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NET PRIMARY PRODUCTIVITY, VEGETATION INDEX ANALYSIS, AND ASSESSMENT OF PROTECTED AREAS, VULNERABILITIES, AND MANAGEMENT STRATEGIES: REVIEW

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Abstract

This bibliographic analysis focused on various methods for estimating net primary productivity, vegetation indices and their various applications, as well as vulnerability assessment and management strategies for protected areas. To do this, a bibliography on the different topics collected using search engines Scopus, Science Direct, ResearchGate, and Google Scholar via the Publish or Perish portal was analyzed. Of the 1128 scientific papers on the selected topic after refining the database, 978 were journal articles, 59 were books, 52 were reports, 20 were conference proceedings, and 19 were theses. These documents detail numerous methods for estimating net primary productivity, a key parameter for assessing ecosystem performance. Methods using remote sensing data, especially vegetation indices, appear to be the easiest, least costly, and least labor-intensive today, ensuring reliable results. These innovative methods are best suited for assessing fragile ecosystems. This is the case for protected areas which have been facing the combined effects of anthropogenic actions and climate change in recent years. Considering the challenges posed by the management of Togolese protected areas, particularly since the socio-political disturbances of the 1990s, it is urgent to assess the health status of these specific ecosystems, focusing on their performance.

Keywords: net primary productivity, vegetation indices, protected areas, vulnerability, management, Togo

PIERWOTNA PRODUKTYWNOŚĆ NETTO, ANALIZA WSKAŹNIKA WEGETACJI I OCENA OBSZARÓW CHRONIONYCH, PODATNOŚCI NA ZAGROŻENIA I STRATEGIE ZARZĄDZANIA: PRZEGLĄD

Abstrakt

Niniejsza analiza bibliograficzna skupia się na różnych metodach obliczania wskaźnika pierwotnej produktywności netto, wskaźników wegetacji i różnych ich zastosowaniach, a także ocenie podatności na zagrożenia i strategiach zarządzania obszarami chronionymi. W tym celu przeanalizowano bibliografię dotyczącą różnych tematów, zebraną za pomocą wyszukiwarek Scopus, Science Direct, ResearchGate i Google Scholar za pośrednictwem portalu Publish or Perish. Spośród 1128 artykułów naukowych na ten temat zachowanych po oczyszczeniu bazy danych, 978 to artykuły w czasopismach, 59 to książki, 52 to raporty, 20 to materiały konferencyjne, a 19 to prace magisterskie lub doktorskie. Dokumenty te szczegółowo opisują wiele metod szacowania pierwotnej produktywności netto, kluczowego parametru oceny wydajności ekosystemu. Metody wykorzystujące dane teledetekcyjne, w szczególności wskaźniki wegetacji, wydają się dziś najłatwiejsze, najtańsze i najmniej żmudne, gwarantujące wiarygodne wyniki. Te innowacyjne metody najlepiej nadają się do oceny wrażliwych ekosystemów. Dzieje się tak w przypadku obszarów chronionych, które w ostatnich latach stanęły w obliczu połączonych skutków działań antropogenicznych i zmian klimatycznych. Biorąc pod uwagę wyzwania, jakie stwarza zarządzanie obszarami chronionymi w Togo, zwłaszcza od czasu niepokojów społeczno-politycznych, jakie miały miejsce w latach 90. XX wieku, należy pilnie ocenić stan zdrowia tych konkretnych ekosystemów, ze szczególnym uwzględnieniem ich funkcjonowania.

Słowa kluczowe: pierwotna produktywność netto, wskaźniki wegetacji, obszary chronione, wrażliwość, zarządzanie, Togo

1. INTRODUCTION

Global ecosystems are undergoing significant upheaval due to anthropogenic activities necessary to address the challenges of a rapidly growing population [1]. This situation leads to the degradation and fragmentation of ecosystems, making their habitats vulnerable [2]. The reduction of forested areas is more pronounced in Africa due to its high vulnerability to climate change [3]. In West Africa, 1.2 million hectares of forests are destroyed each year [4, 5]. This conversion of forests into other land use units represents 0.15% of the forest area in the Congo Basin [6].

Protected areas, aimed at conserving biodiversity and the associated natural and cultural values, were initially a perfect response to attempt to curb the staggering loss of biodiversity and natural landscapes [7], while ensuring the socio-economic development of populations. At their inception, African protected areas struggled to reconcile their dual objectives of protecting biodiversity while ensuring the well-being of local populations. Some protected areas were established solely for tourism, recreational, historical, or cultural purposes, or because their sites were not intended for other uses instead of biodiversity protection [8]. According to [9, 10], the conservation objective largely dominated the delineation of these spaces in Togo, while in Cameroon [11] and Benin [12], socio-economic considerations guided decision-makers more in choosing areas to be protected. These situations have resulted in an unequal distribution of protected areas across ecosystems and territories.

In Togo, the management of these areas has caused discontent among local populations. Indeed, the failure to consider the needs and aspirations of local communities despite their strong dependence on the resources therein has led to the degradation of these once-protected ecosystems during the socio-political upheavals of the 1990s [13–15]. Sacred groves, traditional forms of protection recognized in 2008 by the IUCN as protected areas, are also heavily degraded, mainly due to the spread of monotheistic religions [16].

Following the resumption of forest administration actions, the Togolese government has embarked on a series of programs and projects aimed at rehabilitating protected areas, notably the first one called the "Rehabilitation Program for Togo's Protected Areas (PRAPT)". In this context, it is imperative to assess the ecosystems of these specific sites to evaluate their contribution to combating climate change, with a focus on biomass accumulation.

Net Primary Productivity (NPP), representing the net carbon accumulation from the atmosphere to green plants per unit of time [17], emerges as a crucial parameter for assessing the performance of these ecosystems [17]. The integration of spatial data, including vegetation indices [18–20], combined with information from ground measurements [16], has enabled the assessment of the impact of anthropogenic activities on vegetation in Togo. Folega et al. [18] assessed the health of agroecosystems in southern Togo using NPP. Exploring different approaches to evaluating net primary productivity would be a means to enrich our understanding of ecosystems, improve the quality of collected data, adapt methodologies to local specificities, and guide conservation policies. Vegetation indices play a crucial role in evaluating Net Primary Productivity (NPP) of ecosystems. They are essential tools for monitoring and assessing NPP at different spatial and temporal scales. The questions that will be addressed in this article include understanding: What are the different approaches to evaluating NPP, their advantages, and limitations? [2] What roles do vegetation indices play in understanding biological processes in ecosystems? Are the different strategies for managing protected areas suitable for biodiversity conservation and providing socio-economic services?

This study constitutes a significant contribution to the sustainable management of protected areas. It provides a comprehensive literature review on the quantification of net primary productivity, analysis of vegetation indices, vulnerability, and specific management modes for protected areas. The ultimate goal is to provide crucial information to guide decisions and actions aimed at preserving and strengthening these essential ecosystems in the current context of growing concerns for biodiversity conservation and climate change mitigation. This literature review will identify gaps in current research, thus encouraging the direction of future studies and research to fill these gaps. It provides a solid foundation for understanding ecological processes in protected areas, facilitating informed decision-making regarding the conservation and sustainable management of these crucial areas for biodiversity and ecological balance maintenance.

