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Facilitating the Management of Protected Areas through Multi-Level Ecosystem Accounting on an Example in West Africa

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Abstract: West Africa, already highly influenced by the negative effects of climate change, is additionally characterized by rapid population growth, endemic poverty, and insecurity. This is affecting the natural capital of its ecosystems and the services they provide. Natural capital accounting (NCA) provides the fundamental evidence base required for informing economics and environmental decisions, thus strengthening the conservation and management of natural resources. The objective of this study is to showcase the development and evaluation of a semi-automated NCA platform (Sys4ENCA) designed to support decision making in the context of protected areas management in a multi-level example in western Africa. The accounting results highlight that simulations at the broader scale using national public data show that the natural capital of ecosystems in western Africa depends strongly on the mean climate and its variability. Evaluating regional datasets, the simulation with the platform shows that pressure on land in combination with weak governance reduces the capability of the ecosystem to deliver the required services in a sustainable manner, i.e., in the eastern part of the Bafing-Falémé landscape, where mining and intensive agriculture are fueling loss of natural capital. The results of Tier-3 accounting using local datasets enhanced the spatial variability and highlighted additional hotspots of degradation compared to the regional results, i.e., the prospective construction of a hydro-electricity dam (Koukoutamba) in the southern part of the Moyen-Bafing National Park located in the Bafing-Falémé landscape. The Sys4ENCA platform, combined with a multi-level approach, showed itself to be a valuable tool to facilitate protected area management as it provides not only consolidated information at a local scale but also the broader context and external pressures, i.e., climate change and demand for land. Given its automatized nature, the platform reduces human errors and increases the efficiency, speed, and harmonisation of computation over long timeframes and spatial scales.

Keywords: natural capital; tiered approach; NCA; national parks; degradation; ecological value; decision making

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1. Introduction

West Africa, which is already feeling the devastating effect of climate change [1–3], is characterized by rapid population growth, endemic poverty, and insecurity [4,5]. This situation is affecting the natural capital as well the ecosystem services it provides within the region [2,3,6]. Faced with these threats, the European Union (EU), the Economic Community of West African States (ECOWAS), and the West African Economic and Monetary Union (UEMOA) setup the "Support Program for the Preservation of Biodiversity and Fragile Ecosystems, Regional Governance and Climate Change in West Africa—PAPBio"

(ROC/FED/039-269) [7], which aims to improve the management of major African natural ecosystems in order to increase the resilience of both the ecosystems and the population to climate change.

Conservation and management of natural resources, which is necessary to sustain our planet, requires well-informed decision making towards sustainable growth and long-term development. Natural capital accounting (NCA), also known as ecosystem accounting, provides the fundamental evidence base required for informing economic and environmental decisions [8–10].

Legal and political commitments related to natural capital accounting have been established through a wide variety of international instruments, including under the auspices of several multilateral environmental agreements; for example, the 193 states party to the 1992 Convention on Biological Diversity (CBD) have committed, in one of the 2011–2020 Aichi Biodiversity Targets, to integrate "biodiversity values" into their national accounting. In October 2014, the CBD meeting of the conference of the parties (COP 12) produced the publication "Ecosystem Natural Capital Accounting (ENCA): A Quick Start Package" [11]. ENCA is a technical accounting framework for measuring the sustainable capacity of ecosystems to supply the services needed by humankind and assess human accountability for ecosystem degradation by inappropriate management. It follows the methodology of the international System of Environmental–Economic Accounting Experimental Ecosystem Accounting (SEEA EAA)— in short, "ecosystem accounting"— and has strongly participated in the definition of the SEEA biophysical accounts [10] but differs as it describes the integration of indicators into an index [10]. The SEEA EA, adopted in March 2021 by the UN Statistical Commission, provides, therefore, more detailed guidance on how to measure the extent and condition of ecosystems, and how to quantify ecosystem services [12,13].

ENCA's approach to quantifying degradation starts from the capability of the ecosystem and not from the loss of services benefits, where capability includes ecosystem productivity and health. This integrated approach is an added value in the context of natural capital accounting for protected area management. Several reports on its applications have been published recently [14–18]. Next to proof-of-concept tests such as on the Rhone watershed in France [17], the Guiana Shield [18], and the islands of Mauritius [18], the ENCA methodology was applied on a continental scale by the Observatory of Sahara and Sahel (OSS) Organization, producing the AfrikENCA accounts [18].

The main objective of this study is to showcase the development and evaluation of an effective and harmonized natural capital accounting platform (Sys4ENCA) to support decision making in the context of protected areas management in an example in western Africa (Moyen-Bafing National Park). Via this showcase, we want to facilitate the usage of the platform by stakeholders to assess the ecological value of areas, identifying hotspots of degradation or low ecological value, and trace back the potential causes of changes in ecological value.

2. Materials and Methods

In the context of this study, a semi-automatized ecosystem accounting system (Sys4ENCA) has been developed to quantify the state natural capital and, in particular, to support the management of protected areas. The system is based on the ecosystem natural capital accounting (ENCA) framework as described in the "Ecosystem Natural Capital Accounting—Quick Start Package" (ENCA-QSP) [11]. Once developed, the Sys4ENCA platform has been evaluated using a multi-level approach [12] for the Moyen-Bafing National Park, located in a transboundary region between Senegal and Guinea and including the Niokolo protected areas and the Bafing-Falémé landscape. These different elements are described in the sections below.

2.1. The Ecosystem Natural Capital Accounting Framework: ENCA-QSP

The ecosystem natural capital accounting (ENCA) quick start package (QSP), ENCA-QSP [11], is a response to the requirement of the Convention on Biological Diversity (CDB) for incorporating biodiversity values into national accounting [10,14,19,20]. Based on the land characteristics, the ENCA framework quantifies the stock and natural flows of the ecosystem in three domains—carbon (expressed in tons per hectare); water (expressed in cubic meter); and infrastructure functional services (expressed in weighted hectares) (see Figure 1).

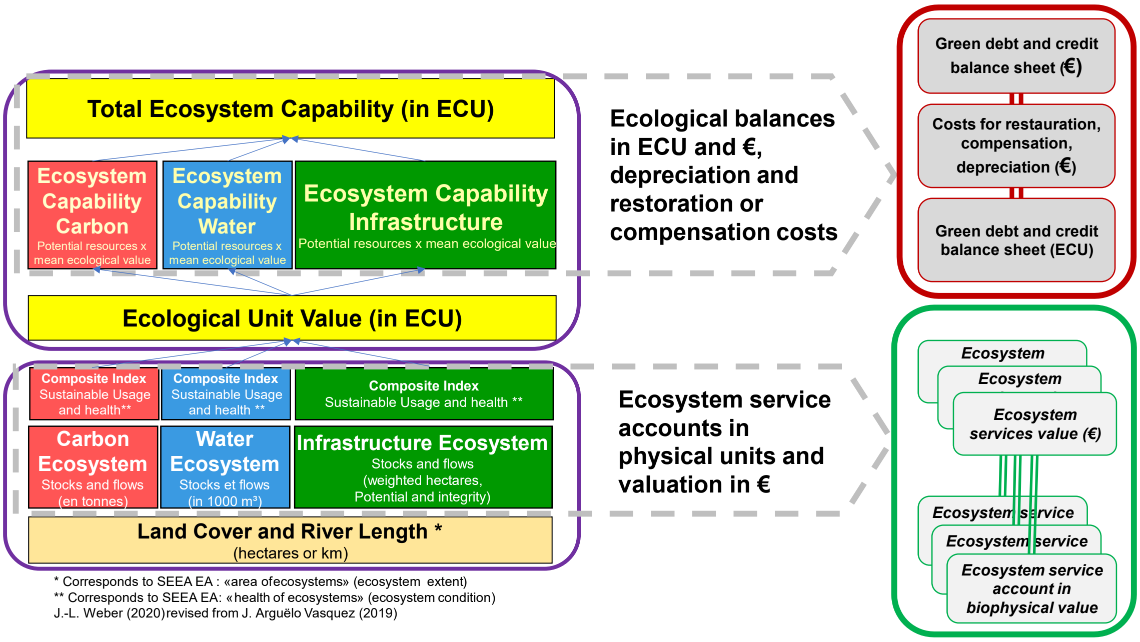


Figure 1. Overview of the ecosystem natural capital accounting (ENCA) framework (adapted from [14]).

