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Spatial analysis *vis a vis* local perception of anthropogenic pressures on natural habitats of ectomycorrhizal fungi in Wari–Maro Forest Reserve in Benin

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Abstract

Forest ecosystems undergo profound changes due to the combined effects of human activities on carbon footprints and climate change. Although we have evidence of such disturbances, the direct impact on the availability of food resources for local populations is still poorly understood. The present study aims to assess the different changes induced by humans in the natural habitats of ectomycorrhizal fungi (ECM) over time. Two complementary approaches were used: spatial analysis by remote sensing and a survey approach to local perception. In the latter, Landsat satellite images from 2000, 2010, and 2020 were used to assess the spatio-temporal dynamics of land use over the past 20 years and to project changes for 2040. Land use of natural habitats of EcM over the past two decades was mapped using supervised classification to determine the changes. During the field survey, 238 individuals from eight villages surrounding the Forest Reserve of Wari–Maro (FR–WM) were interviewed. The spatial analysis results showed a 49.05% decline in the natural habitats of ectomycorrhizal fungi, from 72.39 % in 2000 to 23.34% in 2020, with a projected decline to 12.8 % by 2040. In contrast, anthropogenic land uses such as tree savannah, shrub savannah, cropland–fallow, and bare soil-housing have increased. Additionally, 87% of interviewed respondents confirmed that they have reduced their visits to the natural habitats of fungi in the FR–WM. The threats to fungal habitats, in increasing order, are agricultural expansion (13.87 %), logging (24.37 %), and grazing, especially overgrazing (43.7 %). Increasing demographics (35,29 %), land scarcity (23.05 %), and poverty (21 %) are considered the main drivers, leading to the above threats. These anthropogenic pressures have led to a significant loss of natural ECM habitats, resulting in a decrease in the natural production of edible fungi from 16,999.92 tons of fresh biomass in 2000 to 5,481.05 tons in 2020, a 58% reduction over 20 years. If this trend continues without intervention, this production is projected to decrease to 3,006.82 tons of fresh biomass by 2040. To mitigate these

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threats and establish sustainable conservation of these EcM natural habitats, appropriate measures must be applied and monitored by all stakeholders involved in the sustainable management of the Wari-Maro Forest reserve.

Keywords – Human disturbance – Benin – Dynamic – Ectomycorrhizal fungi – Natural habitat – Natural production

Introduction

Ectomycorrhizal fungi (EcM) represent vital resources for rural populations in tropical Africa, providing ecosystem services, particularly in terms of food, economy, and medicine (Yorou & De Kesel 2001, Diansambu et al. 2014, Yorou et al. 2017, Ediriweera et al. 2022). A number of these fungi are among the most sought-after wild edible mushrooms in rural communities (Boni & Yorou 2015, Fadeyi et al. 2017). Especially when stocks run out or during periods of food scarcity, they are highly regarded as genuine and cheap alternatives to meat or fish (Eyi Ndong 2009, Yorou et al. 2017). Moreover, by establishing mycorrhizal symbiosis with specific tree species, EcM fungi play an important role in sustaining and regulating forest ecosystems, preserving their ecological balance (Bâ et al. 2011, Yorou et al. 2014).

Under anthropogenic factors such as agricultural expansions, bushfires, deforestation, and overgrazing, wild edible EcM fungi are dwindling populations (Soulama et al. 2015, Charbel & Hassan 2021). Increased anthropogenic pressures result in the disruption of forest ecosystems, often visible through significant alterations in the vegetation structure, and floristic composition, leading to changes in the diversity and productivity of forest food resources (Bouko et al. 2007, Hirissou 2020), or disrupting life cycles and fruiting body production (Denchev et al. 2005, Yorou & De Kesel 2011, Hirissou 2020).

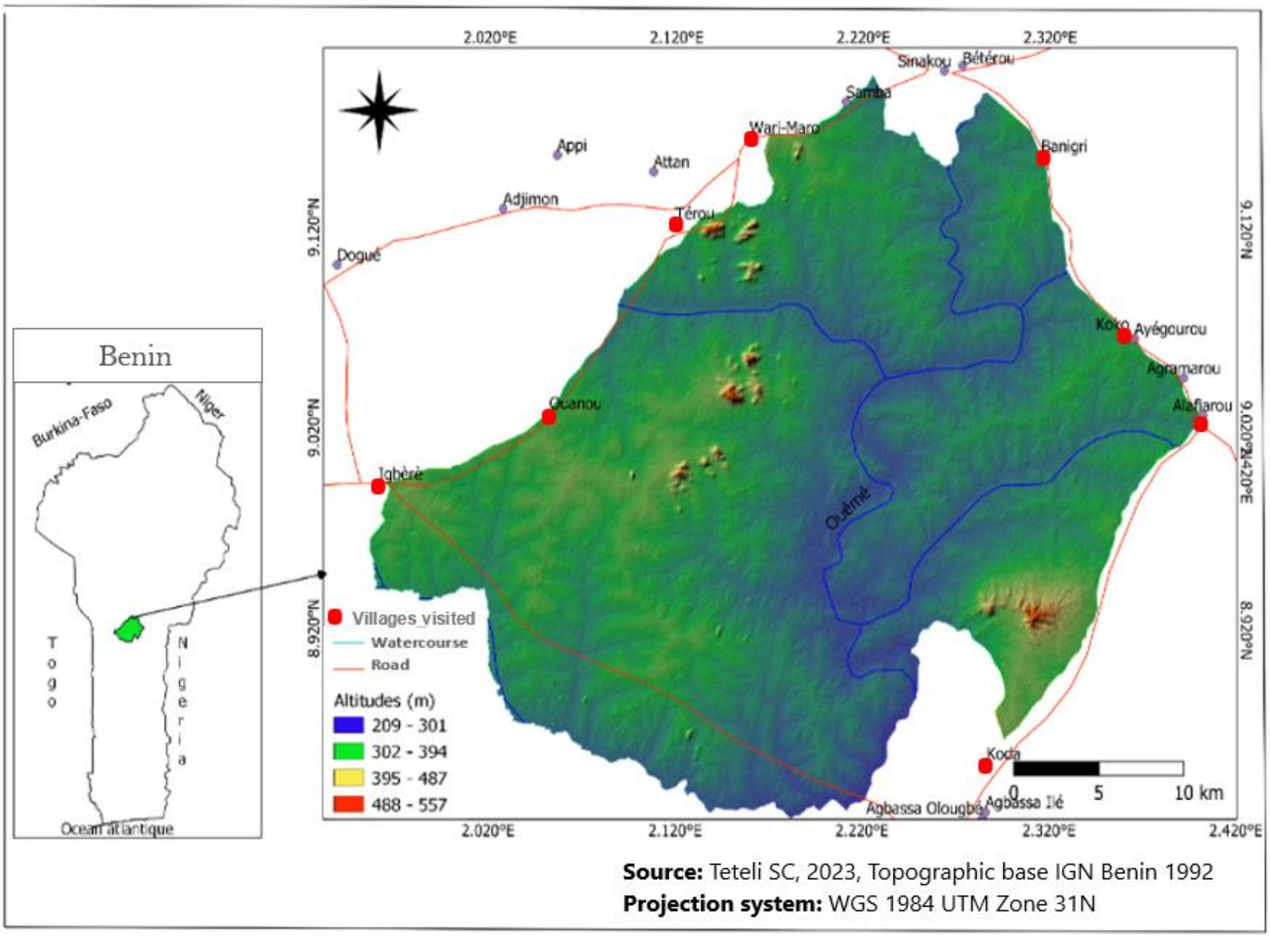
Like in many other parts of the world, Benin is not exempt from the global trends of natural habitat degradation and biodiversity loss, often directly resulting from anthropogenic activities. In this paper, we focus on the Wari–Maro Forest Reserve, once a sanctuary for EcM fungi, known for its high annual productivity of edible EcM fungi (210 kg ha^{-1} yr^{-1}, see Yorou et al. 2001). Due to the increased population growth of the surrounding villages and the settlements of non-local populations in search of land, it has become an enclave of increased anthropogenic pressure. This has led to vegetation cover degradation (Yaya & Issifou 2016), and a change (for the worse) in the conservation status of various rare species found hitherto in the forest reserve (Yorou & De Kesel 2011). To understand the scale and dynamics of this problem, it is imperative to monitor changes in the forest landscape and natural habitats of EcM fungi. Fortunately, remote sensing and spatial data have revolutionized the analysis of habitat and ecosystem dynamics (Iorgulescu & Schlaepfer 2002, Burel & Baudry 2003, Betbeder 2015). These tools enable the extensive study of terrestrial habitats from the space above (Betbeder 2015). While their application has been limited to higher organisms, it is also possible to apply these tools to fungi (Fisher et al. 2016). In contrast to most studies that have focused on habitat dynamics, it is increasingly preferable to integrate human perception with spatial data. This approach is essential for understanding the drivers and factors contributing to the changes observed through remote sensing (Sambieni et al. 2015, Ahononga et al. 2020).

