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RESEARCH ARTICLE

INTEGRATION OF OBJECT-BASED CLASSIFICATION USING SENTINEL-2 IMAGERY AND IN SITU DATA TO IDENTIFY AND MAP FOREST FACIES IN THE HUMID AND HYPER-HUMID TROPICAL FOREST CONTINUUM OF TAI NATIONAL PARK, SOUTHEASTERN COTE D'IVOIRE

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Abstract

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Satellite remote sensing, particularly through high-resolution satellite imagery, is a vital tool for mapping and sustainably managing tropical forests. While significant progress has been made through its application in various regions around the world, Taï National Park—one of the last major tracts of primary forest in West Africa—remains relatively undocumented using this approach. Existing data for this site are limited to outdated maps based on aerial photographs and a binary "forest / non-forest" classification, which fails to capture the diversity of its vegetation formations. In this context, the present study aims to update the forest formation map of the park and to propose a typology of ecological facies based on the physiognomy and heterogeneity of the environment.The data used consists of six Sentinel-2 scenes acquired in January and May 2020, pre-processed to provide surface reflectance values. Additionally, 9,287 observation points were collected in the field between November 2019 and April 2020 along 293 transects of 2 km each, in order to document the physiognomic characteristics of forest formations. These data were used both to train the classification algorithm and to validate the results. Object based image classification was carried out using the ORFEO TOOLBO X library in several steps: image segmentation using the "LargeScaleMeanShift " module, which generated 459,268 homogeneous spatial entities; training of the SVM algorithm with the "TrainVectorClassifier" module; and classification of the segmented image using the "VectorClassifier" module. Validation was performed through confusion matrix analysis.The results identified four major forest formations: open-understory forest (61%), closed-understory forest (30%), forest on hydromorphic soils (6.9%), and shrublands or non-woody vegetation (0.02%).A grid-based analysis of spatial heterogeneity further enabled the mapping of eight forest facies, revealing ecologically significant transitional zones.Ultimately, this study confirms the effectiveness of object-based classification applied to satellite imagery for accurately mapping forest typologies in Taï National Park

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The integration of satellite data and field observations enhances the robustness of the results and provides a relevant spatial reference for differentiated management and ecological monitoring of this protected area.

Introduction:-

Satellite remote sensing, defined as the acquisition of information from space without direct contact (Verger, 1984), has become an essential tool for the analysis and sustainable management of tropical forests. Through its innovative approaches and technologies, this discipline enables the characterization of forest ecosystems and contributes to a better understanding of their condition and dynamics. Among these tools, high spatial resolution satellite imagery, combined with advanced processing techniques, has significantly advanced the study of tropical forests in South America, Southeast Asia, and Africa (Pain-Orcet, 1994; Dupuy, and al., 1999); Polidori et al., 2003; Bonnet and al., 2011; Hansenand al., 2013; FFA, 2020; FAO, 2024).

In West Africa—home to the continent's second-largest forest block after the Congo Basin—Taï National Park spans approximately 560,000 hectares in southwestern Côte d'Ivoire. This protected area, recognized globally for its conservation value, represents one of the last remnants of primary rainforest in the region (Bousquet, 1978; Adou, 2005) and harbors exceptional floral and faunal biodiversity.

Despite the ecological importance of Taï National Park and the availability of advanced Earth observation technologies, no updated and detailed map of the forest formation types within the park currently exists. To date, the main efforts in this regard are limited to a forest formation map derived from aerial photographs taken in the 1960s (Guillaumet and Adjanohoun, 1967), and a global satellite monitoring initiative launched by park managers in 2011 based on a binary "forest / non-forest" classification. Yet, other vegetation types have been reported since (Guillaumet, 1994), although their spatial distribution has not been precisely established.

The persistence of a binary representation of forest cover—either "forest / non-forest" or based on outdated typologies—hampers a detailed understanding of the spatial organization of forest ecosystems and limits the implementation of conservation strategies tailored to the diversity of ecological facies.