These three accounts, i.e., carbon, water, and infrastructure functional services, are built following similar steps and accounting structures. Each of the accounts consists of quantitative tables describing the balance of resources (basic balance of stock and flows; estimation of surplus and potential of accessible resources; total use/consumption of resources) and a synthesis table including two indices, i.e., a quantitative index of sustainable intensity of use of the resources and a qualitative index of ecosystem health. These two indices are then combined to obtain an index of internal ecological value for each resource. This index of internal ecological value provides an indication of the state of the resource based on its use and resilience capacity. These indices can further be combined to calculate an overall index of ecosystem capability, which summarizes the various quantitative and qualitative changes recorded in the ecosystem carbon, water, and infrastructure accounts and is expressed in a unit called the ecosystem capability unit (ECU). The ecosystem capability for carbon, water, and infrastructure can be aggregated into a total ecosystem capacity (TEC).

The account's results are compiled and reported by socioecological landscape units (SELUs). These spatial units can be aggregated at any level, e.g., at the regional and national level. At country level, the aggregated TEC expressed in ECU can provide a measurement of performance in terms of ecological value in a similar way as the GDP does in terms of economic value. More detailed information on the technical aspects of ENCA-QSP can be found in Weber [11], where Argüello, Weber, and Negrutiu [17] provides a detailed documentation of the applied ENCA methodology.

Please note, a detailed definition and the summarized calculation formulae of the mentioned account indicators, as well as a glossary, can be found in Argüello, Weber, and Negrutiu [17]. Detailed account calculations and examples can be found in Weber [11].

2.2. Development of a Semi-Automatized ENCA Platform: Sys4NCA

Due to the huge amount of data needed to set up an ENCA account and its complexity in processing [11,17], statistical offices and environmental agencies which emerge as new user communities need support. Therefore, we developed the Sys4ENCA platform, which supports the implementation of ecosystem natural capital accounting by bringing together different data infrastructures to unlock the value of big data for policy matters from a global to a local scale (Figure 2). Sys4ENCA contains not only global datasets and the tools used to update them; it also contains automated workflows to generate and pre-process various national, regional, and local input data (geo-data, non-located statistical data, earth observation data, etc.) and ingests them in the ENCA data structure (Figure 3). The system generates automatic reports for aggregation units and ingests the information into webservices and databases to connect from a user's perspective. The platform can be deployed on a regional scale and users can connect at three levels to this system—policy and decision makers, GIS experts who want to further analysis the data, and IT experts who can alter models or input datasets (right hand side of Figure 2). Access of the platform to the policy and decision makers is provided through the OBAPAO platform [21]. OBAPAO is a repository of data and information on biodiversity and protected areas in Western Africa that has been set up in the context of the BIOPAMA Program [22] (https://biopama.org/, accessed on 4 May 2023), an initiative funded by the European Union. Access to the platform for IT experts is provided through virtual machines in a cloud infrastructure.

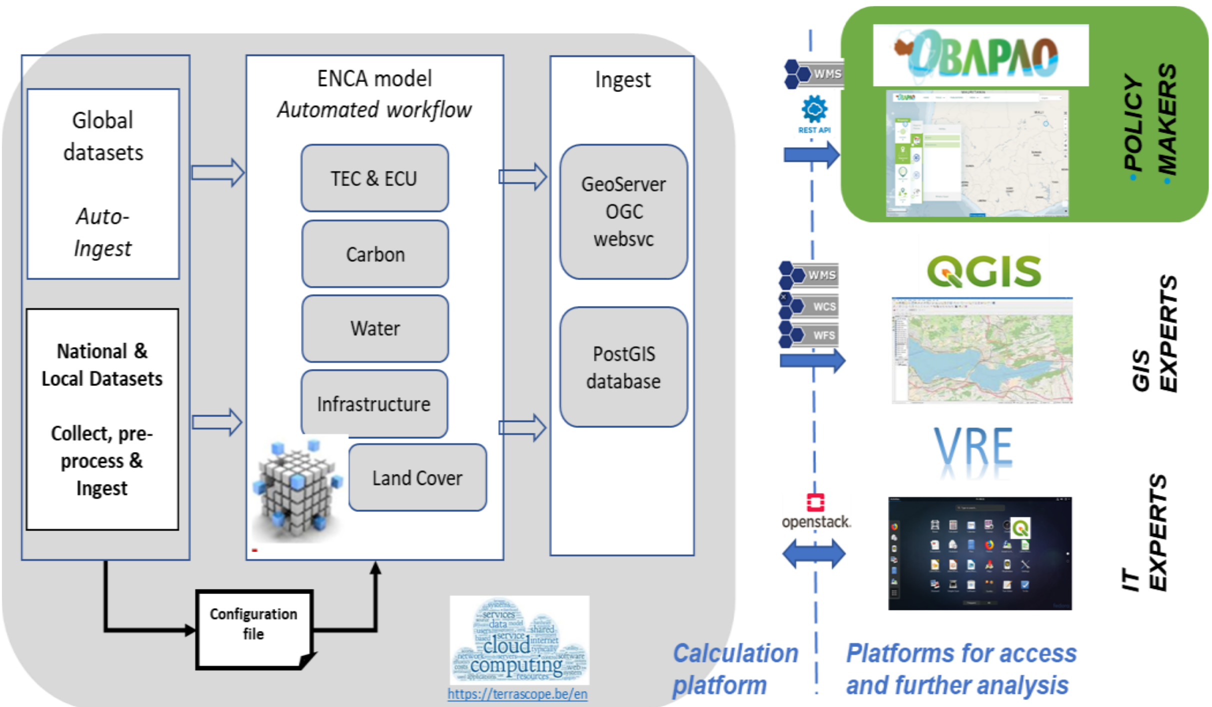


Figure 2. The Sys4ENCA processing platform for semi-automatic ecosystem natural capital accounting (ENCA) following the ENCA quick start package (QSP).