This study carried out in the Wari–Maro Forest Reserve (FR–WM) in Benin, adopts an approach that integrates spatial analysis and qualitative data from local perceptions. We investigated changes observed in the natural habitats of ectomycorrhizal fungal communities, anthropogenic pressures, their drivers, and impacts on the natural production of edible EcM fungal communities. The specific objectives are to: (**i**) examine the spatio-temporal dynamics of land use in the natural habitats of EcM fungi from 2000, 2010, and 2020, with projections to 2040; (**ii**) identify the factors contributing to the degradation of the natural habitats of EcM fungi based on the perceptions of local populations; (**iii**) understand the local population's perception on changes in the natural production of EcM fungi, and (**iv**) estimating the dynamics of EcM biomass fresh production between 2000 and 2040 in the FR–WM.

Materials & methods

Study area

Wari–Maro Forest Reserve (FR–WM) is located in central Benin, between 8° 50' and 9° 20' North latitudes and 2° 10' and 3° 10' East longitudes (Fig. 1). It spans an area of 116 807.72 ha (Amagnide et al. 2015) and has a Sudanian sub-humid tropical climate, with a long dry season, followed by a unit to slightly bimodal rainy season with an average annual precipitation of 1150 mm (Amagnide et al. 2015). Its vegetation consists of a mosaic of forest and savannas (Yaya & Issifou 2016). The landscape features several inselbergs with rounded peaks and slopes ranging from 50 to 300 meters (PAMF 2007). The primary economic activities of the local populations, particularly those bordering the forest reserve, include agriculture, livestock farming, logging, charcoal production, fishing, and hunting (INSAE 2015). The methodology adopted in this study combines spatial analysis of EcM fungal habitat dynamics with qualitative data obtained from the perceptions of local populations.



Source: Teteli SC, 2023, Topographic base IGN Benin 1992
Projection system: WGS 1984 UTM Zone 31N

Fig. 1 – The map of the study area, including the villages considered

Spatio-temporal dynamics of land use in EcM habitats within FR-WM: Analysis from 2000, 2010, 2020, and projections to 2040

Acquisition of satellite images

To investigate the spatio-temporal dynamics of natural habitats, Landsat 7 ETM+ satellite images from 2000 and 2010, and Landsat 8 OLI from 2020 were obtained. All images had a spatial resolution of 30 meters and were captured in February during the dry season to optimize satellite visibility. These images were sourced from the EROS Data Centre of the USGS (https://earthexplorer.usgs.gov/).

Image classification

The acquired images were classified using ENVI software version 5.3 with the Maximum Likelihood algorithm (supervised classification). The selection of this method was guided by our interest in specific land cover classes, particularly the natural habitats of EcM fungi. The official land cover classification of Benin was used to extract classes present in the study area, corresponding to the vegetation types known to be natural EcM habitats (Fisher et al. 2016). The targeted classes included gallery forests, woodlands, and savannah woodlands (Yorou et al. 2014, 2017, De Kesel et al. 2002, Dramani et al. 2022). After performing atmospheric and geometric corrections, the study area was extracted from the image bands to create multispectral images following the method of Sidi et al. (2018). Seven land cover classes were selected for training, and 223 regions of interest were defined on the basis of spectral signatures and field visits during the dry season in February. Sixty-four validation points were collected using GPS for validation, covering all classes of classification assessment (Dossa et al. 2021). Based on training and validation data, a confusion matrix was generated to evaluate the accuracy of the classification through the calculation of overall accuracy and the Kappa index (Salomon et al. 2022).

Quantification of EcM habitat dynamics

To quantify landscape and forest type dynamics, the following tools were used.

Transition matrices revealed the various forms of conversions that different land cover classes underwent (Bogaert et al. 2004). To quantify landscape dynamics at the study scale, two transition matrices were generated, one for the period 2000–2010 and another for 2010–2020.

Landscape structure indices were evaluated for classes associated with EcM habitats. The landscape ecology analysis software FRAGSTATS 4.2 was used to compute the following indices: Number of patches (nj) quantifies the number (n) of patches belonging to a given class (j). An increase in the number of patches in a class is generally assumed to be indicative of an increased fragmentation of that class (Bogaert et al. 2018). Dominance index (Dj) or the Largest Patch Index (LPI) indicates the proportion of the area occupied by the dominant patch in class (j), computed using McGarigal et al. (2002) formula. Anthropization index is derived from landscape composition, representing the ratio of anthropogenic classes to natural classes (Bogaert et al. 2018).

