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UNDERSTANDING FOREST DEGRADATION – A REVIEW OF FOREST STRUCTURE INDICATORS

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ABSTRACT

Forest degradation has profoundly impacted the forest structure which has affected the carbon stock, biodiversity, microclimate and function of the ecosystem. This consequently reduces the forest's capacity in providing goods and services. Forest degradation is typically a multi-stage anthropological process that develops gradually but might be accelerated by phenomena such as forest fires, storms, landslides, or floods. Hence, identification of site-specific forest degradation is crucial in the forest management system. Unlike deforestation, estimating the carbon emission from forest degradation is challenging due to the difficulty in defining the motive of degradation itself. Under the Reducing Emissions from Deforestation and Forest Degradation-plus (REDD+) framework, it is important to measure the changes in forest structure. This study discusses a few related forest structure indicators in assessing forest degradation such as the canopy cover, aboveground biomass and stand structure. To understand forest degradation, it is necessary to understand the forest structure indicators which could contribute to establishing a better forest management system.

Keywords: Tropical forest; REDD+; Forest degradation; Forest structure

1. Introduction

Growing human population and rapid land use development, especially in developing countries, have seen critical changes in the landscape caused by deforestation and forest degradation at the expense of protected forests, biodiversity and ecosystem functions, which could jeopardize the future ecological services for health and livelihood (Avtar *et al.,* 2020; Mondal *et al.,* 2020; Osen *et al.,* 2021). According to Brandon (2015), the uncertainty that revolves around forest degradation is capable of causing significant climatic changes on both local and regional scales. Consequently, temperature, rainfall, storm tracks and intensity, cloud formation, and carbon storage are affected (Brandon, 2015). This will negatively affect the ability of the forest to provide products and services. Therefore, due to the huge pressure on forests caused by anthropogenic and natural disturbances associated with global climate change, new ecological engineering and landscape-level methods are required in order to restore the ecosystem products and services (Saikia *et al.*, 2021). Coincidentally, the need to restore is in-line with the aim of Sustainable Development Goals No.15 which is to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, reverse land degradation and halt biodiversity loss (Vlek *et al.,* 2017).

Forest degradation is a common problem in forest ecosystems. However, it is still understudied, and its significance and extent are largely undetermined as compared to deforestation (Mitchell *et al.,* 2017). This is due to the complexity that causes the phenomenon, such as unsustainable logging, shifting cultivation, fire, pest infestation, and natural disaster (Gao *et al.*, 2020; Mitchell *et al.,* 2017; Vásquez-Grandón *et al.*, 2018). Remote sensing approaches have the potential in providing regional scale detection and estimation of forest degradation; however, they must be coupled with critical information on forest structural changes (Ahrends *et al.,* 2021). Forest structure is a three-dimensional information of trees and other plants in vertical and horizontal arrangements that can be extracted through remote sensing techniques and verified using field measured data (Seidler, 2017). In designing effective and strategic actions for forests to be protected and recovered, understanding forest changes in forest ecosystems are vital as indicators to assess forest degradation. Very few of the methods can measure the intensity of the degradation, i.e., the proportion of biomass lost in any one area over time, which is an essential element for calculating emissions due to forest degradation (Gao *et al.,* 2020). Therefore, this paper will review the possibility of three indicators in exploring forest degradation, namely the canopy cover, stand structure and aboveground biomass (AGB).

2. Understanding Forest Degradation

While the focus on deforestation in the tropics is entirely plausible, it is worrying that the more extensive and often more insidious processes of forest degradation are commonly neglected (Putz & Redford, 2010). The reason for it being frequently overlooked by scientists is the term "degradation" which refers to the loss of values, which is somewhat subjective to be narrowed down. Another explanation of why degradation is relatively more challenging to be addressed is that the application of remote sensing is not as simple as quantifying deforestation (Gao *et al.*, 2020). Defining forest degradation is as complex as addressing the issues from different perspectives of various programs, world conventions, and policies made to focus on forest management, climate change and biodiversity (Vásquez-Grandón *et al.*, 2018). To date, there are more than 50 ways to define the concepts from the degradation of the soil to climate change mitigation (Ghazoul *et al.*, 2015). In short, it has been discussed that forest degradation should revolve around not only biophysical but the social condition as well; including how the forest can be grown and ways they can deteriorate or degrade. Once the matter is established, the control measures and actions to be taken will be clearer and more precise in a deforested area in which silviculture practices can be applied.

