Non-Timber Forest Products, Forest Structure, and Climate Variability: Implications for Household Livelihood Dependence in the Yangambi Biosphere Reserve, Democratic Republic of Congo

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ABSTRACT

Non-timber forest products are central to rural livelihoods in tropical forest regions, yet their availability is increasingly threatened by forest structural degradation and long-term climatic variability. This study investigates the interactions among forest structure, historical climatic trends, and household NTFP dependence in eight villages surrounding the Yangambi Biosphere Reserve. Using a convergent parallel mixed-methods design, the research integrates biophysical forest inventories based on 20 × 20 m quadrats in primary and secondary forests, historical climatic records from 1931 to 2010, stratified household surveys ($n = 46$), Rapid Rural Appraisal tools, focus group discussions including a women-only group, and key informant interviews. Quantitative data were analyzed using descriptive statistics, Pearson correlations, and chi-square tests in SPSS v26, while qualitative data were subjected to thematic analysis in NVivo 12. Results indicate that primary forests display significantly greater structural complexity than secondary forests, including higher species richness (38 vs. 21), basal area (4.2 vs. 1.8 m^2/ha), and canopy cover (70% vs. 40%), which support stronger NTFP diversity and seasonal stability. Climatic analysis shows a 1.2 °C rise in mean annual temperature and a 15% decline in rainfall over the study period, trends that are negatively correlated with perceived NTFP availability ($r = -0.62$, $p < .05$) and seasonality ($r = -0.58$, $p < .05$). Household dependence on NTFPs is significantly higher among communities located within 5 km of primary forest edges ($\chi^2 = 6.47$, $df = 2$, $p < .05$). Women and female-headed households, representing 30.4% of the sample, demonstrate greater reliance on NTFPs and heightened vulnerability linked to gendered labor roles and structural constraints. Adaptation responses are dominated by agricultural expansion (45.7%) and agroforestry adoption (30.4%), whereas non-farm diversification remains limited (15.2%) due to persistent socio-economic and cultural barriers. These findings demonstrate that interacting ecological degradation and climatic stress are reducing NTFP provisioning, intensifying spatially and gender-differentiated vulnerability, and constraining adaptive capacity. The study highlights the urgency of integrated management strategies that combine forest restoration, climate-resilient agroforestry, spatially targeted livelihood support, and gender-sensitive interventions to sustain ecosystem integrity and rural wellbeing in biosphere reserve transition zones.

Keywords: forest structure, climate variability, primary forest, secondary forest, Yangambi Biosphere Reserve.

INTRODUCTION

Non-timber forest products (NTFPs), including fruits, nuts, honey, medicinal plants, fibres, resins, and other forest-derived biological resources harvested without tree felling, constitute essential components of rural livelihoods in tropical forest regions. They provide food, nutrition, income, medicinal resources, and cultural continuity (Arnold & Ruiz Pérez, 2001; Shackleton et al., 2011). In the Congo Basin, one of the largest contiguous tropical forest blocks globally, NTFPs contribute between 20 and 40 percent of household income for communities adjacent to forests and act as critical safety nets during periods of agricultural shortfall, market fluctuations, or environmental stress (Ndoye & Tieguhong, 2004; Ingram et al., 2014; Sunderland et al., 2015). These resources are particularly important for vulnerable groups, including women and indigenous populations, who often serve as primary collectors and local traders of NTFPs (Womeni et al., 2016; Chakona & Shackleton, 2019). The sustainability of NTFP-dependent livelihoods is increasingly threatened by two interlinked drivers: progressive forest structural degradation and escalating climatic variability. Primary forests, characterized by high species richness, large basal area, dense multi-layered canopies, and stable regeneration dynamics, provide