Modelling and prospective simulation of EcM habitat land use in FR–WM by 2040

The simulation of land use in vegetation types suitable for EcM fungi by 2040 involved using the "Land Change Modeler" tool in the TerrSet software (formerly IDRISI) (Eastman 2009). The process involved the following steps:

Analysis of potential transitions – A transition is defined as the change from one land cover category to another (Maestripieri 2012). This step marked the beginning of prospective scenario design, using data from 2000 and 2010 to analyze transitions between land cover classes, aiding in the specification of transitions. Based on these transitions, trends and the dominant scenarios for future land use predictions were determined.

Definition of change factors (Selection of explanatory variables) – After assessing the strength of variables on transitions, six variables were considered. Two were physical (static) variables: altitude and soil aspect. The four socio-economic (dynamic) variables included the distance from agricultural areas, housing, rivers, and roads, all of which impact land cover change (Serneels & Lambin 2001, Li et al. 2016).

Model calibration – This was performed using previous data, specifically land cover images from 2000 and 2010. Calibration aimed to validate or improve the model's alignment with actual data. Based on observed changes between 2000 and 2010 and the explanatory variables, probability transition maps were generated using neural networks (Mishra & Rai 2019).

Model validation and 2040 Simulation – The classified image from 2020 served as a reference. A 2020 simulation was carried out and compared with the actual classified image from 2000. A chi-squared test at ~~a~~ 5% significance level was performed on the areas of land cover classes in these two maps to evaluate the degree of similarity between the simulation and the reference map (Osseni et al.

2023). After model validation, the land use map of the Wari–Maro Forest Reserve was simulated for the year 2040.

Local perception on the evolution of natural habitats of EcM, factors and drivers of degradation, and impact on the natural production of EcM in FR–WM

Sampling and Selection of Survey Villages

To determine the number of individuals to be surveyed in each village, an exploratory study was first conducted with a few people in villages around FR–WM. Respondents were asked a two–way question: "Do you have knowledge of changes in FR–WM and the fungi?" The number (n) of people to be surveyed in each village was determined using the normal approximation of the binomial law (Dagnelie 1998), as follows:

$$\boldsymbol{n = U^2_{1-\frac{\propto}{2}} \times P\ (1 - P)/d^2}$$

U - The standardized normal variable at 1–α/2, squared to give 4; **P -** The proportion in a given village of people with knowledge of changes in FR–WM and the fungi; **d -** The margin of error, with a value of 8%.

For village inclusion, a zone of 1 km around the reserve was created, and eight villages within this zone were selected. In each village, respondents were chosen on a rational basis, with a preference for knowledge of fungi and indigenous expertise. The surveyed individuals represented various sectors involved in the use and management of FR–WM, including farmers, loggers, artisans, traders, and semi-nomadic farmers. A total of 238 individuals were interviewed separately, distributed across the eight villages: Wari–Maro, Ouanou, Térou, Igbérè, Banigri, Alafiarou, Koda, and Koko.

Data collection

A field survey was conducted among the local populations living around FR–WM and those involved in its management in the form of a semi-structured interview based on a questionnaire prepared in advance and integrated into the electronic data collection tool KoboCollect. Focus group interviews were also conducted in each selected village (Berthier 2006). The collected data were primarily qualitative and focused on the local population's perceptions of changes in EcM habitat over time, the factors and drivers of habitat degradation, and their effects. The study also aimed at understanding changes in the production of EcM in the reserve. Lastly, it investigated whether there was a link between habitat degradation and EcM production. At the beginning of the survey, its context was explained to the respondents in the local language, if necessary. The questions asked were of single-choice type. For example, regarding the perception of the evolution of EcM fungal habitats and the evolution of EcM production over time, respondents provided a single opinion (Progression, Regression, or Impact). For each of the following parameters: EcM degradation factors, drivers of EcM degradation, and anthropic threats to EcM production, respondents were asked to indicate the single choice factor they found most important. The questionnaire was administered with the consent of the respondents.

Data processing and analysis

Descriptive statistics were used to describe the local population's perception of habitat evolution, the level of evolution, factors of habitat degradation, and their drivers. This statistical approach also described the status and the level of EcM fruiting body harvest. The relative frequencies of each of the parameters considered were determined, namely the evolution of EcM habitats, degradation factors and drivers of EcM habitat, EcM production dynamics, and anthropogenic threats impacting EcM habitat production according to the perception of the local population.

The formula for obtaining citation frequencies (Fc) is as follows:

$$Fc = nc / N$$

nc - The number of respondents who mentioned the citation c; N - the total number of respondents.

All analyses were performed using the R statistical software version 3.5.0.

Estimation of the dynamics of EcM biomass fresh production between 2000 and 2040

To estimate the natural production of EcM in the FR–WM, the study of Yorou et al. (2001) was used as the basis for calculating the productivity of EcM in this reserve. According to their study, EcM natural productivity in the FR–WM varies between 196.2 – 225.4 kg ha^{-1} yr^{-1} of fresh biomass (mean: 210.8 kg ha^{-1} yr^{-1}). Based on this estimate, and taking into account the surface area of EcM habitats, the total production (*Pa*) of EcM for a given year was determined using the following formula;

$$Pa = Pv * Sa$$

Where *Pv* is the average productivity of EcM in FR–WM; *Sa* is the area of EcM habitats in the year *a*.

Results

Analysis of historical dynamics from 2000, 2010, 2020, and projections to 2040

The overall accuracy and Kappa coefficient values of the classifications ranged from 92.02% to 99.81%. The classification results are, therefore, acceptable, with significant discrimination among different land cover classes (Fig. 2).

Table 1 illustrates the land cover of different classes in FR–WM in 2000, 2010, and 2020, respectively. A noticeable decline in the coverage of EcM fungal habitats is observed between 2000 and 2020. These habitats decreased from 72.39% in 2000 to 30.32% in 2010 and to 23.34% in 2020. In 2000, the landscape was dominated by woodlands (70.47%), followed by tree shrub savannah (20.28%). At the same time, cropland–fallow (0.09%), bare soil–housing (0.08%), and plantations (0.07%) were nearly non–existent in the year 2000. Over the course of 20 years, the EcM-dominated ecosystems experienced a significant decrease, especially the gallery forests and woodlands, which lost 1.53% and 47.51% of their respective areas between 2000 and 2020, respectively. In contrast, anthropogenic land cover classes, such as tree savannah–shrub savannah, cropland–fallow, and bare soil–housing, have increased by 48.8%, 4.94%, and 0.25%, respectively, in the same period. The land cover transition matrix for the periods 2000–2010 and 2010–2020 clearly demonstrates that the natural habitats of EcM have lost their areas yielding to anthropogenic land uses.