In this context, the present study aims to address this knowledge gap by leveraging high spatial and spectral resolution remote sensing products, object-based classification methods combined with descriptive field data, and spatial analysis tools in geographic information systems to:
1. Update the mapping of forest formations in Taï National Park using recent satellite imagery and physiognomic criteria.
2. Propose a typology of ecological forest facies based on the updated forest map, integrating vegetation physiognomy and environmental heterogeneity, with the goal of supporting differentiated management and ecological monitoring of the park's natural resources.

Materials and Methods;-

Study area

This study was conducted in Taï National Park (TNP) and the N'Zo Partial Faunal Reserve (NPFR), two contiguous protected areas forming a forest block of 536,016 hectares in southwestern Côte d'Ivoire. This forest block, usuallycalled "Taï National Park" (TNP)is located in the Cavally–Sassandra interfluve, between 5°08′ and 6°24′ North latitude, and between 6°47′ and 7°25′ West longitude.

The region experiences a sub-equatorial climate with four alternating seasons: a major rainy season from March to June, a short dry season from July to August, a minor rainy season from September to October, and a long dry season from November to February (Avenard, and al., 1971). Rainfall patterns define two distinct zones, with average annual precipitation of approximately 1,700 mm in the north and 2,200 mm in the south (Van Rompaey, 1994). Temperatures range between 24°C and 27°C throughout the year.

Data Collection
Two types of data were used in this study: (1) five satellite images acquired by the MSI sensor onboard the Sentinel-2A satellite, and (2) field-based observations of vegetation formations collected within the park.

Regarding the satellite data, five scenes were acquired on January 3 and May 12, 2020, by the MSI sensor of the Sentinel-2 satellite system. These scenes, which together cover the entire study area, were downloaded from the official imagery provider via the Copernicus portal (https://dataspace.copernicus.eu/). Preference was given to images that had already been corrected for radiometric and atmospheric effects by the provider, to obtain surface reflectance data directly usable for the study.

As for the descriptive data on vegetation formations, a total of 9,287 observation points were recorded in situ between November 26, 2019, and April 25, 2020, along a network of 293 transects, each 2 kilometers long and systematically distributed across the study area. At each observation point, GPS coordinates were recorded along with a description of the forest formation encountered. This description was based on the following nomenclature shown in table 1:

Table I:- Nomenclature and description of forest formations.

Nomenclature	Abréviation	Description
Mixed forests with open understory	FMSO	Mixed forests with open understory are characterized by a fully closed, unbroken canopy, a dominant layer of tall and large trees, and an understory mainly composed of shrubs. The sparse vegetation allows for easy movement, with visibility exceeding 10 meters.
Mixed forests with closed understory	FMSF	Mixed forests with closed understory feature a dominant layer of large trees and a lower tree layer densely infested with lianas. The understory is dense, with young regrowth and tangled vines, making movement difficult. Visibility is less than 10 meters.
Forests on hydromorphicsoils	FSHD	Forests on hydromorphic soils include formations growing on poorly to moderately waterlogged soils (humid forests), in lowlands (swamp forests), along watercourses (riparian forests), and in areas subject to periodic flooding.
Inselberg or mountainforests	FIMT	Inselberg or mountain forests occur on hilltops, slopes, and rocky outcrops. These formations are characterized by shrub and herbaceous vegetation (savanna-like), occasionally interspersed with exposed rock surfaces.
Young secondaryforests	FSJF	Young secondary forests are dense stands of young trees with interwoven branches that hinder movement. The high density of young woody species distinguishes them from shrublands.
Shrublands or non-woody vegetation	BVNL	Shrublands or non-woody vegetation are difficult to traverse and consist of dense herbaceous cover with a closed understory. The dominance of thick herbaceous plants and sparse shrub layer distinguishes them from typical shrublands.