2. METHODOLOGY

The review of scientific knowledge on net primary productivity, vegetation indices, vulnerability, and management modes of protected areas is based on the analysis of scientific publications from 1980 to 2023. The base year of 1980 is chosen due to the emergence of spatial information in environmental management. A literature search was conducted on the Scopus (https://www.scopus.com), Science Direct (https://www.sciencedirect.com), ResearchGate, and Google Scholar search engines through the Publish or Perish portal. These databases were explored using the following keywords: net primary productivity, protected areas, climate variables, vegetation indices, vulnerability, and management methods. Some keywords (net primary productivity, protected areas, vegetation indices) were used separately. The connector "and" was used to indicate a relationship between the keywords upon which this study relies, thus yielding "protected areas & vulnerability," "protected areas & management methods," "net primary productivity & protected areas," and "net primary productivity & climate variables." The keyword "Togo" was associated with "protected areas," "vulnerability," and "protected areas & management methods" to better understand the Togolese context.

This preliminary work resulted in obtaining 3567 publications consisting of scientific articles, theses, dissertations, reports, books, conference abstracts, and posters related to the keywords used. The raw database obtained was refined, and filtering of certain works was performed. Inclusion, elimination, and exclusion criteria were applied. After filtering, all other publications (a total of 1128 over the specified period) were centralized, reviewed, and categorized according to the four (04) themes identified within the scope of this study.

These identified themes are: [1] net primary productivity, [2] vegetation indices, [3] vulnerability, and [4] management modes of protected areas. Information from each publication such as author, article title, publication year, journal, geographic origin of the publication, and other citation metric elements were exported into Excel 2019 spreadsheet from EndNote, a reference management software used to record metadata from search engines. These data were processed in a spreadsheet to highlight the proportions of topics addressed by themes, by country, and by publication year.

3. RESULTS AND DISCUSSION

3.1. Evolution of research on thematic topics

3.1.1. The temporal variation of publications

The number of publications on the themes of this study (PPN, vegetation indices, vulnerability, and management modes of protected areas) increased globally over the period 1980–2023, with some rare observable fluctuations (Figure 1). Publications on these themes remained constant until the early 2000s. In fact, 94.59% of the publications collected from various databases were published between 2000 and 2023. The improvement in spatial exploration capacity and the increasing availability of high-resolution images, accessible for free over time, explain the constant evolution of publications related to these themes. Indeed, spatial data analysis is the easiest, least expensive, and least tedious method to ensure convincing results [19]. The increase in population from the 1980s, mainly in sub-Saharan Africa, has exerted immense pressure on the coveted resources of protected areas, hence the need occurred to take stock to draw lessons from the management modes implemented.

3.1.2. Thematic variation in publications

Among the 1128 publications examined, 978 correspond to journal articles, 59 to books, 52 to reports, 20 to conference proceedings, and 19 to theses. Detailed analysis reveals that the theme centered on "Vul-

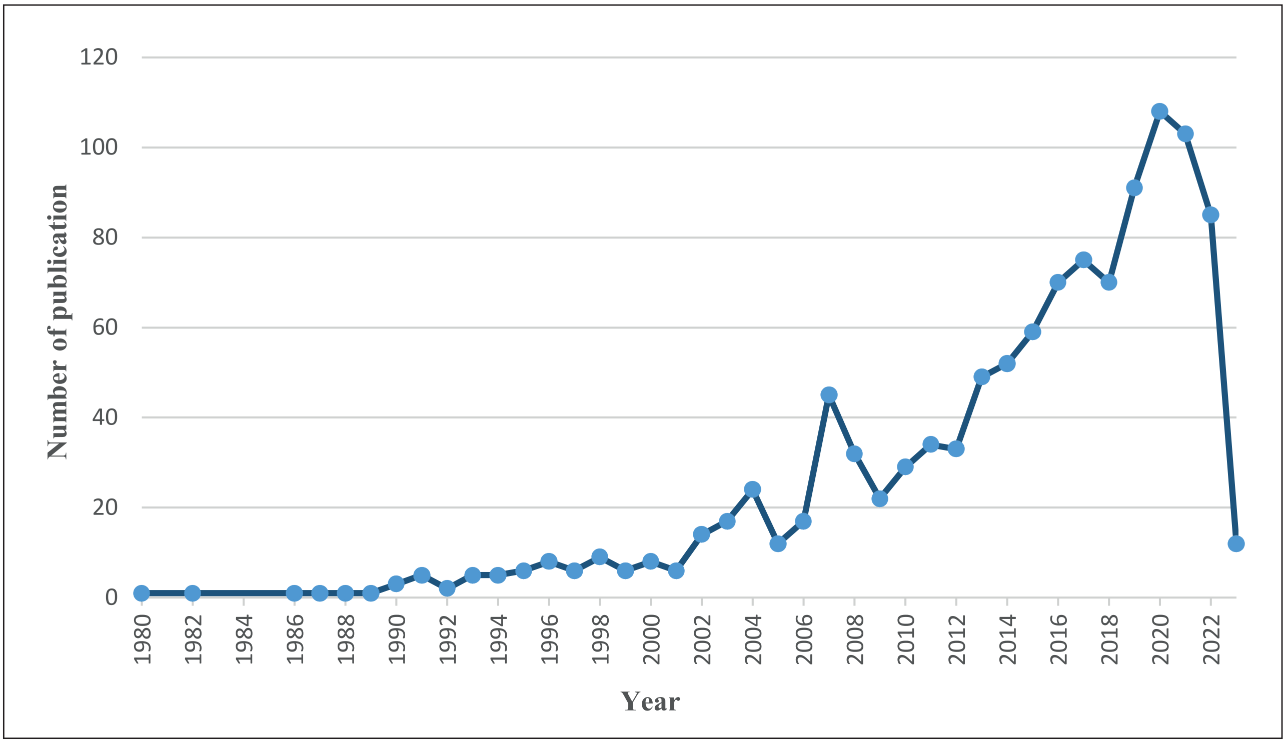

Fig. 1. Temporal variation in publications on net primary productivity, vegetation indices, vulnerability and protected area management modes

Ryc. 1. Zmienność w czasie liczby publikacji na temat produktywności pierwotnej netto, wskaźników wegetacji, podatności na zagrożenia i sposobów zarządzania obszarami chronionymi nerability and management modes of protected areas" is addressed in a total of 817 publications. In parallel, the specific themes of "Net primary productivity" and "Vegetation indices" receive particular attention, with 247 and 64 publications respectively dedicated to these subjects. This diversity of sources and focus on specific areas attest to the breadth of research conducted in these fields, emphasizing the importance placed on various facets of ecosystems, from their vulnerability to their productivity.

3.1.3. Spatial variation in publications

The 1128 publications selected for this study are distributed worldwide. Africa is the most represented continent, with 389 publications (34.48%), followed by Asia with 297 publications (26.33%), and the Americas with 166 publications (14.72%). Europe and Oceania are the least represented continents, with 121 and 22 publications respectively, accounting for 10.72% and 1.95%. It should be noted that 11.8% of the publications were either conducted globally, in multiple countries belonging to different continents, or are opinion pieces, syntheses, or reports (Figure 2).

China has seen the highest number of publications on these themes (210 publications), followed by Togo (60 publications). In Africa, Togo, followed by Madagascar (35 publications), Côte d'Ivoire (29), Benin (25 publications), and Cameroon (20 publications), are the countries with the highest number of publications (Figure 3).