Fig. 3 shows the evolution of landscape structure indices between 2000 and 2020. The anthropization index for this forest increased from 0.26 in 2000 to 2.93 in 2020 (Fig. 3a). This increase in the anthropization index confirms the progression over time of anthropogenic land use at the expense of natural land use. A reduction in the proportion occupied by the largest patch is observed in different land use classes associated with the natural habitats of EcM fungi (Fig. 3b). This means that the patch sizes are decreasing over time. Consequently, land use classes related to the natural habitats of EcM fungi are characterized by a progressive dominance of smaller patches. The decrease in the number of patches in gallery forests over time indicates their reduction (Fig. 3c). In contrast, the increase in the number of patches in woodlands reflects their fragmentation.

Table 1 – Land cover in FR–WM from 2000 to 2020.

Habitat type	Land use class	Year 2000		Year 2010		Year 2020	
		Area (ha / %)	Total (ha / %)	Area (ha / %)	Total (ha / %)	Area (ha / %)	Total (ha / %)
EcM Habitat	Gallery forest	2,138.91 / 1.92	80,643.83 / 72.39	1,230.02 / 1.11	33,776.01, / 30.32	423.33 / 0.38	26,001.2 / 23.34
	Woodland–Savannah woodland	78,504.92 / 70.47		32,545.99 / 29.21		25,577.87 / 22.96	
Non–EcM Habitat	Dense dry forest	7,911.76 / 7,10	30,747.61 / 27.58	4395.97 / 3.95	7,7625.9 / 69.68	2,352.81 / 2.11	87,497.45 / 76.66
	Tree savannah–Shrub savannah	22,593.18 / 20.28		70,269.65 / 63.08		76,959.65 / 69.08	
	Plantation	73.53 / 0.06		82.06 / 0.07		120.31 / 0.11	
	Cropland–Fallow	73.53 / 0.06		2,763.37 / 2.48		5,604.63 / 5.03	
	Bare soil–Housing	95.61 / 0.08		114.86 / 0.10		369.85 / 0.33	

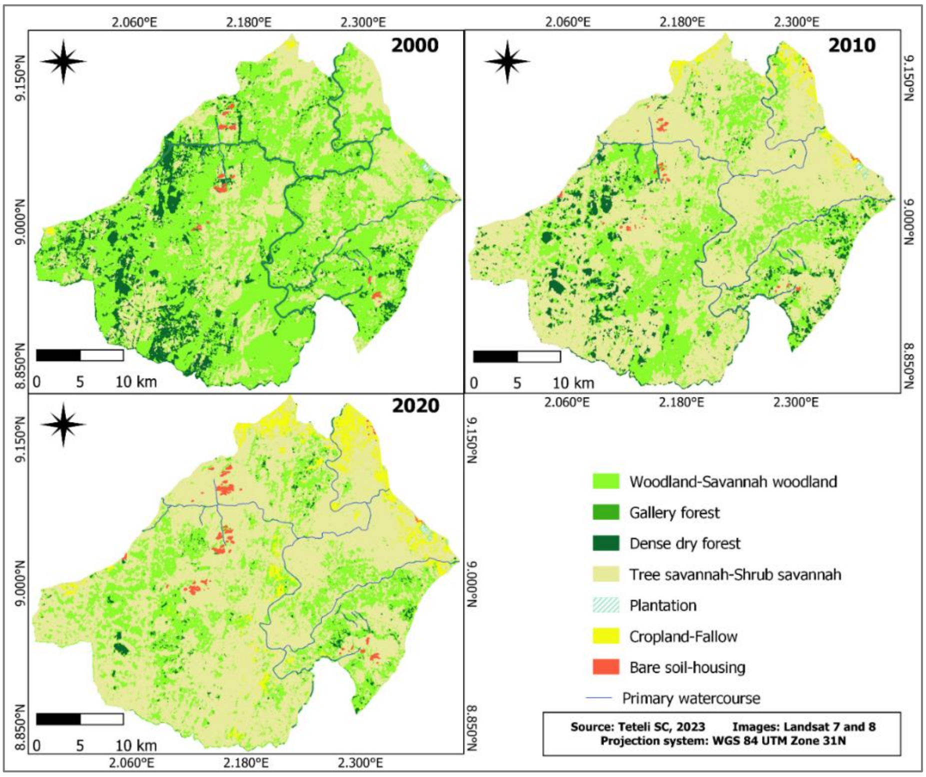


Fig. 2 – Spatial structures (vegetation types) of FR–WM in 2000, 2010 and 2020)

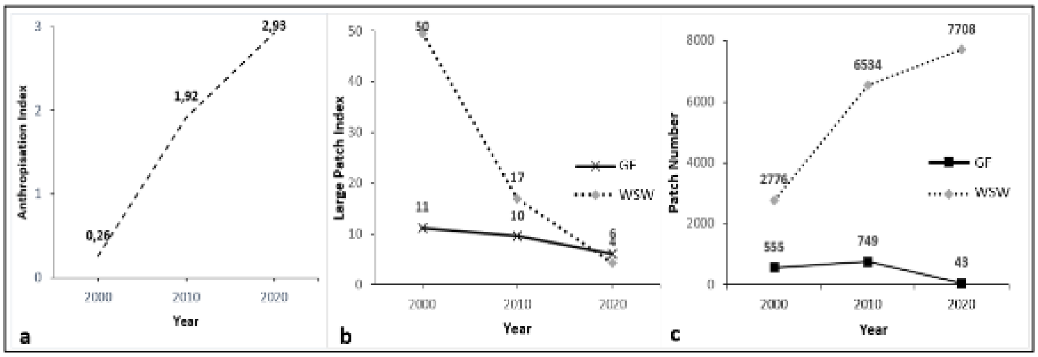


Fig. 3 – a Anthropization index. b dominance index, and c number of patches. GF - Gallery Forest, WSW - Woodland-Savannah Woodland

The accuracy rate of 71.25% demonstrates that the selected variables (altitude, soil aspect, agricultural areas, housing, rivers, and roads) significantly explain the observed transitions (Fig. 4). The multi-layer perceptron (MLP) method showed that, among the six variables, the distance to farms (agriculture) is the most influential variable in explaining the observed transitions, followed by the variables, buildings and roads. Both agriculture and building variables represent 71.33% of the accuracy rate when the other variables remain constant. This highlights the significant impact of agriculture and buildings on the changes in the FR–WM and their effect on EcM habitats. After simulating the land cover map for the year 2020, the proportions of land cover classes obtained were compared to those in the classified 2020 map using the chi-square test to assess the level of similarity. Statistically, the difference in the proportion of land cover classes between the two maps is not significant (*P* value = 0.94 > 0.05).

