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Indigenous Knowledge and Sustainable Management of Forest Resources in a Socio-Cultural Upheaval of the Okapi Wildlife Reserve Landscape in the Democratic Republic of the Congo

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Abstract

The Okapi Wildlife Reserve (OWR) in northeastern Democratic Republic of the Congo represents both a biodiversity hotspot and the ancestral homeland of the Indigenous Mbuti and Efe peoples, whose livelihoods and knowledge systems are closely tied to forest resources. This study investigates how Indigenous knowledge and practices contribute to sustainable resource management under conditions of rapid socio-cultural transformation. A mixed-methods approach was applied, combining socio-demographic surveys (n = 80), focus group discussions, floristic inventories, and statistical analyses (ANOVA, logistic regressions, chi-square, MCA). Results show that hunting, fishing, gathering, and honey harvesting remain central livelihood activities, governed by customary taboos and restrictions that act as de facto ecological regulations. Agriculture, recently introduced through intercultural exchange with neighboring Bantu populations, complements rather than replaces traditional practices and demonstrates emerging agroecological hybridization. Nevertheless, evidence of biodiversity decline (including local disappearance of species such as *Dioscorea* spp.), erosion of intergenerational knowledge transmission, and increased reliance on monetary income indicate vulnerabilities. Multiple Correspondence Analysis revealed a highly structured socio-ecological gradient (98.5% variance explained; Cronbach's α = 0.977), indicating that perceptions of environmental change are strongly coupled with demographic identity and livelihood strategies. Floristic inventories confirmed significant differences in species abundance across camps (ANOVA, $p < 0.001$), highlighting site-specific pressures and the protective effect of persistent customary norms. The findings underscore the resilience and adaptability of Indigenous Peoples but also their exposure to ecological and cultural disruptions. We conclude that formal recognition of

Indigenous institutions and integration of their knowledge systems into co-management frameworks are essential to strengthen ecological resilience, secure Indigenous rights, and align conservation policies with global biodiversity and climate agendas.

Keywords: indigenous peoples; traditional ecological knowledge; socio-ecological resilience; biodiversity conservation; sustainable management; OWR; DRC

1. Introduction

The forests of the Congo Basin, encompassing over 200 million hectares [1], constitute the world's second largest tropical forest ecosystem after the Amazon [2]. These forests are central to global challenges related to climate change and biodiversity conservation [3]. They provide numerous ecosystem services critical to the survival of local populations, offering diversified income sources at both local and national scales [2]. Approximately 60 million people living in or near these forests depend on them for their livelihoods, while some 40 million urban inhabitants benefit from forest resources [1]. The region hosts over 150 distinct ethnic groups [4] and encompasses the ancestral lands of many Indigenous Peoples (IPs).

IPs, recognized as the original inhabitants of the Democratic Republic of Congo (DRC) [5], number an estimated two million within forested areas [6]. Their cultures, belief systems, and subsistence strategies are deeply intertwined with forest ecosystems [7]. The forest supplies them with bushmeat, gathered and fishery products, medicinal plants, and materials essential for tools and housing; resources vital for their existence [5,7]. The diversity of ethnic groups, languages, histories, and intercommunity relations [8] has fostered unique lifestyles among IPs.

Ref. [9] reports a correlation between Indigenous territories and areas of high biodiversity conservation value. Leveraging their local and ancestral knowledge, IPs contribute substantially to the sustainable management of tropical forests, safeguarding approximately 80% of global biodiversity [7]. The significance of such local knowledge systems was underscored during the 1992 Earth Summit in Rio, highlighting their potential to inform sustainable development policies for biodiversity preservation [10]. Indigenous resource acquisition practices reflect a harmonious coexistence with nature, emphasizing their critical role in biodiversity management [11].

According to [12], the traditional lifestyles of IPs promote forest ecosystem protection and facilitate natural resource regeneration, as their exploitation practices exert minimal ecological disturbance and do not degrade resource bases [13]. Nonetheless, development policies, including the allocation of forestry and mining concessions, establishment of protected areas, and infrastructure development on customary lands, have profoundly disrupted Indigenous sociocultural systems [14]. Such intensive resource exploitation threatens Indigenous livelihoods [15] and drives progressive sedentarization [16], jeopardizing the cultural richness and traditional knowledge that underpin forest conservation [5].

Although numerous studies have emphasized the importance of Indigenous knowledge in sustainable forest management [4,17,18], few adopt a holistic approach integrating sociodemographic dynamics, endogenous practices, environmental perceptions, intergenerational knowledge transmission, and floristic inventories concurrently. Global [19,20] and regional [21,22] assessments often remain general, normative, or focused on non-Congolese contexts, neglecting the hybridization of traditional practices with innovations emerging from interethnic contact. To address this gap, empirical multisource data are critical to comprehensively document the complexity of endogenous knowledge in the specific landscape of the Okapi Wildlife Reserve (OWR). Such insights are essential to elucidate mechanisms of adaptation, resilience, and vulnerability among IPs amid contemporary sociocultural and ecological changes, thereby substantiating the imperative for integrated approaches to rights recognition and co-management frameworks.

In the OWR, notable transformations are occurring in the livelihoods of IPs who historically depended solely on hunting, fishing, and gathering. In response to shifting local socioeconomic conditions and evolving needs, these traditional activities are insufficient to ensure subsistence [23]. Consequently, these communities are developing nature-based knowledge systems aimed at sustainable resource and land use.

It is thus imperative to investigate the following fundamental questions:

Q1. *Who are the IPs of the OWR?*

Q2. *What activities do they do?*

Q3. *How do they know and regulate nature?*

Q4. *Where and how do they prefer to live and feel satisfied?*

Q5. *What changes do they perceive in their habitat?*

This study aims to investigate how Indigenous knowledge and practices contribute to sustainable resource management under conditions of rapid socio-cultural transformation. It specifically analyzes:

(1) the sociodemographic profiles of IPs in relation to their activities and indigenous forest conservation strategies;
(2) their traditional ecological knowledge and customary resource governance;
(3) their social perceptions of environmental change and their future aspirations;
(4) the pathways of intergenerational knowledge transmission; and
(5) the abundance of woody species within their habitats.

2. Materials and Methods

2.1. Overview of the Study Area

According to [24], the OWR is located in the northeastern part of the DRC, straddling the provinces of Ituri and Haut-Uélé. It lies between 0° and 3° North latitude and 27° to 30° East longitude, at altitudes ranging from 700 to 1000 m above sea level. Covering a total area of 1,372,625 hectares, the reserve is situated within the territory of Mambasa (90%), followed by Wamba (7%) and Watsa (3%) (Ministerial Decree No. 045/CM/ECN/92 of 2 May 1992).

The climate is transitional, falling between the Af and Am designations within the Köppen classification system. Precipitation follows a bimodal distribution, with rainy seasons peaking around the equinoxes and dry periods coinciding with the solstices. Annual rainfall ranges from 1600 to 1800 mm, averaging 1700.9 mm. The lowest mean monthly precipitation occurs in January (60.3 mm), while the highest is observed in October (205.3 mm). Notably, precipitation patterns have shifted over the past two decades, resulting in considerably extended dry seasons. These changes have exerted marked effects on the agricultural calendar.

The reserve is predominantly situated in the eastern lowland forests of the central Congo Basin, at the threshold of the transition to the country's eastern montane forests. While most of the terrain is flat, the northern sector of the reserve features extensive granitic rock outcrops (inselbergs). Elevation ranges from approximately 600 m in the southwest to around 1200 m atop the inselbergs in the northeast. Soils in the Ituri forest are primarily derived from weathered granites and quartzites of the Gondwanan Shield, ranging from highly weathered, fine-textured red oxisoils to yellow or brown sandy clays. Alluvial deposits are found along riverbanks and in poorly drained basins at the headwaters of numerous rivers. Soils are generally highly acidic, with a thin humus layer (0–6 cm), and this acidity is associated with low fertility, particularly limited availability of nitrogen and phosphorus. Locally more fertile patches occur, especially in association with red oxisoils.

The OWR is intersected by National Road No. 4, along with several secondary roads that connect it to major urban centers in the region, including Isiro, Bunia, Beni, and Butembo. Functionally, the reserve is divided into several zones: core conservation zones, hunting zones, buffer zones, and agricultural zones. The core conservation zones are strictly protected and reserved exclusively for scientific research activities. Hunting zones allow for regulated hunting and gathering, provided such practices are compatible with the sustainable regeneration of natural resources; however, land clearing for agricultural or residential purposes is prohibited, except for the establishment of temporary hunting camps by IPs. Agricultural zones are designated for human activities, where subsistence agriculture, hunting, and gathering are permitted. The reserve is bordered, particularly along its agricultural zones adjacent to road networks, by numerous villages inhabited by Indigenous Mbuti and Efe peoples, as well as migrant Bantu populations. The present study focuses on villages inhabited by IPs. Data were collected from six camps distributed across three villages: Meiako and Mananasi in the village of Epulu; Matchenje and Apeyole in the village of Bapukeli; and Mapendo and Putakasembe in the village of Babama (Figure 1).

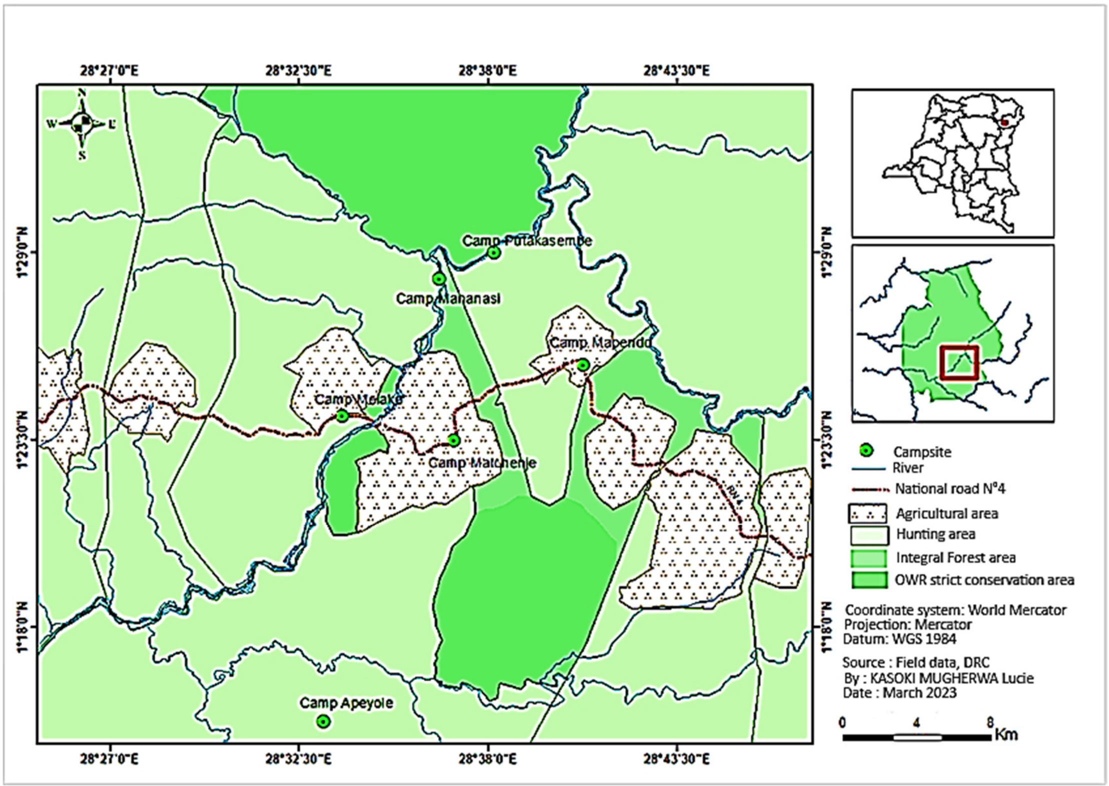


Figure 1. Location map of the study area.

