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Monitoring Forest Recovery in Protected Forests of Northern Côte d'Ivoire Using Landsat Imagery and Intensity Change Analysis

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Abstract

In this paper, the initiatives of reforestation of the national forests of the North of the Côte d'Ivoire were examined using geomatics and the analysis of change of intensity by taking the case of the protected Forest of Badénou (PFB). A spatial analysis based on multi-spectral and multi-temporal Landsat imagery was carried out to assess land cover changes in the (PFB) over the past two decades and determine whether patterns of change in terms of the intensity of gains/losses of each of the land cover classes were active or dormant between the period before (2000-2013) and after (2013-2019) the reforestation initiative. Five main classes were identified: forest (dry deciduous and gallery forests), tree savannah, shrub/grassy savannah (including agricultural lands), bare lands (bare soils and degraded land areas), and water course. All classes were satisfactorily classified, with an excellent producer's and user's and overall accuracies and very good Kappa coefficients. The results showed that between 2000 and 2019, the forest cover in the PFB increased from 7778 ha to 5054 ha, a decrease was marked between 2000 and 2013 of approximately 60% compared to its size in 2000, while a slight increase between 2013 and 2019 (4645 ha to 5054 ha) *i.e.* around 9%) certainly due to the reforestation since 2016. As for the annual intensities of change for each class in both study periods, changes (gain or loss) in forest and tree savanna were relatively dormant after reforestation, while annual bare land gain was relatively active and marked, indicating that degradation of forests remains a threat to the sustainability of the PFB. Forest degradation has occurred mainly in the eastern parts of the PFB, while the central parts have regained more tree cover. These results can help identify conservation and restoration priorities and improve the overall management of the PFB.

Keywords

Forest Degradation, Reforestation, Forest Cover Monitoring, Intensity Change Analysis, Desertification

1. Introduction

Forests play an integral part in the carbon and water cycles, regulate climate and ecosystems, provide goods and services to society and human well-being, and are essential for conservation of natural resources and biodiversity [1] [2] [3]. In several African and South American countries forests are increasingly facing various challenges due to pressures from rapidly growing population, rapid and most often unplanned urbanization, increased economic activities, and low agricultural productivity coupled with a lack of non-farm income opportunities. These pressures have resulted in noticeable forest cover losses [4] [5] [6] [7]. Between 2000 and 2010 Africa lost annually approximately 3.4 million ha of forest cover; a rate comparable to that estimated for the preceding decade 1990-2000 [8].

In Côte d'Ivoire, the permanent domanial forest consists of eight national parks, five reserves and 233 protected forests. Between 1960 and 2007, the Ivorian forest cover was reduced substantially, from ca. 12 million ha to ca. 2.8 million ha [9]. Protected forest areas were estimated in 2017 at ca. 2.2 million ha [6]. In the northern regions of the country, the rapid deforestation and forest degradation have resulted in advanced desertification, losses of soil fertility and biodiversity, and increased vulnerability to food insecurity [6]. The alarming state of Ivoirian forests has prompted greater attention from the Government of Côte d'Ivoire, materialized through, for example, the 1988-2015 Forest Master Plan [10] and the National Forest Investment Plan [6]), as well as several reforestation campaigns across the country. Preserving or restoring forests and improving forest management are crucial to sustaining the various yet critical roles of forests at the local, national, and global scales [11] [12]. Hence the need for scientific and technological information, data, and evidence to support decision-making process and policies implementation for forest preservation and biodiversity conservation.

Several studies have been carried out to investigate the dynamics of forest cover in various regions worldwide using remote sensing derived information (e.g., [5] [7] [10] [13]-[20]). For example, Ahammad *et al.* [7] investigated forest cover changes and associated drivers, along with impacts of these changes on ecosystem services in the Chittagong Hill Tracts region of Bangladesh between 1989 and 2014 using Landsat satellite imagery. They found a net gain in forest areas between 1989 and 2003, followed by a net loss between 2003 and 2014, which was attributed to increased harvesting of timber and fuel wood, and swidden farming, depending of the region [7]. Similarly, Huang *et al.* [13] assessed transitions among three land categories (agriculture, natural and built) in a subtropical coastal watershed of southeast China using satellite images from Landsat-5 Thematic Mapper (TM) and Landsat-7 Enhanced Thematic Mapping plus (ETM+). The land cover changes across their study region were found to be associated with the overall economic growth and decline in agricultural activities [13]. In Côte d'Ivoire, Soro *et al.* [14] investigated land cover changes across the upper Bandama catchment between 1986 and 2000 using images acquired from Landsat-5 TM and Landsat-7 ETM+ sensors. The authors found a decrease of 29% and 1.4% in land area for savannahs and forests, respectively, whereas crops areas, bare soils and built increased by 21.6%, 6.6% and 3.1%, respectively, negatively impacting the hydrological patterns across the catchment [14].

The literature review of published papers dealing with the assessment of land cover changes in forests in Côte d'Ivoire (*i.e.*, [9] [10] [14] [16] [17] [21]) revealed that they all felt short in addressing the intensity of land cover transitions and analysing differences among land cover classes over time, which have important implications for policy reforms to improve the management of protected forests in Côte d'Ivoire. Such limitations could be addressed through intensity analysis. Intensity analysis is a quantitative framework that compares a uniform intensity to observed intensities of temporal changes among land cover categories [22]. The methodology has been extensively applied to analyse changes in land cover in various regions (e.g., [22]-[28]). However, its application for investigating changes in land cover in protected forests in the Ivorian context has yet to be fully investigated.

The main objective of this study was to assess the dynamics and intensity change of land cover between 2000 and 2019 across the protected forest of Badénou (PFB), a 26,980-ha forest located in northern Côte d'Ivoire, using a cost-efficient remote sensing method coupled with GIS techniques. The PFB ensures the same functions as national parks and reserves in preserving flora and fauna biodiversity, and it is also vital to slow the advance of desertification in the region. An intensive reforestation campaign was carried out in 2012-2013 to address the alarming state of forest degradation resulting from the absence of administrative oversee during the 2002-2010 for socio-political reasons. In addition to providing insight into landscape transformation across the PFB and the vulnerability of forest to transition to other land cover classes, this study can help to identify conservation priorities and improve the overall management of the PFB using remote sensing-based approaches.