Fig. 4 illustrates the land use prediction for FR–WM in the year 2040. A visual inspection of this map indicates a significant trend characterized by a substantial dominance of anthropogenic land uses compared to the natural habitats of EcM fungi.

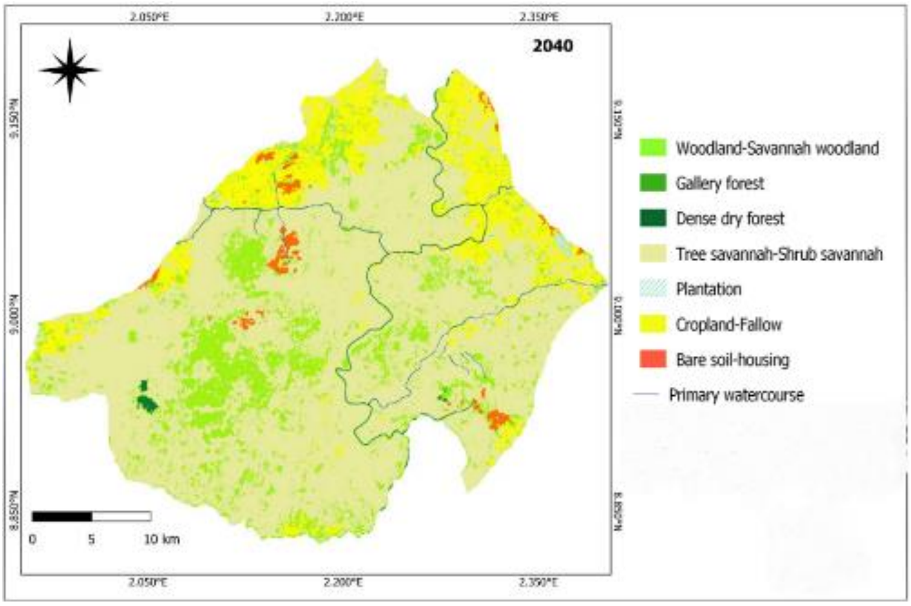


Fig. 4 – Prediction of land use in the FR–WM in 2040

Table 2 presents the prediction of the evolution of different land use classes by 2040 in the FR–WM when the considered change factors are maintained. A continuous growth in anthropogenic land use areas will be observed in 2040. In contrast, classes affiliated with the natural habitats of EcM fungi are expected to further by 2040, especially the woodlands, which will decrease from 22.96% in 2020 to 12.57% in 2040, and gallery forests to decrease from 0.38% in 2020 to 0.23% in 2040 (Table 2).

Table 2 – Predicted Land Use Evolution for 2040

Habitat type	**Land use class**	**Year 2020 Area (ha / %)**	**Year 2040 Total (ha / %)**	**Relative evolution (%)**	
EcM Habitat	Gallery forest	423.33 / 0.38	256.37 / 0.23	-0.11	-10.5
	Woodland-Savannah woodland	25,577.87 /22.96	14,007.56 / 12.57	-10.39	
Non-EcM Habitat	Dense dry forest	2,352.81/2.11	329.43 / 0.30	-1.81	+9.94
	Tree savannah-Shrub savannah	76,959.65 / 69.08	81,846.74 / 73.47	+4.39	
	Plantation	120.31 / 0.11	120.31 / 0.11	0	
	Cropland-Fallow	5,604.63 / 5.03	13,603.53 / 12.21	+7.18	
	Bare soil-Housing	369.85 / 0.33	572.55 / 0.51	+0.18	

Local perception of the population regarding the evolution of ectomycorrhizal natural habitats

Fig. 5 illustrates the local population's perception of the evolution of ectomycorrhizal natural habitats. The 87.4% of the population investigated have found that the ectomycorrhizal natural habitats declined over time.

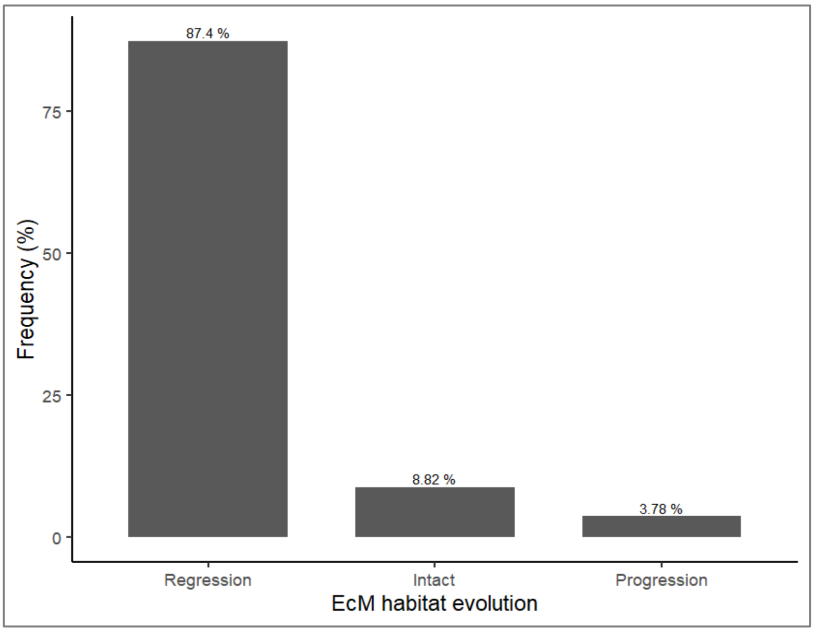


Fig. 5 – Evolution of EcM habitats according to local population perception

Fig. 6 below presents the various degradation factors identified. According to the local population, several factors contribute to the degradation of ectomycorrhizal habitats, with the factors ranked in terms of frequencies as follows: overgrazing by cattle (43.7%), timber harvesting (24.3%), agriculture (13.87%), charcoal production (7.98%), urbanization (6.72%), bushfires (2.1%), and herbicides (1.26%) (Fig. 6).