2.2. Methodological Strategy

The Multidisciplinary Landscape Assessment (MLA) methodology, developed by the Center for International Forestry Research (CIFOR) in 2000 as mentioned by [25], was employed in the present study. This approach aims to characterize a landscape and assess its value based on the needs of local communities who rely on the goods and resources it provides. A mixed qualitative and quantitative approach was adopted to holistically understand endogenous practices, patterns of change, IPs' perceptions of their environment, and the diversity of their ecosystems.

2.2.1. Secondary Data Collection

The preparatory phase consisted of a targeted literature review focused on IPs, the OWR, traditional ecological knowledge, and conservation policies in the DRC, as well as the identification of study sites in collaboration with local and customary authorities.

2.2.2. Primary Data Collection

- Sociodemographic data
  Sociodemographic data were obtained through comprehensive surveys conducted with 80 individuals (heads of households), representing the entire number of households enumerated across the six campsites. The distribution of respondents was as follows: Meiako (17), Mananasi (12), Matchenje (15), Apeyole (11), Mapendo (15), and Putakasembe (10). Collected variables included age, sex, marital status, educational level, household size, and duration of involvement in traditional activities.
- Data on the integration of indigenous knowledge
  Twelve focus group discussions and semi-structured interviews were conducted with camp leaders and "elders" (both men and women), with an average of seven participants per camp. The themes addressed included perceived environmental changes, resource management practices, knowledge transmission, cultural taboos, and relations with Bantu populations.
  An inventory of empirical indicators related to soil fertility (presence of certain plants empirically used as bio-indicators to assess soil fertility; ants and earthworms) and the technical itineraries employed was compiled through these focus groups.
- Floristic inventory data
  For each camp, 500 m transects were established, along which three plots measuring 100 m × 25 m (plots 1, 3, and 5) were sampled, with orientation varying according to local geography (e.g., 180° at Meiako, 110° at Matchenje, and 68° at Mapendo). Species selection criteria were based on their usage, cultural significance, and species abundance, while also recording disturbance factors such as fire, land clearing, and exploitation.

2.2.3. Data Analysis

Descriptive statistics were performed using Excel 2019, and further analyses were conducted with R software (v4.2.2). Binary and multinomial logistic regressions (using the stats and nnet packages) were employed to examine the effects of sex, education level, seniority, and marital status on the perception of environmental changes. Floristic inventory data were analyzed using a two-way analysis of variance (ANOVA) to assess differences in abundance both among settlements and across the species utilized by indigenous peoples. When significant differences among means were detected ($p < 0.05$), post hoc multiple comparisons were conducted using Tukey's test to determine which means differed significantly.

The Chi-square test was employed to assess the dependence between the qualitative variables that constitute the core of this study (with the assumption that variables are independent, at the threshold of 5%). A Multiple Correspondence Analysis (MCA) was performed to explore the relationships between the various socio-demographic, perceptual, and environmental variables.

2.3. Ethics and Results Validation

To ensure scientific ethics and validate the findings of this research, the following measures were implemented:

- Free, prior, and informed consent was obtained from each participant;
- Results were returned to the community representatives for validation through participatory feedback;
- No protected species were destroyed or collected during the floristic inventory.

3. Results

3.1. Socio-Demographic Characteristics of the Respondents

The analysis of the sociodemographic data (Table 1) collected from a sample of 80 individuals reveals a male dominance, with 57.5% men compared to 42.5% women. However, this trend is not observed in the Apeyole and Putakasembe campsites, where the proportion of females is slightly higher, reaching 7.5%, compared to 6.25% and 5% males in the respective locations.

Table 1. Main sociodemographic characteristics of the respondents.

Variable	Classification	Number	Proportion (%)
Sex	Women	34	42.50
	Men	46	57.50
Campsites	Putakasembe	10	12.50
	Apeyole	11	13.75
	Mananasi	12	15.00
	Mapendo	15	18.75
	Matchenje	15	18.75
	Meiako	17	21.25
Level of study	Illiterate	36	45
	Primary	42	52.50
	High school	2	2.50
Age	18–25 years	24	28.75
	25–30 years	11	13.75
	30–35 years	10	12.50
	35–40 years	11	13.75
	40–45 years	5	7.50
	40–45 years	1	1.25
	45–50 years	5	6.25
	>50 years	13	16.25
Marital status	Single	8	10
	Married	70	87.50
	Widow	2	2.50

According to Table 1, the age distribution indicates a dominant young population. The 18–25 age group represents 28.75% of the sample, followed by the 25–30 and 35–40 age groups, each accounting for 13.75%. Individuals over 50 years old constitute 16.25% of the surveyed population.

Regarding marital status, the majority of respondents (87.5%, or 70 individuals) are married. Singles comprise 10%, while widowed individuals represent only 2.5% of the sample.

In terms of educational attainment, only 2.5% of respondents have reached secondary education. A significant proportion (52.5%) attended primary school, whereas 45% were illiterate, reflecting limited access to formal education among the Indigenous populations under study.

The average household size (Figure 2) remains generally consistent across the six camps surveyed, typically around three individuals per household. However, variations were noted, particularly in Putakasembe and Mananasi, where average household sizes were two and four individuals, respectively. The minimum household size recorded across all camps was one individual per household. The Mananasi camp thus exhibits the largest average household size, whereas Putakasembe displays the smallest.

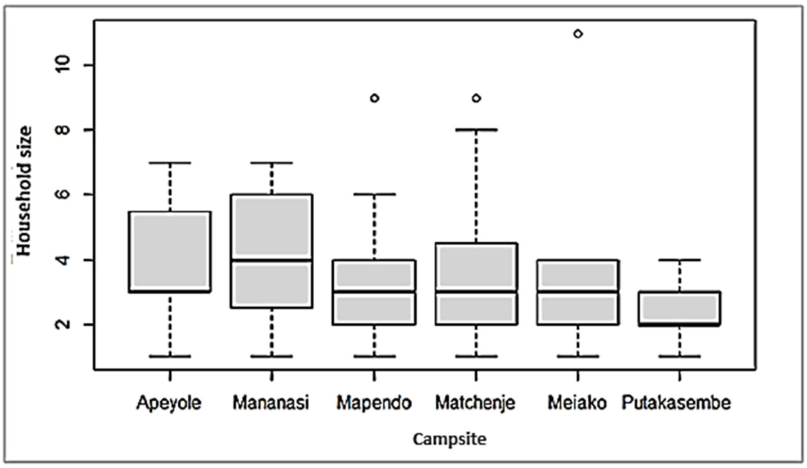


Figure 2. Household size by campsite.

3.2. Economic Activities and Endogenous Resource Conservation Strategies

3.2.1. Traditional and Contemporary Activities

The analysis of traditional and current activities (Table 2) reveals a strong cultural resilience among IPs in the six camps surveyed, characterized by the continued practice of ancestral activities related to the sustainable exploitation of natural resources. Hunting, gathering, fishing, honey harvesting, and artisanal crafts are ubiquitous across all camps, indicating a deep-rooted integration of these practices within their lifestyle, and lack of alternatives.

Table 2. Traditional (historical) and current activities practiced by IPs.

Traditional Activities								
Village	**Campsite**	**Hunting**	**Picking**	**Fishing**	**Agriculture**	**Handicraft**	**Manpower for Bantus**	**Honey Harvesting**
Babama	Mapendo	+	+	+	−	+	+	+
	Putakasembe	+	+	+	−	+	+	+
Bapukeli	Matchenje	+	+	+	−	+	+	+
	Apeyole	+	+	+	−	+	+	+
Epulu	Meiako	+	+	+	−	+	+	+
	Mananasi	+	+	+	−	+	+	+
Current activities								
Babama	Mapendo	+	+	+	○	+	+	+
	Putakasembe	+	+	+	○	+	+	+
Bapukeli	Matchenje	+	+	+	○	+	+	+
	Apeyole	+	+	○	○	+	+	+
Epulu	Meiako	+	+	+	○	+	+	+
	Mananasi	+	+	+	○	+	+	+

Note: +: Priority activity; ○: Less practiced activity; −: Unpracticed activity.

Agriculture is identified as a recent innovation. It does not replace traditional activities but rather complements them. Additionally, labor provided by IPs to neighboring Bantu populations serves as a supplementary source of income and reflects an increasing degree of economic dependency.

Figure 3 illustrates the current distribution of the main activities practiced by Indigenous Peoples (IPs). Hunting remains the most frequent activity, engaged in by 37.5% of respondents. It is followed by labor work for Bantu populations (28.75%), fishing (13.75%), agriculture (10%), artisanal gold mining (3.75%), collection of Marantaceae leaves; particularly *Megaphrynium macrostachyum*; for commercial sale (3.75%), and finally, artisanal crafts (2.5%).

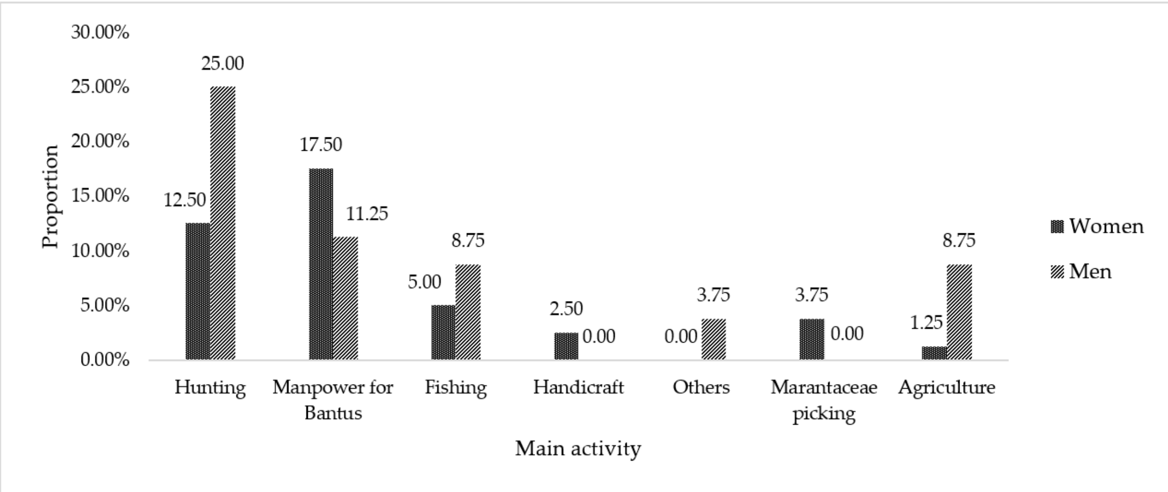


Figure 3. Distribution of respondents by main activity according to gender.

A gender-based analysis highlights a differentiated distribution of activities. Hunting is a male-dominated activity, practiced by 25% of men compared to only 12.5% of women. Conversely, agricultural labor performed for the Bantu primarily involves women (17.5%) compared to 11.25% of men. The collection of Marantaceae leaves and artisanal crafts are exclusively female-dominated activities, reflecting a gendered specialization of tasks.