Data Processing
Classification of SENTINEL image by using object-based classification method involves two essential operations: the segmentation of the image into homogeneous entities and the classification of these segments according to the adopted nomenclature of vegetation formations (Nicolas B., Mehrez Z. And Clement M., (2018). In object-based classification methodologies, the segmentation step is of paramount importance, as it determines the structure of the spatial entities being analyzed and directly influences the quality of the classification results (Blaschke, 2003; 2010). In the present study, this step was implemented using the "LargeScaleMeanShift" module from the ORFEO TOOLBOX library. This process is based on a sequence of four successive operations: (1) smoothing of the source image, (2) segmentation of the smoothed image, (3) merging of small segments with the most homogeneous neighboring entities, and (4) conversion of the segmented results into vector objects(Passy,2021). The segmentation algorithm was calibrated to produce a fine segmentation capable of detecting homogeneous areas of at least 25 hectares. The segmentation process applied to the image covering the park thus generated 459,268 homogeneous entities or segments.

Following segmentation, the classification of forest formations was carried out using also the ORFEO TOOLBOX library, by mobilizing several of its processing modules. The “TrainVectorClassifier” module was used to train a Support Vector Machine (SVM) classifier. The SVM classifier was chosen for its robustness in handling multidimensional data and its ability to produce accurate classifications, even in complex feature spaces (Thamilselvan, 2015; Hosseini and Kandovan, 2017;Sheykhmousa and al., (2020).

The “TrainVectorClassifier” module, which takes as inputs, the training and validation segment samples, produced as output, a confusion matrix and a classification model. This trained model was then applied to the segmented image using the “VectorClassifier” module in order to classify all image segments. These segments were assigned to different classes representing forest formations.

At the end of the classification process, validation was performed through the analysis of the confusion matrix and the interpretation of quality indices derived from the matrix data.

A grid composed of 500-meter-wide cells was applied across the entire perimeter of Taï National Park (TNP), generating 22,006 spatial units, each covering an area of 25 hectares. These cells served as the basis for the physiognomic analysis of forest cover heterogeneity. Using Geographic Information System (GIS) tools, particularly QGIS 3.2, we performed a union between the land cover layer and the grid, in order to segment the data according to the grid cells. The forest formation data layer was then aggregated by cell, calculating for each analysis unit, the percentage of area occupied by each type of formation present. Based on this evaluation, the cells or analysis units were assigned to one of the forest facies.

Table II below defines the rules for assigning analysis units to the different types of facies based on the proposed forest formation and the distribution of the identified facies, as well as the total areas attributed to each.

Table II:- Rules for assigning analysis units to proposed forest facies.

Facies Name	Assignment Rule for Analysis Units
1. Non-woody Dominant Forest Facies	Units where non-woody vegetation (BVNL) covers more than 50% of the area were assigned to this facies.
2. Hydromorphic Forest Facies	Units where hydromorphic forest occupies more than 80% of the area were assigned to this facies.
3. Semi-hydromorphic Forest Facies	Units where hydromorphic forest is dominant, covering between 50% and 80% of the area, were assigned to this facies.
4. Mixed Forest Facies	Units where at least three forest formations are present, but none is dominant were assigned to this facies.
5. Semi-closed Understory Forest Facies	Units where closed-understory forest dominates, covering between 50% and 80% of the area, were assigned to this facies.
6. ClosedUnderstory Forest Facies	Units where closed-understory forest occupies more than 80% of the area were assigned to this facies.
7. Semi-open Understory Forest Facies	Units where open-understory forest dominates, covering between 50% and 80% of the area, were assigned to this facies.
8. Open Understory Forest Facies	Units where open-understory forest occupies more than 80% of the area were assigned to this facies.

Results:-

Distribution of Forest Formation Types

The object-based classification of the 2020 SENTINEL image, supported by field-collected descriptive data on forest formations, provided a detailed spatial representation of the different forest types across Taï National Park (TNP).

To assess the reliability of the classification, a confusion matrix was generated and presented below (table III). The results yielded an overall accuracy of **0.83** and a **Kappa coefficient of 0.72**. According to Landis and Koch (1977), this level of agreement is considered substantial, indicating that the classification model performs well beyond random chance and confirming its robustness.

Table III:- Confusion matrix of the object-based classification applied to the 2020 SENTINEL image.

