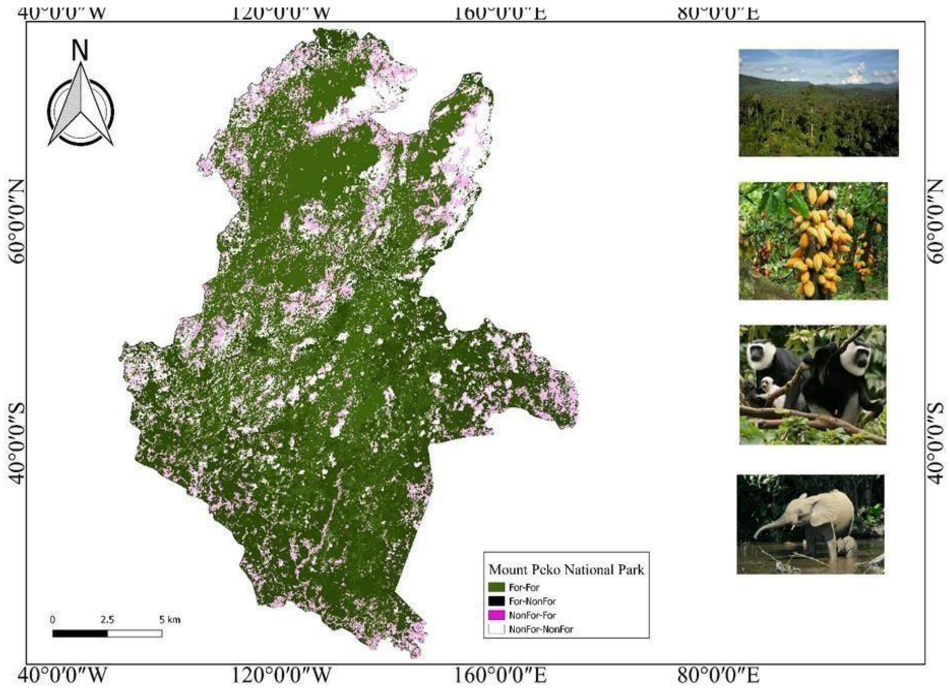

Figure 9. *represents the final forest cover change map of PNMP. Visual assessment of this map shows a significant loss of forest cover (1985-2020)*

The RF method allows to evaluate the significance of specific predictors in the model. The random forest model's variable importance graph (*Fig. 8*) shows the reduction in model accuracy (i.e., the percentage rise in the OOB error rate) caused by the permutation of each predictor variable. A decrease in accuracy indicates the variables increased significance for model performance.

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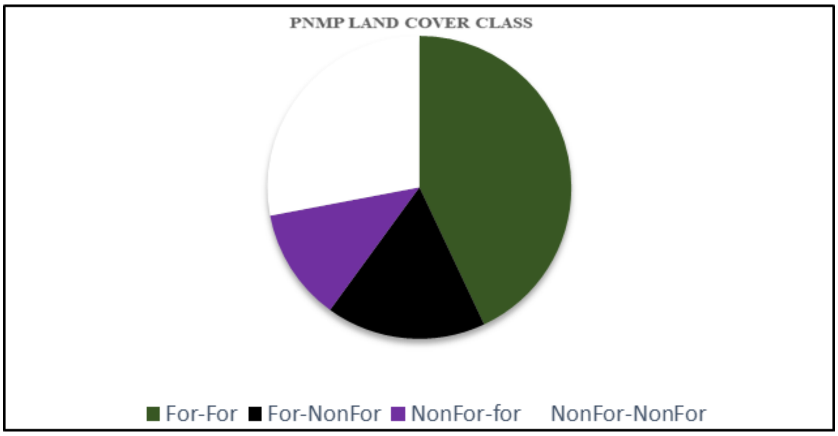

Figure 10. *Statistic land cover class (1985-2020)*

Discussion

We used a multitemporal pixel-based change detection technique tailored to the usage of multitemporal satellite pictures from various sensors. This research analyzed satellite images spanning the years 1985 to 2020. In contrast to prior research, the authors divided the forest cover change detection study into two or three time periods by distinguishing the time before, during, and after the crisis, following the suggestions of Lu and Weng, 2007, 2005; Churches et al., 2014; Lillesand et al., 2015; Wu et al., 2017; Garai and Narayana, 2018.