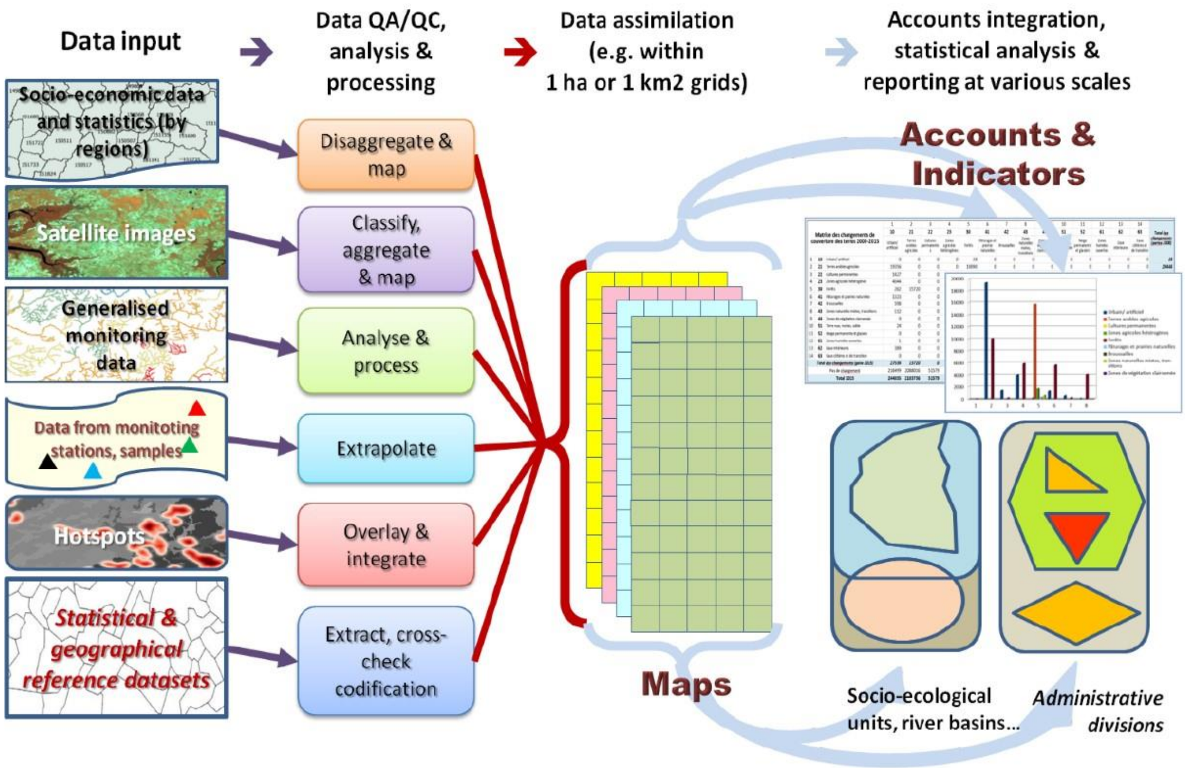


Figure 3. The ecosystem natural capital accounting (ENCA) quick start package (QSP) data structure—assimilation and data integration of statistics and geo-data (adapted from [11]).

Sys4ENCA assimilates the input datasets into a grid fitting scale where accounts are produced (Figure 3). Data assimilation to grids allows for the easy extraction of data as well as the ingestion of earth observation data to fill data gaps and provide objective high-detailed information. Data sources and formats can be of many types—geographical references, social and economic statistics (typically in administrative divisions), satellite/drone images, and in situ monitoring data. Data processing depends on the type of data available, but in every case, it starts by the quality assessment of the input data. Then, according to the data type, processing will consist in classification, resampling, extrapolation, etc., to feed into the reference grid format. For the analysis and reporting, the resulting gridded accounts are resampled to SELUs, which can further be aggregated to an administrative unit such as a country or protected area. The Sys4ENCA platform allows semi-automatic generation of natural capital accounts without the hassle to be an expert in data pre-processing. Compared to the original ENCA-QSP [11], an additional indicator has been implemented in the Sys4ENCA, i.e., the TEC trend indicator (TEC-TI). The TEC-TI is an indicator of ecosystem degradation based on the temporal analysis of the TEC for a reporting area compared to a reference year and is currently based on a linear model.

2.3. The Ecosystem Accounting Area

The Moyen-Bafing National Park is located in the north of Guinea (Figure 4) along the Bafing River [23,24]. With an area of 6767 km^2, this park hosts the largest continuous population of chimpanzees in West Africa, a subspecies classified as "critically endangered" by the International Union for Conservation of Nature (IUCN) [23]. The Moyen-Bafing National Park was introduced in 2021 [23]. The park is currently managed by the WCF and OGPR [23]. The design of the National Park includes several zones with different degrees of anthropogenic usage—a core area incorporating at all connected forest area, a buffer area in which only sustainable activities may be conducted, and a zone called the "development zone" [25]. The Moyen-Bafing National Park and was chosen as test site due to its involvement in the PAPBio project and thus the availability of local experts who are critical for the generation of Tier-3 accounts.

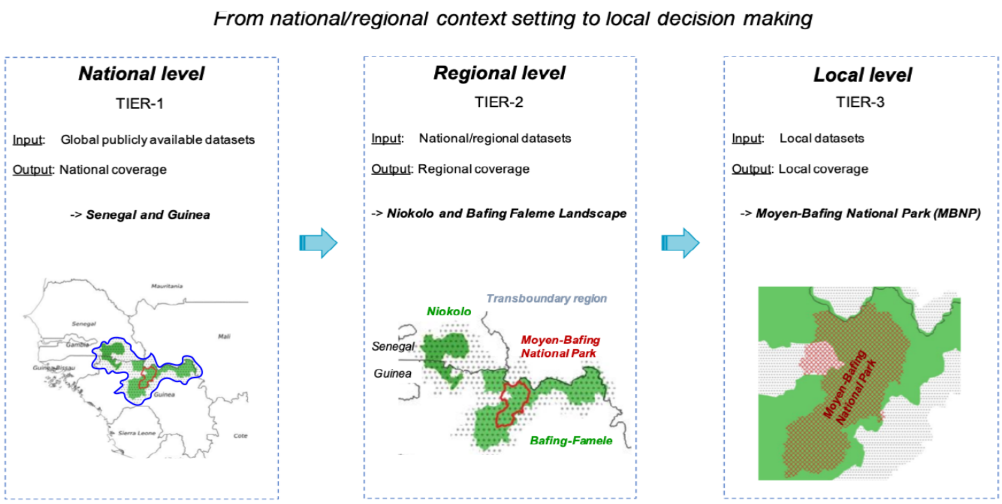


Figure 4. The ecosystem accounting area for the three levels of accounting—the national level, including Senegal and Guinea (Tier-1); the transboundary region between Senegal and Guinea (Tier-2), covering the Niokolo and the Bafing-Falémé landscapes (blue outlined area, left image, and zoom-in in middle image); and the Moyen-Bafing National Park located in the center of the Bafing-Falémé landscape (red dotted region, right image) (Tier-3).

The Moyen-Bafing National Park is located within the Bafing-Falémé landscape (Figure 4, middle panel), which covers an area of 32,000 km^2 along the Bafing and Falémé rivers [26]. In 2021, Guinea received funding from the Global Environmental Facility (GEF) for the "Integrated management of natural resources in the Bafing-Falémé landscape" project [26]. The objective of this project is to promote integrated and sustainable management of natural resources by introducing a landscape approach, creating and operationalising a cluster of protected areas, i.e., (i) the Moyen-Bafing National Park, in the centre of the landscape as presented earlier; (ii) the Gambia-Falémé Faunal Reserve, in the northwest, which plays a role as a migration corridor for large fauna between the Moyen-Bafing National Park to the east and the Niokolo Koba National Park, the Niokolo Badiar National Park, and the Badiar Biosphere Reserve to the west; and (iii) three community forests that will be rehabilitated in the northeast of the landscape [27,28]. The establishment of ecovillages around the protected areas is also part of this project.

Therefore, in the context of this study, the whole transboundary region between Senegal and Guinea that includes the Niokolo Koba National Park, the Niokolo Badiar National Park, the Badiar Biosphere Reserve, and the Bafing-Falémé landscape has been considered in the accounting.

2.4. Building and Evaluating the Ecosystem Accounts

A multi-level approach [12] was used to assess the capacity of the ENCA platform (Sys4ENCA) to provide consolidated information for the management of protected areas with the case-study of the Moyen-Bafing National Park. These accounts were developed at three levels of increasing ecological detail (called tier), as represented in Figure 4:

- Tier-1 level, which is a contextual level where country accounts for Senegal and Guinea are computed based on global publicly available datasets (national level);
- Tier-2 level, which focusses on the accounting of the transborder region between both countries Senegal and Guinea, based on national datasets and customisations (regional level);
- Tier-3 level, which focusses on the Moyen-Bafing National Park within the Bafing-Falémé landscape, using local datasets and customisations (local level).

At Tier-2 and Tier-3 levels, it is important to create the accounts jointly with local experts, as local knowledge for the identification and integration of local data from multiple disciplines is crucial. Therefore, an iterative process has been set up through committees of national and local stakeholders from Guinea and Senegal. A detailed list of the committee members and involved organizations is provided in the acknowledgment section. Following from the data inventory and development of the ecosystem accounts, the results of the accounting at the Tier-1 level were used to engage further with national and local stakeholders in order to collect and set up the customization of the Sys4ENCA tool for the accounting at the Tier-2 and Tier-3 levels. As well as highlighting obvious data gaps and uncovering further supporting ancillary datasets, this iterative engagement provided opportunities to raise awareness as to the approach and gain further input and support from potential end-users. In total, eight monthly iterations were conducted to arrive at the final Tier-2 and Tier-3 accounts. Each iteration followed a process to (i) identify local datasets that could replace global datasets and hence provide more detailed information for the area under investigation; (ii) verify the use of the local datasets; and (iii) verify the accounting results and indicate the ones of interest to be integrated in the OBAPAO monitoring platform.