2. Materials and Methods

2.1. Study Area

The PFB is located at 23 km southeast of M'Bengue in Northern Côte d'Ivoire (**Figure 1**) and covers an area of approximately 26,980 ha [29]. The PFB belongs to the Sub-Sudanese phytogeography zone, which is characterized by islets of dry dense forests, gallery forests, tree savannahs, shrub savannahs, and grassy

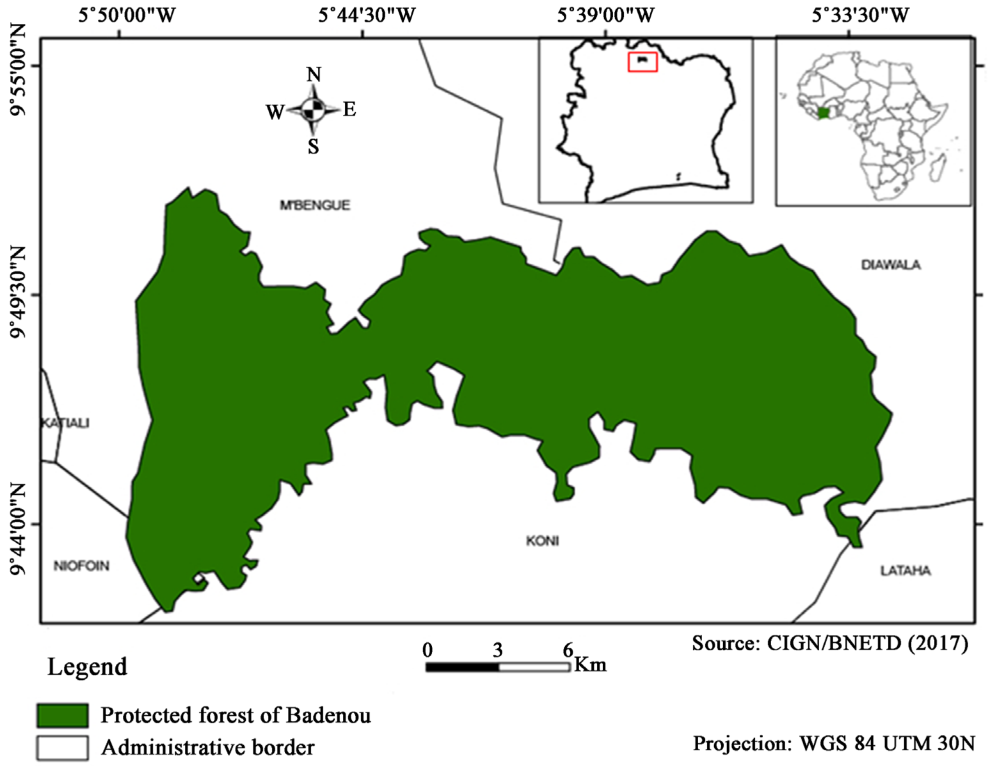

Figure 1. Location of the protected forest of Badénou in northern Côte d'Ivoire.

savannahs [30]. The PFB is characterized by a Sudan-Guinean tropical climate with two seasons, a dry season spanning November to May, and a rainy season from June to October [30]. The mean annual rainfall is around 1200 mm, with most of rainfall events occurring during July-September. Mean daily temperatures vary between 24˚C and 29˚C, with an annual average of 27˚C [31].

Native populations (Senoufo and Malinke) and migrants from other regions of Côte d'Ivoire or neighbouring countries inhabit the PFB or its surroundings [31]. Historically, native populations have been living in the PFB since its creation in 1937, with farming being their dominant activity.

2.2. Data Collection

Three high-resolution Landsat images (path 197; row 53) acquired on 16 December 2000, 12 December 2013, and 20 December 2019, were downloaded from the United States Geological Survey (USGS) data portal (https://earthexplorer.usgs.gov/) and used to classify land cover across the study area. These satellite images were from the instruments Landsat-7 ETM+ (2000 image) and Landsat-8 Operational Land Imager (OLI) (2013 and 2019 images). The bands used for analysis were 1, 2, 3, 4, 5, and 7 Landsat-7 ETM+, and bands 2, 3, 4, 5, 6, and 7 for Landsat-8 OLI. The spatial resolution for all the bands was 30 m.

Global Positioning System (GPS) points and digital photos collected during a field campaign in the PFB in 2019 were used to select the regions of interest

(ROIs) for image processing and classification, along with historical data provided by villagers and administrative authorities. The GPS points were acquired using a Garmin GPSmap 64S (Garmin International Inc., Olathe, KS, USA). Digital photos were taken using a 13MP $f/2.0$ lens rear camera from a smartphone (BLU Studio M5 Plus LTE, version 7.0). The results are recorded in Table 1.

2.3. Data Processing and Analysis

Five main land cover classes were assessed: forest (consisting of dry deciduous and gallery forests), tree savannah, shrub/grassy savannah (also including agricultural lands), bare lands (consisting of bare soils and degraded land areas resulting from mining and logging activities), and water course (including swampy shallows). Based on the historical data provided by villagers and administrative authorities, and visual interpretations of Google Earth high resolution imagery of the study area, spatially homogeneous known areas for each of the land cover classes were delineated by a polygon and identified as a ROI. For each land cover class, the same number of ROIs was selected on each of the three satellite images (119 ROIs on total; Table 2).

The raw data of an image acquired by remote sensing contain geometric distortions large enough that they are not directly superimposed on spatial data (images or maps) made to known projections [32]. This is why all satellite images were pre-processed before being processed.