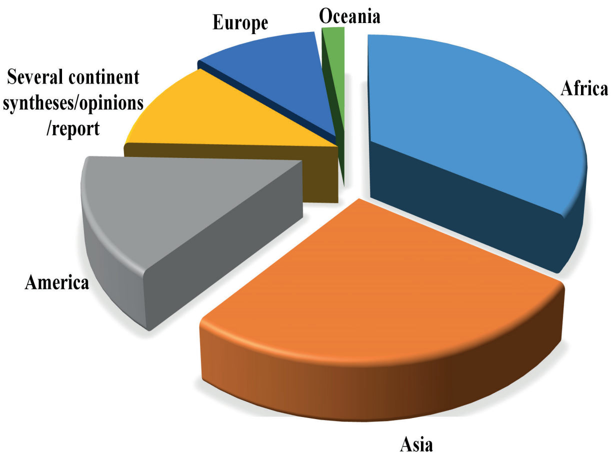

Fig. 2. Variation across continents of publications on net primary productivity, vegetation indices, vulnerability, and management modes of protected areas

Ryc. 2. Zróżnicowanie publikacji na temat produktywności pierwotnej netto, wskaźników wegetacji, podatności na zagrożenia i sposobów zarządzania obszarami chronionymi pod względem kontynentów

3.2. Net primary productivity

The primary productivity of vegetation is the quantity of organic matter synthesized from mineral elements and light energy [20]. This process is photosynthesis, a physiological process during which organic matter is synthesized [21]. Primary producers (autotrophs), the first link in a food chain in a trophic network, are the source of all the food, fibers, and fuels that enable humans to survive [22]. According to [23], carbon exchanges between the terrestrial biosphere and the atmosphere are influenced by solar radiation and the local environment. Net primary productivity (NPP), along with gross primary productivity (GPP), constitutes the primary productivity of vegetation. The latter corresponds to the total amount of assimilated energy (amount of carbon dioxide (CO_2) fixed) by autotrophs during photosynthesis, while net primary productivity is the amount of energy accumulated in plant biomass (growth and reproduction) Gonsamo and Chen [24]. NPP is thus the net production of organic matter in the ecosystem per unit area and time; therefore, it represents GPP minus carbon losses resulting from autotroph respiration. A very important parameter of vegetation, net primary productivity (NPP) is an ecological index that can reflect changes in the ecological environment and the level of vegetation carbon [25]. According to Sun, Yang [26], NPP estimation is generally done through field measurements and simulation models.

3.2.1. Field measurements

NPP estimation through measurements integrates several methodologies. It begins with inventories to estimate the annual variation in aboveground and belowground biomass [27]. Evaluating the variations in volumes and biomasses is not easy because it is difficult to measure the biomass of different parts of the tree and stand [28]. Methods of biomass measurement vary according to species phenology. Aboveground NPP corresponds to the maximum aboveground biomass over one year for herbaceous plants [29]. It is determined using allometric equations for trees. Equations developed by [30] are the most commonly used in calculating aboveground biomass in several studies [2, 31–34].

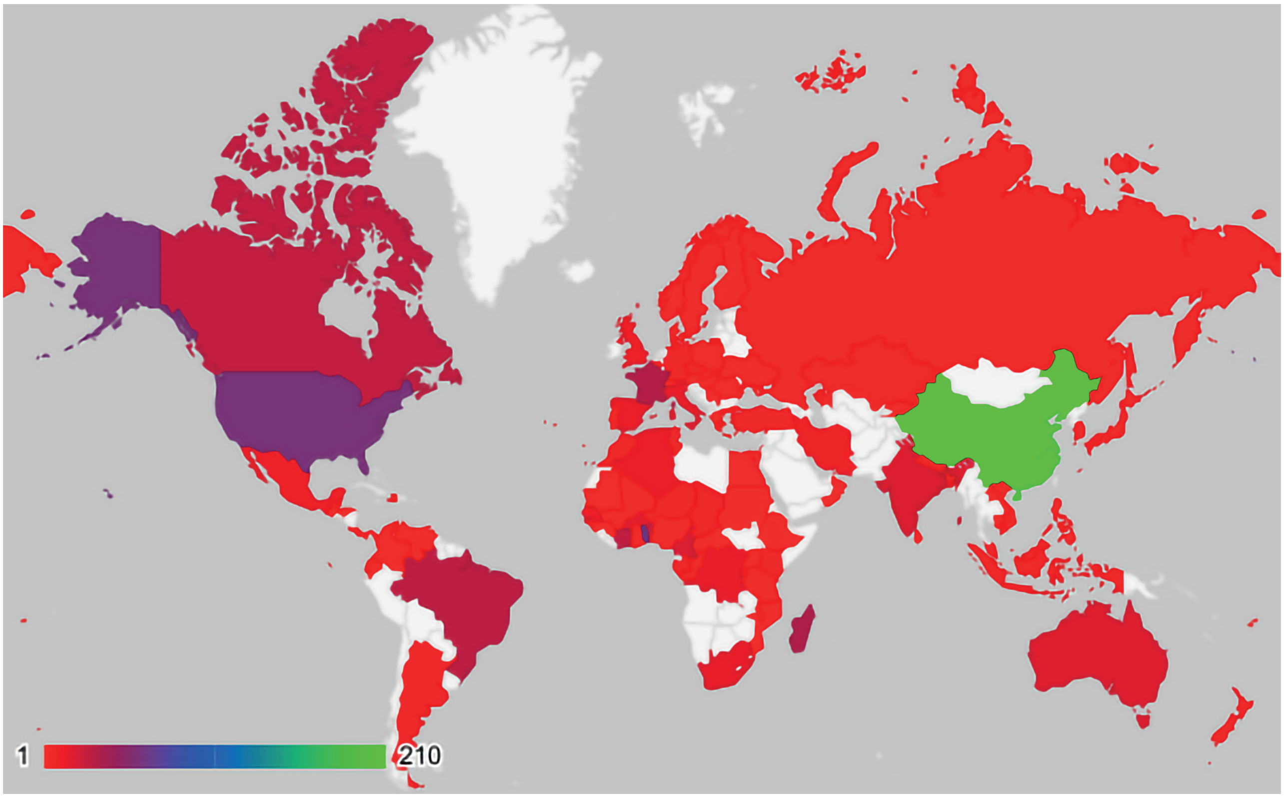

Fig. 3. Variation of publications according to countries on net primary productivity, vegetation indices, vulnerability, and management modes of protected areas
Ryc. 3. Zróżnicowanie publikacji według krajów na temat produktywności pierwotnej netto, wskaźników wegetacji, podatności na zagrożenia i sposobów zarządzania obszarami chronionymi

Age and growth parameters are factors that influence NPP [35]. Belowground biomass is assessed from aboveground biomass and according to the model developed by [36] or by measurements involving complete digging. Regarding measurements, three methods estimate belowground NPP through measuring belowground biomass: direct measurement to assess changes in biomass of living roots and losses due to decomposition and animal browsing, calculating the difference between maximum and minimum root biomass during the study period, and using both belowground root biomass and root turnover fraction to estimate belowground NPP, the most commonly used method [37].