		#Reference labels							Total
		BVNL	EAU	FIMT	FMSF	FMSO	FSHD	FSJF	
#Produced labels	BVNL	12	0	0	6	11	1	0	30
	EAU	0	3	0	0	0	0	0	3
	FIMT	0	0	0	1	2	0	0	3
	FMSF	0	0	0	478	26	25	0	529
	FMSO	0	0	0	66	769	32	0	867
	FSHD	0	0	0	30	59	67	0	156
	FSJF	0	0	0	1	0	0	0	1
	Total	12	3	0	582	867	125	0	1589

The classification revealed four distinct forest formation types. Open-understory forests, predominantly located in the central and southern parts of the park, represent the largest share of forest cover, accounting for **61%** of the total area. These are followed by closed-understory forests, which cover **30.6%** of the park.In contrast, inselberg forests and secondary or young thicket forests were not detected by the classification due to their limited representation in the field data.

Table IV and Figures 1 and 2 below show the areas occupied by forest formations and their spatial distribution in the NTP area:

Table IV:- Area and percentage of mapped forest formations.

Land use	**Area in hectares**	**Percentage (%)**
Bush or non-woody vegetation (BVNL)	84,84	0,02
Water body	7136,05	1,33
Forest with closed undergrowth (FMSF)	164200,94	30,63
Forest with open undergrowth (FMSO)	327468,41	61,09
Forest on hydromorphicsoils (FSHD)	37127,03	6,93
Total	536017,27	100,00

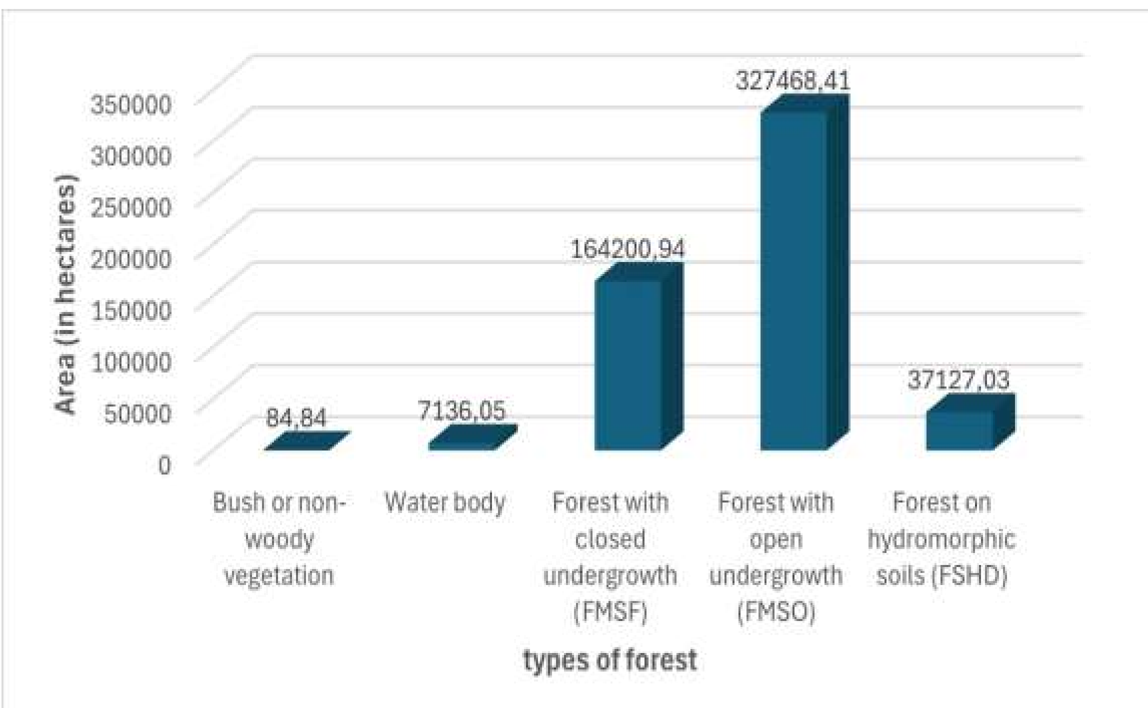

Figure 1:- Area of forest formations mapped using SENTINEL satellite imagery.