An extensive list of the globally publicly available datasets for the accounting at the Tier-1 level is provided in Appendix A. The national/regional and local datasets used for the Tier-2 and Tier-3 accounts can be found, respectively, in Appendices B and C. The accounts were generated in 5-year intervals for the time frame 2000–2018, where the year 2000 is used as the reference year. Due to low temporal data availability of several primary data sources, the annual account could be not generated, which reduces the possibility of statistical and economic analyses of seasonality, structural breakage, and other impacts. The data processing started via the quality assessment of the input data. The establishment of time series was an important point of the process as it is a powerful way of controlling the consistency of the available data sources. The accounts' results were first compiled and reported at the highest level of the sub-basin breakdown of the HydroBASINS from the HydroSHEDS database [29]. Subsequently, these were aggregated at country level for Guinea and Senegal (Tier-1), at regional level for the transboundary region (Tier-2), and at local level for the Moyen-Bafing National Park (Tier-3).

Due to the low amount of time steps, only a linear regression could be conducted in the trend analysis where the t-test (p-value < 0.1) was used to specify the significance of the trend. The p-value represents a probability of the error when expecting the trend to differ from zero (i.e., there is no time change, and the value is based on random fluctuations only).

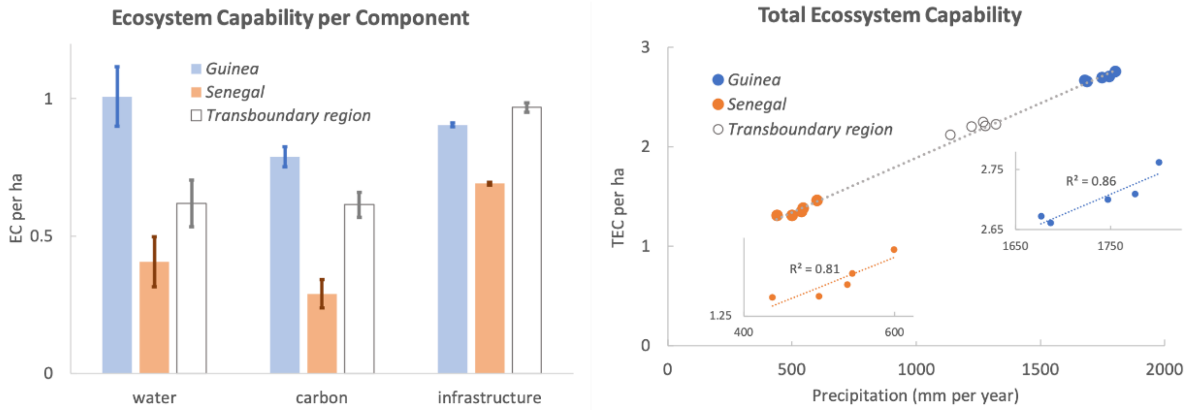
3. Results

In this section, the results of the accountings are presented for the three different levels—national level (Tier 1); regional level (Tier 2); and local level (Tier-3). Please note, we will present mainly the results of the ecosystem's capability in total and of its components as well as the capability trends. Detailed accounting tables for all components can be found in two additional reports [15,16], and the key accounting results on SELU levels are available as vector files via the OBAPAO webpage [21].

3.1. Ecosystem Capability at Country Level: Guinea and Senegal

The average yearly total ecosystem capability (TEC) per ha over the five accounting years, i.e., 2000, 2005, 2010, 2015, and 2018, as simulated by Sys4ENCA using globally and publicly available datasets (Tier 1), is 2.70 (±0.04) for Guinea and 1.36 (±0.06) for Senegal. The trend analysis of the TEC time series at Tier-1 showed no significant trend.

Figure 5a shows that the three components; i.e., water-, carbon-, and infrastructure-based services, contribute more or less evenly to the total ecosystem capability of Guinea. In Senegal, on the other hand, the contribution of the water- and carbon-based services is significantly smaller than the contribution of the infrastructure-based services. The latter accounts for more than half of the total ecosystem capability of Senegal (Figure 5a). None of the three components showed a significant trend over time. The ecosystem capability provided by the infrastructure-based services is fairly constant over the five accounting years. However, this is not the case for the capability provided by the carbon- and water-based services. The TEC interannual variability is primarily driven by the interannual variability of the water-based services, and secondly by the carbon-based services (error bars in Figure 5a). Figure 5b shows that the yearly TEC of Senegal and Guinea are strongly correlated to the yearly rainfall. Mean rainfall seems to explain not only a significant fraction of the interannual variability but also the spatial variability, notably the difference in TEC values between Senegal and Guinea.



(**a**) (**b**)

Figure 5. (**a**) Bar chart of the mean ecosystem capability (per ha) per component; i.e., water-, carbon-, and infrastructure-based services for Guinea, Senegal, and the transboundary region over the five accounting years as simulated by Sys4ENCA (Tier-1). Two standard deviation error bars representing the interannual variability; (**b**) scatterplot of the total ecosystem capability (per ha), as simulated by Sys4ENCA (Tier-1), against the precipitation (in mm) during 2000, 2005, 2010, 2015, and 2018 for Guinea, Senegal, and the transboundary region ($y = 0.0011x + 0.7908$). The colored inlays represent the linear regression through the measurements for Guinea and Senegal.

Focusing now on the transboundary region crossing Senegal and Guinea, Figure 5b shows that the average TEC for this region, as simulated by the account platform over the five accounting years (white circles in Figure 5b), is very close to the TEC estimate from the regression line through the TEC versus rainfall rate for Senegal and Guinea, given an average rainfall rate of 1245 mm per year over the transboundary region. The TEC simulated with the ENCA platform, which is more or less halfway between the values of Guinea and Senegal, is, however, slightly higher than the estimates based on the regression line. The mean ecosystem capability provided by the carbon- and water-based services for the transboundary region, as simulated by Sys4ENCA, falls between the values simulated for Guinea and Senegal in a similar way as the TEC does, while the capacity provided by the infrastructure-based services is larger than the values simulated for both countries (Figure 5a).

3.2. Ecosystem Capability at Regional Level: The Transboundary Region between Senegal and Guinea

Figure 6 shows the spatial distribution of the TEC over the transboundary region at the highest level of the sub-basin breakdown of the HydroBASINS from the HydroSHEDS databases, as simulated by Sys4ENCA for the year 2000 using regional datasets and customisations for the region (Tier-2). It shows that the northern part of the Niokolo, which corresponds to the Niokolo Koba National Park (NKNP), and the central part of the Bafing-Falémé landscape, which corresponds to the Moyen-Bafing National Park (MBNP), have a significantly higher ecological capability compared to the whole transboundary region (1.86 per ha), with averages value of 2.80 and 3.00 per ha, respectively. These values are 1.5 times above the regional average. On the other hand, the southern part of the Niokolo, which corresponds to the Ramsar site Gambie-Kouloutou, has a similar TEC value (2.01 per ha) as the regional average.