Table 1. Tools and materials used for data collection.

Materials/Tools	Role
Interview guide	Collect the information necessary for the analysis and interpretation of the perception of traditional chiefs, officials of local village management committees living around the Badénou Classified Forest and administrative authorities, ARK NGOs related to resource management and/or FPB territory in terms of use, ownership and protection.
Questionnaires	Assess the right of use, land ownership and the commitment of the populations linked to the forest protection of the FCB
Android camera (BLU)	Take photos for illustration of results
Garmin GPSmap 64S (Garmin International Inc., Olathe, KS, USA)	Validate the results of the pretraitement and the land cover classes of the Badénou Classified Forest by taking a ground control point
Excel software	Present graphic illustrations and create tables
Sphinx Millenium 14.5 software	Develop the questionnaire, enter the data of the result and present the illustrations.
Software ARCGIS 10.2, QGIS 3.10, ENVI 5.1, Adobe Illustrator CS3 and RStudio	Map the study area, classify Landsat-7 ETM+ (2000), Landsat-8 OLI (2013 and 2019) satellite images for multidate land use (2000, 2013 and 2019) and spatial results from the processing of the intensity analysis

Table 2. Number of the regions of interest (ROIs) selected to classify the different land use classes of the protected forest of Badénou. For a given LULC class the same number of ROIs was selected on each of the three Landsat images.

Class	Number of ROIs
Forest	25
Tree savannah	24
Bare lands	21
Shrub/grassy Savannah	27
Water course	22
Total	119

The pre-processing method consists of assembling the useful bands and geometric correction (projection in the projection system UTM 30 N, WGS 1984), accompanied by an enhancement and a coloured composition of the satellite images. We did not find it necessary to make the radiometric correction because the proposed directed classification methods do not require it [33].

The processing method is the supervised classification method using the Maximum Likelihood algorithm without zero values. Data processing was carried out using a supervised classification following the maximum likelihood algorithm of the semi-automatic classification plugin (SCP; [34]) of the Quantum Geographic Information System (QGIS) software (version 3.10; https://qgis.org/) in order on the one hand to identify the different types of land cover and to estimate the change in these different types of land cover (2000, 2013 and 2019) and on the other hand to make an analysis processing of the intensity of change with the R software in order to identify at the spatial level the detection of the changes made between 2000 and 2013 and 2013 and 2019. After classification of the images, the proportions of land area covered for each of the five classes were quantified by the QGIS software.

Indeed, classification consists of grouping pixels according to their spectral similarity to form thematically interpretable spatial units. It is a process that uses algorithms including the maximum likelihood algorithm that considers the spectral signature as a normal (Gauss) distribution. It thus minimizes possible errors when assigning a pixel to a class. The maximum likelihood algorithm classifies and quantitatively evaluates both the variance and the covariance of the spectral signature categories by specifying their statistical values [35].

2.4. Image Classification Assessment

The accuracy of image classification was assessed based on the overall accuracy (OA), user's accuracy (UA; which corresponds to error of commission), producer's accuracy (PA; corresponding to error of omission), and the Kappa coefficient [36] [37] [38] [39]. The corresponding formulas of these statistics can be found in Olofsson *et al.* [39]. The OA denotes the correctness of classification.

The closer to 100% the OA value, the better the classification. Similarly, the closer to 100% the value of UA or PA, the better the classification. The Kappa coefficient is a precision indicator and varies between 0 and 1 [37] [38] [40]. Kappa coefficient values ≤ 0.20 indicate extremely poor classification; values ranging from 0.21 to 0.40, 0.41 to 0.60, and 0.61 to 0.80 indicate poor, moderate, and good classification, respectively; and very good to excellent classification are denoted by Kappa coefficient values ≥ 0.81 [40]. Following Olofsson *et al.* [39] a recent map of land occupation and cover of the PFB, sourced from the *Centre de Gestion de la Société de Développement des Forêts of Korhogo* (CGK-SODEFOR) was also used to assess the classification accuracy. The map was produced using a Sentinel-2 image acquired on 27 December 2019.

2.5. Intensity Change Assessment

An intensity analysis was carried out to assess the changes in land cover across the PFB between the period before (2000-2013) and after (2013-2019) the reforestation initiative and determine whether the pattern of a given class was stable in terms of the intensity of gains and losses during the study period. The reforestation initiative in 2012/2013 targeted ca. 2,698 ha of the PFB (ITTO 2013). We followed the approach described in Aldwaik and Pontius [25]. Typically, the intensity analysis helps answer three main questions [25]: 1) is the annual rate of overall change relatively slow or fast? 2) which land cover classes are relatively dormant or active, and is this pattern stable across the time interval? and 3) which transitions are intensively avoided versus targeted by a given class in the defined tie interval, and is this pattern stable across time? Further information about the conceptual and mathematical details of the method can be found in Aldwaik and Pontius [25] and Pontius *et al.* [22]. The intensity analysis was performed using the package "intensity.analysis" [41] in R version 4.0.0 [42].

2.6. Investigating the Causes of Land Cover Changes to Improve the Management of the Protected Forest of Badénou

A survey was conducted in 2019 to collect information about the possible causative factors of deforestation and forest degradation across the PFB. A total of randomly selected 80 stakeholders were interviewed using structured questionnaires. The interviewees included landowners, managers of PFB local managing committees in five villages located in the vicinity of the forest, administrative authorities from the CGK-SODEFOR, and officials of the non-governmental organization Animation Rurale de Korhogo. The main topics of the questionnaires were related to land ownership and rights, the nature of crops cultivated in the forest (annual or perennial), and resources from the forest, engagement of villagers with administrative authorities, and management of the forest. Through the identification of the causes of deforestation and forest degradation, and hurdles hampering a sustainable management of the forest, it would be possible to improve the different reforestation initiatives in the PFB to ensure beneficial outcomes for the forest and all the community.