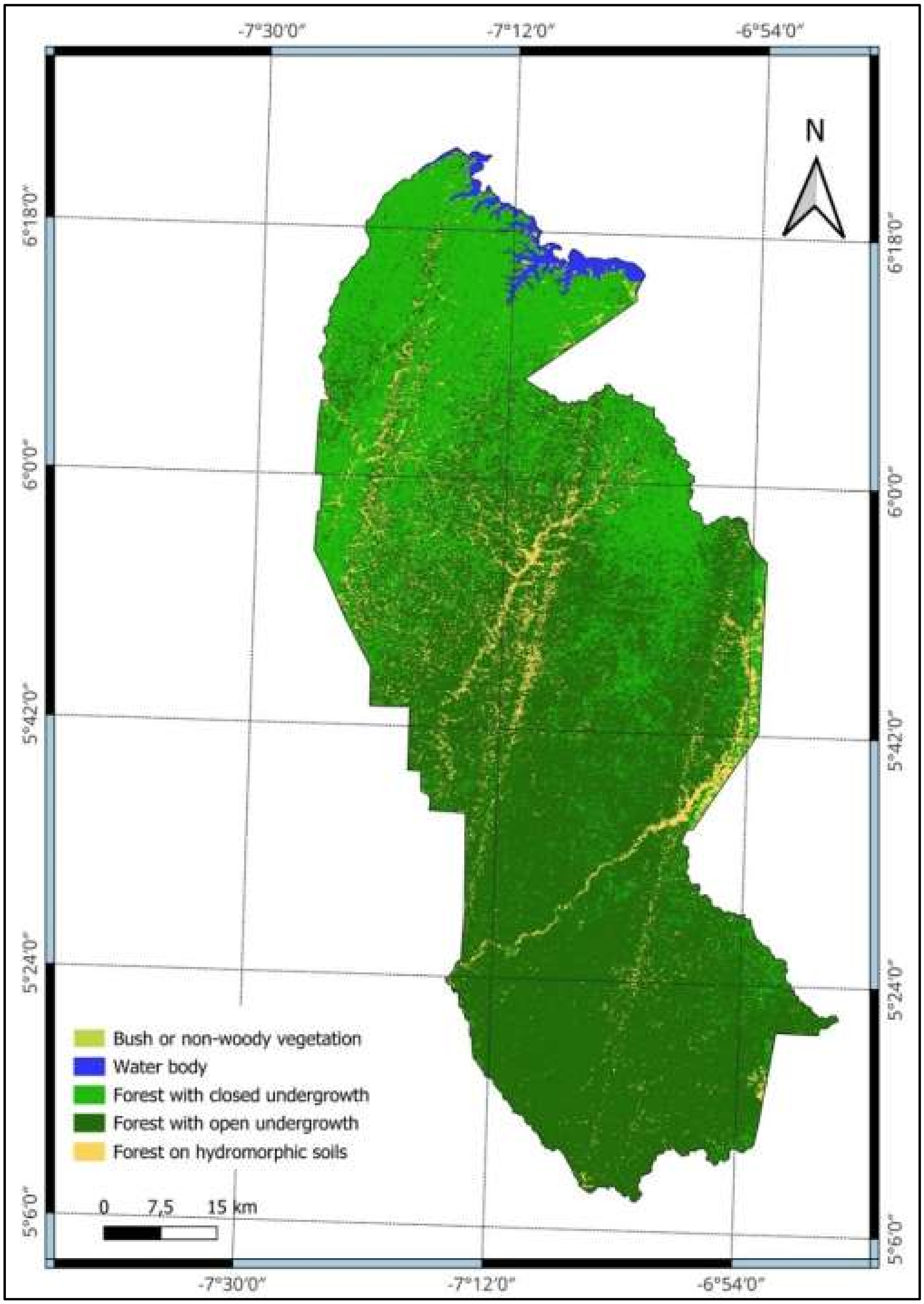

Figure 2:-Spatial distribution of forest formations mapped by image classification.