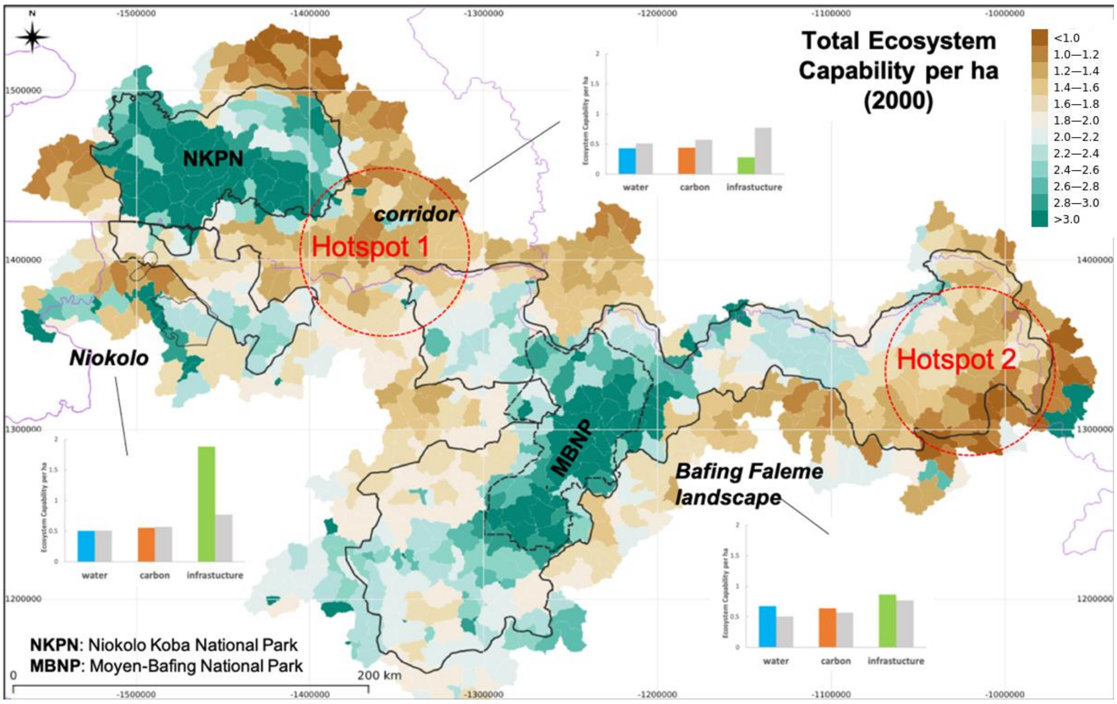


Figure 6. Total Ecosystem Capability (TEC) per hectare of the transboundary region including Niokolo and Bafing-Falémé landscape as simulated by Sys4ENCA for the year 2000 using regional datasets (Tier-2) at the highest level of the sub-basin breakdown of the HydroBASINS. The greener the sub-basin, the higher the ecosystem capability. The inlay histograms represent the breakdown of the TEC for the Niokolo, the Bafing-Falémé landscape, and the corridor between both in its three components (water-, carbon-, and infrastructure-based services; blue, orange and green bars) and the comparison to the whole transboundary region (grey bars).

In Figure 6, two hotspots of low ecological capability can be detected; i.e., the corridor between the Niokolo and the Bafing-Falémé landscape ("hotspot 1" in Figure 6), with a value of 1.39 per ha, and the far eastern part of the Bafing-Falémé landscape ("hotspot 2" in Figure 6), with a value of 1.32 per ha. These values are around 30% less than the regional average of 1.86 per ha. These two hotspots are characterized by the significantly lower capability of the of the ecosystem to provide regulating and sociocultural services (hereafter mentioned in the text as "infrastructure-based services"), with a value of 0.40 per ha, compared to the regional average for the same component of 0.77 per ha. Over the whole transboundary region, this component contributes to more than 40% of the total ecosystem capability, while within the hotspots, it represents less than 30%.

Figure 7 presents the spatial distribution of the trend in TEC (TEC-TI) over the 2000–2018 period, as simulated by Sys4ENCA, using regional datasets and parameters customized for the transboundary region (Tier-2). The results of the Sys4ENCA simulation show a weak increase in TEC within both national parks (5–7%), while outside the parks, the ecosystem capability has remained more or less stable over the period under consideration. In the eastern part of the Bafing-Falémé landscape, however, the TEC values are gradually decreasing eastwards, with a hotspot in the far east. Here, the ecological value has decreased by around 15% over the 2000–2018 period (Figure 8). The time series of the TEC values over the 2000–2018 period for the two national parks, Moyen-Bafing (MBNP) and Niokolo Koba (NKNP), as well as for the hotspot in the far eastern part of the Bafing-Falémé landscape and for the whole transboundary region, are represented in

Figure 8. Outside the boundaries of the national parks, small spots of degradation are also noticeable (in red-orange in Figure 7). At the center of the MBNP, a zone of degradation is noticeable as well.

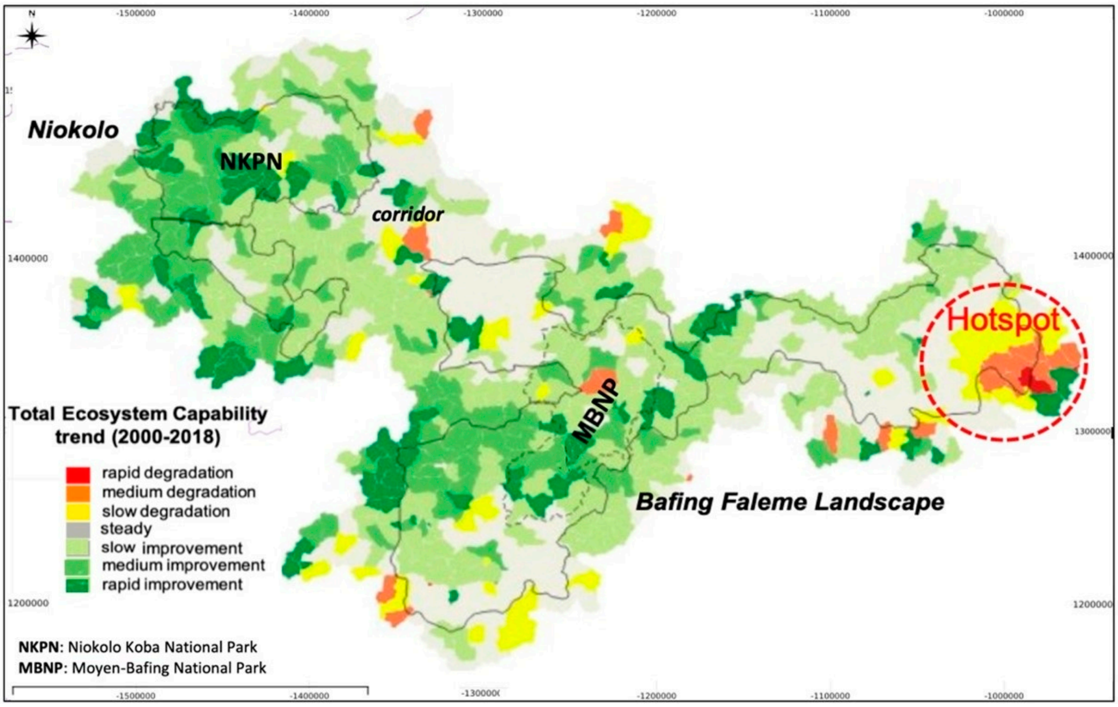


Figure 7. Trend of the total ecosystem capability (TEC-TI) per hectare over the 2000–2018 period for the transboundary region, as simulated by Sys4ENCA using regional datasets (Tier-2) at the highest level of the sub-basin breakdown of the HydroBASINS. The yellow-reddish color indicates degradation, while the green color highlights increased TEC over the indicated period.

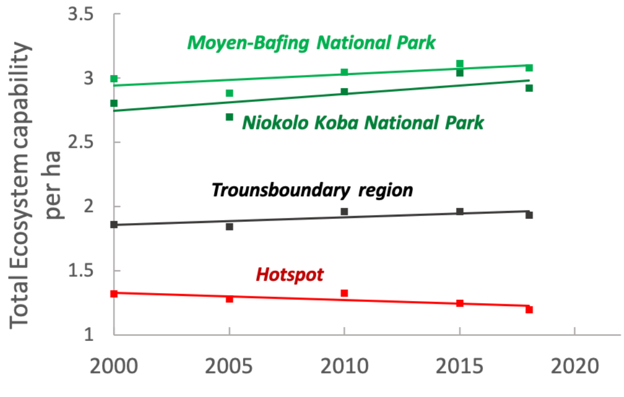


Figure 8. Time series of the total ecosystem capability per ha, over the 2000–2018 period for the whole transboundary region (black squares), for the two national parks, Moyen-Bafing and Niokolo Koba (green squares), and for the hotspot in the eastern part of the Bafing-Falémé landscape (red squares), as simulated by Sys4ENCA using regional datasets (Tier-2). The lines represent the trends of each time series individually ($p < 0.1$).