The RF classification approach was used to rigorously identify the changes that occurred by simple image discrimination between 1985 and 2020.

Indeed, the PNMP's land cover has altered considerably throughout the research period from 1985 until 2020. Because of the growing population and the scarcity of arable land in the region, we observe a substantial reduction in vegetated areas and an increase in cultivated land, putting further strain on the forest environment (Mather and Needle, 2000; SEP-REDD+, 2016). Much of the natural forest has been transformed into large expanses of farmed land, most of which is controlled by cocoa. Our findings are consistent with those of Sidibe et al. (2018), Ousmane et al. (2020), and Sangne et al. (2015), who found that conflicts facilitated the spread of illicit cocoa production in the PNMP and the Haut Sassandra Classified Forest. The outbreak of war in November 2002 resulted in the collapse of protection services in the PNMP and a reduction in conservation and tight protection due to severe ecological imbalances.

The armed war created an environment conducive to illicit operations such as poaching. This is supported by research conducted by Bi et al. (2012) and Bitty et al. (2013, 2015), which revealed that six elephants were murdered at Mount Péko National Park. Aside from that, there was a lack of governmental authority over protected zones in regions controlled by the armed insurrection. As a result, many protected woody species, unique flora, and animals were lost, and agricultural penetration grew.

During severe armed conflict from 2002 to 2007, cocoa bean prices rose globally as forest cover decreased. This area lost 622,000 ha of tree cover between 2001 and 2020, a 24% reduction since 2000 (https://www.globalforestwatch.org/).

These unlawful operations had become evident and noticeable, leading government officials to evict about 9,000 individuals who had established huge plantations and communities inside the PNMP (Woods, 2003). Some endangered species in the PNMP

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were almost wiped out as a result of these clearings. For example, forest elephant populations have been devastated due to forest clearings to support cocoa production (Barnes, 1999). Human activities have pushed chimp and forest elephant species to reside beyond their native biological habitat (Short, 1981; Powell, 1997; Symstad et al., 1998; Morris, 2010; Kouakou et al., 2015).

Indeed, the loss of natural habitat boosted elephant and chimp poaching (Symstad et al., 1998; Bouché and Lungren, 2004; Graham et al., 2009; Bitty et al., 2013), mainly owing to the spread of weapons of war in the area. The armed conflict has significantly affected the Ivorian forest system, particularly the PNMP, by degrading it and converting it to cocoa production (Kone et al., 2014; Sidibe et al., 2018; Ousmane et al., 2020). These impacts have led to the reduction of animal species' ecological niches and indicate that recurrent crises are the primary causes of the deterioration of Ivorian tropical forests (Gorsevski et al., 2013; Nackoney et al., 2014; Ordway, 2015). Because the PNMP's security had been abandoned due to the conflict, the extinction of wildlife and flora had risen (McPherson and Nieswiadomy, 2000; Woods, 2003; Kouakou et al., 2015). Indeed, this tendency persists across the globe when nations conflict, as shown by studies such as Robert-Charmeteau (2015) on the landscape dynamics of A-Li forests during the Vietnam War and Rwanda's civil war (Kalpers et al., 2003; Plumptre et al., 2007).

Our findings are consistent with those of Ousmane et al. (2020), who examined the same region of the PNMP with Landsat 4-5TM and Landsat 8OLI/TIRS images in 1998, 2002, 2011, and 2016. Between 1985 and 2020, land usage and land cover in Côte d'Ivoire have changed significantly. The effects of this battle on the natural environment have been severe; the PNMP has lost a significant portion of its biological resources.