3.2.2. Simulation models

Gonsamo and Chen (26) identified three categories of methods to estimate vegetation primary productivity through remote sensing. Empirical models based on a statistical relationship between remotely sensed environmental variables and measured primary productivity values; models based on light use efficiency (LUE) which estimate vegetation primary productivity using incident photosynthetically active radiation (PAR) by a remotely sensed fraction of PAR absorbed by vegetation (fAPAR) and a conversion factor of energy into biomass generally called LUE coefficient; and enzymatic kinetic models (EK) which estimate vegetation primary productivity by following enzymatic kinetics at the leaf scale [38, 39].

3.2.2.1. Empirical models

Two main models are encountered:

- The Photochemical Reflectance Index developed by [40] is used as an indicator of photosynthetic efficiency,
- Solar-induced chlorophyll fluorescence developed by [41] is based on the analysis of chlorophyll fluorescence for estimating NPP.

The drawback of simple empirical models for estimating NPP is that these approaches lack mechanisms that would allow extrapolation over time.

3.2.2.2. Light use efficiency models

Satellite data, since their appearance in the late 1970s, have allowed monitoring ecosystem behavior over time [23]. Models based on Light Use Efficiency (LUE) are most commonly used to estimate NPP [42–45]. According to (48), LUE models are based on two assumptions: (1) terrestrial ecosystem NPP is directly related to APAR through LUE, reflecting the amount of CO_2 fixed per unit APAR, and (2) LUE can be reduced below its theoretical potential value by environmental constraints such as temperature or water stress [47,48]. LUE-based models have been used in estimating and assessing the variability of net primary productivity in a humid tropical forest in Malaysia [49], and in quantifying and comparing LUE coefficient variation across years and environmental conditions [50]. Table 1 summarizes these models.

The main models are:

The Carnegie-Ames-Stanford approach model

Designed by [51], this model is one of the earliest LUE-based models used to estimate NPP. It combines satellite data, monthly temperatures, precipitation, soil attributes, and potential LUE independent of biome, with a value of 0.389g C-2 MJ-1 APAR when estimating global terrestrial NPP [52]. This model enabled the estimation of NPP in the Atakora chain in Togo using vegetation indices (NDVI and SR) (19). One advantage of this model is that the potential LUE value is empirically calculated due to environmental constraints [23]. It is influenced by FPAR, temperature, actual and potential evapotranspiration.

The global production efficiency model

The Global Production Efficiency Model (GLO-PEM) estimates NPP based on the concept of production efficiency, developed by [53]. A second-generation model (GLO-PEM2) was developed to simulate vegetation primary productivity using a series of algorithms entirely based on remote sensing measurements. The improved version of GLO-PEM2 (56) has an enhanced surface temperature retrieval algorithm, autotrophic respiration, and a moisture measurement method. This model simulates both GPP and NPP by extracting APAR directly from satellite data as well as environmental variables that influence APAR utilization [52]. This model has been used to study the characteristics and changes of NPP in Chongqing, China [55]. Its advantage is that it does not use any observed climate variables on the ground except for distinguishing between C3 and C4 plants. Climate variables are all derived from satellite observations. Although based on remote sensing, this model is not an efficiency production model because production is not linearly linked to canopy APAR through light use efficiency.

The terrestrial uptake and release of carbon model

This model calculates GPP based on actual LUE (Light Use Efficiency), assuming a constant LUE for all ecosystem types. The drawback of this model is its use of a constant value for all ecosystems.

The physiological principles in predicting growth model

The Physiological Principles for Predicting Growth (3-PG) model calculates NPP (Net Primary Productivity) from APAR (Absorbed Photosynthetically Active Radiation) and LUE, considering the effects of temperature, soil moisture deficit, atmospheric vapor pressure deficits, soil fertility, carbon, and stand age. A spatial version of 3-PG is based on spatially derived climatology from soil studies and vegetation fPAR (Fraction of Photosynthetically Active Radiation) estimates from remote sensing [52]. The 3-PG model was explicitly designed to bridge the gap between forest growth models based on complex processes and empirical growth and yield models familiar to forest managers. A spatial version of 3-PG is based on empirical growth and yield models derived from climatic space, soil studies, and remote sensing observations [56]. The 3-PG model (Physiological Principles for Predicting Growth) has yielded different results in fragmented landscapes depending on the spatial resolution of remote sensing data [57].

The MODIS GPP (MOD17) model

The Moderate Resolution Imaging Spectroradiometer (MODIS) GPP (MOD17) product is the most widely used operational product worldwide. The GPP product, which utilizes remote sensing data, is developed based on LUE principles with MODIS LAI/fPAR climatological data (MOD15A2), land cover, and biome-specific climatological data from NASA's Goddard Space Flight Center [46]. NPP is calculated using meteorological observation data and computed from the MODIS NPP algorithm using daily mean temperature, daily minimum temperature, actual vapor pressure (derived from specific humidity), and incident shortwave solar radiation [46]. Abd Wahid Rasib, Ab. Latif Ibrahim [49], using this data, estimated NPP of tropical rainforests in Malaysia through Micrometeorological approach following Monteith's equations.

The vegetation photosynthesis model

The Vegetation Photosynthesis Model (VPM) divides leaf and canopy into active photosynthetic vegetation (APV) and non-photosynthetic active vegetation (NPV) [58–60]. Forest GPP is affected by the fPAR of active photosynthetic vegetation [59].

The C-Fix model

This model exploits the relationship between absorbed active photosynthetic radiation by vegetation cover and productivity. Its original version, proposed in 1994, has been applied in Europe and enhanced through the use of richer ancillary information and more effective techniques for processing NDVI (Normalized Difference Vegetation Index) data [61].

The eddy covariance-light use efficiency model

The eddy covariance-light use efficiency model estimates GPP from LUE, accounting for constraints imposed by temperature and humidity. Eddy covariance measurements allow estimation of GPP and development of LUE models. Simultaneous measurements of meteorological variables such as temperature and vapor pressure, as well as water balance variables including evapotranspiration and soil water status, provide datasets to study the dynamics and driving variables of NPP.

Light use efficiency from Photochemical reflectance index and SIF Solar-induced fluorescence observations

Light use efficiency (LUE) is closely related to biochemical processes involved in plant tissue's photoprotective response to excessive radiation when more solar radiation is absorbed than available for photosynthesis. Therefore, observation of Photochemical Reflectance Index (PRI) and Solar-induced Fluorescence (SIF) provides the most direct measurements of biochemical processes involved in photoprotective reactions and hence LUE. One such process is non-photochemical quenching, controlled by the xanthophyll cycle, involving reversible deep oxidation of violaxanthin pigment into zeaxanthin via antheraxanthin 62]. The xanthophyll cycle can be monitored using PRI, representing the relative decrease in LUE mainly caused by high light intensity.