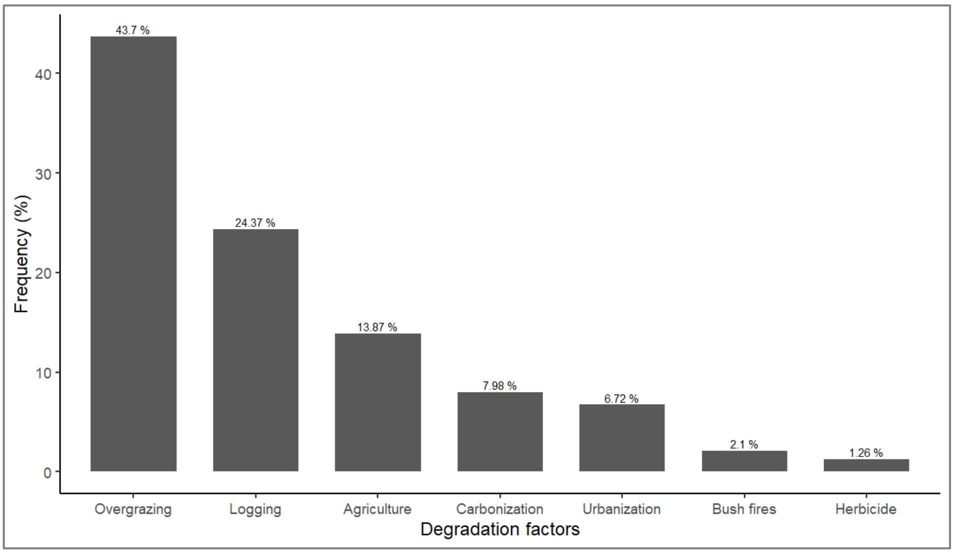


Fig. 6 – Factors contributing to the degradation of EcM habitats according to the perception of the local population

Fig. 7 illustrates the various drivers of degradation as mentioned by the local population. The degradation of ectomycorrhizal habitats is attributed to several drivers (indirect factors), with demography (35.29%) ranking first, followed by land scarcity (26.05%), poverty (21%), and migration (17.65%).

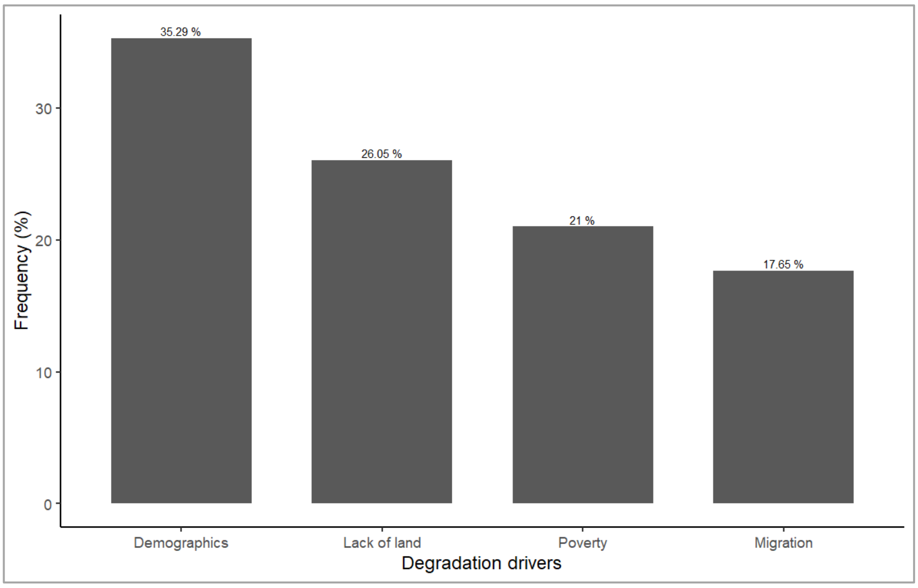


Fig. 7 – Degradation drivers of EcM habitats according to the perception of the local population

According to the results, 54.62% of the local population indicated that EcM production has declined over time (Fig. 8). Only 6.72% of individuals reported an improvement in EcM production. For 26.47% of the respondents, there has been no change in EcM production (Fig. 8).

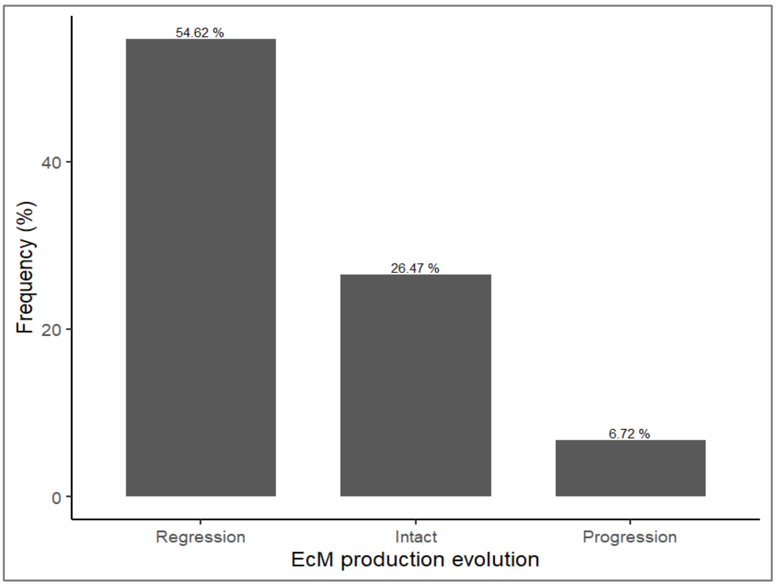


Fig. 8 – Evolution of EcM production according to the perception of the local population

Impact of Degradation of Natural Habitats on the Natural Production of EcM

Fig. 9 shows the dynamics of EcM production in the FR–WM over time. EcM production in the FR–WM has decreased, corresponding to the reductions in their habitat area. Thus, EcM production, fresh biomass estimated at 16,999.92 tons in 2000, fell to 7,119.98 tons in 2010 and 5,481.05 tons in 2020. If the trend of EcM habitat loss continues in the future, natural EcM production will continue to decline, possibly falling to 3,006.82 tons of fresh biomass in 2040 (Fig. 9).

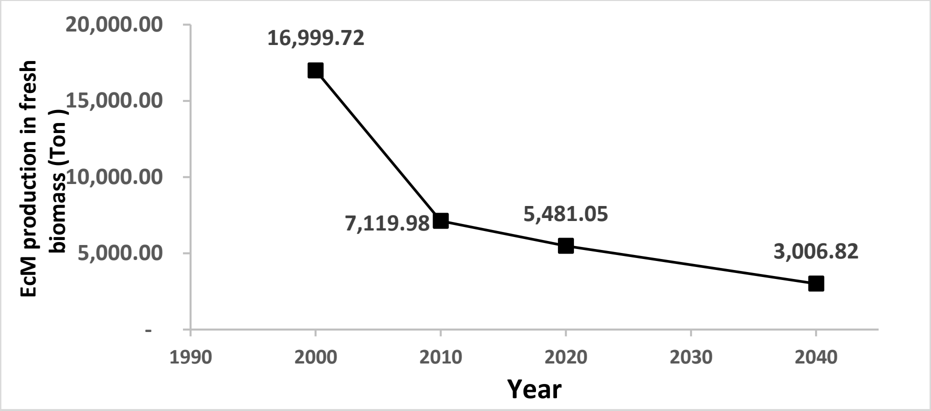


Fig. 9 – Dynamics of EcM natural production from 2000 to 2040

According to the results, 80% of the respondents perceived that there is a connection between the degradation of natural habitats and the natural production of EcM. This connection is explained by several threats that affect the natural production of EcM (Fig. 10).