3.3. Ecosystem Capability at Local Level: The Moyen-Bafing National Park

The mean TEC of the Moyen-Bafing National Park (MBNP) for the year 2000, as simulated by Sys4ENCA using local datasets (Tier 3), is 2.38 per ha. This is more than 20% less than the capability computed for this park based on national/regional datasets (Tier 2). Figure 9 represents the capability of the MBNP ecosystem to provide water-, carbon-, and infrastructure-based services, as simulated by Sys4ENCA using national/regional (Tier-2) on one hand, and local datasets (Tier 3) on the other hand. The contribution of the water-and carbon-based services to the total ecosystem capability of the park is similar for both levels, Tier 2 and Tier 3, and fluctuates between 0.65 and 0.75 per ha, while the capability of the ecosystem to provide infrastructure-based services is significantly lower when using local datasets—0.94 per ha at Tier-2 vs. 1.62 ha at Tier-3. This represents a difference of 40%. The capability of the ecosystem to provide infrastructure-based services varies significantly over the extent of the park and has a standard deviation of around 0.7. For the water and carbon-based services' components, the spatial variability is only around 0.3. The ranges of these spatial variabilities are more or less similar at Tier 2 and Tier 3.

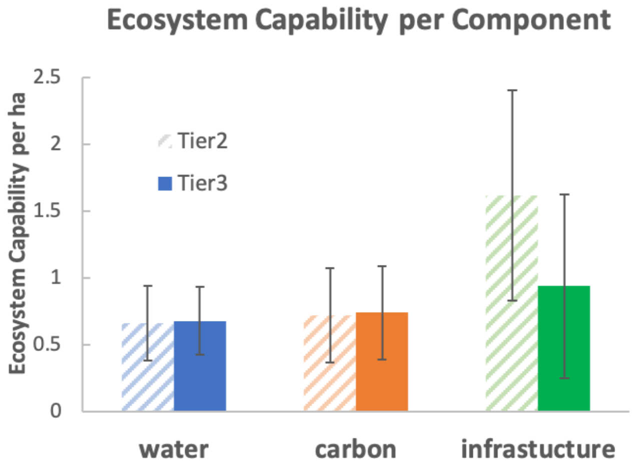
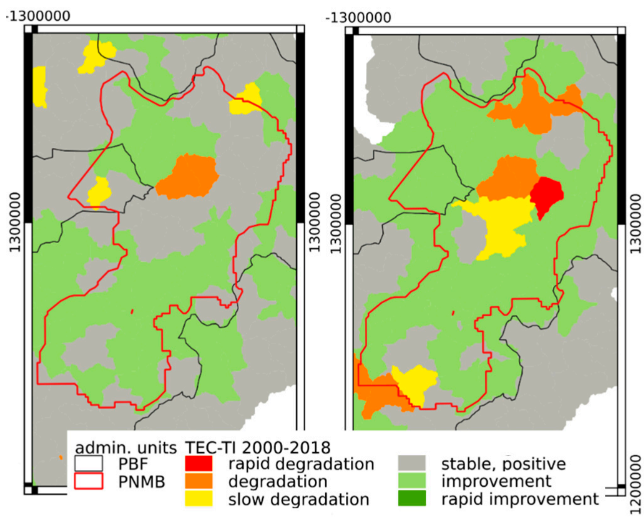


Figure 9. Comparison of the mean ecosystem capability per ha for the Moyen-Bafing National Park to provide water-, carbon-, and infrastructure-based services during 2000 using national/regional (Tier2) on one hand, and local datasets (Tier 3) on the other hand. The spatial variability around the mean for each component is represented by the one-standard deviation error-bars.

Figure 10 shows the spatial distribution of the TEC-TI over the 2000–2018 period, as simulated by Sys4ENCA using regional datasets (Tier-2) on the left and local datasets (Tier-3) on the right. At Tier-3 level, the zone of degradation in the centre of the park is more prominent. Some additional hotspots of degradation can be detected in the northern and southern parts of the park as well.



(**a**) **Tier-2** (**b**) **Tier-3**

Figure 10. Trend of the total ecosystem capability (TEC) per hectare over the 2000–2018 period for the Moyen-Bafing National Park, as simulated by Sys4ENCA using (**a**) regional datasets (Tier 2) and (**b**) local datasets (Tier 3).

4. Discussion

From the national analysis (Section 3.1), it became apparent that the total capability of ecosystems in western Africa is strongly correlated to the yearly rainfall. Rainfall variability significantly explains the spatial distribution, as well as more than 80% of the TEC interannual variability; the lower the rainfall, the lower the TEC. In water-limited environments in sub-Saharan Africa, precipitation is a key factor influencing vegetation growth and development [30]. By consequence, it significantly affects the capacity of the ecosystem to provide water- and carbon-based services. Guinea, which is characterized by a tropical climate [31], has a higher mean TEC with a lower interannual variability compared to Senegal. Senegal is indeed much drier, and the amount of rainfall that falls each year varies proportionally more. The transboundary region located between both countries presented intermediate values in TEC's mean and variability. Given the strong dependency of TEC on rainfall, it is expected that climate change and variability have and will continue to have a significant impact on the natural capital of the protected areas in Western Africa [32]. The interpretation of the results has, however, to be taken with care as currently, only 5-yearly intervals have been evaluated. Due to the strong interannual variability of the TEC values, no trends could be detected. Longer time series would be required with annual accounting.

The ecosystem accounting also highlights the high ecological value of the transboundary region, and in particular, of the natural parks within this region, mainly through their ecosystem's ability to provide regulating and sociocultural services (infrastructure-based services). The nature protection status and low fragmentation seem to be important drivers of their ecological integrity. The analysis at the regional level in Section 3.2 showed that the corridor between the Niokolo and Bafing-Falémé landscapes has a significantly lower ecosystem capability, compared to the regional average, to provide the required services in a sustainable manner. This corridor is, however, expected to be developed into a functional zone of passage for fauna between the parks and hence to increase its biodiversity [33]. To achieve this, a strengthening of the landscape management plans of the region would be required.

Important differences in ecological values were also observed within the protected areas; the southern part of Niokolo and the eastern part of the Bafing-Falémé landscape have ecological values of more than 10% below the regional average. Different management practices in the neighboring countries, Guinea and Senegal, explain the difference in ecological value between north and south of the Niokolo protected areas. In the southern part, located in Guinea, conservation activities are in practice in the core area of the Badiar Biosphere Reserve, while on the periphery, a co-management system is in place to allow the various communities to use the site for agricultural (rice cultivation) and wood supply [34]. The northern part, located in Senegal, covers largely the Niokolo Koba Natural Park, where conservation activities are in practice over the whole area.

Concerning the Bafing-Falémé landscape, the variability in ecological value is gradual and goes from west to east. The eastern part of the Bafing-Falémé landscape is characterized by human activities such as intensive agriculture and mining, which significantly reduce the capability of the ecosystem. In this part of the landscape, however, there is an objective to rehabilitate three community forests [33]. To achieve this target, significant changes in management practices would be required. The ecosystem capability of the center of the landscape, on the other hand, is far above the regional average. The core of the Bafing-Falémé landscape has recently been recognized as a National Park, the "Moyen-Bafing National Park" (2021), and is characterized by high biodiversity [23]. The park, however, faces important threats—housing and urban area, annual and perennial non-timber crops, livestock farming and ranching, the planned Koukoutamba dam project, hunting, and wood harvests and bush-fires for cleaning the agricultural area [35]. It is therefore crucial to keep monitoring this park to preserve its ecological value.