3. Results

3.1. Assessment of Image Classification

All the five classes were classified satisfactorily using Landsat images. The resulting classified maps are presented in **Figure 2**. For each of classes the commission errors (UA) and omission errors (PA) were relatively low on average. The UA on 2000, 2013 and 2019 classified maps ranged from 86% to 98%, 88% to 93%, and 90% to 98%, respectively (**Table 3**). Regarding PA, the corresponding ranges were 86% - 100%, 82% - 100%, and 91% - 98%, respectively (**Table 3**). The highest UA values were found for the bare lands class in 2000 and 2019, and shrub/grassy savannah class in 2013. Whereas the highest PA values were found for water course in 2000 and 2013, and tree savannah in 2019. The UA and PA values resulting from the classification of a 2021 Sentinel image carried out by the CGK-SODEFOR to map land use across the PFB as of March 2021 are presented. Although some classes differ from those in our study (for example, agricultural land areas were classified in detail in the CGK-SODEFOR 2021 map), the ranges of UA and PA were similar. For instance, for dry deciduous and gallery forest, UA and PA values were 91% and 97%, respectively; the same statistics for tree savannah were 96% and 82%, respectively.

Overall, the OA values for all three classified maps ranged from 90.40% to 94.80%; Kappa coefficients ranged from 0.88 to 0.93 (**Table 4**), indicating "excellent" classification according to [36] and [43]. The performance statistical indicators (UA, PA, OA, and Kappa coefficients) found in the study denote our

Table 3. User's accuracy (UA) and producer's accuracy (PA) for the main land cover classes of the protected forest of Badénou. Three Landsat images were used in the study: Landsat ETM+ (2000) and Landsat OLI (2013 and 2019).

Class	2000		2013		2019	
	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)
Forest	93	86	88	88	95	91
Tree savannah	86	97	91	97	94	98
Shrub/grassy savannah	96	90	93	82	90	96
Bare lands	98	97	89	86	98	92
Water course	96	100	91	100	97	97

Table 4. Statistics of the accuracy assessment of image classification

	Overall Accuracy (%)	Kappa coefficient	Agreement[1]	Standard error	Confidence interval
Landsat ETM+ (2000)	93.80	0.92	Excellent	0.06	[0.15; 0.24]
Landsat OLI (2013)	90.40	0.88	Excellent	0.06	[0.15; 0.24]
Landsat OLI (2019)	94.80	0.93	Excellent	0.06	[0.15; 0.24]

[1]According to Landis and Koch [36] and Streiner and Norman [43].

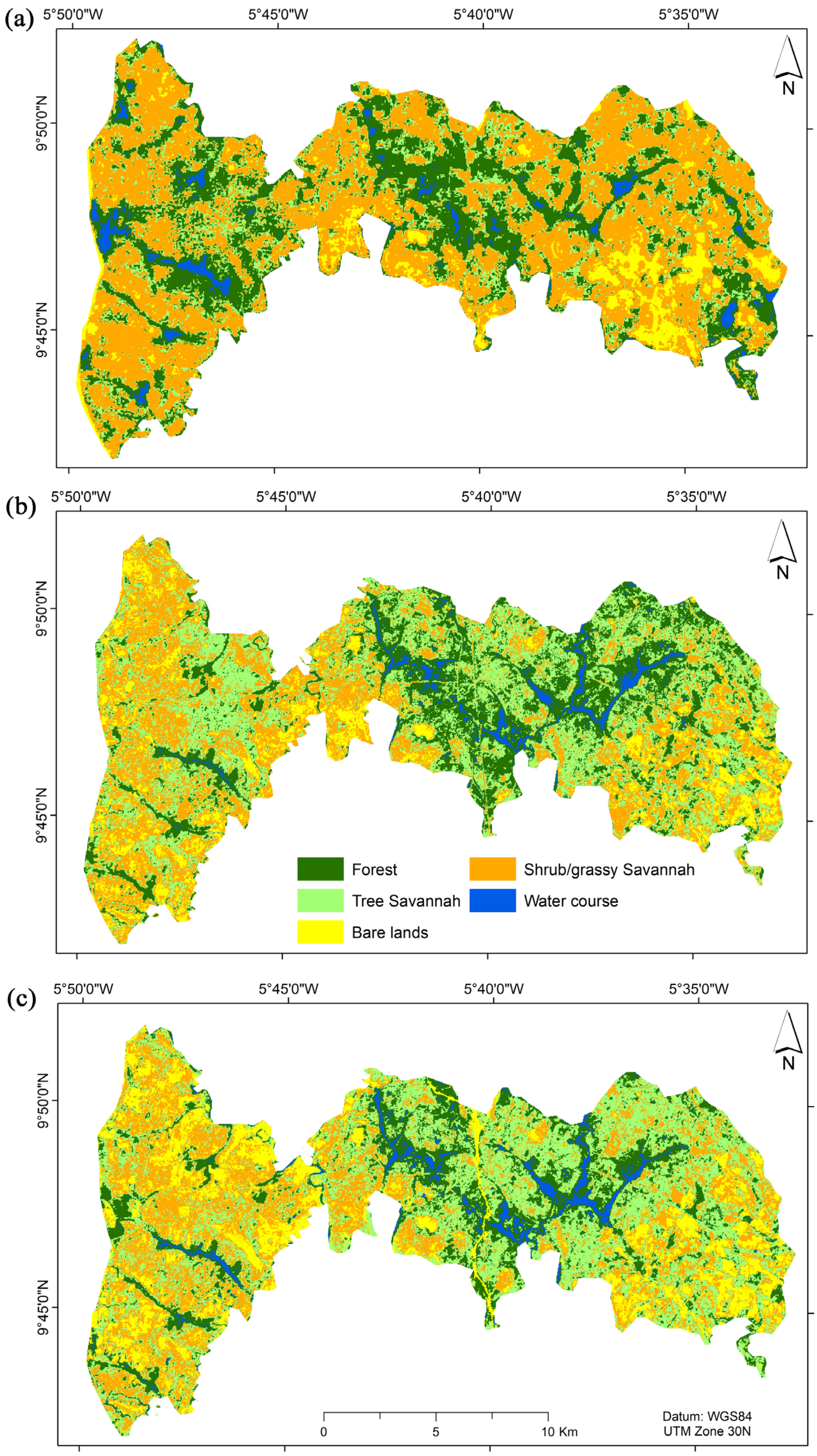

Figure 2. Classification of the different satellite images for the protected forest of Badénou, Côte d'Ivoire. (a) Landsat-7 ETM+ image (16 December 2000); (b) Landsat-8 OLI image (28 December 2013); (c) Landsat-8 OLI image (20 December 2019). Maps were created using ArcMap version 10.5.1 [44].

results can be interpreted and analysed confidently [40].