Anthropogenic pressures affect the natural production of EcM in various ways. These include soil compaction due to cattle grazing (41.18%). Secondly, according to the local population, EcM partner trees are limited (31.51%). Additionally, agricultural expansion (20.59%) affects EcM production, where farming practices such as ploughing and the use of chemical fertilizers reduce EcM fruiting and development (Fig. 10). Other threats mentioned by a minority included bushfires, herbicide use, and poor water infiltration.

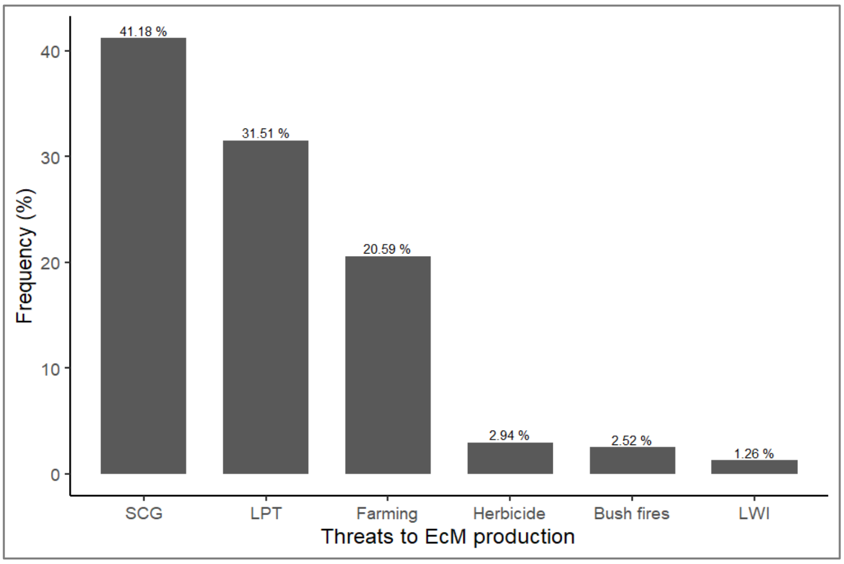


Fig. 10 – Different anthropogenic threats recognised by local populations as impacting the natural production of EcM SCG - Soil compaction Grazing, LWI - Low water infiltration, LPT - Low presence of partner trees

Discussion

Methodology criticism

Spatial analysis based on satellite images has enabled us to observe land use over a period of twenty years and to perceive the various changes that have occurred. This method, used in many studies, has now become a standard approach in the study of spatio-temporal dynamics of ecosystems in general, more specifically of forest ecosystems (Toko 2014, Sidi et al. 2018, N'Davaro et al. 2023). The spatial analysis of the natural habitats of ectomycorrhizal fungal communities in the FR–WM was carried out by focusing on the vegetation types sheltering the tree species that are partners of

EcM. This technique was also used by Fisher et al. (2016) to map the distribution of EcM fungi by remote sensing, identifying partner tree species from space. Through this study, it is confirmed that remote sensing alone is insufficient, as it cannot explain certain aspects related to human actions. Hence, it is important and relevant to integrate and complement local knowledge with the results obtained from remote sensing in the study of natural ecosystem dynamics. Similar remarks were made by Sambiéni et al. (2015) and Bourque (2017), who reported that local knowledge helps to better understand the social, economic, and environmental issues related to the management of natural resources and the changes they undergo. Local communities are often the first to be affected by the impacts of anthropization, and also the beneficiaries of the ecosystem services provided by EcM. Hahn-Hadjali (2000) aligns with these perspectives and suggests exploring local perceptions to dispel any ambiguity about changes in vegetation composition and to understand the underlying factors. In Benin, Ahononga et al. (2020) applied this method to explain deforestation and degradation of forest ecosystems in the Sudanian and Sudanian–Guinean regions of Benin and agreed that involving community opinion is an effective approach.

The estimation of natural EcM production in FR–WM is supported by the study of Yorou et al. (2001), which previously determined the EcM productivity of this reserve. The area occupied by EcM habitats is also a necessary parameter for determining this productivity and its dynamics over time. Clearly, EcM production is influenced not only by the spatial dynamics of their habitats but also by climatic conditions. Nevertheless, in this study, we have attempted to illustrate the influence of habitat loss dynamics on natural EcM production. This non–inclusion of climatic parameters is mainly due to the short duration of the study, which made it impossible to include a data collection system over a sufficiently long period.

Past and future spatial dynamics of the habitats of EcM in the FR–WM

The results indicate a significant regression of the natural habitats of ectomycorrhizal fungal communities from 2000 to 2020. In the FR–WM, these habitats, namely gallery forests and woodlands, have regressed in favor of anthropic classes, namely tree savannah-shrub savannah, cropland-fallow, and bare soil-housing. These findings and observations are in line with studies by Bouko et al. (2007) and Yaya and Issifou (2016), conducted in the same forest. Similar observations were made in the classified forest of Monts Kouffé, adjacent to the FR–WM by Toko (2014). This evolution reflects the increasing demand for fertile land for agriculture and related activities (charcoal production, illegal logging, overgrazing, etc.). These corroborate the findings of Tovihessi (2018), Ahononga et al. (2020), Dossa et al. (2021), and Teteli et al. (2023), who demonstrated that the shortening of fallow periods and demographic growth contribute to the expansion of anthropic areas. It also highlights the effects of population growth on the regression of natural forests in the Ivory–Coast over the past two decades. This increase in anthropic areas in the last two decades can be explained by the discontinuation in 2006 (Yaya & Issifou 2016) of the Forest Massif Management Program of Agoua, Monts Kouffé, and Wari–Maro (PAMF). This program aimed primarily at the integrated management of the FR–WM through sustainable ecosystem management systems, with the participation of local populations (PAMF 2007). Indeed, during field surveys, a progressive advance of agricultural and housing plots beyond the reserve boundaries was observed, due to reduced forest surveillance. In conclusion, it should be noted that the natural habitats of ectomycorrhizal fungi have regressed over time due to anthropogenic actions on the reserve.