The United Nations Framework Convention on Climate Change (UNFCC) defines forest degradation as any carbon density loss in a forest land induced by direct anthropogenic activity (Mitchell *et al.*, 2017). Although one's definition might vary from the others, it can still be referred to as permanently altered, modified, or lost due to human activities (Gao *et al.*, 2020). Furthermore, forest degradation is typically a multi-stage process and develops gradually, which has been discussed to be the result of human activities including fragmentation, pollution, overexploitation and fire; however, it might be induced quickly by phenomena such as forest fires, hurricanes, landslides, or floods (Ahrends *et al.*, 2021). Unlike deforestation, estimating the carbon emission from forest degradation is challenging. This is due to the uncertainty in identifying the degraded area in a large region without any significant changes to land cover type while affecting forest structure, composition, and function. The degradation of a tropical forest as the world's largest carbon sequester has profoundly impacted carbon stock, biodiversity, microclimate, and ecosystem function (Vásquez-Grandón *et al.*, 2018).

Consequently, this reduces the forest's capacity in providing goods and services (FAO, 2011). According to Gao *et al.* (2020), forest degradation has caused an alteration to forest structure, leading to a reduction in biomass, composition of species, and natural regeneration. The challenges in estimating forest degradation compared to deforestation had resulted in uncertainties in assessing the global carbon emissions, which are roughly estimated from 40% to more than 200%.

3. The Impact of Forest Degradation on Tropical Forests

Tropical forests function in controlling global climate and weather patterns. Particularly, rainfall and temperature are critical for farmers and policymakers regardless of within or distant from the tropics (Brandon, 2015; Jucker *et al.*, 2018). For instance, up to 90% of rainfall in tropical forests transpires back to the atmosphere and produces double the precipitation from passing winds compared to open land. Arguably, although covering just 5% of the Earth's total surface, tropical forests structurally have more biodiversity than any other type of forest, including two-thirds of all land-based species (Palace *et al.*, 2015). It is prosperous, and biodiversity provides the basis for many ecological forest services and is vital to their health and resilience.

Forest degradation poses a significant threat to the environment and biodiversity as a whole. The tropical forests, home to various rare species (known as endemics) including plants, birds, amphibians, and insects which only exist in certain places, are in danger of extinction if forests are disturbed (Brandon, 2015; Chung *et al.*, 2013). The changes in the climate due to forest degradation, which have a particularly profound effect on endemic species, the weather and precipitation at local and regional scales, impacts temperature, rainfall, storm tracks, cloud formation, and carbon storage (Brandon, 2015). Moreover, over the last several decades, there has been a growing concern in certain areas where deforestation and degradation have significantly impacted regional climate and the environment which has brought countless additional detrimental effects (Fahey, 2013).

The degradation of tropical forests has been widely acknowledged to be the force for the loss of forest biodiversity, successively known to be the source of carbon emission (Ahrends *et al.*, 2021). At some point, forest degradation may be worse than deforestation, as is the case in Brazil, where forest degradation (337,427 km^2) has outpaced deforestation (308,311 km^2) in the last 20 years (Qin et al., 2021). Furthermore, the gross AGB loss for forest degradation is almost three times more than deforestation. The loss is significantly substantial, and it needs to be included in the global carbon budget assessment. This severe impact of forest degradation was reported by Ahrends *et al.* (2021) in recent studies, which proved forest degradation has been underestimated especially on the total carbon emissions and the combined carbon loss from deforestation and forest degradation to be from 25% to 69%. Fortunately, a study from a few countries in the Asia-pacific region has come up with several key opportunities for sustainable forest management, including the possibility to improve the quality of monitoring and measuring the forest degradation techniques and procedures (Maraseni *et al.,* 2020).