Over the 2000–2018 period, the overall ecological value of the transboundary region remained more or less stable, albeit with some spatial variability. The ecosystem capability of the national parks increased slightly, while the eastern side of the Bafing-Falémé landscape, already characterized by a low capability, showed a gradual but significant decrease in ecosystem capability. As mentioned earlier, this area is subject to intensive agriculture and mining practices. An increase in these human activities might be the underlying cause of this rapid degradation. To counteract this trend, good governance and adaptations of the practices in place will be required. The increased pressure on land due to increased population, poverty, and insecurity in the neighboring villages probably also explains the small spots of degradation outside the boundaries of the Niokolo and the Bafing-Falémé landscape.

At the center of the Moyen-Bafing National Park, within the Bafing-Falémé landscape, a zone of degradation was also noticed, despite the high ecological value of the park. This hotspot is probably connected to the activities related to the prospected construction of anhydro-electricity dam (Koukoutamba) in the southern part of the park [36]. This dam is expected to affect the natural capital of the entire park, as the Bafing river, on which the dam will be constructed, is running northwards through the park. The development of scenario models could help to assess the impact of such a dam on the natural capital of the park and to anticipate the required management to avoid further degradation.

To better assess the ecological value and sustainability of the Moyen-Bafing National Park, local datasets (Tier-3) were ingested into the Sys4ENCA tool. The results of this Tier-3 accounting, presented in Section 3.3, enhanced the spatial variability within the park and highlighted additional hotspots of degradation compared to the results of the Tier-2 accounting. The most significant difference between both simulations—Tier-2 and Tier-3—was, however, the reduced ecosystem capability of the National Park when accounting at the Tier-3 level. It is believed that introducing more detailed datasets at the Tier-3 level, such as those including higher resolution land cover, smaller/dirt roads, more detailed biodiversity indicators, etc., simulated a higher fragmentation of the ecosystem and resulted in the reduced capacity of the ecosystem to provide regulating and sociocultural services. This is an artefact of this multi-level approach, which highlights that the ecological value of one level cannot be directly compared to the value of another level. The results from the accounting at those different levels are, by contrast, complementary. These results also put forward the impact of data availability on the ecosystem accounting; the use or not of some data might enhance or inhibit the contribution of one of the three components, i.e., water-, carbon-, and infrastructure-based services, to the total ecosystem value. This implies that a trade-off might have to be made between accuracy and precision when introducing more detailed information at the local level.

The results of these pilot accounts must, therefore, be interpreted with caution. In addition, given the limited access to consistent data at regional and local level, data extrapolation or crossing of spatial data with statistical information were required and might have introduced additional uncertainties. Although not in accordance with the ENCA method, which recommends annual monitoring, the accounting was performed at 5-year intervals only due to lack of data. Consequently, the results of the accounting were particularly sensitive to extreme weather events.

Finally, it has to be mentioned that the relevance of the results depends not only on input data, used method, and platform functionalities but also on the interpretation and use of the results. All these elements require local insight and knowledge; collaboration with local experts is therefore capital. COVID-19, however, has significantly impeded this process as physical meetings could barely take place during the timeframe of the project. Despite this, an important issue came forward during the meetings, namely, that the interpretation of the ENCA results by decision makers is not straightforward. The need for a common and tangible term to express the ecological value of the protected areas has been put forward.

5. Conclusions

A semi-automatized ecosystem natural capital accounting (ENCA) platform, Sys4ENCA, was developed to support the regional capacity building for ecosystem natural capital accounting. The platform computes yearly ecosystem capability of targeted areas by combining the contribution of the ecosystem's carbon-, water-, and infrastructure-based services. The results are available on the platform through maps and tables, which can be used by the stakeholders to assess the ecological value of the area, identify hotspots of degradation or low ecological value, and trace back potential causes of changes in ecological value.

An initial platform evaluation was performed on a transboundary area between Senegal and Guinea including two protected areas, namely, the Niokolo and the Bafing-Falémé landscape. The results highlighted that different protection and restoration targets, and hence different management practices, lead to different ecological values, i.e., north vs. south of the Niokolo protected area, and the center of the Bafing-Falémé landscape vs. the outer zones. The simulation with the platform also showed that pressure on land in combination with weak governance reduces the capability of the ecosystem to deliver the required services in a sustainable manner, i.e., in the eastern part of the Bafing-Falémé landscape, mining and intensive agriculture are fueling loss of natural capital. It underpins the relevance of implementing the protection status of the Natural Parks and providing guidance for the management actions in the corridor between Niokolo and Bafing-Falémé landscape [37]. Simulations at a broader scale showed that the natural capital of ecosystems in western Africa depends strongly on the mean climate and its variability. It is therefore expected that climate change will have a significant impact on the natural capital of the protected areas in Western Africa.

We may conclude that our fully scalable ENCA platform provides a well-structured basis for the monitoring and evaluation of the impact of current and prospective programs, projects, or management practices on the ecological value of protected areas. Our platform allows us to assess the ecological value of an ecosystem at a specific time as well as its trend, and consequently to anticipate the required management practices necessary to avoid further degradation or to take recovery actions. The information is presented in a harmonized manner, which enables assessments across country borders by different stakeholders, which can result in better aligned management actions to preserve our natural capital. In the case of the Moyen-Bafing National Park, this might be of relevance for the planned construction of the Koukoutamba dam in the southern part of the park.

The Sys4ENCA, combined with a multi-level approach, is a valuable tool to facilitate protected area management as it provides not only consolidated information at a local scale but also a broader context, which allows us to evaluate the impact of external pressure such as climate change and, more generally, global change, i.e., the increased demand for land. Given its automatized nature, the platform reduces human errors and increases the efficiency, speed, and harmonization of computation. This allows for harmonized accounting over long timeframes and spatial scales. In addition, the structure of the platform is such that it is accessible to a wide range of stakeholders.

The results of these pilot accounts must, however, considering the availability and accuracy of input data and the scale of analysis, be interpreted with caution and hindsight. As discussed in the previous section, a trade-off between increased precision and loss of accuracy might have to be considered when introducing more detailed information at the local level. The Sys4ENCA platform is solely a tool to facilitate protected area management through ecological accounting; the analysis and evaluation of the generated accounts requires the knowledge and input of local experts.

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Appendix A

This appendix contains the sources of the data used to generate the accounts for the study area at the Tier-1 level. Table A1 contains the data sources for setting up the land characteristics. The sources of the data used as input to compute the water-, carbon-, and infrastructure-based service accounts are provided, respectively, in Tables A2–A4.

Table A1. List of publicly available datasets used to set up the land characteristics.

Content	Source
Administrative borders, countries, and admin from Level 0 to Level 2	FAO (http://www.gadm.org/, accessed on 8 November 2020)
Copernicus Global Land Cover layers (10 continuous fraction layers)	VITO (http://lcviewer.vito.be/, accessed on 15 October 2020)
Global Forest Cover, Hansen	University of Maryland (https://earthenginepartners.appspot.com/science-2013-global-forest, accessed on 15 October 2020)
Global Human Settlement Layer	JRC (https://ghsl.jrc.ec.europa.eu/, accessed on 15 May 2020)
Global Surface Water, Pekel	JRC (https://global-surface-water.appspot.com/, accessed on 14 May 2020)

Table A1. *Cont.*

Content	Source
Global Mangrove Watch maps	UNEP-WCMC (https://data.unep-wcmc.org/datasets/45, accessed on 10 April 2020)
CCI Land Cover map, ESA/UCL	UCL (http://maps.elie.ucl.ac.be/CCI/viewer/download.php, accessed on 28 May 2020)
Hydrological data and maps (HydroSHEDS)	WWF (https://www.hydrosheds.org/, accessed on 12 April 2020)

Table A2. List of publicly available datasets used to generate the carbon-based services account.