3.2. Land Cover of the Protected Forest of Badénou in 2000, 2013 and 2019

The estimated proportions of land area for forest, tree savannah, shrub and grassy savannah and bare lands in the PFB after image classification are presented in **Figure 3**. Between 2000 and 2019 forest cover across the PFB decreased from 7778 ha to 5054 ha; the decrease was marked between 2000 and 2013 (~60% decrease from its size in 2000), whereas there was a slight increase between 2013 and 2019 (4645 ha to 5054 ha). The noticeable change in land cover was observed for tree savannah, which total area varied from 4534 ha in 2000 to 6883 ha in 2013 to 10,811 ha in 2019. Shrub and grassy savannah, on the contrary, decreased by approximately 43% over the study period, from 14,399 ha in 2000 to 8076 ha in 2019 (**Figure 3**). For bare lands, the proportion of land area almost tripled between 2000 and 2019, from 1846 ha in 2000 to 5507 ha in 2013 to 4424 ha in 2019 (**Figure 3**). Such increase can be explained by the intensity of illegal mining and lodging activities across the PFB, which between 2000 and 2013 resulted mainly from the absence of administrative authority during most of this period. It can also be explained by the farming activities still occurring within the PFB, namely across the south-eastern parts of the PFB.

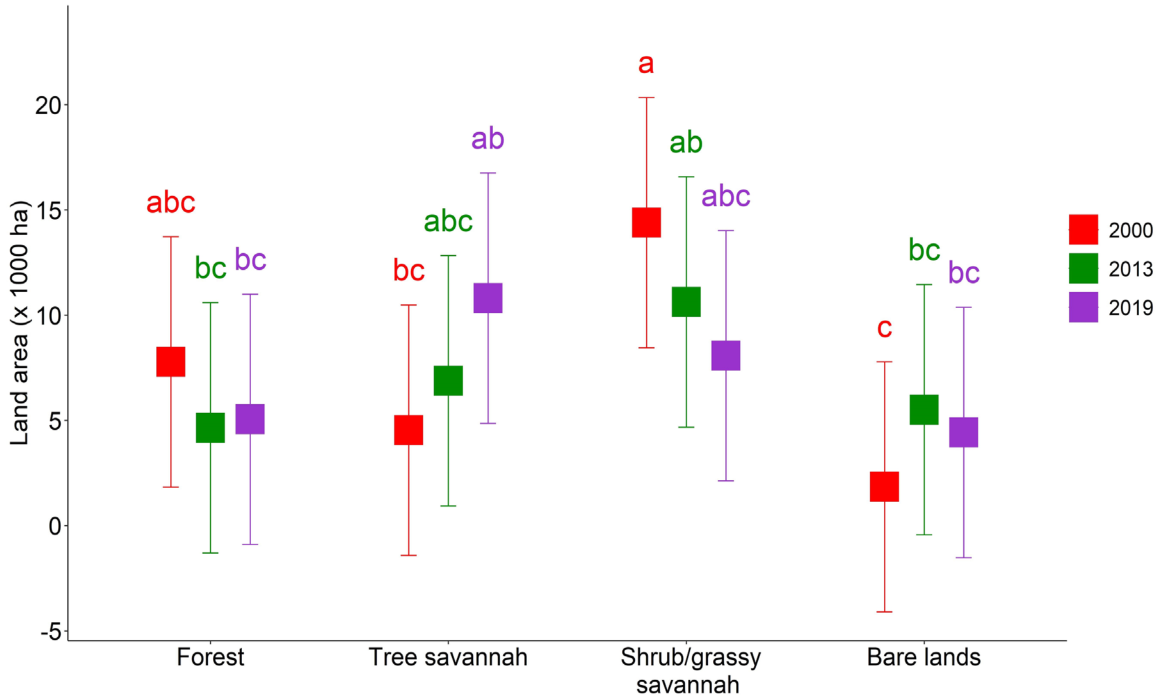

Figure 3. Estimated land area covered by forest, tree savannah, shrub/grassy savannah, and bare lands in the protected forest of Badénou, Côte d'Ivoire. Areas were estimated based on the image classification of Landsat-7 ETM+ image (2000), Landsat-8 OLI image (2013) and Landsat-8 OLI image (2019). Boxes indicate the least square (LS) means of the proportions of land area derived from the ANOVA between land cover classes for the three dates. Error bars indicate the 95% confidence interval of the LS mean. Means sharing similar letter(s) are not significantly different (significance level, $\alpha = 0.05$).

3.3. Change Intensity of Land Cover across the Protected Forest of Badénou

The annual change intensity for each class between the 2000-2013 and 2013-2019 periods is presented in Figure 4. During the period preceding the reforestation campaign (2000-2013) the annual loss in forest and bare lands were relatively active, whereas that of tree savannah and shrub/grassy savannah were dormant (Figure 4(a)). Active gain in land area during the same period was observed for tree savannah and bare lands. Although both changes were active, the proportion of gain in bare lands was slightly greater than the proportion of loss. The other class with active gain and loss over the 2000-2013 period was water course.