3.2.2.3. Enzymatic kinetic models

Vegetation primary productivity models based on processes vary considerably in their intended application, complexity, and representation of physical, chemical, and biological processes to estimate NPP and GPP. Enzymatic kinetic (EK) models, unlike light use efficiency or empirical models, represent leaf-scale enzymatic kinetics with simulated electron transport and product limitations on simulated NPP and GPP. Almost all EK models include a representation of stomatal conductance balancing photosynthesis and water loss through leaf stomata [63–65]. There is a wide diversity of EK models, both in terms of model structure and formulation complexity and the types of simulated Carbon components. Some models with well-defined processes for water, carbon, and soil nutrient dynamics can simulate net carbon flux between terrestrial biosphere and atmosphere, while simpler models are designed to simulate vegetation primary productivity only. Therefore, each EK model is a complex combination of assumptions and scientific choices, and their estimates depend on these inherent assumptions. Some EK models are empirical or statistics-based, with relatively simple relationships between driving variables and fluxes; others are more complex, simulating coupled carbon, nutrient, and water cycles in terrestrial areas, and still others are more intricate.

3.3. Vegetation indices

In remote sensing, vegetation indices are part of a processing method called multispectral transformation. This involves converting the radiation density measured by satellite sensors into significant quan-

Table 1. Summary of NPP calculation approaches for light use efficiency models listed in subsection from [24]

Tabela 1. Podsumowanie podejść do obliczania produktywności pierwotnej netto (NPP) dla modeli wydajności wykorzystania światła w [24]

Model	NPP as f(GPP, R_a)	Total Ra	Ra[a] Rm	Ra[a] Rg	References
CASA (original)	0.5 · GPP				[51]
CASA (new)	0.5 · GPP				[66]
GLO-PEM	*GPP · Ym · Yg*	$\boldsymbol{Rm + Rg = GPP \cdot (1 - Ym \cdot Yg)}$	$\boldsymbol{fYm(0<Ym<1) = 1 - \frac{0.4}{0.75}\left(\frac{1000W}{1000W+50}\right)}$ where W is the viable above-ground biomass ($W=716.61Redmin^{-2.6}$) and Redmin is the minimum reflectance of red spectral band of AVHRR	$f_{Yg}(0<Yg<1) =$ 0,75	[67]
GLO-PEM2	*GPP – Ra*	W is the viable above-ground biomass W = $\boldsymbol{716.61Redmin^{-2,6}}$ Redmin is the minimum reflectance of red spectral band of AVHRR, Tc is the annual average temperature, and T is the air temperature			[54]
TURC	*GPP – Ra*		$\boldsymbol{M \cdot (1 + 0.16 \cdot T)}$ where M is maintenance respiration at 0C temperature (T)	$\boldsymbol{0.28 \cdot (GPP - Rm)}$	[68]
3-PG	0.47 · GPP				[48]
MOD17	***GPP – Ra***	***Rm + Rg***	$\boldsymbol{(LM \cdot LMB \cdot (3.22 - 0.046 \cdot T)^{\left(\frac{T-20}{10}\right)} + (FM \cdot FMB \cdot (3.22 - 0.046 \cdot T)^{\left(\frac{T-20}{10}\right)}}$ where T is temperature, LM and FM are leaf and fine root masses, respectively, and LMB and FMB are leaf and fine root base respiration rates, respectively 20°C	**0.25 · NPP**	[46,69]
VPM	**0.47 · GPP**				[58–60]
C-Fix	$\boldsymbol{GPP \cdot (1 - Ad)}$	**GPP · Ad** where $\boldsymbol{Ad = (7.825 - 1.14 \cdot T)/100}$			[70]
EC-LUE					[52]

[a] $\mathbf{R_a}$ is autotrophic respiration, R_m is maintenance respiration, and R_g is growth respiration

tities in the environmental domain. Remote sensing techniques, models, and indices aim to convert spectral information into an easily usable format: establishing a close relationship between radiometric response and vegetation cover [71]. According to [72], a vegetation index is a quantitative measure indicating the vigor of vegetation. To date, more than forty vegetation indices have been developed. The principle is to relate certain vegetation properties (such as water content, evapotranspiration, etc.) recorded in two or more spectral bands of the sensor to radiometric measurements (reflectance values). The calculation of the index essentially relies on differences in reflectance observed in different spectral bands and on the variation in reflectance levels within the same spectral band reflecting surfaces of different natures. Differences in optical properties of plants are primarily exploited. Near-infrared reflectance increases with vegetation presence, while red reflectance decreases. Table 2 lists the most encountered indices.

Table 2. Vegetation indices from remote sensing
Tabela 2. Wskaźniki wegetacji z teledetekcji

Indices	Formulas	Authors
NDVI	$NDVI = \frac{(NIR - Rouge)}{(NIR + Rouge)}$	[87,88]
GNDVI	$GNDVI = \frac{(NIR - Vet)}{(NIR + Vet)}$	[77]
EVI	$EVI = G \cdot \left(\frac{(NIR - R)}{(NIR + C1 \cdot R - C2 \cdot B + L)}\right)$ G – gain factor (2.5); L – soil adjustment factor C1 and C2 – atmospheric diffusion correction coefficients	[81]
AVI	$AVI = [NIR \cdot (1 - Rouge) \cdot (NIR - Rouge]^{\frac{1}{3}}$	
SAVI	$SAVI = \left(\frac{(NIR - R)}{(NIR + R + L)}\right)C(1 + L)$ L – constant equal to 0.5	[89]
NDMI	$NDMI = \frac{(NIR - SWIR)}{(NIR + SWIR)}$	
MSI	$MSI = \frac{\text{MidlR}}{NIR}$	[78]
GCI	$GCI = \frac{\text{NIR}}{Green - 1}$	
NBRI	$NBRI = \frac{(NIR - SWIR)}{(NIR + SWIR)}$	
BSI	$BSI = \frac{(Red + SWIR) - (NIR + Blue)}{((Red + SWIR) + (NIR + Blue)}$	
NDWI	$NDWI = \frac{(NIR - SWIR)}{(NIR + SWIR)}$	[90]
NDSI	$NDSI = \frac{(Green - SWIR)}{(Green + SWIR)}$	

NDGI	$\boldsymbol{NDGI = \frac{(NIR - Green)}{(NIR + Green)}}$	
ARVI	$\boldsymbol{ARVI = \frac{(NIR - (2 \cdot Red) + Blue)}{(NIR + (2 \cdot Red) + Blue)}}$	[84]
SIPI	$\boldsymbol{SIPI = \frac{(NIR - Blue)}{(NIR - Red)}}$	
DVI	$\boldsymbol{DVI} = \text{NIR} - \text{Red}$	[73]
RVI	$\boldsymbol{RVI = \frac{NIR}{Red}}$	[74,75]
PVI	$\boldsymbol{PVI} = \frac{SWIR}{NIR}$	[80]
GEMI	$\text{GEMI} = \frac{\eta \cdot (1 - 0.25\eta) - (\text{Red} - 0.25)}{NIR} + Red + 0.25$ $\eta = \frac{2 \cdot (\text{NIR}^2 - \text{Red}^2) + 1.5 \cdot \text{NIR} + 0.5 \cdot \text{Red}}{NIR + Red + 0.5}$	[85]
TSAVI	$\boldsymbol{TSAVI} = \frac{\alpha \cdot (NIR - \alpha \cdot Red - b)}{Red + NIR - ab + 0.08 \cdot (1 + \alpha^2)}$ $\boldsymbol{L} = 1 - 2 \cdot \alpha \cdot \text{NDVI} \cdot \text{WDVI}, \text{WDVI} = \text{NIR} - \alpha \cdot \text{Red}$	[91]
MSAVI	$\boldsymbol{MSAVI} = \left(\frac{(NIR - Rouge)}{NIR + Rouge + L}\right) \cdot (1 + L)$	[83]
TDVI	$\boldsymbol{TDVI} = \frac{(Ts = TsI(\text{min}))}{(a + b \cdot NDVI - Ts(\text{min}))}$ Ts – surface temperature, Ts(min) – minimum surface temperature, a and b respectively y-intercept and slope of the line linking surface temperature to maximum NDVI	[86]