Mapping of Forest Facies

The assessment of the areas occupied by forest formations within each of the 22,006 grid cells covering the TNP analysis area made it possible to determine the level of heterogeneity of forest formations within these cells. Based on the nature of the dominant forest formation and the degree of homogeneity or heterogeneity revealed by the spatial analysis, the analytical units were assigned to the forest facies corresponding to the physiognomic context described by these two parameters.

Table V and Figures 3 and 4 below show the areas occupied by forest facies and their spatial distribution in the TNP area:

Table V:-Area and Percentage of Forest Facies in Taï National Park.

Facies code	Nom	Number of analysis units assigned to facies	Area (ha)	(%)
Facies 1	Non-woody Dominant Forest Facies	3	6,74	0,001
Facies 2	Hydromorphic Forest Facies	103	1899,02	0,354
Facies 3	Semi-hydromorphic Forest Facies	356	8373,08	1,562
Facies 4	Mixed Forest Facies	877	21002,28	3,918
Facies 5	Semi-closed Understory Forest Facies	2801	68084,91	12,702
Facies 6	ClosedUnderstory Forest Facies	3314	80196,75	14,962
Facies 7	Semi-open Understory Forest Facies	4829	118616,73	22,129
Facies 8	Open Understory Forest Facies	9313	229414,37	42,800
	Water Bodies	410	8422,98	1,571
	Total	22006	536016,86	100,000