For the period following the reforestation campaign (2013-2019), different patterns were found. For forest and tree savannah, both gain and loss were relatively

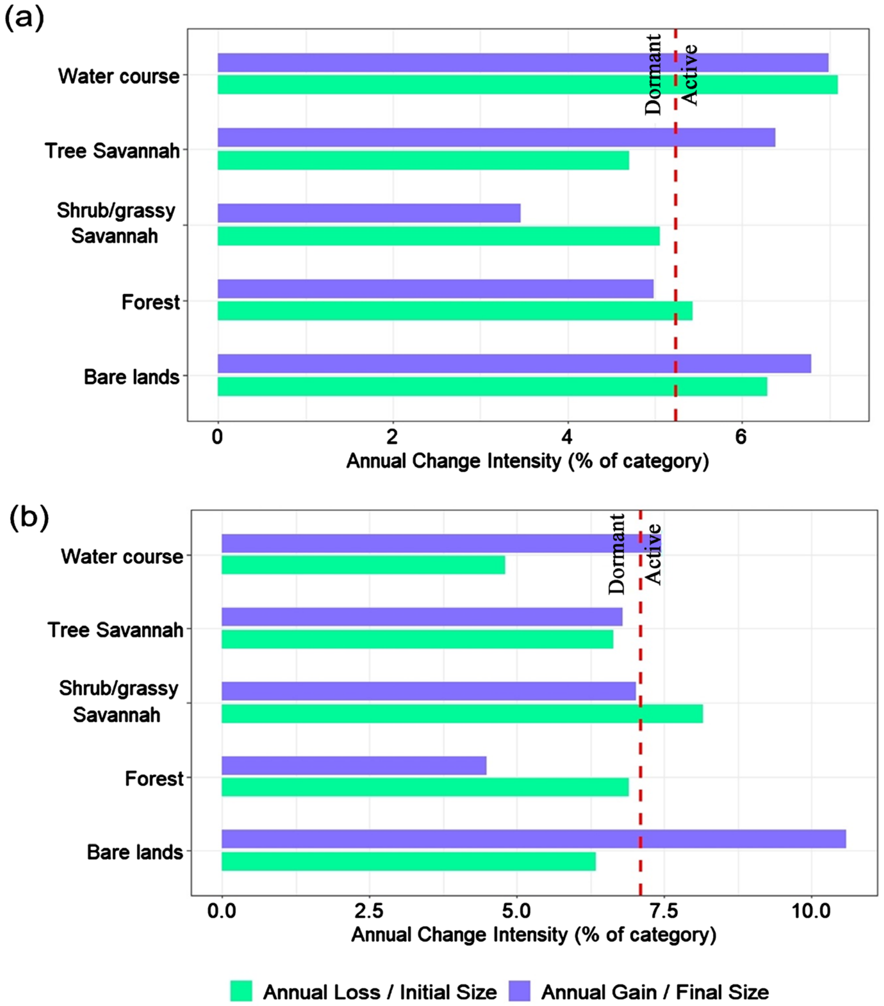

Figure 4. Annual change intensity for forest, tree savannah, shrub/grassy savannah, and bare lands across the protected forest of Badénou between (a) 2000 and 2013, and (b) 2013 and 2019. The dashed line indicates the uniform line [22] [25]. If a bar extends to the right of the uniform line, then the change is relatively active during the time interval. (Note differences in scales).

dormant between 2013 and 2019, though the loss in forest was relatively higher compared to its gain (for tree savannah the rate of annual gain and loss was similar) (**Figure 4(b)**). Shrub/grassy savannah experienced relatively active annual loss. The annual gain in bare lands was relatively active and marked (annual change intensity > 10%), while its annual loss was dormant (**Figure 4(b)**). This indicates that forest degradation remains a constant threat to the sustainability of the PFB.

Figure 5 shows the annual transition intensity for gain of each of the LULC classes across the PFB between the pre- and post-reforestation campaign. Forest gained more intensively from tree savannah and water course in both periods, with its transition intensity targeting systematically these two classes (**Figure 5(a)**, **Figure 5(e)**). Water courses were found typically in gallery forest across the PFB. Thus, the transition intensity of forest as captured through the analyses was not surprising. Likewise, the transition intensity for water course systematically targeted forest. Nevertheless, an increase in gain of water course (**Figure 4**) could be indicative of a loss in gallery forest. Transition to tree savannah across the PFB during the pre- and post-reforestation campaign occurred more in areas occupied by shrub/grassy savannah and forest (**Figure 5(b)**, **Figure 5(f)**). Such transition can be explained, partly, by the fact that during reforestation initiatives, new trees are mostly planted in shrub/grassy savannah. However, while the rate of transition from shrub/grassy savannah to tree forest was virtually similar between the 2000-2013 and 2013-2019 periods, that from forest increased (**Figure 5(b)**, **Figure 5(f)**). More attention could be required to avoid all forest cover being turned in tree savannah over the long term in the PFB.

The intensity change analysis also showed that bare lands gained intensively from shrub/grassy savannah, and vice versa (**Figure 5(c)**, **Figure 5(d)**, **Figure 5(g)**, **Figure 5(h)**), indicating that activities contributing to forest degradation occurred generally across those areas. This is also supported by the intensive transition to shrub/grassy savannah from tree savannah (**Figure 5(c)**, **Figure 5(d)**).

3.4. Factors Hindering the Reforestation of the Classified Forest of Badénou

The survey revealed various endogenous and exogenous factors that constitute the factors that hinder the reforestation of forest cover throughout the PFB. Endogenous factors were related to the decision-making process and property ownership of the PFB; whereas exogenous factors included all activities (farming, extensive and transhumance farming, illegal logging, and illegal gold mining) carried out within the PFB by surrounding populations for their economic and social survival.