3.3.1. Simple indices

The simplest vegetation indices are based on arithmetic operations between two spectral bands (usually red and near-infrared, but also near-infrared and mid-infrared). The most encountered ones are:

- Difference Vegetation Index (DVI) developed by [73], which corresponds to a simple difference between near-infrared and red bands.
- Ratio Vegetation Index (RVI). This index corresponds to the ratio between NIR and the red band [74,75]. RVI values for bare soil are generally close to 1 and increase as the amount of green vegetation increases. RVI values go up to 30.
- These two indices, simple unbounded ratios, are known to be highly sensitive to atmospheric variations and soil spectral effects. The value of RVI saturates when vegetation is very dense as the red band reflectance becomes very low.
- Normalized Difference Vegetation Index (NDVI) developed by [76], unlike the previous two, has a value ranging from –1 to 1, with negative values corresponding to snow, water, clouds, etc., values close to zero for bare soils, and positive values for vegetation formations with values close to 1 for dense vegetation. Pre-processing must be done to reduce the effects of clouds, sensor degradation, sensor viewing angle, sun position, and atmospheric effects during scientific work. This index remains very useful in studies on seasonal vegetation dynamics. It is widely used in estimating net primary productivity, particularly through Light Use Efficiency Models [19].

- Green Normalized Difference Vegetation Index (GNDVI), a modified version of NDVI to be more sensitive to variations in vegetation chlorophyll content. This index is more relevant than NDVI when it comes to identifying chlorophyll concentration rates (79).
- Advanced Vegetation Index (AVI). This is a numerical indicator, similar to NDVI, which uses red and near-infrared spectral bands. It is used to monitor vegetation variations over time. Combining AVI and NDVI helps discriminate different vegetation types and extract features such as phenological parameters.
- Greenness Chlorophyll Index (GCI). This index is used to estimate the chlorophyll content of leaves of various plant species. Since chlorophyll content reflects the physiological state of vegetation, it decreases in stressed plants and can thus be used as a measure of plant health.
- Water stress indices are also simple indices that use mid-infrared spectral bands instead of red bands. These indices depend on leaf moisture content. They can detect plant water stress, making them very useful for monitoring vegetation in arid regions. The most used ones are:
- Moisture Stress Index (MSI) developed by [78]. It is used to analyze forest cover stress, productivity forecasting, and biophysical modeling. Its interpretation is reversed compared to other aquatic vegetation indices; higher index values indicate greater plant water stress and therefore lower soil moisture content. Index values range from 0 to over 3.
- Normalized Difference Water Index (NDWI) developed by [79]. It is used for water body analysis. The index can effectively enhance water information. It is sensitive to built-up areas and leads to overestimation of water bodies. NDWI can be used with NDVI to assess the context of apparent change areas.
- Normalized Difference Moisture Index (NDMI). This index is used to determine vegetation water content. It is calculated as a ratio between NIR and SWIR values.
- Bare Soil Index (BSI). This is a numerical indicator that combines blue, red, near-infrared, and shortwave infrared spectral bands to capture soil variations. Shortwave and red spectral bands are used to quantify soil mineral composition, while blue and near-infrared spectral bands are used to enhance vegetation presence.
- Structure-Insensitive Pigment Index (SIPI). This is the ideal index for analyzing variable canopy structure vegetation. It estimates the carotenoid/chlorophyll ratio.

3.3.2. Indices considering soil influence

These indices were proposed to correct or reduce the influence of soil under vegetation cover on signals measured by satellite sensors.

- Perpendicular Vegetation Index (PVI) by [80] assumes that the vertical distance is linearly related to vegetation cover. This creates vegetation cover of the same density parallel to the ground line, which does not correspond to reality as SAVI has shown that the slope of the vegetation line increases with increasing vegetation biomass.
- Soil Adjusted Vegetation Index (SAVI) developed by [81]. It introduces an adjustment parameter, denoted as L, which characterizes the soil and its vegetation cover. Its developer has shown that vegetation isolines are not parallel to the ground line, but intersect at points depending on the density of the vegetation cover. The parameter L takes the value of 0.25 when vegetation density is high and 1 when vegetation density is very low, and 0.5 for medium density. It is used to correct the vegetation index by normalized difference for the influence of soil brightness in areas where vegetation cover is low.
- Transformed Soil Adjusted Vegetation Index (TSAVI) by [82]. It relies on a prior determination of the ground line from the sensor's spectral bands. The slope (a) and the intercept (b) of the line are used instead of arbitrary values defined in the SAVI index.
- Modified Soil Adaptation Vegetation Index (MSAVI) proposed by [83]. This model is also an improvement of SAVI. In MSAVI, the parameter L is no longer constant and is automatically adjusted to local conditions. The formula for MSAVI indices is the same as for SAVI indices. The difference lies in the factor L, which depends on both the surface line, NDVI, and the weighted differential vegetation index (abbreviated as weighted differ-

ential vegetation index). WDVI – [80] (distinction between basic vegetation and soil information).

3.3.3. Indices considering the combined effects of the atmosphere

The atmosphere influences electromagnetic radiation through scattering processes and needs to be corrected for.

- Atmospherically Resistant Vegetation Index (ARVI) developed by [84]. This index is the first vegetation index relatively sensitive to atmospheric factors (such as aerosols). It corrects NDVI for atmospheric scattering effects in the red reflectance spectrum using measurements in the blue wavelengths.
- Global Environmental Monitoring Index (GEMI) proposed by [85]. It is similar to NDVI but less sensitive to atmospheric effects.

3.3.4. Indices considering the combined effects of soil and atmosphere

- Enhanced Vegetation Index (EVI) developed by [81]. Similar to NDVI, it is used to quantify vegetation greenness. This index corrects for certain atmospheric conditions and canopy background noise. It is more significant in densely vegetated areas. It is obtained by combining SAVI and ARVI.

3.3.5. Indices accounting for surface temperature

- Temperature, Vegetation and Dryness Index (TDVI) developed by [86].
- Normalized Burn Ratio Index (NBRI). Forest fires are a serious phenomenon of both human and natural origin that destroy natural resources, livestock, disrupt ecosystems, and release vast amounts of greenhouse gases. This index is based on near-infrared and shortwave infrared spectral bands that are sensitive to changing vegetation to detect burned areas and monitor ecosystem recovery.
- Normalized Difference Snow Index (NDSI), a numerical indicator showing snow cover on land surfaces. Green and shortwave infrared (SWIR) spectral bands are used to map snow cover. Since snow absorbs most of the incident radiation in the SWIR unlike clouds, this allows NDSI to distinguish snow from clouds. This index is used for mapping snow cover, ice, and in glacier monitoring.
- Normalized Difference Glacier Index (NDGI), used to aid in detecting and monitoring glaciers using green and red spectral bands. This index is applied in glacier detection and monitoring.