Agriculture concerns 10% of the respondents and remains strictly oriented towards subsistence, with a predominance of food crops such as cassava, maize, beans, and peanuts. The cultivated areas are small, not exceeding 10 m^2 per household, indicative of a subsistence strategy rather than a commercial production approach.

Across the surveyed settlements, forest-based products are predominantly allocated to subsistence consumption. A smaller proportion is either commercialized or redistributed through intra-community exchange. The revenues derived from these activities are largely directed toward meeting essential household needs, including the purchase of salt, oil, soap, and clothing. Conversely, practices of financial saving or investment remain largely absent, reflecting the subsistence-oriented nature of local livelihoods.

3.2.2. Technical Knowledge and Exploitation Tools

Regarding the techniques and tools employed (Table 3), hunting primarily relies on the use of nets made from *Manniophyton fulvum* fibers (locally known as "Mukila" in the Mbuti language), bows, arrows, traps, and dogs. Fishing is conducted using hooks, fish traps, and nets. The increasing use of nylon nets with mesh sizes ranging from 2 to 3 cm currently poses a threat to aquatic biodiversity due to the capture of juvenile individuals.

Table 3. Tools used by IPs.

Village	Campsite	Traditional Net	Nylon Net	Arrow	Arc	Fishpot	Trap	Dog	Hook	Gun
Traditional Used Tools										
Babama	Mapendo	+	−	+	+	+	○	+	+	−
	Putakasembe	+	−	+	+	+	○	+	+	−
Bapukeli	Matchenje	+	−	+	+	+	○	+	+	−
	Apeyole	+	−	+	+	+	○	+	+	−
Epulu	Meiako	+	−	+	+	+	○	+	+	−
	Mananasi	+	−	+	+	+	○	+	+	−
Current used tools										
Babama	Mapendo	+	+	+	+	○	○	+	+	○
	Putakasembe	+	+	+	+	+	○	+	+	○
Bapukeli	Matchenje	+	○	+	+	○	○	+	+	○
	Apeyole	+	○	+	+	○	○	+	+	○
Epulu	Meiako	+	+	+	+	○	○	+	+	○
	Mananasi	+	+	+	+	+	○	+	+	○

Note. +: Priority tools; ○: Less used tools; −: unused tools.

3.3. Traditional Ecological Knowledge and Customary Resource Regulations

Traditional Taboos

Among the Indigenous Peoples (IPs) studied, there exists

- An ancestral normative system for sustainable management
  The Indigenous communities under study possess strict customary rules governing access to and use of natural resources. These traditional taboos constitute genuine ecological regulatory tools, deeply rooted in potent spiritual and social representations.
  - Prohibitions related to fauna: Certain animal species must not be hunted or consumed, particularly in specific circumstances such as pregnancy or breastfeeding. For example, the consumption of meat is forbidden for pregnant women up to 3–4 months postpartum to avoid potential adverse effects on the infant's health.
  - Prohibitions related to flora: Species such as *Monodora tenuifolia* and *M. angolensis* may not be cut with a machete or hoe, under threat of invoking curses (e.g., tooth loss, skin diseases, unsuccessful hunting). Due to fear of mystical or spiritual repercussions, some species receive implicit customary protection.
- Ecological, social, and spiritual functions of taboos
  Traditional taboos fulfill several key functions (Table 4).
- Diversity and specificities of taboos
  Not all camps uniformly enforce these taboos. This variability may reflect cultural differences among lineages, clans, or indigenous tribes; differential influence from proximity to Bantu populations or the OWR administration; and cultural erosion in certain camps due to modernization or the weakening of traditional structures.
- Strategic interpretation for conservation
  These systems of taboos demonstrate that IPs are not merely users of nature but traditional managers thereof; they possess empirical and spiritual knowledge that can complement modern conservation policies; and they can be genuine allies in the co-management of OWR ecosystems if their customary institutions are recognized and valorized.

Table 4. Ecological, social, and spiritual functions of taboos among IP.

Function	Details
Ecological	They contribute to the conservation of vulnerable species (animal and plant), often without a formal conservation framework.
Social	They structure social roles and life cycles (e.g., pregnant women), strengthening community cohesion.
Spiritual	Mystical sanctions ensure compliance with rules even in the absence of material oversight, thereby reinforcing a symbolic form of environmental control.

3.4. Perceptions and Dynamics of Change

According to perceptions within the OWR landscape, the advent of a monetary economy, artisanal and industrial logging, artisanal mining, nature conservation efforts (notably within the OWR), and infrastructure projects on indigenous customary lands substantially reduce IPs' access to and control over forest resources within their territories. Sedentarized and subjected to the adoption of agriculture, they develop a nature-based ingenuity (including identification of fertile lands and technical itineraries, arising from symbiosis with Bantu populations) to sustainably exploit the land.

3.4.1. Access to Resources and Lifestyle Changes

Focus group discussions with IPs identified several transformations in their lifestyle, mainly induced by coexistence with Bantu communities. While traditional knowledge remains vibrant, the ancestral way of life, rooted in an empirical relationship with the forest, is gradually eroding in favor of a more sedentary lifestyle influenced by modernity.

3.4.2. Importance Attributed to the Forest over Time

Figure 4 illustrates the evolution of the importance attributed to primary forests over time (past—20 years ago, present—2023, future—in 20 years). This importance is perceived as declining for most ecosystem services: food, medicine, recreation, hunting, hunting tools, and fibers for basketry. However, the forest's functions as a source of firewood and construction materials remain stable, or even increase, due to projected population growth.

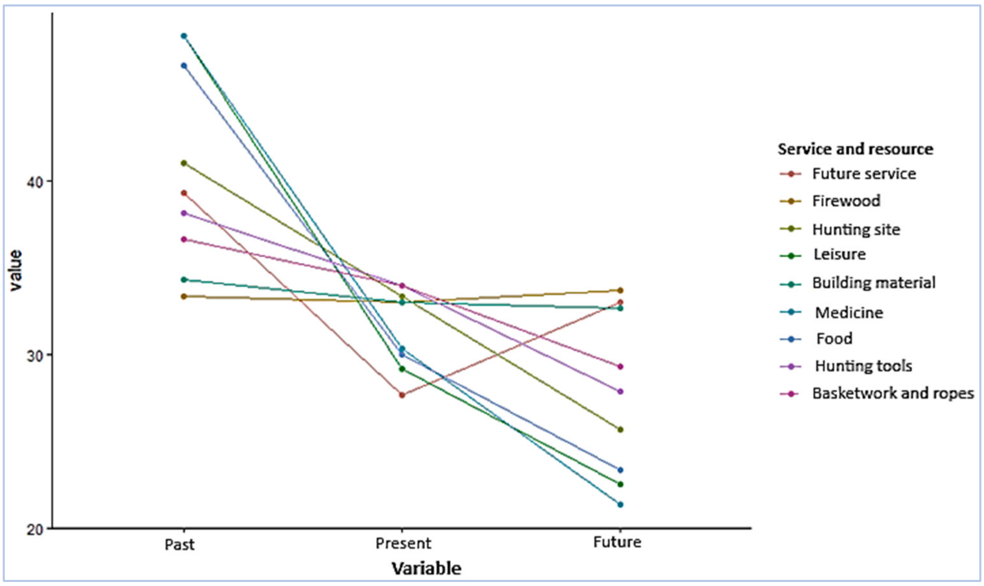


Figure 4. Evolution of the importance attributed by IPs to primary forests over time.

The proportions of importance attributed to the forest shifted from 39% in the past, to 27% currently, with an anticipated rise to 33% in the future.

The ANOVA test presented in Table 5 reveals significant differences in the perceived importance of various forest services and resources across the three time periods. The table shows a highly significant difference over time for food provision (p-value = 8.9×10^{-6}), medicinal resources (p-value = 1.51×10^{-8}), and recreational services (p-value = 5.86×10^{-6}). In contrast, no statistically significant differences were observed for firewood and construction materials.

Table 5. ANOVA of the perceived importance of various services and resources across the three time periods.

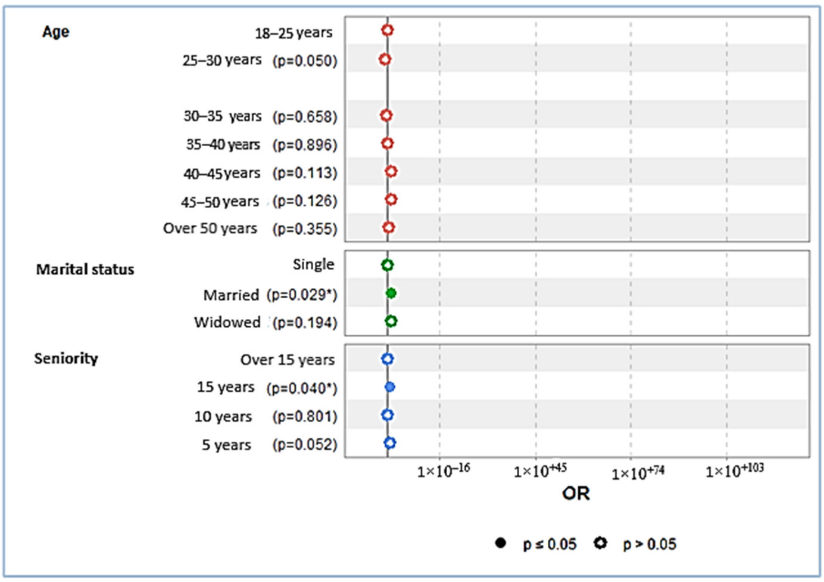
Services and Resources	*p*-Value
Food	0.0089 ***
Medicine	0.0015 ***
Building material	0.1976 Ns
Firewood	0.2548 Ns
Basketwork and ropes	0.0085 **
Hunting tools	0.0145 *
Hunting site	0.0132 *
Leisure	0.0058 ***

Note. * = significant p-value < 0.05; ** = significant p-value < 0.01, *** = significant p-value < 0.001, Ns = Non-significant p-value > 0.05.

3.5. Social Perceptions and Future Projections

3.5.1. Evolution of Living Conditions

Figure 5 illustrates respondents' perceptions regarding the evolution of their living conditions over the past five years. The results indicate a general perception of stability across all age groups, suggesting a relatively harmonious coexistence with neighboring Bantu populations. However, married individuals exhibit a significantly higher likelihood of reporting an improvement in their living conditions, which is attributed to mutual support within the household. Moreover, respondents with more than ten years of experience in forest resource collection are the most likely to report an improvement, compared to other tenure groups.



Legend: * = significant p-value < 0.05

Figure 5. Assessment of living conditions in comparison to the past five years.

3.5.2. Perceptions of Resource Availability

Perceptions of changes in forest resource availability also vary according to gender, experience in resource harvesting, and level of education (Figure 6). The majority of respondents (83.75%) perceive resource availability as stable, while 13.75% report a decrease and only 2.5% observe an increase.