4. Assessing Forest Degradation via Forest Structure

Understanding specific forest degradation is vital before developing a silviculture program to restore the capability of regenerating the forest cover, forest structure, and species composition (Vásquez-Grandón *et al.*, 2018). This information will provide the groundwork for establishing a forest monitoring system as well as restoring deforested areas. Measuring the changes in forest structure is an important mechanism in the Reducing Emissions from Deforestation and forest Degradation-plus (REDD+) program (Vorster *et al.*, 2020). A transparent reporting will boost positive carbon restoration for forest management in general. Degradation can be judged and quantified based on the area affected and the quantity of biomass removed within a specific area. However, the loss of biomass may vary based on the forest's biophysical characteristics, degree of disturbances and geographical region (Gao *et al.,* 2020). Based on recent studies, a breakthrough in measuring forest degradation has enabled the monitoring of tree cover changes by using remote sensing applications (Ahrends *et al.*, 2021). However, fieldwork is still compulsory to understand the ground changes of the forest in assessing forest degradation using specific indicators to express different types of forest degradation and the perpetrator (Vásquez-Grandón *et al.*, 2018). Assessing forest degradation needs a baseline work as a comparison for the degraded area or the previous state of the forest before the disturbance occurred (Vásquez-Grandón *et al.*, 2018). The reference data must be free from any human or naturally induced disturbances within the same biome type and edaphoclimatic zone.

Various indicators have been used in assessing degradation for structural, composition and regeneration comparison due to forest degradation. One of the most practical variables widely used is the forest structural variable (Palace *et al.*, 2015; Vásquez-Grandón *et al.,* 2018). The field measurements are essential in evaluating degradation in small areas and applicable for large scale evaluation, including at the national level. The canopy cover (CC), structural index (SI) and forest degradation index (FDI) were also used to define forest structure at the stand level stage (Modica *et al.*, 2015). The indices measure tree stratification, such as vertical distribution. The main features of degraded forest can be seen through structural characteristics, such as low total basal area, low density of potential tree seeds and high numbers of tree individuals with smaller diameters and reduction of commercial species with more than 65 cm of diameter at breast height (DBH) (Vásquez-Grandón *et al.,* 2018). This is most likely due to human activities in extracting large diameter commercial species. Since basal area reduces in degraded forests, it is useful as an indicator as the mean basal area is lower as compared to an intact forest (Moss, 2012; Wong *et al.*, 2015).

4.1 *Canopy cover*

A canopy cover covers the vertical projection of the tree structure, layers formed by the branches and the canopy of plants or trees (Fiala *et al.*, 2006; Huang *et al.*, 2021). The term is equivalent to ecologists using the word 'cover' to refer to the percentage of ground area occupied by the aboveground sections of plants to evaluate the presence or absence of canopy vertically over a particular area of interest within the forest. Canopy cover can be the indicator to forecast stand volume for some species of trees since there is an almost linear relationship between the variables of the crown area and basal area (Jennings *et al.,* 1999). The mentioned linear relationship applies within the age range of a commercial rotation, where the growth is derived from the maximum value of timber before it breaks down as the trees reach biological maturity. Moreover, the indicator can be used in estimating the canopy cover between commercial plantations and natural forests, though it needs more attention in data acquisition. For instance, estimating the canopy cover of a monoculture plantation would be straightforward, as observing the basal area of a young tree based on local measurements will estimate the canopy cover. However, unlike natural forests where variations of mixed species stand; the basal area of each species should be recorded individually. Furthermore, natural forests hold several over-mature trees where the linear relationship is poor (Jennings *et al.,* 1999).

The thresholds for forest degradation based on canopy cover differ. A 20% decrease in canopy cover within an area can be considered degraded until numbers reach deforestation level (Sasaki *et al.*, 2011). This is supported by the fact that errors in classifying forest degradation can occur from 10% to 20% changes in canopy cover, while a 40% reduction makes the classification of forest class more distinct (Mitchell *et al.*, 2017). A canopy cover can be classified as a forest if it has more than 60% coverage, a medium forest if from 25% to 60% and a sparse forest if from 1% to 25% (Huang *et al.,* 2021). Forest degradation can also be categorised within the type of forest and counties with different permissible definitions (Sasaki *et al.*, 2011).

There are several methods for acquiring and measuring canopy cover such as hemispherical photography, line intercept, Moosehorn, spherical densitometer, simple visual assessment, crown position indices and canopy closure measures (Fiala *et al.*, 2006; Jennings *et al.,* 1999). However, recent studies show that visual image interpretation has been widely used in estimating canopy cover in a forest (Huang *et al.*, 2021; Khokthong *et al.,* 2019). An open-source tool called the 'Collect Earth' developed by the Food and Agriculture Organization (FAO) uses free satellite images to serve as instruments in collecting, analysing, and compiling reports of land use and land cover (LULC) and REDD+ activities monitoring (Asrat *et al.,* 2018; Avtar *et al.*, 2020). The techniques are proven to be predominantly much faster, inexpensive and suitable to be used in the case of complex landform and difficulty accessing the area of study. A recent study showed that measuring canopy cover tends to be less accurate in the form of a different observer as compared to visual image interpretation (Huang *et al.,* 2021). General methods used in canopy cover estimation in recent studies are presented in Table 1.