3.4.1. Lack of Active Participatory Management

The populations living in and the surrounds of the PFB were not actively involved in the decision-making process for managing adequately and sustainably

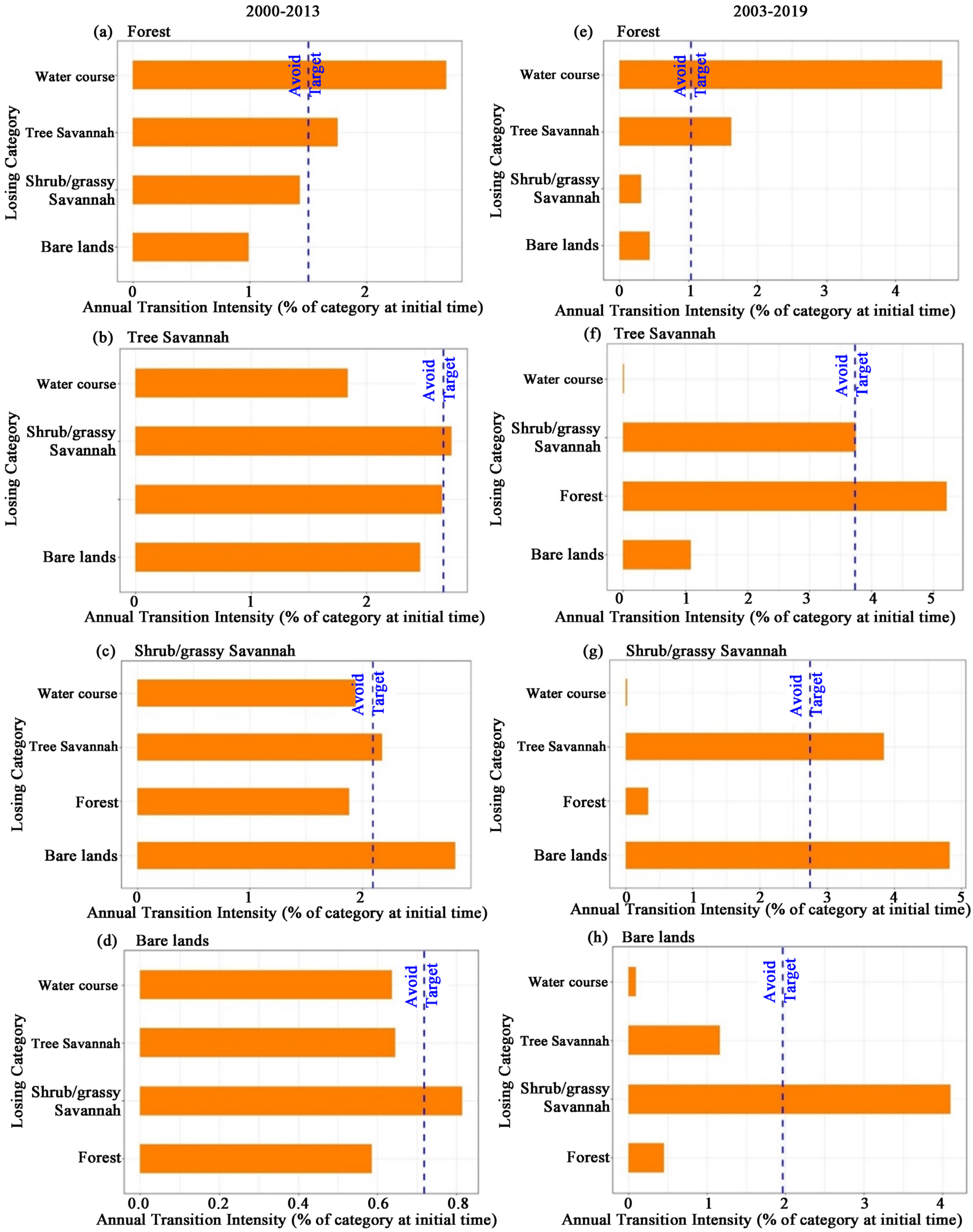

Figure 5. Annual transition intensity for gain of forest, tree savannah, shrub/grassy savannah, and bare lands across the protected forest of Badénou between 2000 and 2013 (a)-(d) and between 2013 and 2019 (e)-(h). The dashed line indicates the uniform line [22] [25]. If a bar extends to the right of the uniform line, then the transition systematically targets that category. (Note differences in the x-axis scales).

the forest. Despite the local (village) committee for forest defence and bushfire control, which is chaired by the Prefect of the Poro region, our survey revealed a lack of interest from populations, which impacts the capacity of this local committee to effectively attain its objectives. Moreover, the native populations consider themselves as sole owners of the PFB because they have been living there well before the creation of the PFB. They were willing to cede land area within the PFB for farming and other activities or explore it themselves, ignoring the reasons for protecting such areas from human activities. Such a situation has led to conflicts between the riverside and landlocked populations of the PFB and the State office in charge of forest protection and conservation, the SODEFOR, making it difficult better participatory management.

3.4.2. Burning Itinerant Agriculture and Extensive Animal Breeding and Transhumance

With rural forest cover depleting over years, the populations living around the PFB increasingly were relying on the protected forest for their energy and farming needs. This reliance and its corollaries (*i.e.*, destruction of the forest, shift to other activities within the forest) have worsened over years due to adverse climate conditions and the 2002-2011 political-military crisis, which prevented relevant administrative authorities from carrying out their duties. Illegal farming practices within the PFB has not entirely ceased despite the return to normal in terms of the activities of the SODEFOR, as per our visits within the PFB in 2019 and 2020. Uncontrolled pastures and animal transhumance, namely from migration of herds from neighbouring countries (e.g., Mali and Burkina Faso), were also conducive to the increased forest cover loss and soil degradation. Soil compaction due to repeated animal crossings over the same areas make it unfit for the natural regeneration of vegetation. Herds crossing the PFB typically destroy or graze the leaves of the young plants, impeding any reforestation efforts.