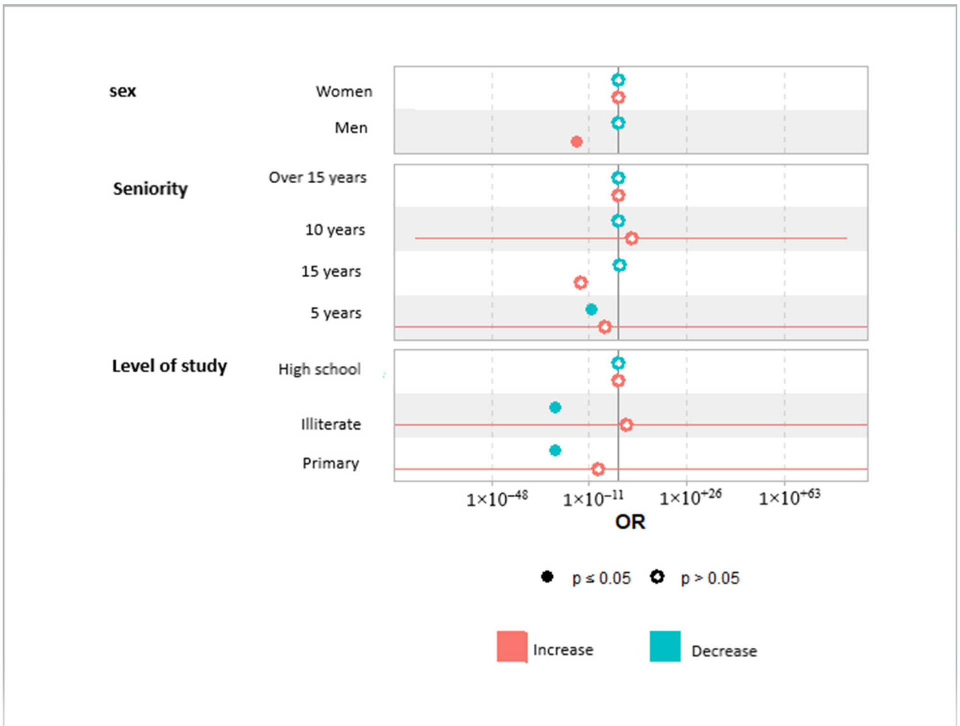


Figure 6. Local perceptions regarding changes in the availability of natural resources.

Regarding gender, men and women exhibit broadly similar perceptions, with a predominant view that resource availability has remained stable. However, a slightly higher proportion of women than men report a perceived decline in resources.

Length of experience in resource harvesting also emerges as a key explanatory factor. Individuals with more than 15 years of experience in natural resource exploitation serve as the reference group. Comparatively, those with 10 to 15 years of experience similarly perceive resource stability. In contrast, respondents with less than 5 years of experience are more likely to perceive a decline in availability, although this perception remains a minority within that group.

With respect to educational level, perceptions of declining resource availability are more prevalent among individuals with secondary education. Conversely, illiterate respondents and those with only primary education exhibit a significantly lower likelihood of reporting such perceptions. This may reflect a more limited capacity to assess temporal changes or reduced access to external sources of information.

3.5.3. Future Habitat Preferences

Figure 7 shows that the habitat preferences expressed by respondents reveal a dominant tendency (69%) to favor residence in villages located along National Road No. 4. This choice is motivated by considerations of security, access to humanitarian aid, and employment opportunities with Bantu populations. However, a minority of respondents (30%) express a desire to reside in the forest, seeking to remain close to natural resources.

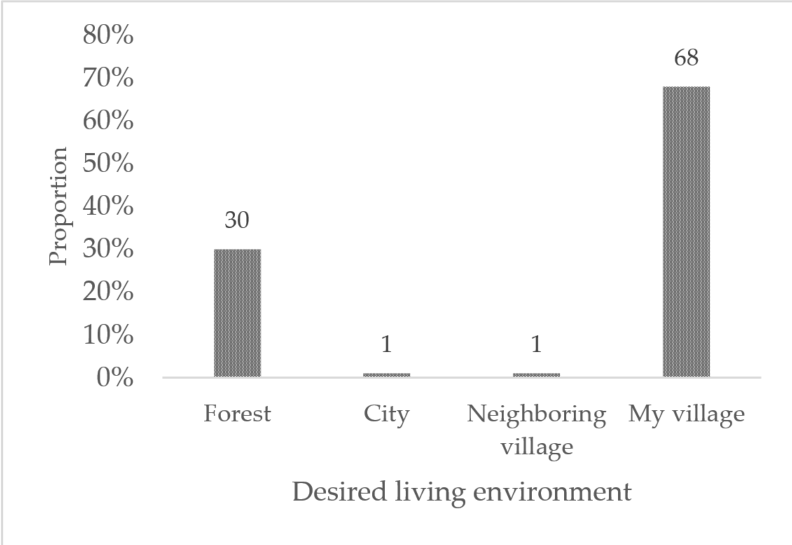


Figure 7. Preferred living environment of IPs for the future.

3.6. Association Between Socio-Demographic, Livelihood, and Perceptual Variables

Across the matrix of bivariate tests (Table A1 in Appendix A), associations are overwhelmingly non-random (almost uniformly $p < 0.001$), indicating a tightly coupled socio-ecological system in which demographic identity, livelihood structure, cultural rules, and environmental perceptions co-vary.

Gender (G), ethnic group (EG), and level of study (LOS) each show strong associations with multiple outcomes. The omnibus statistics for these blocks (e.g., G: $\chi^2 \approx 97.5$, df = 14; EG: $\chi^2 \approx 81$, df = 7; LOS: $\chi^2 \approx 112.3$, df = 21; all $p \ll 0.001$) suggest that demographic identity stratifies livelihood roles, cultural rule adherence, and environmental perceptions.

Core livelihood activities (hunting, picking, fishing, and livestock) are each strongly associated with socio-demographic attributes and with indigenous local knowledge-mediated variables. Hunting shows consistent links to demographic factors and to perceptions of resource dynamics (all $p \ll 0.001$), implying that those engaged in hunting are also those most likely to report changes in wildlife availability and to be embedded in relevant cultural norms (Taboos and Restrictions (TR)). Parallel, highly significant patterns appear for picking and fishing; livestock keeping, though different in ecological niche, also aligns with demographic and perceptual structure. TR is consistently associated with demographic identity, livelihood activities, and perceived change metrics (all $p \ll 0.001$). This indicates that customary institutions remain operative in structuring resource access and behavior—particularly in communities where sacred rules and lineage authority intersect with hunting and plant harvesting practices. The breadth of significant links implies that taboos/restrictions are not isolated beliefs but systemic governance tools that travel with identity and occupation.

Preferred living environment (PLI) exhibits some of the strongest chi-square signals (including $\chi^2 \approx 324$, df = 16, $p \ll 0.001$), linking residence preferences to identity, livelihoods, cultural rules, and environmental perceptions. This suggests that place attachment and settlement choice are co-determined by both socio-cultural membership and ecological opportunity constraints. Lifestyle satisfaction (LS) is likewise associated with multiple blocks, indicating that subjective well-being is embedded in the same socio-ecological fabric that structures livelihoods and rules.

Signals for hunted wildlife decrease (HWD) and biodiversity decrease (BD) are uniformly strong across demographic and livelihood strata (e.g., HWD and BD comparisons yield χ^2 values >80 with $p \ll 0.001$), indicating shared and patterned perceptions of faunal and broader biotic decline among groups most engaged with these resources. Such patterned perception aligns with the idea that users closest to the resource (e.g., hunters, pickers) detect change earliest and most acutely.

Change in resource location (CRL) and change in resource quantity (CRQ) are also widely significant—CRL shows a notable high ($\chi^2 \approx 162$, df = 4, $p \ll 0.001$)—consistent with spatial reconfiguration of resource patches and potential displacement effects (e.g., range shifts, altered migration corridors, or access restrictions).

Weather-related perceptions—rainfall decrease (RD), temperature increase (TI), and strong winds (SW)—are strongly associated with demographics, livelihoods, and cultural variables (nearly all $p \ll 0.001$). Importantly, RD and TI co-vary with livelihood domains that are exposure-sensitive (e.g., fishing, plant harvesting), implying that climate-proximate occupations are structuring how change is noticed and reported.

ASA is significantly related to demographic blocks and to multiple perception variables (all $p \ll 0.001$), suggesting that even when agriculture is not the main livelihood, it modulates exposure and coping in ways that register in people's readings of resource change.

The MCA (Figure 8) revealed a highly structured perceptual landscape among respondents. The exceptional explanatory power of the first dimension (98.53% of variance; eigenvalue = 33.502), coupled with a mean Cronbach's alpha of 0.977 (Table 6), indicates that the socio-demographic, livelihood, and perceptual variables form a single, highly coherent construct. This dominant dimension represents a primary gradient of socio-ecological change, starkly differentiating respondents based on their reported experiences of environmental degradation, including pronounced decreases in hunted wildlife (HWD), non-timber forest products (NTFPD), and biodiversity (BD), alongside perceived climatic shifts such as temperature increase (TI) and rain decrease (RD).

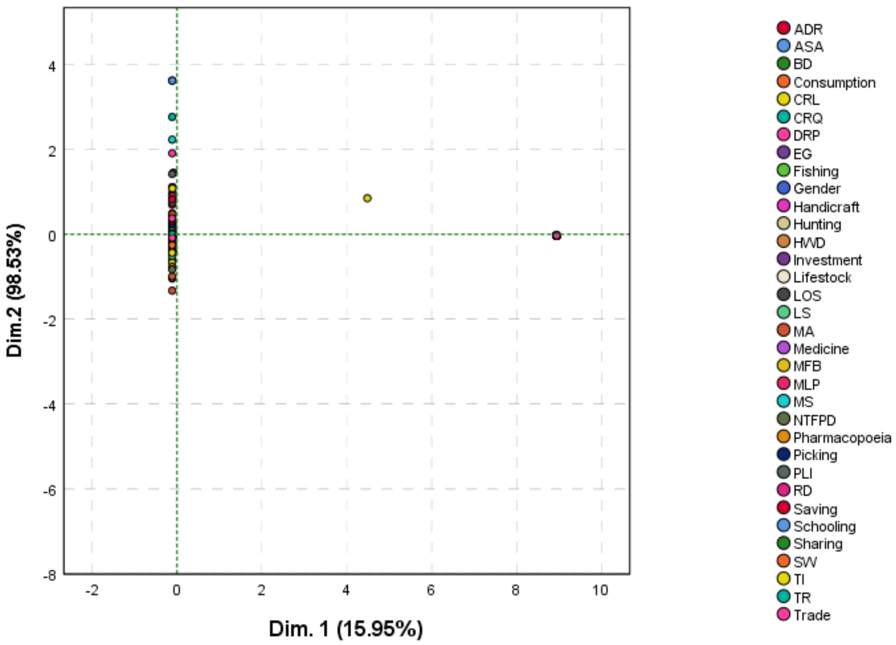


Figure 8. Variable distribution according to MCA dimensions 1 and 2. ADR = Perception of actual distance to the resource; DRP = Perception of past distance to the resource; PLI = preferred living environment; LS = lifestyle satisfaction; TR = taboos and restrictions; CRQ = Change in the resource quantity; CRL = Change in resource location; MA = main activity; MS = marital status; EG = Ethnic group; LOS = level of study; ASA = agriculture as second activity; MLP = Marantaceae leaf picking; MFB = Manpower for Bantus; NTFPD = NTFP decrease; BD = Biodiversity decrease; HWD = hunted wildlife decrease; RD = Rain decrease; TI = Temperature increase; SW = Strong winds; TR = Taboos and restrictions.

Table 6. Summary of the models.

Dimension	Cronbach's Alpha	Total (Eigenvalue)	Inertia	% of Variance
1	1.000	33.502	0.985	98.534
2	0.840	5.422	0.159	15.948
Total		38.924	1.145	
Means	0.977 a	19.462	0.572	57.241

Note. a—The Cronbach alpha mean is based on the mean eigenvalue.

The second dimension (15.95% variance; eigenvalue = 5.422) provides secondary differentiation, primarily driven by variables denoting specific resource declines (HWD, NTFPD, BD) and livelihood activity (MA). This suggests that while the overarching experience of change is widespread, the specificity and intensity of this experience are moderated by livelihood strategies, indicating nuanced vulnerabilities within the community.