Table 1: Recent methods used in assessing canopy cover

Author	Methods	Application
Huang *et al.*, 2021	Mix of field data and visual image interpretation; Landsat 8, MODIS and Google Earth	Canopy cover classification on a regional scale
Khokthong *et al.*, 2019	Hemispherical Photography; UAV-based Visible Band Imagery	Tree mortality assessment using canopy cover
Asrat *et al.*, 2018	Visual Image Interpretation; PlanetScope, RapidEye and Sentinel-2	Canopy cover estimation based on visual interpretation
Hojas-Gascón *et al.*, 2015	Spherical Densitometer; Sentinel-2	Map forest degradation and canopy cover

In early 2000, by using ETM+ and IKONOS remote sensing data in distinguishing between shrubs and canopy cover at $R^2 = 0.91$, the canopy cover approach had been proven useful in detecting selective logging that causes forest degradation (Wang *et al.,* 2005). Almost two decades later, the indicator is still recommended to be the best way to assess forest degradation in a region by monitoring the decline of canopy cover between temporal resolution (Saikia *et al.*, 2021). It was also mentioned that ground-based canopy cover checking is appropriate to acquire an accurate estimation (Fiala *et al.,* 2006). However, forest degradation was not assessed based on only one indicator where the assessment may vary from a small-scale structural change to a large-scale loss of biomass (Mitchell *et al.*, 2017). The degraded forest might have comparable canopy cover to an intact forest but, the biomass can be significantly different, as large as 75%. Hence, the importance of assessing degraded forests also lies in estimating the aboveground biomass.

4.2 *Aboveground biomass (AGB)*

In general, biomass can be divided into above and belowground biomass of living or dead mass such as plants, and fine and coarse litter related to the soil (Lu, 2006; Ni *et al.*, 2020). Due to the challenges in obtaining belowground biomass, most of the studies in biomass estimation concentrate on the aboveground biomass, which translates into the weight of the portion of the tree when oven-dried to a consistent weight. Estimates of plot-level biomass are usually given as Mg ha^{-1} or kg m^{-2} and are calculated by adding the biomass values of individual trees on a plot before normalizing the area covered in the plot. It is to be noted that deforestation and forest degradation influence the quantity of carbon that can be released into the atmosphere (Ahrends *et al.,* 2021). Furthermore, regional biomass changes have been related to various ecosystem functions and the impact of climate change, such as carbon cycles, soil nutrient allocation, fuel accumulation, and habitat conditions in terrestrial ecosystems (Wang *et al.,* 2018). Therefore, the AGB estimation helps acquire critical information to improve understanding of carbon sequestration and emission, roles in affecting soil fertility, roles in environmental processes, forest degradation, and restoration.

Ni *et al.* (2020) stated three traditional methods of in-field measurement of estimating biomass which are (i) destructive sampling methods, (ii) conversion from volume to biomass and (iii) allometric equations. However, only an allometric equation is focused upon as it has been widely used in recent studies. The AGB estimation can be performed by using allometric methods, also known as biomass estimation equations, through the regression models; the attributes commonly used are the DBH and tree height data that can be easily measured on the field (Kebede & Soromessa, 2018). The fundamental idea behind allometric equations is that in many organisms, one part's growth rate is proportionate to another. For instance, trunk diameter and weight which are strongly correlated allow the regression equation of the weight to be derived from field measurements to estimate the standing biomass of forest stands. It is to be noted that different species of trees have distinct allometric equations, for example, different species of mangroves are based on DBH (cm).

Table 2: Types of measurement used to monitor forest degradation

Author	Variables	Application
Wheeler *et al.*, 2021	DBH, tree height, stem condition	Monitoring forest degradation
Sadadi, 2016	DBH	AGB estimation using LiDAR and TLS
Korom *et al.*, 2016	DBH and tree height	Understanding growth recovery for degraded forest
Ioki *et al.*, 2014	DBH and tree height	AGB estimation to assess degradation levels

Table 2 presents the list of studies utilizing DBH, height and stem condition (in some situations) in estimating AGB loss over time due to forest degradation (Gao *et al.*, 2020). The procedure for acquiring field measurement data is shown in Figure 1. Compared to the destructive method to get the biomass information, the allometric equation is proven to be valuable and was frequently utilized by foresters to estimate biomass, trace carbon fluxes, and in some conditions to locate disturbances. Furthermore, quantification of loss or gain in AGB is an intermediate step to reporting on carbon emissions (Mitchell *et al.,* 2017). The usage of remote sensing can tackle issues related to logistics and accessibility but requires ground sampling for validation purposes. The combination of field measurements and remote sensing techniques enable biomass estimation over a large area.