3.4. Protected areas: vulnerability and management approaches

3.4.1. Historical background of protected areas

Serving as the backbone of all biodiversity conservation strategies, natural resource preservation, and ecosystem functioning [92], the concept of protected areas has evolved over time to encompass a broader variety of zones, including marine reserves, biosphere reserves, national parks, conservation areas, and other dedicated spaces for nature preservation. While the history of protected areas dates back several centuries, the concept of contemporary protected areas has evolved over the past few decades. The earliest practices of nature preservation trace back to antiquity, where some societies already placed special importance on preserving certain areas for religious, cultural, or practical reasons. Several European nations established royal parks and hunting reserves during the Middle Ages and Renaissance to protect wildlife and flora for the aristocracy.

The notion of modern national parks developed in the 19th century. Yellowstone National Park, established in the United States in 1872, is often considered the world's first national park. The creation of Banff National Park in Canada followed in 1885. Many countries established protected areas during the 20th century to preserve biodiversity, protect fragile ecosystems, and provide recreational spaces. Globally, international organizations such as the International Union for Conservation of Nature (IUCN) [93] have played a significant role in promoting conservation. The United Nations Educational, Scientific and Cultural Organization's (UNESCO) Man and the Biosphere Programme (MAB) was introduced in 1971. This concept of biosphere reserves combines biodiversity conservation, sustainable development, and scientific research. Subsequently, the Convention on Biological Diversity (CBD) was adopted at the Rio Earth Summit in 1992, emphasizing the importance of protected areas in biodiversity preservation. The CBD also established goals to increase global coverage of protected areas. The Aichi Biodiversity Targets, adopted by the Conference of the Parties to the

CBD in 2010, aimed to substantially increase the global network of protected areas by 2020. The history of protected areas is characterized by increasing global commitment to biodiversity conservation, resource sustainability, and forest mass diversity. The United Nations List of Protected Areas, born out of Economic and Social Council resolutions 713 and 810 respectively adopted in 1959 and 1962, is evidence of the importance the United Nations places on protected areas in conserving biological diversity [94]. All discussions on the post-2020 global biodiversity framework aim to establish new goals for biodiversity conservation, including those related to protected areas.

3.4.2. Protected areas in Togo

3.4.2.1. Establishment of protected areas

the establishment of protected areas became a focal point for the colonial powers of French West Africa with the creation of 15 such sites materialized in 1926 [9]. Networks of protected areas emerged in the colonies to better conserve biodiversity. In Togo, the advent of the circular from the General Governor on February 1, 1933, where he outlined his plan for creating wooded areas under state control to reduce deforestation [95], led, as early as 1938, to the regulation of hunting with the promulgation of a forestry code [10]. This was followed by the establishment between 1937 and 1958 of eighty-three sites (ranging from a few hectares to tens of thousands of hectares) covering approximately 14% of the country's land area, as the Togo National Network of Protected Areas [96].

3.4.2.2. Policy for the management of the Togo national system of protected areas

From 1968, with the aim of improving the management of these genetic reserves, centralized management was established with the prohibition of hunting (except for small game with special permission) as well as the possession of firearms. This new policy subsequently resulted in the enlargement and transformation into national parks of three protected areas. The establishment in 1977 of June 1st of each year as the day when every Togolese citizen must plant a tree is among the actions taken by the forestry administration for the protection of the country's forest massif. Unfortunately, the impact of these actions on the socio-economic situation of the populations was not to their liking. The relocation of displaced persons caused by the creation of protected areas, loss of hunting areas, fishing bans, inaccessibility of livestock to lowland pastures and water points, and the absence of new deforestation despite population growth are some of the problems faced by the populations [10]. Meanwhile, initial assessments of protected area management indicated the fragility of ecosystems, including animal overpopulation that would venture out of reserves and invade and destroy the fields and crops of local residents, as well as the proliferation of diseases caused by sick animals [10,97,98]. The socio-political turmoil of the 1990s facilitated the invasion and partial or total degradation of certain protected areas in Togo. To attempt to secure some sites, forest plantations were established by the Office of Forest Development and Exploitation (ODEF). According to [99], 27% of classified forests have been completely occupied either by local populations or by forest plantations, while 55% are partially occupied by human and physical occupation, with only 18% retaining their full extent.

Starting in 1999, with the return of the forestry administration, a process of rehabilitation of protected areas was initiated with a series of accompanying measures, the first of which was the Togo Protected Areas Rehabilitation Program (PRAPT), aiming at the restoration and securing of 578,245.741 hectares, or 10.21% of the territory, in the perspective of sustainable development. Decree No. 2003–237/PR of September 26, 2003, which established a standardized framework for the management of protected areas, with partial demarcation of certain protected areas (Oti Kéran, Fosse aux Lions, Oti Mandouri), the reclassification of six protected areas: Doungh, Bayémé, Amou Mono, Togodo Sud, and Galangachi respectively, and Order No. 005/MERF/CAB/SG/DFC of May 21, 2004, prescribing protocols for the reorganization of protected areas.

3.4.2.3. Vulnerability of Togo's protected areas

The invasion of protected areas observed from the early 1990s with the exploitation of resources, the establishment of villages, and cultivation within them has led to drastic loss of biodiversity in these sites [13]. Various studies conducted within protected areas have identified a plethora of anthropogenic pressures with drastic consequences. These parameters endanger their survival, ranging from illegal logging, shifting cultivation, poaching, vegetation fires, illegal fishing, to trans-

Table 3. State of the art of PA conservation
Tabela 3. Stan wiedzy na temat ochrony obszarów chronionych

Protected Areas Classes	Conservation status	Number of PAs concerned	Area (ha)
Class I	Converted areas (complete occupation, irreversible degradation of natural vegetation, exploited plantations	18	20034,52
Class II	Areas essentially comprising highly secondary and degraded vegetation formations, urbanized and non-restorable.	6	1959,34
Class III	Areas partly occupied by productive artificial woodlands, with the remaining portion consisting of highly degraded and difficult-to-restore natural vegetation formations.	8	15688
Class IV	Mixed areas composed of natural and artificial vegetation formations with high regeneration potential, which may justify restoration and conservation actions (if a conservation vocation is chosen) or be allocated for forestry production.	48	755451,95
Class V	Forest fetish	2	155

humance and the effects of climate change. The absence of management and development plans for most of these protected areas, the effects of climate change, invasive species, habitat fragmentation, and urbanization represent the threats facing Togo's protected areas today. According to the typology established by the Togo Ministry of Environment and Forest Resources under the COM-STABEX 91–94 project, funded by the European Union, five classes of protected areas stand out based on their conservation status (Table 3). Protected areas from the first three classes have been used for reforestation and forestry development by ODEF, while the last two classes, included in classes IV and V, have been declared priorities due to their significant forest potential.