3.4.3. Illegal Logging and Gold Mining

Although prohibited in the northern region of the country, lumbering exploitation is still prevalent within the PFB (**Figure 6(a)**). Such illegal activities, combined with man-made bushfires hampered all reforestation and land restauration initiatives. Because of the increasing demand of stems or poles for the construction of habitats and livestock parks, as well as the demand for traditional manufacturing of agricultural tools, trees in the PFB are under constant threat as they are regularly destroyed.

Moreover, illegal gold mining has seen an increased activity in several parts of the department including the PFB [9]. Gold mining in the PFB is handcrafted and involves several individuals acting in groups, generally at nightfall. The resulting wells and pits constitute potential risks of injuries for wild animals, and even for the SODEFOR agents during their surveillance patrols. Other negative consequences include soil pollution which hampers a proper development of forest ecosystems. Although encouraging efforts from the SODEFOR have reduced noticeably illegal gold mining activities across the PFB (e.g., one of the largest

Figure 6. Illustrations of illegal timber cutting (a) and illegal gold mining (b) in the protected forest of Badénou, Côte d'Ivoire. Photos taken in July 2020 (Credit Photos. Coulibaly P.)

illegal gold mining sites was dismantled in December 2019 [45]), there remain some areas where this activity still occurs. Example of the impact of such activities is shown in **Figure 6(b)**.

4. Discussion

Three multi-temporal Landsat images were used to assess land cover changes in the PFB between 2000, 2013 and 2019, and determine whether the change patterns in terms of intensity of gain/loss of each of the classes were active or not between the period before and after the 2012-2013 reforestation initiative. Between 2013 and 2019 the total areas of forest (dry deciduous and gallery forests) and tree savannah increased, whereas those of shrub/grassy savannah (also including agricultural lands) and bare lands slightly decreased. Such increase in proportion of forest cover and tree savannah between 2013 and 2019, which can partly be attributed to the reforestation campaign, must not hide the fact that forest cover has disappeared at an alarming rate in some parts of the PFB, namely its eastern part (**Figure 2(b)**). Moreover, the spatial distribution of forest cover and tree savannah across the central parts of the PFB based on the classified map of 2019 suggests that parts of the reforested section remain under threat and can experience more degradation over time if not properly managed.

The performance of image classification found in our study was comparable for most classes to that of Soro *et al.* [14], whose study area (the upper Bandama catchment in northern Côte d'Ivoire) shared some similarities with ours. For example, in their study, the PAs for forest and tree savannah classes using Landsat ETM+ image (year 2000) were 82% and 91%, respectively [14]. The corresponding PA values in our study for the same year were 86% and 97%, respectively (**Table 2**). Although the use of Landsat images for assessing land cover changes resulted in acceptable performance, it would be interesting for future studies to use higher spatial resolution images such as those from Sentinel imagery as they become available.

The intensity change analysis revealed different patterns in terms of annual change intensity and annual transition intensity for each of the classes across the PFB. Annual change intensities were not uniformly distributed across the PFB, as illustrated through the spatial distribution of land cover classes in **Figure 3**. Likewise, the transition intensity from one class to another was not uniformly distributed across the PFB. The intensive gain of tree savannah from shrub/grassy savannah between 2013 and 2019 can be explained by the increased proportion in land area of tree savannah in the central-eastern part of the forest, likely resulting from the reforestation initiative. Although the end goal of reforestation is to regain a full forest cover, transitions from shrub/grassy savannah to tree forest still are encouraging outcomes, which highlight the need for undertaking such reforestation initiatives more frequently.

The 2012-2013 reforestation initiative was a fruitful collaboration between populations and public (SODEFOR) and private partners (the International Tropical Timber Organization). Stakeholder engagement and participatory management are possible and can be effective in restoring forest cover in protected areas and national parks located in the northern regions of Côte d'Ivoire. When populations living in the surrounds of a protected forest are involved in the decision-making process for managing the forest, e.g., through awareness and capacity building training sessions organized by administrative authorities and non-governmental organizations, they fully adhere to the forest heritage conservation policy. Through those training sessions there are opportunities for the populations to provide feedbacks and develop consensual strategies to manage the forest. The anthropogenic pressures on the PFB resources could be reduced through such an active participatory of population. An example of successful participatory forest management is the Kamonon Forest Station [46], which is located in the same administrative region as the PFB and share several similarities. To date, the Kamonon Forest Station remains fully protected; dead and dry woods are only harvested with the permission of the SODEFOR [46]. Reconciling economic growth and forest protection, analysing the current and emerging pressures on forests of the different sectors of the economy (agriculture, energy, transport, logging and mining), and implementing strategic policies that could support sustainable and equitable development, constitute various means which rely on participatory land management [47].

5. Conclusion

The dynamics of land cover change across the protected forest of Badénou between 2000 and 2019 were assessed using a remote sensing-based method coupled with GIS techniques. Overall, as of 2019 the land areas covered by forest (dry deciduous and gallery forests), tree savannah, shrub/grassy savannah (including agricultural lands), and bare lands (bare soils and degraded land areas resulting from mining and logging activities) were estimated at 5054 ha (17%), 10,811 ha (37%), 8076 ha (28%), and 4424 ha (15%), respectively. Results showed that the annual gain or loss in terms of land area for a given class, as well as the transition intensity from one class to another, were not uniformly distributed across the PFB between the 2000-2013 and 2013-2019 periods. Although the total areas of forest and tree savannah increased between 2013 and 2019 (period post-reforestation initiative), the results presented indicate that activities contributing to forest degradation remain prevalent across the PFB, threatening the sustainability of the forest if such activities are not properly managed. For forests located in regions prone to noticeable adverse climate conditions and increasingly threatened by desertification, as it is the case for the northern regions in Côte d'Ivoire, it is necessary to critically evaluate past reforestation initiatives for improvement when needed. As such, the study provided additional insights into the causes of deforestation and forest degradation; it can help identify conservation and restauration priorities and improve the overall management of the PFB to ensure sustainable beneficial outcomes for the forest and all the community.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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