The strong influence of socio-economic variables such as urban growth, road development, and agricultural fields shows the impact of human presence and activities on land use changes in the FR–WM. These results align with those of Li et al. (2016), who showed that socio-economic variables are potential driving forces behind changes in vegetation types. The simulation results predict an increase in cultivated areas and housing at the expense of vegetation types, which are the natural habitats of EcM. According to various previous research studies, including those of Serneels and Lambin (2001) and Reza (2016), the main causes of housing expansion are the explosion of population growth and subsistence activities. Local populations, in their efforts to meet their daily needs, exert pressure on the natural environment, consequently impacting biodiversity, including fungal resources (Reza 2016).

Local population perception of evolution, the factors and the drivers of degradation of EcM natural habitats

The results from local populations indicate that the FR–WM is severely degraded. This perception aligns with the conclusions of Bouko et al. (2007) and Toko (2014), who highlighted the reality of forest landscape fragmentation in northern Benin. The perception of the local population thus confirms the results obtained from spatial analysis by remote sensing. Therefore, the local population is aware of the loss of natural habitats of fungi in the FR–WM.

Several factors were identified by the local population as drivers of forest cover degradation and regression, including grazing, agriculture, wood harvesting, bushfires, and urbanization. These results are consistent with those of Biaou et al. (2019), Ahononga et al. (2020), and Sambiéni et al. (2015), who assessed the same factors from the local population living near the forests of northern and central Benin. Grazing was the most frequently mentioned factor of degradation by local populations. In the dry season, the protected areas in northern Benin are a destination for Sahelian herders from Burkina Faso and Niger in search of pastures (Lesse 2016). The same author showed that pasture areas are increasingly threatened with overgrazing problems, leading to landscape changes and, consequently, disruption of the productivity of natural resources, including fungal resources.

Concerning the drivers of degradation, population growth was cited most frequently by local communities. The implication of population growth to the process of habitat degradation has been widely reported by Munthali et al. (2019). The growth of the number of individuals in households leads to an increase in the number of people to feed and the need for more income more agricultural produce, and therefore more agricultural land (Avakoudjo et al. 2014). The local populations, namely the populations of the Tchaourou and Bassila municipalities that share the FR–WM, have experienced constant population growth with growth rates of 4.86 and 4.87, respectively, between 2002 and 2013 (INSAE 2015). In this context, implementing actions to improve the forest management system would be an urgent means to reduce deforestation and degradation caused by unsustainable agricultural activities. To do this, the promotion of sustainable soil conservation actions such as Improved Production Systems and agroforestry, which enhance soil fertility, combined with agricultural intensification actions, would contribute to preserving forest areas and their biodiversity. Similarly, mentioning poverty as a degradation factor suggests the implementation of strategies to improve the livelihoods of the local populations through income–generating activities compatible with forest resource conservation and sustainable use practices.

Impact of anthropogenic pressures on the production of EcM

The results indicate that the degradation of forest ecosystems, including the natural habitats of EcM, has an impact on their natural production. Hirissou et al. (2020) demonstrated that anthropization affects the natural production and diversity of mycorrhizal fungi. Several threats hindering the natural production of EcM were mentioned by local populations, including the low presence of partner trees for EcM, soil compaction due to grazing, herbicide use, bushfires, agricultural expansion, etc. The local populations themselves confirmed the consequences of anthropogenic pressures on the natural habitats of EcM. Similar threats have also been reported by Yorou and De Kesel (2011) and Denchev et al. (2005). According to Yorou and De Kesel (2011) and Kolimedje et al. (2021), the threats to fungi in Benin are related to the destruction of forests and the qualitative changes to their natural habitats. In particular, for EcM, these studies reveal that selective logging without the enrichment of partner trees has an impact on the natural production of EcM.

The estimated natural production of EcM has fallen over time from 16,999.92 tons of fresh biomass in 2000 to 5,481.05 tons in 2020, reporting a loss of 58% in 20 years. If appropriate measures are not taken and the same pressures continue to persist, the decline in natural EcM production could continue until it reaches 3,006.82 tons of fresh biomass in 2040. These numbers are not completely reliable, as they illustrate production when referring only to the loss of EcM habitat niches. Undoubtedly, other factors not directly related to the loss of habitat area, such as climatic variabilities and restoration efforts, would also have an influence on this loss of EcM production. Taking these additional climatic factors into account is, therefore, an important aspect for future studies, in order to include the maximum number of parameters influencing EcM production. To this end, the 2040 production forecast made in this study may not be observed in the event of future restoration and protection interventions in the reserve.

The dynamics of the loss of natural habitats have a significant impact on the production of EcM. These fungi establish a symbiosis with plant roots, promoting the absorption of nutrients from the soil. However, the degradation of natural habitats due to urbanization, deforestation, or other human activities alters the environmental conditions necessary for the growth of EcM in particular and that of the host trees. Also, the disappearance of specific host trees and the disruption of mycorrhizal networks influence the diversity and abundance of EcM. These fungi play a crucial role in the health of forest ecosystems by facilitating the exchange of nutrients between plants. Thus, the loss of their natural habitats leads to a reduction in their natural production, thus compromising the regeneration of forests and the stability of forest ecosystems. Therefore, the conservation of natural habitats becomes essential to preserve this symbiosis which is crucial for biodiversity and the health of forest ecosystems.

Conclusions

The mapping of forest cover dynamics obtained from satellite images from 2000 to 2020 revealed a significant regression of approximately 49.05% in forest formations dominated by ectomycorrhizal fungi. This adverse change in the natural habitats of EcM is also confirmed by the perceptions of the surveyed local communities. Several degradation factors were mentioned by the local population, mainly related to human activities. In principle, edible EcM fungi are a renewable food resource, but the changes observed in the FR-WM and the degradation of EcM habitats have significant negative influences on their biomass production. Without the implementation of appropriate measures and adherence to conservation efforts, these EcM habitats will continue to regress, thereby reducing the production of EcM and possibly jeopardizing many other ecosystem services connected to it. To ensure the sustainability of invaluable ectomycorrhizal fungal resources in the FR-WM, reducing human pressure on this reserve is crucial. To do so, it is necessary to raise awareness and provide environmental education to the population about the importance of protecting and conserving the FR-WM for its sustainable management, initiate projects to promote income-generating activities compatible with the local population, especially those involved in the degradation of the reserve, upgrade the management plan for the FR-WM by adopting a landscape approach that considers all sources of threats to forest conservation, involve local populations in reforestation by encouraging them to plant trees on their parcels and in the surrounding areas and strengthen security and increase surveillance to restrict access to the forest and to prevent its plundering.

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