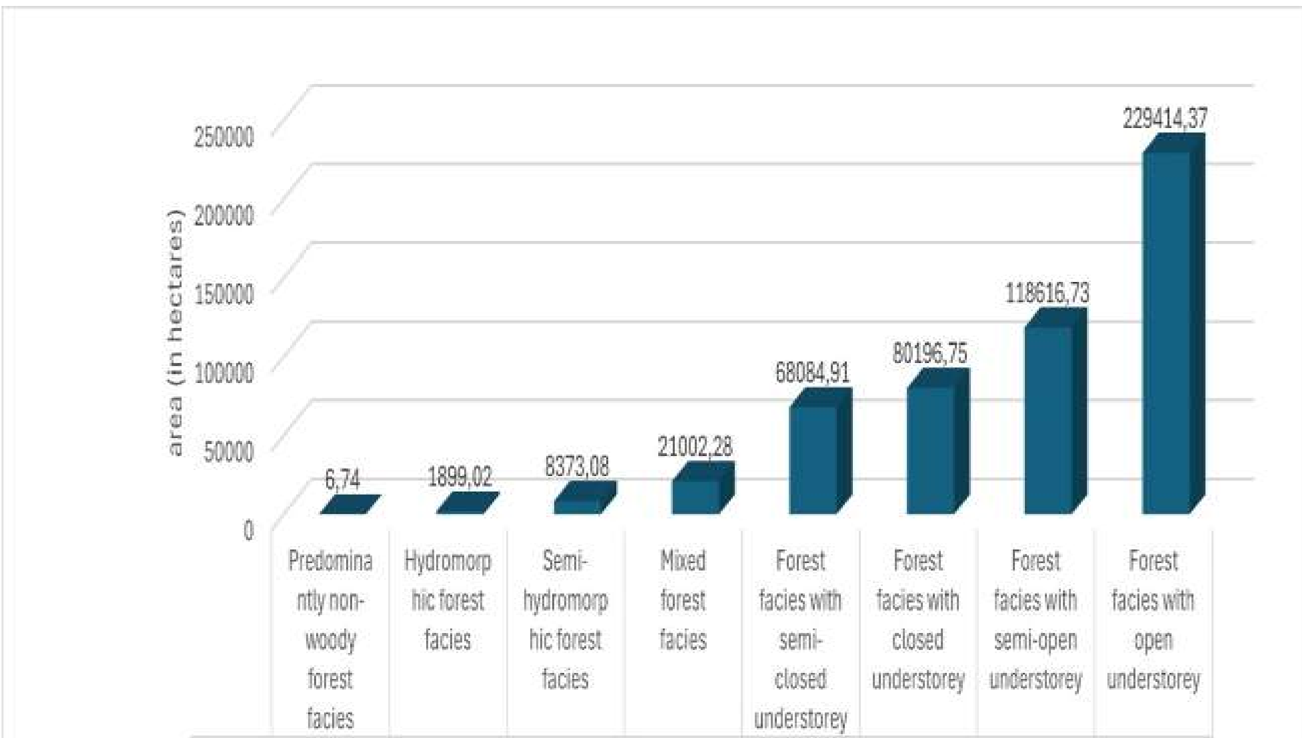

Figure 3:-Graphical representation of the areas occupied by forest facies in the TNP.

Discussion:-

Object-based image analysis for discriminating forest formations in a humid dense forest continuum.

High-resolution satellite imagery, combined with ground-based forest formation surveys, enabled the mapping of forest types within the study area. The sub-hygrophilous and hyper-humid forest types described by Guillaumet and Adjanohoun (1968) were successfully delineated by satellite classification, both in terms of spatial extent and distribution. This confirms the ability of high-resolution imagery to discriminate between these two forest typologies based on understory physiognomy—specifically, closed-understory forest for the sub-hygrophilous type and open-understory forest for the hyper-humid type.This discriminative capacity is largely attributable to the object-based classification approach. Recognized for itseffectiveness in distinguishing structurally complex forests, this method enhances mapping accuracy and facilitates the analysis of forest typologies (Selin et al., 2015;Akoguhi et al., 2022).

Moreover, the use of in situ data collected during the same period as the satellite imagery acquisition significantly improved classification performance (Marais-Sicre and al., 2017). In our study, systematically collected field data across all compartments of the study area enabled the SVM classifier to be trained with representative samples(Melgani and al. 2002). This not onlyallowed for the accurate identification of the two major forest types mentioned above, but also for the detection of additional formations—such as hydromorphic forests and thicket formations—previously noted by Guillaumet (1994), but not yet formally mapped across the park.

Contribution of spatial heterogeneity analysis to the definition of physiognomic forest facies in TNP.

In parallel, the land cover classification—analyzed through functional spatial units of 25 hectares—enabled the grouping of forest cover into distinct facies. This wasbased on both the physiognomy of the dominant forest formation and the degree of spatial heterogeneity, particularly in areas where multiple forest types co-occurred and intermingled.