The collective position of variables on the factor maps implies strong intercorrelation between ecological perceptions and socio-cultural factors. The distribution of respondents suggests that perceived environmental change is not a homogenous experience but is likely structured by underlying social factors, potentially forming distinct socio-ecological groups. This analysis empirically validates that local knowledge systems are coherent and structured, systematically documenting a pervasive socio-ecological transition in the Reserve.

3.7. Agroecological Knowledge and Practices

3.7.1. Indicators of Soil Fertility

Indigenous peoples retain ancestral agroecological knowledge that enables them to identify fertile lands based on empirical natural indicators (Table 7).

Table 7. Soil fertility indicators mentioned by the IPs.

Indicators	Justifications Provided by IPs
Presence of reeds (*Echinochloa pyramidalis* (Lam.) Hitchc. et Chase)	Reed leaves decompose rapidly, contributing to a rich organic litter layer. Drawing from experiential knowledge, local communities have noted that these areas are particularly conducive to high yields of cassava and groundnut crops.
Presence of ants and earthworms	Irrespective of crop type, the presence of ants and earthworms is consistently linked to enhanced agricultural productivity.
Unburned field	Although emphasized by only a small proportion of the population (≤1/10), unburned lands remain fertile over extended periods and consistently provide good long-term agricultural yields
Presence of certain tree species	Species such as *Floribunda olive* L., *Erythrophleum suaveolens* (Guill. et Perr.) Brenan, *Strombosa grandifolia* Hook.f, *Cassia occidentalis* L., *Chromolaena odorata* (L.) R.M.King & H. Rob., *Dioscorea bulbifera* L., *Massularia acuminata* (G. Don) Bullock ex Hoyle, *Ricinodendron heudelotii* (Baill.) Pierre ex Heckel, and *Irvingia gabonensis* (Aubry-LeComte ex O'Rorke) Baill. are empirically used as bio-indicators to assess soil fertility.
Absence of stones in the ground	The greater the abundance of stones in the soil, the more difficult it becomes for roots to grow and nourish plants. Cultivation of cassava and other tuber crops must take this factor into account, as these crops produce tubers in the soil that require loose and well-aerated substrates.

3.7.2. Technical Pathways

Two agricultural approaches (Figure 9) are employed by IPs:

- Slash-and-burn cultivation, an ancestral and more widespread practice;
- Non-burn clearing, a more recent and sustainable method developed through symbiotic interaction with Bantu populations.

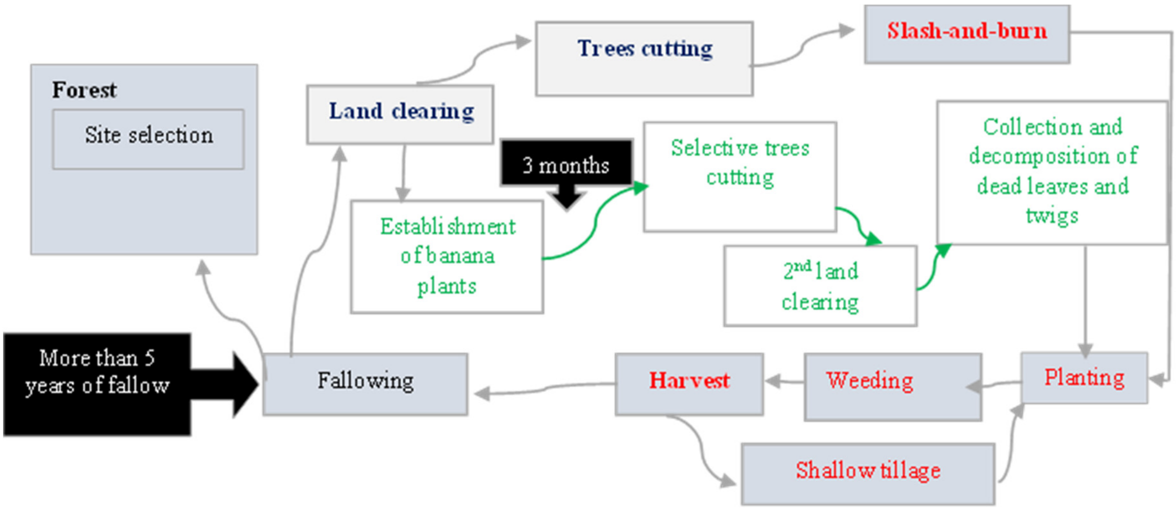


Figure 9. Agricultural technical itinerary based on two approaches: slash-and-burn (in red) and slash-and-mulch (in green).

3.7.3. Conservation of Useful Species

These ecological knowledge systems not only inform the spatial organization of cultivation but also guide field maintenance practices. Certain plant species are deliberately retained within cultivated plots (Table 8) due to their medicinal, nutritional, or symbolic significance.

Table 8. Species conserved in agricultural fields.

Species	Reason
Allablackia floribunda Oliv.	Fruits highly consumed by wildlife
Strombosia grandifolia Hook.f *Myriathus preussii* Engl. *Aida micrantha* (K. Schum.) F. White	Leaves grazed by the Okapi
Anonidium mannii (Oliv.) Engl. et Diels	Fruit highly consumed by monkeys
Afzelia bella Harms	Bee niche (source of honey)
Ricinodendron heudolotii	Fruit consumed by antelopes and caterpillar niche (consumed by Indigenous Peoples).

3.8. Transmission of Endogenous Knowledge

Four primary channels of indigenous knowledge and know-how transmission were identified among the IPs across the six studied camps. These include father-to-son, mother-to-daughter, elder-to-youth, and intra-family transmission (involving uncles, aunts, cousins, grandparents, etc.). As shown in Figure 10, the dominant mode of transmission is from father to son (33.8%), followed by intra-family transmission (29.7%)—involving younger members and close relatives such as grandparents, uncles, aunts, and cousins—then elder-to-youth (19.6%), and finally, mother-to-daughter transmission (16.9%).

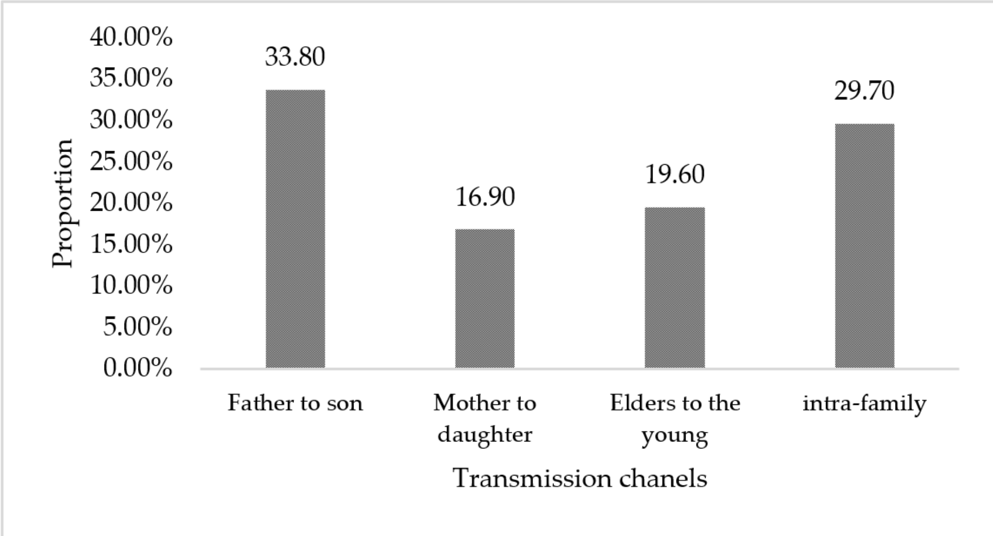


Figure 10. Intergenerational transmission pathways of knowledge and skills among Indigenous Peoples.

The timing of transmission varies according to both the age of the recipient and the nature of the knowledge. Spiritual or magico-religious knowledge is typically reserved for young adults (considered adolescents in the context of the study area) who are deemed trustworthy and initiated through secret rituals; such knowledge is expected to remain confidential. Conversely, knowledge related to survival and communal well-being—such as gathering techniques, craftsmanship, agriculture, and medicinal plant use—is transmitted from early childhood through observation and active participation in daily activities.

3.9. Plant Abundance

3.9.1. Forest Camps

A floristic inventory was conducted across the six camps to identify the plant species most frequently used by Indigenous Peoples (IPs), assess their specific abundance, and analyze the effects of harvesting on their distribution. In total, 27 species were recorded. Table 9 presents the mean individual counts (calculated from three plots per site) for the forest campsites.

In the forest camps (Table 9), the average abundance of species varies considerably, ranging from 140.00 ± 19.99 to 0.33 ± 0.33 individuals. *S. dewevrei* is the most abundant species overall. Conversely, several species exhibit very low or even zero counts, particularly at Putakasembe. Dioscorea sp. 2, although reported by elders as historically present in the area, was not found in any of the surveyed camps, potentially indicating a case of local extinction. Certain species such as *G. dewevrei*, *J. seretii*, and *L. owariensis* were recorded exclusively at Apeyole.

Overall, Mananasi is the most species-rich camp, hosting *S. dewevrei* (140.00 ± 19.99 individuals, dominant species), *E. mildbraedii* (73.67 ± 21.52), *D. spinodentata* (57.33 ± 12.41), and *I. congolana* (53.33 ± 4.25). There is also a notable presence of useful liana species such as *E. haullevilleana* (5.67 ± 5.17) and *Dioscorea* sp. (8.33 ± 2.9). This camp retains a high availability of utilized species, likely due to moderate exploitation levels, relative isolation, or the persistence of traditional conservation practices.

Apeyole ranks second, exhibiting intermediate species diversity. It is primarily characterized by the presence of *G. dewevrei* (160.00 ± 0.00 individuals), *E. mildbraedii* (27.33 ± 3.93), and D. spinodentata (26.33 ± 4.63). While floristically rich, certain species are absent (e.g., *Dioscorea* sp. 2, *E. haullevilleana*). The floristic composition of Apeyole is therefore marked but heterogeneous, suggesting selective harvesting pressures and customary management practices focused on specific species such as *G. dewevrei*.

Table 9. Species abundance in campsites located within the forest.