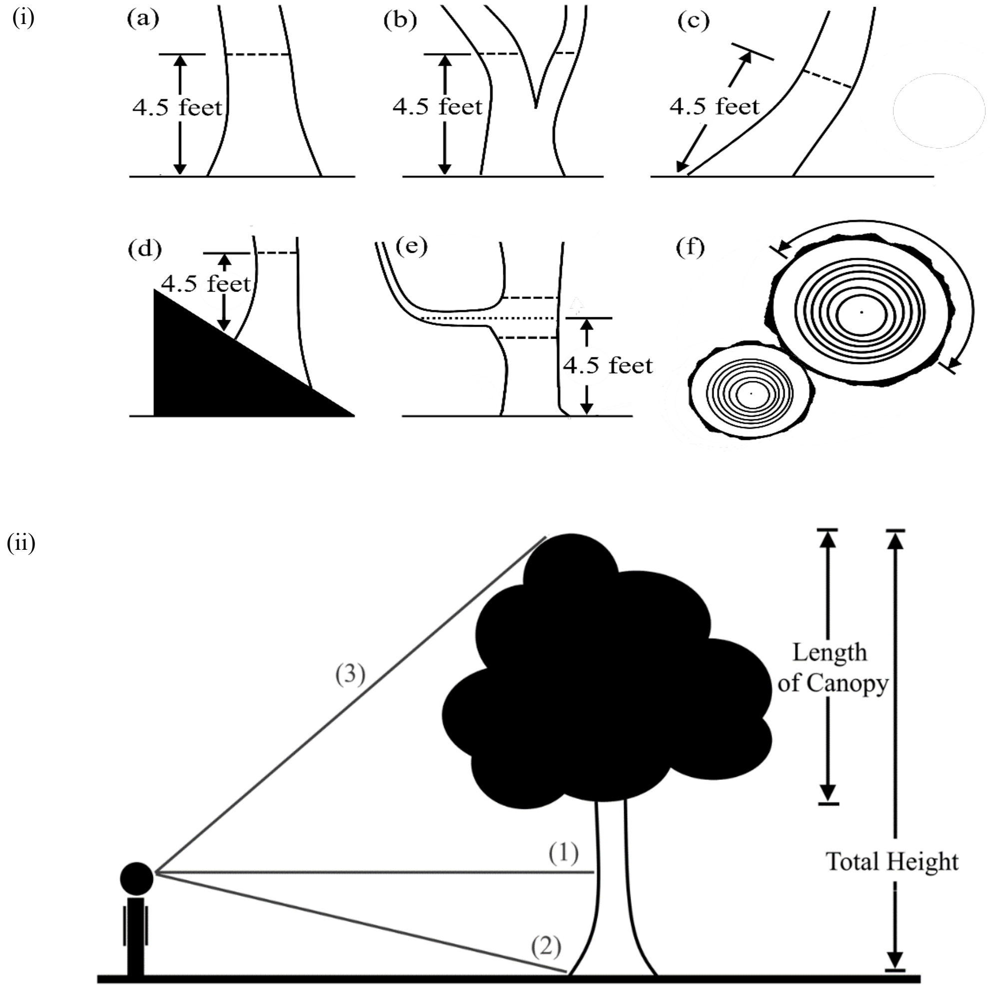

Figure 1: (i) Measuring diameter at breast height (DBH);
(a) level ground, (b)forked below DBH, (C) leaning tree (d) slope, (D), (E) irregular bole at breast height and (F) tree boles touched at breast height. (ii) Tree height measurements; distance between (1) operator and the tree, (2) operator and ground base and (3) operator and the top of the tree (Malone *et al.,* 2009)

4.3 *Stand structure*

The structural component serves as an indicator to differentiate reactions and changes of landscape within times. It provides fundamentals in assessing relative abundance of species habitats, identifying stages of succession in stand development, illustrating the outcomes of silviculture approach, quantifying the potential of wood products value and assessments of forest degradation (Moss, 2012). The stand structure can be considered and defined as spatial distribution, diametric and differences in the height of trees in a forest. Horizontally, stand structure refers to diametric tree distribution, and vertically, it refers to the tree height difference. A high diversity forest which has multiple tree species, and various sizes in clumped spatial distributions promote a greater stability of forest integrity (Pastorella & Paletto, 2013).