The PNMP has been occupied like the invasion of Rwandan parks and reserves during the civil war (1986-2003) and following the conflict (2003-2011), with armed rebels and refugees overexploiting forest resources (Kanyamibwa, 1998; Kalpers et al., 2003; Glew and Hudson, 2007).

Undoubtedly, the expansion of agricultural land at the cost of tropical rainforests is a major cause of tropical forest degradation in Côte d'Ivoire (Geoghegan et al., 2001; Ochoa-Gaona, 2001; Geist and Lambin, 2002; Lepers et al., 2005). Our results of reduced plant cover in the PNMP in favor of the development of large cocoa fields are consistent with the Mighty Earth team's studies in various protected areas across Côte d'Ivoire, including the PNMP. They were able to detect illicit cocoa cultivation in areas covered by woods (UNEP-WCMC, 2017). This statement is easily justified because, in 2010, Côte d'Ivoire had 13.9 million ha of natural forest or more than 43% of its surface area. In 2019, it lost 242000 ha of natural forest, accounting for approximately 56.1 Mt of CO_2 emissions (http://www.globalforestwatch.org/country/CIV).

This forest conversion was mainly caused by establishing cocoa plantations and logging, which activity was significant in the area (Myers et al., 2000; Sangne, 2009).

Cote d'Ivoire has many significant pioneer regions where cocoa is grown, with the bulk coming from the country's center-west, south-west, and west. These three major regions, which account for more than three-quarters of national output, were under the control of rebel forces, who utilized money from illicit production in the woods to fund their operations. These forces acquired foreign money by selling cocoa beans when the government officials could not meet demand on the international market due to the crisis.

The crisis has resulted in PNMP vegetation loss and the fragmentation of natural shelter niches for certain monkeys (McGraw, 1998; Grubb et al., 2003; Campbell et al., 2008). Furthermore, this dispute has resulted in a shift in harmful behavior to the

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environment, namely selling tropical forests, unfortunately, as several authors have verified (Alvarez, 2003; Boulanger et al., 2011).

The crisis has exacerbated deforestation via mineral trafficking in the regions and massive environmental harm. As a result of the loss of a significant portion of the floral and faunal variety in the country, the Ivorian woods, in this instance, the PNMP, may have lost their essential role in development of the country (Bi et al., 2013).

Conclusion

We established the present status of the distribution of forest cover change classes inside the PNMP using Landsat 4-5 TM, and Landsat 8 OLI/TIRS time-series satellite images combined with NDVI data, with 43.16% of unaltered, intact forest. 27.95% of the forest land has been turned into nonforest (agricultural plantations, fallow, and other), 16.65% of nonforest has been converted into forest, and 12.22% nonforest areas have been converted into forest. The reduction in forest cover has benefited anthropic settings that diminish natural habitat. It is also important to note that population growth is a factor that has significantly altered the spatial structure of the natural environment. In general, the PNMP suffered a significant loss in forest cover at the start of the 2002 crisis due to abandoning the PNMP conservation (2007-2020). We were able to detect substantial deforestation throughout the research period because of satellite analysis of the PNMP. The armed conflict in Côte d'Ivoire and the conversion of forest lands to cocoa plantations were critical causes that exacerbated the PNMP's decrease in forest cover. The environmental consequences have been catastrophic. The repercussions have been twofold, with wildlife suffering as a result, including the loss of endemic species such as chimps and forest elephants, as well as other animal populations. Faced with environmental difficulties imposed by human demands, it is essential to assess existing natural resources to manage them rationally and sustainably. This research demonstrates how land cover may be monitored throughout time to give important information that can be used in the future to enhance forest management and biodiversity protection.

Recommendations

In response to this study, we would like to offer the following recommendations:

- research is needed to determine the impact of agricultural fertilizers and pesticides on soil pollution.
- research should be conducted on the impact of deforestation on soil erosion in the study area.
- assessment of the impact of population pressure on natural areas that have been designated as off-limits to development is necessary.

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Conflict of interests. The authors declare that there is no conflict of interests regarding this paper.

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