Campsites	**Putakasembe**		**Apeyole**		**Mananasi**	
Species	**Mean + SD**	**Group**	**Mean + SD**	**Group**	**Mean + SD**	**Group**
Afromomum alboviolaceum (Ridl.) K. Schum	0.33 ± 0.33	g	0.00	g	2.67 ± 1.45	fg
Aidia micrata	1.00 ± 0.99	g	8.00 ± 1.15	efg	16.33 ± 7.85	defg
Annonidium manii	0.33 ± 0.33	g	1.00 ± 0.57	g	0.33 ± 0.33	g
Canarium schweinfurthii Engl.	0.33 ± 0.33	g	0.00	g	1.00 ± 0.99	g
Cola acuminata (P.Beauv.) Schott & Endl.	1.67 ± 1.66	g	3.00 ± 1.15	fg	1.33 ± 1.33	g
Combretum marginatum G. Don	1.00 ± 0.99	g	7.00 ± 1.15	efg	7.33 ± 3.93	efg
Cynometra alexandri C.H.Wright	3.00 ± 3.00	fg	10.33 ± 1.20	defg	37.67 ± 6.74	cdefg
Desplatsia dewevrei (De Wild. & T. Durand) Burret	0.67 ± 0.66	g	4.00 ± 1.73	fg	14.33 ± 4.84	defg
Diospyros bipindesis Gürke	0.67 ± 0.66	g	15 ± 2.00	defg	12.67 ± 6.76	defg
Discorea sp. 1	0.33 ± 0.58	g	0.33 ± 0.33	g	8.33 ± 2.90	efg
Discorea sp. 2	0.00	g	0.00	g	0.00	g
Dryptes gossweileri S.Moore	1.67 ± 1.66	g	26.33 ± 4.63	cdefg	57.33 ± 12.41	cd
Eremospatha haullevilleana De Wild.	0.00	g	0.00	g	5.67 ± 5.17	efg
Erythrina mildibraedii Harms	1.33 ± 1.33	g	27.33 ± 3.93	cdefg	73.67 ± 21.52	bc
Garcinia kola Heckel	0.00	g	0.33 ± 0.33	g	1.00 ± 0.00	g
Gilbertiodendron dewevrei (De Wild.) J.Léonard	0.00	g	160.00 ± 0.00	a	0.00	g
Isolana congolana (De Wild. et Th. Dur.) Engl. et Diels	0.33 ± 0.33	g	11.00 ± 3.05	defg	53.33 ± 4.25	cde
Julbernadia seretii (De Wild.) Troupin	0.00	g	12.67 ± 1.85	defg	0.00	g
Lendolphia owariensis P. Beauv	0.00	g	4.00 ± 0.99	fg	0.00	g
Loeseneriella africana (Willd.) N.Hallé	0.00	g	3.33 ± 1.76	fg	4.00 ± 1.15	Fg
Macaraga spinosa Müll.Arg	0.33 ± 0.33	g	0.33 ± 0.33	g	4.00 ± 0.99	Fg
Manniophyton fulvum Müll. Arg.	5.00 ± 4.99	efg	12.33 ± 0.66	defg	26.67 ± 3.71	cdefg
Megaphrynium macrostachyum (Benth. et Hook. f.) Milne-Redh.	0.00	g	2.67 ± 1.66	fg	0.33 ± 0.33	g
Plukenetia conophora Müll.Arg.	0.00	g	0.33 ± 0.33	g	3.00 ± 3.00	fg
Pyrenacantha puberula Engl.	0.00	g	0.67 ± 0.66	g	0.67 ± 0.33	g
Rourea obliquifoliolata (Gilg) G. Schellenb	0.67 ± 0.66	g	6.67 ± 0.66	efg	4.67 ± 2.40	fg
Scaphopetalum dewevrei De Wild. et T. Durand	53.33 ± 53.33	cde	34.33 ± 5.45	cdefg	140.00 ± 19.99	a

Note. For each parameter, values sharing the same letter (group) are not significantly different at $p < 0.05$.

Putakasembe presents the lowest species diversity and abundance, with most species ranging from 0 to 1.67 individuals per plot. Dominant species include *S. dewevrei* (53.33 ± 53.33) and *M. fulvum* (5.00 ± 4.99). Several species are entirely absent: *G. dewevrei*, *I. congolana*, and *E. mildbraedii*. The low vegetation density at Putakasembe may reflect historical or ongoing overexploitation, higher anthropogenic pressure, or increased ecological degradation (e.g., erosion, fire, or agriculture).

A comparative synthesis of the camps is presented in Table 10.

Table 10. General trend observed in forest campsites.

Dominant Species	Putakasembe	Apeyole	Mananasi
		Mean + SD	
G. dewevrei	0.00	160.00 ± 0.00	0.00
S. dewevrei	53.33 ± 53.33	34.33 ± 5.45	140.00 ± 19.99
E. mildibraedii	1.33 ± 1.33	27.33 ± 3.93	73.67 ± 21.52
D. spinodentata	1.67 ± 1.66	26.33 ± 4.63	57.33 ± 12.41

The general trend shows that vegetation densities increase from left to right in Table 9, with Mananasi ranking highest. Some species appear to be strictly localized, such as *G. dewevrei*, which is predominantly present only at Apeyole. This gradient may reflect ecological variations as well as cultural dynamics related to harvesting or traditional conservation.

The ecological and cultural implications are as follows:

- The indigenous peoples do not exploit resources randomly; differences in abundance can be explained by the presence of traditional taboos, the utility value of species, or ecological availability.
- The case of Mananasi demonstrates that resource use can remain compatible with high biodiversity, especially when governed by sustainable harvesting practices.
- Conversely, Putakasembe may represent a critical area requiring ecological restoration.

3.9.2. Campsites in Bantu Villages

In the campsites of the Bantu villages (Table 11), abundances also vary considerably, ranging from 113.30 ± 32.82 to 0.33 ± 0.33 individuals. *M. macrostachyum* is the most significantly abundant species observed. Table 11 presents the mean individual counts (calculated from three plots per site) for the camps within neighboring Bantu villages.

According to Table 10, the least represented species (0.33 ± 0.33) include *A. alboviolaceum*, *A. manii*, *Cola acuminata*, *Rourea obliquifoliolata*, and *C. schweinfurthii*, as well as *C. marginatum* and *D. bipindensis*.

Overall, within the villages, Matchenje is the camp with the highest density of a single species, *M. macrostachyum* (113.3 ± 32.82). Other well-represented species are *Discorea* sp. 1 (21.67 ± 14.40), *G. dewevrei* (3.33 ± 6.69), *S. dewevrei* (13.33 ± 7.88), and *M. fulvum* (10.33 ± 5.45). This camp is thus characterized by a strong specialization around a few key species. The dominance of *M. macrostachyum*, a plant used for roofing and food packaging, suggests intensive exploitation, yet also a strong natural regeneration capacity.

Meiako camp exhibits the greatest species richness, with *G. dewevrei* (50 ± 28.57) as the dominant species, alongside other species with high abundances such as *M. macrostachyum* (34.67 ± 32.67), *J. seretii* (12.67 ± 4.67), and *S. dewevrei* (9.00 ± 1.99). It is the only site encompassing all the recorded species, thus exhibiting the highest floristic diversity. This may be explained by less selective or intensive exploitation practices; the coexistence with traditional practices favoring preservation; and the intrinsic ecological richness of the area.

Mapendo, meanwhile, is the camp with the lowest floristic density, with *M. macrostachyum* (34.33 ± 32.34) as the most frequent species and very low abundances of *A. alboviolaceum*, *A. manii*, *Cola acuminata*, and *R. obliquifoliolata*, all around 0.33 ± 0.33. Moreover, several species are entirely absent from the sampled plots. This camp thus shows relative floristic impoverishment, characterized by historical overexploitation; less favorable edaphic conditions; and stronger anthropogenic pressure (clearing, agriculture).

The comparative synthesis between camps is illustrated in Table 12.

Table 11. Species abundance in campsites located within Bantu villages.

Campsite	Mapendo		Matchenje		Meiako	
Species	**Mean + SD**	**Group**	**Mean + SD**	**Group**	**Mean + SD**	**Group**
Afromomum alboviolaceum	0.33 ± 0.33	g	1.00 ± 0.57	g	7.67 ± 2.96	efg
Aidia micrata	2.00 ± 1.15	g	3.67 ± 2.73	fg	14 ± 9.53	defg
Annonidium manii	0.33 ± 0.33	g	2.00 ± 0.99	g	1.33 ± 0.66	g
Canarium schweinfurthii	1.00 ± 0.57	g	0.33 ± 0.33	g	0.67 ± 0.33	g
Cola acuminata	0.33 ± 0.33	g	3.00 ± 2.51	fg	2.67 ± 1.45	fg
Combretum marginatum	0.67 ± 0.66	g	1.00 ± 0.57	g	0.33 ± 0.33	g
Cynometra alexandri	1.67 ± 0.88	g	0.00	g	1.67 ± 1.2	g
Desplatsia dewevrei	0.00	g	0.00	g	1.67 ± 1.66	g
Diospyrose bipindesis	0.00	g	1.67 ± 0.88	g	0.33 ± 0.33	g
Discorea sp. 1	2.67 ± 1.45	fg	21.67 ± 14.40	defg	5.67 ± 4.69	efg
Discorea sp. 2	0.67 ± 0.66	g	0.00	g	1.33 ± 0.88	g
Dryptes gossweileri	1.00 ± 0.57	g	4.00 ± 2.08	fg	3.00 ± 0.99	fg
Eremospatha haullevilleana	1.33 ± 0.88	g	7.67 ± 6.66	efg	0.67 ± 0.66	g
Erythrina mildibraedii	1.33 ± 1.33	g	0.67 ± 0.33	g	2.33 ± 1.85	fg
Garcinia kola	0.00	g	0.00	g	0.00	g
Gilbertiodendron dewevrei	16.67 ± 16.66	defg	13.33 ± 6.69	defg	50 ± 28.57	cdef
Isolana congolana	0.00	g	0.00	g	3.67 ± 2.16	fg
Julbernadia seretii	1.33 ± 0.88	g	1.00 ± 0.99	g	12.67 ± 4.67	defg
Lendolphia owariensis	0.00	g	1 ± 0.57	g	2.67 ± 0.33	fg
Loeseneriella africana	0.67 ± 0.33	g	0.00	g	2.33 ± 0.66	fg
Macaraga spinosa	0.00	g	1 ± 0.57	g	1.00 ± 0.55	g
Manniophyton fulvum	2.33 ± 1.45	fg	10.33 ± 5.45	defg	3.33 ± 0.88	fg
Megaphrynium macrostachyum	34.33 ± 32.34	cdefg	113.3 ± 32.82	ab	34.67 ± 32.67	cdefg
Plukenetiaconophora	0.00	g	0.00	g	1.00 ± 0.99	g
Pyrenacantha puberula	1.00 ± 0.57	g	1.67 ± 1.66	g	0.67 ± 0.33	g
Rourea obliquifoliolata	0.33 ± 0.33	g	0.33 ± 0.33	g	1.33 ± 0.33	g
Scaphopetalum dewevrei	3.00 ± 1.52	fg	13.33 ± 7.88	defg	9.00 ± 1.99	defg

Note. For each parameter, values sharing the same letter (group) are not significantly different at $p < 0.05$.

Table 12. General trend in the village camp settlements.

Campsite	Dominant Species	Abundance (Ind./Plot)	Species Richness
Meiako	*G. dewevrei*	50.00 ± 28.57	High (27 species)
Matchenje	*M. macrostachyum*	113.30 ± 32.82	Medium
Mapendo	*M. macrostachyum*	34.33 ± 32.34	Weak

Table 11 reveals that certain species appear to be favored by local agroforestry practices (e.g., *M. macrostachyum*, *Discorea* sp.); the differences in species richness between village camps reflect unequal exploitation patterns, linked to resource accessibility and lifestyle variations (more agricultural versus more forest-based).

- Statistical analysis (ANOVA and Ranking)

Analysis of variance (ANOVA) highlights highly significant differences in the total abundance of species (Table 13).

Table 13. ANOVA for species abundance across the different campsites.

Source of Variation	df	SSD	MS	F-Value	*p*-Value	Significance
Campsite	5	14,390	2878.10	16.88	0.0078	***
Species	26	63,996	2461.40	14.44	<0.0020	***
Interaction camp. -Spe.	130	146,321	1125.50	6.60	<0.0002	***
Residues	324	55,229	170.50			

Note. *** = significant *p*-value < 0.001; df: degree of freedom; SSD: sum of squared deviations; MS: mean square.