Content	Source
Global Forest Resources Assessments	FAO FRA (http://www.fao.org/forest-resources-assessment/current-assessment/country-reports/en, accessed on 15 April 2020)
ESA CCI biomass	ESA (http://cci.esa.int/biomass, accessed on 28 April 2020)
Global Forest Cover, Hansen	University of Maryland (https://earthenginepartners.appspot.com/science-2013-global-forest, accessed on 15 October 2020)
World Soil Information	ISRIC (https://files.isric.org/soilgrids, accessed on 15 May 2020)
Mangroves soil organic carbon stock	Woods Hole Research Center (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/OCYUIT, accessed on 15 May 2020)
Livestock global distribution maps at 1 km resolution	FAO (https://data.apps.fao.org/map/catalog/static/search?keyword=Modeled%20global%20distribution, accessed on 15 April 2020)
Annual Livestock statistics	FAOSTAT (https://www.fao.org/faostat/en/#data/QCL, accessed on 15 April 2020)
Gross Dry Matter Productivity Copernicus	COPERNICUS (https://land.copernicus.eu/global/products/dmp, accessed on 18 April 2020)
Global Spatially-Disaggregated Crop Production Statistics Data for 2010	IFPRI SPAM (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/PRFF8V, accessed on 16 April 2020)
Annual harvest statistics	FAOSTAT (http://www.fao.org/faostat/en/#data/QC, accessed on 16 April 2020)
Global Soil Erosion data (GloSEM)	ESDAC (https://esdac.jrc.ec.europa.eu/content/global-soil-erosion, accessed on 12 April 2020)
Global Rainfall Erosivity	ESDAC (https://esdac.jrc.ec.europa.eu/content/global-rainfall-erosivity, accessed on 12 April 2020)
World Soil Information	ISRIC (https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/076db4e8-11a9-4262-b6aa-cfa703a3c0af, accessed on 17 April 2020)
MODIS Burnt Area	NASA (https://modis.gsfc.nasa.gov/data/dataprod/mod45.php, accessed on 1 June 2020)
Daily Severity Rating	ERA (https://zenodo.org/record/3250924#.YhTiYIrMI2w, accessed on 1 June 2020)

Table A3. List of publicly available datasets used to generate the water-based services account.

Content	Source
Hydrological data and maps (HydroSHEDS)	WWF (https://www.hydrosheds.org/, accessed on 10 April 2020)
Groundwater ressources and Salinity	WHYMAP (https://www.whymap.org/whymap/EN/Maps_Data/Gwr/gwr_node_en.html, accessed on 15 April 2020)
Lakes and Reservoirs (HydroLAKES)	WWF (https://www.hydrosheds.org/pages/hydrolakes, accessed on 27 October 2020)
Annual precipitation (ERA 5)	ECMWF (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=form, accessed on 15 April 2020)
Long-term monthly precipitation	WORLDCLIM (https://www.worldclim.org/data/worldclim21.html, accessed on 3 November 2020)
Long-term actual evapotranspiration (AET)	CMCC (https://figshare.com/articles/dataset/Global_High-Resolution_Soil-Water_Balance/7707605, accessed on 12 January 2021)
River Network	GloRiC (https://www.hydrosheds.org/page/gloric, accessed on 10 April 2020)
Population Density	JRC GHS-POP (https://ghsl.jrc.ec.europa.eu/download.php?ds=pop, accessed on 3 October 2020)
Statistics water usage for agriculture	AQUASTAT (https://www.fao.org/aquastat/en/, accessed on 15 April 2020)
Statistics of water used by households	AQUASTAT (https://www.fao.org/aquastat/statistics/query/index.html?lang=en, accessed on 15 April 2020)
Drought Code	ERA (https://zenodo.org/record/3250960#.YjniihPMIgp, accessed on 1 June 2020)

Table A4. List of publicly available datasets used to generate the infrastructure-based services account.

Content	Source
Green infrastructure from the World Database on Protected Areas	Protected Planet (https://www.protectedplanet.net/c/world-database-on-protected-areas, accessed on 24 August 2020)
Green infrastructure from the World Database for Key Biodiversity Areas	KBA (http://www.keybiodiversityareas.org/home, accessed on 29 September 2020)
Fragmentation due to roads	Open Street (https://www.openstreetmap.org/#map=7/47.001/28.377, accessed on 15 April 2020)
Fragmentation due to dams	FAO AQUASTAT (http://www.fao.org/nr/water/aquastat/dams/print1.stm, accessed on 15 April 2020)
River network	GloRiC (https://hydrosheds.org/page/gloric, accessed on 10 April 2020)
Vulnerability map from the terrestrial biodiversity indicators	World Bank (https://datacatalog.worldbank.org/dataset/terrestrial-biodiversity-indicators, accessed on 15 April 2020)
Species extinction from the terrestrial biodiversity indicators	World bank (https://datacatalog.worldbank.org/dataset/terrestrial-biodiversity-indicators, accessed on 15 April 2020)

Table A4. *Cont.*

Content	Source
Biodiversity intactness	UK Natural History Museum (https://data.nhm.ac.uk/dataset/global-map-of-the-biodiversity-intactness-index-from-newbold-et-al-2016-science, accessed on 23 June 2020)
Modis burn maps	NASA (https://modis.gsfc.nasa.gov/data/dataprod/mod45.php, accessed on 8 April 2020)
Distribution and density of population from Global Human Settlement Layer	JRC (https://ghsl.jrc.ec.europa.eu/ghs_pop.php, accessed on 15 April 2020)

Appendix B

This appendix contains the sources of the data used to generate the accounts for the study area at the Tier-2 level.

Table A5. List of datasets used to generate the accounts at Tier level 2.

Content	Source
Guinea natural zones (ZAEG)	Dataset provided by G. Jaffrain, IGN-France
FAO map Sénégal-Sud	Dataset provided by M. Diallo, CSE
BRICKS map Sénégal-Sud	Dataset provided by F. Mar, OSS
UTURN regional map	Dataset provided by N. Souverijns, VITO
Regional/local road and rail network (Senegal)	Dataset provided by Mme. Diop
Dams in Senegal	Dataset provided by Mme. Diop
Mining (actual/permits) in Niokolo Koba, Senegal	Dataset provided by Mme. Diop
Annual population of Tamba and Kedo municipalities, Senegal	Dataset provided by Mr. Sadio
Tourism statistics for Niokolo Koba, Senegal	Dataset provided by Mme. Diop
Regional agriculture statistics, Senegal	Dataset provided by Mr. Sadio and Mme. Diallo
Fauna counts and tracking in PNNK, Senegal	Dataset provided by Mme. Diop
Active fire maps (2000–2020), Senegal	Dataset provided by Mme. Diop
Parc zonation for Badiar and Moyen-Bafing, Guinea	Dataset provided by Col. Sedibinet
Regional road and rail network (Guinea)	Dataset provided by Col. Sedibinet and Mr. Camara
Dams in Guinea	Dataset provided by Col. Sedibinet and Mr. Camara
Mining areas in Moyen-Bafing area, Guniea	Dataset provided by Col. Sedibinet and Mr. Camara
Annual population in municipalities, Guniea	Dataset provided by Mr. Oulaye
Agri-Forestation in Bafing and Badiar zones, Guniea	Dataset provided by Col. Sedibinet
Fauna counts and tracking in Moyen-Bafing and Badiar zones, Guniea	Dataset provided by Col. Sedibinet

Appendix C

This appendix contains the sources of the data used to generate the accounts for the study area at the Tier-3 level.

Table A6. List of datasets used to generate the accounts at Tier level 3.

Content	Source
Zoning Moyen-Baying National Park	Dataset provided by P.Kizila, Chimps Foundation
Local land cover maps (2000–2020)	Dataset provided by P.Kizila, Chimps Foundation
Fire frequency in the Moyen-Bafing National Park	Dataset provided by P.Kizila, Chimps Foundation
Mining areas in the MBNP	Dataset provided by P.Kizila, Chimps Foundation
Location and change in village populations	Dataset provided by P.Kizila, Chimps Foundation
Fauna density (chimps and other species)	Dataset provided by P.Kizila, Chimps Foundation
Local roads (dirt roads)	Dataset provided by P.Kizila, Chimps Foundation

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