a. Illegal Exploitation of Timber in Protected Areas

Protected areas suffering from management and surveillance issues are facing illegal logging. Timber exploitation by the local populations within protected areas represents a major cause of degradation [100]. The timber exploitation and trade sector represent a key sector of national economies in countries such as Cameroon, Gabon, and Equatorial Guinea [101]. This activity is the third cause of degradation in the Pama reserve in Burkina Faso, following drought and bushfires [102]. Sebabe [103] identified logging as a factor in deforestation, exacerbated by the establishment of agricultural production plots. Populations often selectively choose timber species with high commercial value [104]. Endemic species with high economic value are not spared, such as mangroves and rosewood (*Aniba rosaeodora*) in Madagascar, where organic laws have been enacted to combat this trafficking [105]. In Togo, illegal exploitation of certain timber species led the government to impose a 10-year moratorium on the exploitation of *Ptérocarpus erinaceus* in 2016, a species whose illegal exploitation threatened its existence [106,107]. This species is subject to trafficking in Côte d'Ivoire [108], an activity that has intensified with socio-political-military crises. Areas of abusive exploitation of forest resources are often located near residential areas, as is the case with the Banco Forest near Abidjan in Côte d'Ivoire [109]. Numerous studies within several protected areas [16,32,110,111] have concluded that small-diameter trees are predominant, evidence of increased exploitation of forest resources. The law in several countries prohibits any form of exploitation of resources within protected areas, but these legal provisions are often not respected, as is the case in Gabon where forest exploitation concessions within protected areas have led to the degradation of several sites [112].

b. Poaching and Illegal Fishing

The fauna of protected areas has faced enormous pressure from local populations. Poaching for consumption and sale, as well as illegal fishing with the poisoning of watercourses by some fishermen, are observed actions in the Oti-Kéran-Mandouri National Park in Togo [113]. Endangered species taking refuge within protected areas are exposed to the risk of extinction. In the Democratic Republic of Congo, poaching tops the list of threats to protected areas according to the national biodiversity conservation strategy in the Democratic Republic of Congo's protected areas. *Astrochélys radiata*, a critically endangered radiated tortoise, is at the heart of a well-organized trafficking operation in southern Madagascar [114]. This illicit activity has led to the loss of nearly three-quarters of the elephant population in Zakouma National Park in Chad, according to the findings of studies [115]. It is challenging to reconcile the urgent need for protection of natural ecosystems, the food needs of populations, and illegal trade, especially in animal-origin resources.

c. Vegetation Fires

Vegetation fires, a widely used practice for renewing forest and savannah ecosystems [116], have detrimental effects on the balance of ecosystems within protected areas. They make the exceptional biodiversity of these sites [117] vulnerable by promoting the proliferation of invasive species [118,119]. Implementing regulations prohibiting uncontrolled fires and encouraging early fires to minimize the damage caused by late fires is a method of preventing their adverse effects [120]. Despite these measures, protected areas in Togo, in particular, experience uncontrolled fires each year, attributed to managers and local residents. Fire is used by poachers and to clear these sites for the establishment of new agricultural plots [122]. Using these sites as grazing lands leads to uncontrolled fires to renew herbaceous biomass. This situation is particularly impactful for protected areas in the tropical zone, as fire intensity and effects depend on available biomass [118]. The humanization of these sites with the installation of cultivable plots increases the occurrence of vegetation fires to cultivate at lower cost and promote plant regrowth [123,124].

d. Transhumance

The increase in livestock size and agricultural plots leads to a decreasing availability of grazing lands. This situation results in illegal encroachment of protected areas by herders, as observed in Burkina Faso in the Mare aux Hippopotames Biosphere Reserve and the classified forests of Maro and Tuy [125]. In Chad, livestock farming is cited as the primary cause of degradation of resources in the classified forest of Djoli-Kera, followed by agriculture and bushfires [33]. Indeed, agriculture and livestock farming are the main activities carried out by local populations in protected areas in Africa [16].

e. Shifting cultivation on burnt land

The need for cultivable land has driven populations within protected areas to encroach upon them. In Côte d'Ivoire, the establishment of cocoa cultivation plots emerged as the primary factor in the degradation of the Haut-Sassandra Classified Forest [126]. The regression of forest formations and savannas in favor of mosaics of crops, fallows, human settlements, and bare soils is predominant within protected areas in West Africa [2, 32, 110, 127, 128]. Deforestation of forested areas for the establishment of agricultural plots persists despite the protected status of the area, as evidenced by the degradation of the Mikea Forest ecosystems despite its protection [114]. The encroachment of these protected areas often leads to conflicts between farmers, between farmers and herders (transhumants), and between these two groups and resource protection agents [129].

3.4.2.4. Methods of management and conservation status of Togo's protected areas

The Law No. 2008–9 concerning the forestry code manages forest resources. Togo's parks and reserves are managed by the Ministry of Environment and Forest Resources (MERF), specifically by the Directorate of Wildlife and Hunting (DFC). The establishment of MERF dates back to 1987 and was reorganized by Decree No. 2005–095/PR of October 4, 2005. It is responsible for environmental policy in general. In most cases, it was the State that managed protected areas (either directly or by entrusting their management to a private operator, as was the case with the Fazao Malfakassa National Park with the Franz Weber Foundation between 1990 and 2015). These leases were due to lack of funds for tourist facilities and visitor infrastructure, especially since, due to budgetary constraints, the meager revenues generated were rarely reinvested in the development and management of protected areas [130]. Most projects within protected areas have been implemented with funding from international aid.

From October 26, 2023, a decree was issued establishing the National Office of Protected Areas (ONAP), outlining its responsibilities, organization, and functioning. This establishment will now implement the national forest policy regarding the sustainable management of national parks, wildlife reserves, habitat and species management reserves, natural resource management areas, hunting areas, and botanical gardens. Togo's protected areas are no longer renowned for their biological diversity as in the past, due to ecosystem degradation resulting from management issues. The network of protected areas is no longer intact, with the level of degradation varying from one protected area to another. Nevertheless, efforts have been made. Countries have ratified international conventions on biodiversity, enacted numerous legal instruments for the protection and use of flora, fauna, and the environment, and protected at least 10% of the territory [113].

According to the same author, some disadvantageous aspects persist, including the lack of human resources, absence of implementing decrees for certain environmental laws, inadequacy of some laws, overharvesting of wildlife and timber, particularly by the military, lack of training and/or retraining of employees, limited benefits for the population, and failure to address their grievances. Ten areas have been identified as priorities and have been reclassified, consolidated, and enhanced with the support of the COM STABEX 91–94 program. These areas include Oti-Kéran, Oti-Mandouri, Togodo-Sud, Togodo-Nord, Bayémé, Amou-Mono, Aledjo, Fosse aux Lions, Galangachi, and Doungh. Restoring Togo's protected area networks and modernizing them for productive management and tangible conservation outcomes will require concerted efforts from all stakeholders, particularly local actors. The priority is not only to restore dialogue with local populations but also to reinstate management practices adapted to the various contexts of protected areas.

4. CONCLUSION

The quantity of primary productivity of vegetation on land determines its capacity to sustain most forms of life in the long term. This productivity, being a key parameter of ecosystem performance, plays a major role in regulating climate and greenhouse gas concentrations in the atmosphere. An efficient ecosystem will have a very high net primary productivity and represent a very important carbon sink to be safeguarded. The assessment of ecosystem performance is done through various methods. Remote sensing data allows for precise simulation of vegetation productivity in ecosystems at reasonable costs and record time. Simple empirical models remain essential, especially for measuring primary productivity on a smaller scale, to validate the results of light use efficiency (LUE) or enzymatic kinetics (EK) models. Remote sensing-based models almost all rely on vegetation indices for reliable results. These methods are essential for assessing the status of Togo's protected areas, specific sites that have faced enormous pressures in the past, the rehabilitation of which is a significant challenge for the country.

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