According to Table 13, the very low *p*-value ($p < 0.001$) for all sources of variation indicates highly significant differences between the campsites themselves, between species, and notably a significant interaction between the two factors (certain species are more abundant in some campsites than in others). This reveals a strong spatial heterogeneity in plant abundance, influenced by site-specific exploitation practices, anthropogenic pressure, and local ecological conditions (e.g., dense forest, proximity to cultivated areas).

According to Table 14, Mananasi is statistically the richest in terms of individual numbers, with 1299 individuals recorded over 300 m × 25 m. It forms a distinct group (“a”). Apeyole follows with 973 individuals, classified within a close group (“ab”). Putakasembe, Mapendo, and Meiako display the lowest counts (136, 219, and 449, respectively), all belonging to group “c” and significantly less rich than Mananasi and Apeyole. The forest campsites (Mananasi, Apeyole) thus present the highest abundances, confirming that the forest environment favors greater floristic richness. In contrast, the village campsites (Putakasembe, Mapendo, Meiako) show a marked decrease in abundance, likely due to agricultural clearing, local urbanization, increased exploitation pressure, or the erosion of traditional preservation norms.

Table 14. Ranking of campsites based on total abundance.

Campsite	Number Total (Individual)	Statistic Group
Mananasi	1299	a
Apeyole	973	ab
Matchenje	556	bc
Meiako	449	c
Mapendo	219	c
Putakasembe	136	c

Note. For each parameter, values sharing the same letter (group) are not significantly different at $p < 0.05$.

4. Discussion

4.1. Sociodemographic and Cultural Characteristics of Indigenous Peoples (IPs)

The study reveals a predominantly young and poorly schooled indigenous population within the OWR landscape. This predominance of youth and low education among the IP aligns with documented exclusion dynamics elsewhere in Central Africa [12,17]. This situation, common among peoples in the Amazon [26] and Southeast Asia [27], limits access to training systems and mechanisms for participation in environmental policy-making. In Southeast Asia, studies by [28] demonstrate the detrimental effects of schooling disconnected from the local cultural context. However, this youth demographic represents an opportunity for revitalizing knowledge if intergenerational transmission mechanisms are strengthened [10,21,29]. Indeed, the low median age observed here enables potentially rapid knowledge transmission if adapted pedagogical tools are implemented, as recommended by [26] for the Brazilian Amazon.

4.2. Endogenous and Ancestral Strategies for Forest Conservation and Sustainable Biodiversity Management

The practices of the IP in the OWR regarding resource management—taboos, prohibitions, shifting cultivation techniques, and selection of useful species—reveal an empirical regulatory system aligned with principles of adaptive conservation, as noted by [30]. The role of such knowledge in ecological regeneration has also been documented elsewhere, notably in Indonesia [21] and Ethiopia [22], confirming its relevance in localized sustainable management contexts. The effectiveness of customary systems is now internationally recognized [18,31].

4.2.1. Traditional Prohibitions and Conservation

Management practices observed within the OWR landscape, including prohibitions on fauna and flora, are part of a "sacred ecology" [11,32]. Similar phenomena are noted in the Amazon, where the Yanomami and Kayapo regulate harvesting through spiritual codes [33,34], and in Indonesia, where the Dayaks apply comparable land taboos [28]. These practices, often overlooked by official institutions, constitute a powerful foundation for localized and culturally embedded conservation [18]. Furthermore, customary rules fulfill social (role structuring), ecological (species preservation), and symbolic functions, and could form a robust basis for co-management programs [9,35].

4.2.2. Adaptation to Current Sociocultural Disruptions

The IPs of the OWR demonstrate both adaptive capacity and vulnerability in the face of disruptions. Integrating their knowledge into environmental governance, as advocated by the Convention on Biological Diversity [36], is strategic. Models exist in Asia (India Biodiversity Act), the Amazon (community-based REDD+), and Africa (APAC).

Within the studied sites, hunting and fishing remain principal activities, reflecting adherence to ancestral subsistence modes [7]. However, the introduction of agriculture, although marginal in area, marks a notable shift toward sedentarization, often constrained by conservation policies [14] or restricted access to forest resources [19], indicating a transition toward a mixed subsistence model. This phenomenon, termed "agroecological hybridization" [37], shows that agricultural adoption is not a rupture but a contextualized adaptation. It has been documented in the Andes [38], the Amazon [37], and Southeast Asia [27] as a response to land marginalization. The gradual shift toward a monetary economy accentuates transformations in traditional subsistence strategies, as highlighted by [37] in other tropical contexts, exemplified here by IP participation in agricultural labor for Bantu populations. Coexistence with the Bantu acts as a catalyst for innovation, confirming the importance of intercultural dynamics in socio-ecological landscapes [39]. Agricultural adoption complements rather than replaces traditional practices; however, without proper management, it may accelerate ecosystem degradation. In both the Amazon and East Africa, shifting cultivation remains a resilient system when well regenerated [22,39].

4.2.3. Risks Linked to Modernization of Certain Current Tools

Certain silent but increased risks threaten biodiversity. Indeed, the evolution of hunting tools, with the adoption of nylon nets, poses a major ecological threat by facilitating the capture of juvenile species. This observation aligns with [12], who warns about the threat certain modern technologies pose to sustainability. Although traditional nets made from *Manniophyton fulvum* fibers persist, their rapid decline intensifies cultural erosion.

4.2.4. Social Perceptions and Dynamics of Change

Perceptions regarding the importance of the forest have evolved over time. Notably, the perceived importance of the forest for food provision has decreased. This trend, significant according to ANOVA, reflects a gradual detachment from forest resources in favor of new food sources. Nonetheless, IPs continue to recognize the forest as a strategic space, particularly for construction ($p > 0.05$), indicating a pragmatic subsistence-based use. However, while 83.75% of respondents perceive resource stability, this perception contrasts with botanical data indicating the rarity of certain species (*Discorea* sp. 2, *Monodora* spp.). This paradox is frequent in social ecology research: environmental perceptions are influenced by factors such as access to information, mobility, and daily interaction with the ecosystem [29]. Younger and more educated individuals tend to be more sensitive to ecological changes, as observed in Tanzania [40]. This discrepancy, also reported in Cameroon [41] and Brazil [42], reflects either cognitive resilience or difficulty in updating empirical referents. It underscores the importance of integrating local knowledge with scientific data for shared analysis. In Tanzania, [40] shows that co-construction of knowledge improves the accuracy of environmental diagnostics.

4.2.5. Adaptative Agroecological Knowledge and Practices

IPs identify fertility indicators such as the presence of earthworms, specific vegetation (*Floribunda Olive*, *Erythrophleum suaveolens*), or soil texture. Two systems coexist: shifting cultivation with burning (ancient, intensive) and shifting cultivation without burning (more sustainable, influenced by the Bantu). These mixed technical itineraries demonstrate adaptive capacity without abrupt rupture from ancestral knowledge.

4.2.6. Implications of the Association Between Socio-Demographic, Livelihood, and Perceptual Variables

The chi-square analyses demonstrate that socio-demographic variables, livelihood practices, cultural institutions, and perceptions of ecological change are strongly interlinked in the Okapi Wildlife Reserve. This pattern illustrates how Indigenous and local knowledge (ILK) systems continue to structure both resource use and ecological awareness [43,44]. Gender, ethnicity, and education significantly stratify livelihood roles and knowledge domains, echoing evidence from other contexts where identity conditions access to ecological knowledge [45,46].

Practice-specific activities such as hunting, fishing, and plant harvesting are tightly coupled with perceptions of biodiversity decline and climate anomalies, confirming that resource users function as sensitive observers of environmental change [47,48]. The consistent significance of taboos and restrictions further underscores the role of customary institutions as informal governance mechanisms that continue to regulate access and sustainability [31,45].

Finally, preferences for living environments and lifestyle satisfaction are embedded within these socio-ecological couplings, highlighting the importance of place attachment for well-being and conservation outcomes [49–51]. These results emphasize the need for conservation strategies that integrate ILK, recognize livelihood-specific ecological knowledge, and reinforce co-management with customary institutions.

Looking at the MCA, the extreme dominance of the first dimension, accounting for over 98% of the variance, is a striking finding. It strongly suggests that the lived experience of the local population is overwhelmingly structured by a single, pervasive gradient of change. This aligns with the concept of "interlinked social-ecological shifts" described by [49], where disturbances in an ecosystem trigger cascading effects on the dependent human systems, and vice versa. The remarkably high Cronbach's alpha further underscores that the variables measuring perceptions, livelihoods, and social characteristics are not isolated but form a highly coherent and interdependent complex, indicative of a system-wide transformation.

The interpretation that Dimension 1 represents a gradient of environmental perception and change is highly plausible. The strong discriminatory power of variables like Hunted Wildlife Decrease (HWD), NTFP Decrease (NTFPD), and Biodiversity Decrease (BD) indicates that the depletion of forest resources is a central, defining concern for the community. This finding resonates deeply with studies across tropical forest regions, which report widespread local perceptions of wildlife decline and "empty forest syndrome" due to hunting pressure and habitat change [52,53]. Furthermore, the close association of these variables with climatic changes (Temperature Increase (TI) and Rain Decrease (RD)) on the factor map suggests that communities perceive these challenges not as separate issues, but as a synergistic crisis. This integrated perception mirrors scientific understandings of how climate change can exacerbate resource scarcity, creating feedback loops that threaten both biodiversity and human livelihoods [54].

Dimension 2, while explaining less variance, offers critical nuance by highlighting specific livelihood adaptations and their link to particular environmental perceptions. The high discrimination of Main Activity (MA) on this axis suggests that responses to the overarching gradient of change (Dim 1) are not uniform but are mediated by livelihood strategies. This supports the thesis that vulnerability and resilience are distributed unevenly within communities, shaped by factors such as access to alternative income sources and cultural identity [55]. For instance, those relying heavily on hunting or NTFP collection might be clustered in the quadrant of the map defined by high values on HWD and NTFPD, indicating they are on the frontline of experiencing resource loss. Conversely, other groups may be adapting by shifting agricultural practices or engaging in trade, positioning them differently within this perceptual landscape.

The spatial distribution of respondents in the individual factor map (Figure 2) is crucial for understanding intra-community dynamics. Should this distribution reveal distinct clusters, it would provide empirical evidence for the existence of distinct "social-ecological groups" within the population. These groups would share not only similar socio-demographic profiles (e.g., Ethnic Group (EG), livelihood) but also a common perception of environmental change. This finding would be significant, as it moves beyond homogenous representations of "local communities" and acknowledges their internal heterogeneity, a critical factor for designing equitable and effective conservation policies [56]. Effective governance must recognize these divergent experiences and knowledges to avoid marginalizing subgroups whose voices may be less heard.

Finally, the position of variables related to Taboos and Restrictions (TR) and Lifestyle Satisfaction (LS) within the MCA space is particularly revealing. If located near the pole of Dim 1 representing greater perceived change, it could indicate that cultural institutions are being eroded or are transforming in response to new pressures, a phenomenon documented by [29]. Alternatively, their position could reflect how these institutions influence environmental outcomes. The link between perceived environmental degradation and lifestyle satisfaction is a vital area for well-being research, suggesting that the loss of natural resources has profound implications for human health and cultural integrity beyond mere material loss.