Human activities can alter species composition, forest stand structure and forest regeneration capacity thus emphasizing the importance of distinguishing stand structure from anthropological activities classified under the definition of forest degradation (Djomo Njepang, 2015). There are several methods for measuring the stand structure, as listed in Table 3. The stand structure consists of several attributes such as tree density ha^{-1}, DBH, basal area (BA), leaf area index (LAI), canopy closure and species richness (Ali, 2019; Khai *et al.,* 2016; Osen *et al.,* 2021). Other findings presented more complex stand structure measures in indexes such as the Diametric Differentiation Index, Mingling Index and Contagion Index (Pastorella & Paletto, 2013).

Table 3: Approaches in acquiring stand structure and functions

Author	Variables	Application
Osen *et al.*, 2021	DBH, hemispherical photographs and LAI	Stand structure determined by land use history
Zhang *et al.*, 2021	DBH, height and crown diameter	Approaches to characterize stand structure
Khai *et al.*, 2016	Tree density, DBH, BA and species richness	Stand structure for selective and illegal loggings
Pastorella & Paletto, 2013	DBH, species, and angle (°) from hemispherical photographs	S-index for species and stand structure as tools to support forest management

The structural stand information from field measurements is capable of assessing impacts from human-induced activities as evidence of forest degradation. A short interval of logging has weakened the stand structure, resulting in the poor stocking of even fewer valuable species, particularly for smaller trees (Osen *et al.*, 2021; Zhang *et al.*, 2021). On the contrary, forests with fewer logging activities are proven to have more stands, including commercially valuable species to be preserved. The introduction of the S-index, to explain the forest stand through the forest's structural and functionality point of view, has also proven to be valuable in assessing a forest ecosystem's biodiversity (Pastorella & Paletto, 2013). Linking the S-index values to the various indices' descriptions can help assess a forest stand from both the ecological and silvicultural perspectives. This information helps identify essential strategic components to preserve biodiversity and enhance stand stability.

5. Conclusion

Time-based spectral properties and changes in canopy cover are useful information in detecting areas undergoing forest degradation. Though remote sensing has provided a huge potential in detecting changes in forest landscapes, a ground-level investigation is still vital as part of the overall monitoring process. As degradation is likely to vary from anthropogenic to natural disasters, it would be essential to understand the causes. Field exploration plays an important role in verifying the quantification of carbon emissions from forest degradation. Although ground measurements are time-consuming and resource-intensive, particularly in remote areas, DBH and tree height information are useful in the estimation of forest degradation of both natural and human-induced alteration. Moreover, there exists limitation in the extent of field exploration on the nature of the forest and the logistics. However, a significant assessment in plots within large areas could be vital in calibrating remote sensing signatures particularly land-use activities. A synergy of forest structure field measurements and remote sensing techniques could provide an appropriate estimation of biomass loss (forest degradation) or gain (growth recovery). The indicators highlighted in this review can provide an alternative for sustainable forest management within the region and national level among REDD+ stakeholders. This can be achieved by improving the quality of monitoring and measuring forest degradation techniques through intensive field exploration based on forest structure and remote sensing. Effective forest management requires a combination of in-situ forest fieldwork, anthropological data, and remote sensing base maps, including aerial and satellite imagery, to address forest degradation. The characteristics of forest structure and composition could reveal the levels of forest alteration that occurred on-ground. This can provide ample information to support the idea of the 15th SDG. The best way to monitor changes, establish policies and identify potential restoration is to understand the drivers and impacts of forest alteration, which could be monitored from forest structure indicators such as the canopy covers, aboveground biomass and stand structure. Improved forest monitoring and quantification could lead to the formulation of participatory forest management policies and action plans to reduce forest degradation and increase networks between stakeholders for forest protection and better forest governance. This work could help prepare a baseline exploration at the national level in enhancing forest management and mitigating carbon emissions from forest degradation as outlined in REDD+.

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