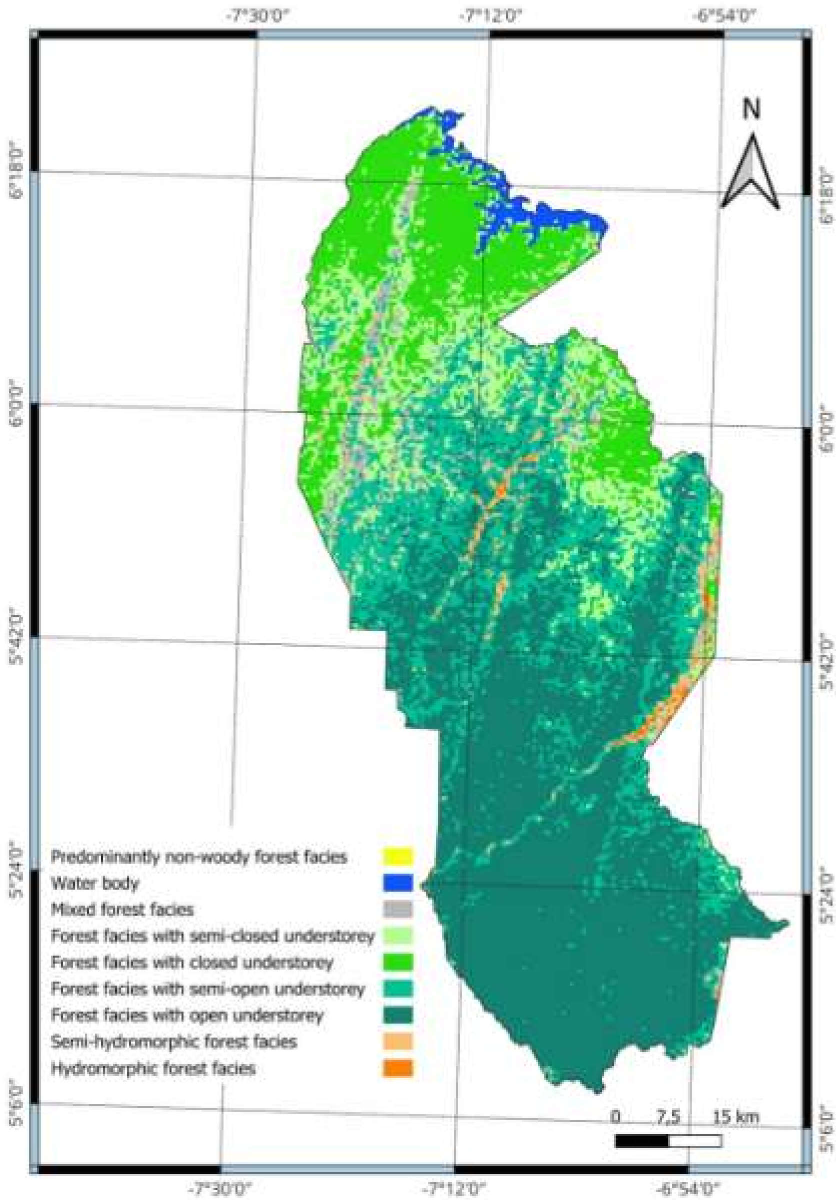

Figure 4:-Spatial distribution of physiognomic forest facies in the TNP.

Forest facies with open undergrowth are the most represented in the TNP in terms of surface area. They are located in the southern half of the protected area, as shown in Figure 4.

This approach allowed us to identify, in addition to the forest formations defined by Ngoran (2015), transitional zones where two or more forest types coexist. These areas exhibit unique physiognomic characteristics and should be distinguished from more homogeneous formations. As transitional zones, they may offer specific habitat conditions for certain faunal groups of ecological interest(Senterre, 2005).

Thus, the mapping of forest facies represents a key contribution of this study to the sustainable and science-based management of Taï National Park. It provides park managers with a consistent and spatially explicit reference framework that can support inventory campaigns, sampling strategies, and a more refined understanding of the spatial distribution of wildlife observations, as explained by studies in other countries (Laurent. 1986;Birnbaum and al., 2013).

Conclusion:-

This study demonstrates that object-based classification of high-resolution satellite imagery enables accurate mapping of forest typologies within a dense forest continuum—particularly when supported by in situ observational data describing the physiognomic characteristics of vegetation formations.

Specifically, our work successfully mapped the spatial distribution of sub-hygrophilous and hyper-humid rainforest types in Taï National Park (TNP), along with other forest units such as hydromorphic forests and thickets. These results, made possible by advanced remote sensing techniques, also owe their robustness to the detailed physiognomic descriptors used in the field—such as canopy density, understory openness, herbaceous layer condition, and the presence of hydromorphic indicator species.

The effectiveness of the proposed mapping approach also relied heavily on the quality and representativeness of field data, which strengthened the reliability of the SVM classification model. This synergy between satellite imagery and ground-based observations enabled the identification of both major and previously unmapped forest formations across the park.

Building on the forest typology mapping, the study further proposed a physiognomic facies map based on spatial heterogeneity analysis within 25-hectare functional units. This approach revealed mixed or transitional facies—zones where multiple forest types interweave—distinct from the more homogeneous, classical facies. These transitional areas may serve as specific habitats for certain faunal species of ecological interest.

Ultimately, the physiognomy-based mapping of forest facies represents a significant contribution to the sustainable management of Taï National Park. It provides a consistent spatial reference framework that can support inventory efforts, sampling strategies, and a more nuanced understanding of biodiversity distribution across the landscape.

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