4.3. Floristic Diversity: An Indicator of Differential Pressures

Floristic inventories reveal strong heterogeneity between campsites. Mananasi, the most isolated forest camp, exhibits the highest abundance, while Putakasembe, more exposed to roads and Bantu populations, shows the lowest counts, highlighting the effect of anthropogenic pressure or ecological isolation. Analysis of variance confirms the significance of these differences. This distribution validates the hypothesis that ecological erosion is strongly correlated with the intensity of human pressures and the dilution of traditional norms [31]. These differences may also relate to the robustness of traditional norms: where they remain vibrant (Mananasi, Apeyole), biodiversity appears better preserved. This observation aligns with findings by [22] in Ethiopia and [21] in Indonesia. Recognition of local norms within territorial management tools (e.g., APAC) is a promising strategy [35].

4.4. Intergenerational Transmission of Knowledge and Skills

The knowledge and skill transmission pathways are gendered and hierarchical: from father to son, mother to daughter, but predominantly through elders and intrafamilial ties. This structure, also documented among the Punan [28], Yanomami [33], and Zuni [32], poorly adapts to formal systems. The importance of elders, family lineages, and secret rituals in knowledge transmission calls for caution against generational ruptures. The oral transmission model remains effective but vulnerable to effects of sedentarization and formal schooling. Spiritual knowledge is reserved for initiated youth, limiting access and increasing vulnerability to erosion [8]. The reservation of spiritual knowledge to initiates, as also documented among the Maasai [57], reveals the complexity of knowledge domains. This experiential and oral transmission mode requires institutional support for preservation. Mechanisms inspired by indigenous bilingual intercultural education, such as those developed in Bolivia [38], could inspire valorization initiatives in the OWR.

5. Recommendations

- Strengthen mechanisms for the recognition of Indigenous Peoples' land and resource rights: Secure access to land and natural resources is a fundamental prerequisite for the sustainability of traditional practices.
- Support the conservation of endogenous knowledge: Programs aimed at documenting, valorizing, and transmitting agroecological and cultural knowledge across generations should be actively encouraged.
- Promote ecologically sustainable livelihood alternatives: Supporting livelihood diversification, particularly through agroforestry, climate-resilient subsistence crops, and local crafts, would enhance the food and economic security of IPs.
- Integrate IPs into decision-making processes: Their active participation in natural resource governance and conservation initiatives (such as participatory management of the OWR) is essential to ensure equity and the effectiveness of environmental policies.
- Raise awareness about the impacts of modern tools: Tailored environmental education programs should be implemented to mitigate the adverse effects of recently introduced practices (e.g., nylon fishing nets, unregulated extensive agriculture).

This study advocates for an inclusive and collaborative approach to biodiversity conservation—one that acknowledges and values the practices, knowledge systems, and aspirations of Indigenous Peoples within a context of global environmental change.

6. Conclusions

This study highlights the importance of traditional knowledge and natural resource management practices among the IPs of the OWR, that continue to play a critical role in biodiversity management and cultural resilience. Despite ongoing socio-environmental disruptions, these communities maintain a strong dependence on the forest, both for subsistence and for the transmission of cultural and spiritual values. The recent introduction of agriculture, the evolution of hunting and fishing tools, and shifts in habitat preferences illustrate not only their adaptive capacity but also the tensions arising from sedentarization and progressive integration into the monetary economy. The perceptions expressed regarding resource availability and living conditions reveal a form of resilience, although underlying concerns about the future are evident. The exceptionally strong coupling of demographic, livelihood, and perceptual variables revealed by statistical analyses indicates that socio-ecological change is neither random nor fragmented, but systemic, and that the indigenous knowledge system is not a static relic but a dynamic and structured body of knowledge that is actively recording and responding to a period of intense socio-ecological upheaval. The analysis validates local perceptions as systematic and empirically coherent, affirming that they are a critical source of data for understanding environmental change and must be central to any sustainable management strategy for the reserve. The local disappearance of certain plant species, the gradual erosion of intergenerational knowledge transmission, and the declining importance attributed to primary forest warrant particular attention. Refs. [58,59], and community-based REDD+ initiatives [31] all recommend the integration of Indigenous knowledge into conservation strategies. Positive examples already exist in Mexico (community-managed territories in Oaxaca), Cameroon (Baka ICCAs), and India (India Biodiversity Act). The Democratic Republic of Congo would benefit from institutionalizing similar models.

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Appendix A

Table A1. Chi-square test of some variables.

	Gender	EG	LS	PLI	HWD	BD	CRL	CRQ	TR
MA	97.509, df = 14, *p*-value = 1.421×10^{-14}	81, df = 7, *p*-value = 8.612×10^{-15}	112.28, df = 21, *p*-value = 1.826×10^{-14}	109.54, df = 28, *p*-value = 1.363×10^{-11}					
ASA	81.016, df = 4, *p*-value < 2.2×10^{-16}	81, df = 2, *p*-value < 2.2×10^{-16}	82.624, df = 6, *p*-value = 1.025×10^{-15}	83.373, df = 8, *p*-value = 1.022×10^{-14}					
CRQ	84.814, df = 6, *p*-value = 3.608×10^{-16}	81, df = 3, *p*-value < 2.2×10^{-16}	96.954, df = 9, *p*-value < 2.2×10^{-16}	127.47, df = 12, *p*-value < 2.2×10^{-16}	83.662, df = 6, *p*-value = 6.249×10^{-16}	84.287, df = 6, *p*-value = 4.639×10^{-16}	50.373, df = 6, *p*-value = 3.957×10^{-9}		

Table A1. *Cont.*

	Gender	EG	LS	PLI	HWD	BD	CRL	CRQ	TR
Hunting	88.056, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	89.851, df = 6, p-value < 2.2×10^{-16}	91.104, df = 8, p-value = 2.776×10^{-16}	81.35, df = 4, p-value < 2.2×10^{-16}	81.054, df = 4, p-value < 2.2×10^{-16}	40.169, df = 4, p-value = 3.994×10^{-8}		
Picking	87.943, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	85.63, df = 6, p-value = 2.444×10^{-16}	85.04, df = 8, p-value = 4.704×10^{-15}	82.074, df = 4, p-value < 2.2×10^{-16}	81.051, df = 4, p-value < 2.2×10^{-16}	45.334, df = 4, p-value = 3.388×10^{-9}		
Fishing	81.15, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	83.842, df = 6, p-value = 5.734×10^{-16}	95.008, df = 8, p-value < 2.2×10^{-16}	81.224, df = 4, p-value < 2.2×10^{-16}	85.774, df = 4, p-value < 2.2×10^{-16}	46.045, df = 4, p-value = 2.41×10^{-9}		
Livestock	82.535, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	82.879, df = 6, p-value = 9.074×10^{-16}	82, df = 8, p-value = 1.933×10^{-14}	81.005, df = 4, p-value < 2.2×10^{-16}	82.314, df = 4, p-value < 2.2×10^{-16}	41.365, df = 4, p-value = 2.258×10^{-8}		
MLP	96.242, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	86.658, df = 6, p-value < 2.2×10^{-16}	83.144, df = 8, p-value = 1.136×10^{-14}	82.295, df = 4, p-value < 2.2×10^{-16}	83.068, df = 4, p-value < 2.2×10^{-16}	40.794, df = 4, p-value = 2.965×10^{-8}		
MFB	85.406, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	81.662, df = 6, p-value = 1.62×10^{-15}	87.686, df = 8, p-value = 1.37×10^{-15}	81.294, df = 4, p-value < 2.2×10^{-16}	81.039, df = 4, p-value < 2.2×10^{-16}	42.077, df = 4, p-value = 1.608×10^{-8}		
CRL	50.129, df = 4, p-value = 3.394×10^{-10}	39.994, df = 2, p-value = 2.068×10^{-9}	42.961, df = 6, p-value = 1.187×10^{-7}	42.528, df = 8, p-value = 1.078×10^{-6}	49.728, df = 4, p-value = 4.115×10^{-10}	45.972, df = 4, p-value = 2.496×10^{-9}	162, df = 4, p-value < 2.2×10^{-16}		
Pharma	84.315, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	82.371, df = 6, p-value = 1.156×10^{-15}	81.521, df = 8, p-value = 2.414×10^{-14}	93.992, df = 4, p-value < 2.2×10^{-16}	96.411, df = 4, p-value < 2.2×10^{-16}	50.091, df = 4, p-value = 3.457×10^{-10}	81.563, df = 6, p-value = 1.698×10^{-15}	
LS	88.556, df = 6, p-value < 2.2×10^{-16}	81, df = 3, p-value < 2.2×10^{-16}	-	84.625, df = 12, p-value = 5.373×10^{-13}	85.389, df = 6, p-value = 2.742×10^{-16}	85.314, df = 6, p-value = 2.842×10^{-16}	42.961, df = 6, p-value = 1.187×10^{-7}	96.954, df = 9, p-value < 2.2×10^{-16}	81, df = 3, p-value < 2.2×10^{-16}
PLI	83.988, df = 8, p-value = 7.672×10^{-15}	81, df = 4, p-value < 2.2×10^{-16}	84.625, df = 12, p-value = 5.373×10^{-13}	324, df = 16, p-value < 2.2×10^{-16}	83.297, df = 8, p-value = 1.058×10^{-14}	85.232, df = 8, p-value = 4.3×10^{-15}	42.528, df = 8, p-value = 1.078×10^{-6}	127.47, df = 12, p-value < 2.2×10^{-16}	81, df = 4, p-value < 2.2×10^{-16}
NTFPD	82.687, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	83.842, df = 6, p-value = 5.734×10^{-16}	84.18, df = 8, p-value = 7.017×10^{-15}	121.17, df = 4, p-value < 2.2×10^{-16}	110.4, df = 4, p-value < 2.2×10^{-16}	58.269, df = 4, p-value = 6.7e $\times 10^{-12}$	83.673, df = 6, p-value = 6.216×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}
HWD	81.005, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	85.389, df = 6, p-value = 2.742×10^{-16}	83.297, df = 8, p-value = 1.058×10^{-14}	-	118.68, df = 4, p-value < 2.2×10^{-16}	49.728, df = 4, p-value = 4.115×10^{-10}	83.662, df = 6, p-value = 6.249×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}
BD	81.727, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	85.314, df = 6, p-value = 2.842×10^{-16}	85.232, df = 8, p-value = 4.3×10^{-15}	118.68, df = 4, p-value < 2.2×10^{-16}	162, df = 4, p-value < 2.2×10^{-16}	45.972, df = 4, p-value = 2.496×10^{-9}	84.287, df = 6, p-value = 4.639×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}
RD	82.532, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	86.178, df = 6, p-value < 2.2×10^{-16}	83.373, df = 8, p-value = 1.022×10^{-14}	91.647, df = 4, p-value < 2.2×10^{-16}	109.23, df = 4, p-value < 2.2×10^{-16}	50.867, df = 4, p-value = 2.379×10^{-10}	81.662, df = 6, p-value = 1.62×10^{-15}	
TI	81.379, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	83.288, df = 6, p-value = 7.467×10^{-16}	98.568, df = 8, p-value < 2.2×10^{-16}	117.12, df = 4, p-value < 2.2×10^{-16}	102.5, df = 4, p-value < 2.2×10^{-16}	41.98, df = 4, p-value = 1.684×10^{-8}	90.977, df = 6, p-value < 2.2×10^{-16}	
SW	81.048, df = 4, p-value < 2.2×10^{-16}	81, df = 2, p-value < 2.2×10^{-16}	81.771, df = 6, p-value = 1.538×10^{-15}	86.708, df = 8, p-value = 2.163×10^{-15}	101.66, df = 4, p-value < 2.2×10^{-1}	104.46, df = 4, p-value < 2.2×10^{-16}	46.55, df = 4, p-value = 1.892×10^{-9}	83.978, df = 6, p-value = 5.375×10^{-16}	

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