higher NTFP diversity and more reliable yields (Whitmore, 1998; Chazdon, 2014). In contrast, secondary forests, emerging from shifting cultivation, selective logging, charcoal production, and settlement expansion, exhibit simplified vertical and horizontal structure, reduced biomass, lower species diversity, and more variable productivity over time (Brown & Lugo, 1990; Guariguata & Ostertag, 2001; Poorter et al., 2016). These structural contrasts generate spatial gradients in resource access, with households near primary forest remnants benefiting from higher NTFP availability and diversity, while those adjacent to degraded secondary stands face increasing scarcity and uncertainty (Fisher, 2004; Paumgarten & Shackleton, 2011). Climatic variability across the Congo Basin compounds these pressures. Observed increases in mean annual temperature of 1-2 degrees Celsius, coupled with declining or erratic rainfall, alongside projections of 2-4 degrees Celsius warming by 2100 under moderate-to-high emission scenarios, disrupt tree phenology, increase evapotranspiration, reduce soil moisture, and alter species composition (Malhi & Wright, 2004; Zhou et al., 2014; IPCC, 2022; Clark et al., 2003; Feeley et al., 2012; Morellato et al., 2016; FAO, 2020). These biophysical changes influence the timing, quantity, and quality of NTFPs, and communities frequently report delayed or reduced seasonal availability, heightening livelihood vulnerability (Roncoli et al., 2001; Tschakert et al., 2010). The Yangambi Biosphere Reserve in northeastern Democratic Republic of Congo exemplifies these intersecting pressures. Despite its historical role as a tropical forest research hub (INERA, 2010), studies that simultaneously examine forest structural variation, long-term climatic trends, and household-level NTFP dependence remain scarce. Previous research has largely treated these dimensions in isolation, focusing either on biophysical degradation, climatic impacts, or socio-economic NTFP use, without exploring the interactive effects of forest structural differences and climatic variability on livelihood reliance and adaptation capacity (Ingram et al., 2014; Sunderland et al., 2015; FAO, 2020). This gap limits the development of evidence-based management strategies capable of supporting rural livelihoods while maintaining ecosystem integrity in biosphere reserve transition zones.

This study addresses these gaps by systematically examining the joint influence of forest structural attributes and long-term climatic variability on household NTFP dependence in villages surrounding the Yangambi Biosphere Reserve. Specifically, it compares structural characteristics of primary and secondary forests, analyses climatic trends over time, assesses spatial and socio-economic determinants of NTFP reliance, and identifies local adaptation strategies. The findings aim to inform integrated socio-ecological management approaches that enhance community resilience and promote sustainable NTFP utilization in protected forest peripheries.

LITERATURE REVIEW

Non-timber forest products and rural livelihoods

Non-timber forest products (NTFPs) comprise biological materials harvested from forests, woodlands, and trees outside forests, excluding industrial timber (FAO, 1999; Belcher, 2003). They include edible products such as fruits, nuts, honey, wild vegetables, bushmeat, medicinal plants, fibres, resins, construction materials, and fuelwood. In tropical forest ecosystems, NTFPs perform multifunctional roles, simultaneously sustaining subsistence consumption, generating income, enhancing dietary diversity, supporting ethnomedicine, and reinforcing socio-cultural identity (Arnold & Ruiz Pérez, 2001; Shackleton et al., 2011). Across the Congo Basin, NTFPs constitute a structural component of rural economies rather than a marginal supplement. Empirical evidence indicates that forest-adjacent households derive between 20 and 40 percent of total income from NTFPs (Ndoye & Tieguhong, 2004; Ingram et al., 2014; Sunderland et al., 2015). Beyond income generation, they operate as counter-cyclical safety nets during agricultural shortfalls, price instability, and climatic shocks (Belcher et al., 2005; Angelsen et al., 2014). This buffering function situates NTFPs within livelihood resilience frameworks, particularly in contexts where formal financial systems and insurance mechanisms are absent. Recent scholarship emphasizes the nutritional dimension of NTFPs. Wild fruits, leafy vegetables, and bushmeat contribute essential micronutrients, amino acids, and vitamins that complement carbohydrate-dominated staple diets (Womeni et al., 2016; Chakona & Shackleton, 2019; Tata Ngome et al., 2017).

Gendered analyses further reveal that women frequently dominate harvesting and petty trade activities, positioning NTFPs as instruments of female economic agency and intra-household bargaining power. Dependence patterns, however, are neither uniform nor random. Forest Dependency Theory posits that reliance on forest products is inversely correlated with asset endowment and livelihood diversification (Vedeld et al., 2007; Fisher, 2004). Poorer households often derive a higher proportional share of income from NTFPs because entry barriers are relatively low and capital requirements minimal. Conversely, wealthier households tend to diversify into agriculture, trade, or salaried employment while maintaining selective engagement in high-value NTFP markets (Shackleton & Shackleton, 2004; Paumgarten & Shackleton, 2011). Spatial proximity to forest edges significantly mediates access and extraction intensity. Households located nearer to forests incur lower opportunity and transportation costs, resulting in greater levels of dependence (Wilkie & Carpenter, 1999; Fisher, 2004). Evidence from the Democratic Republic of Congo indicates that NTFP traders may earn between USD 16 and 160 weekly, with producers retaining 50 to 75 percent of total value, demonstrating tangible market potential for rural actors (Asamoah et al., 2025). Despite these contributions, heavy dependence may generate vulnerability traps. Overexploitation, habitat degradation, and climate-induced productivity decline can erode resource bases, undermining the very safety nets upon which households rely (Shackleton et al., 2008). Global reviews estimate average NTFP contributions of 23.56 percent to rural incomes, with substantial variation across contexts, underscoring both poverty- alleviation potential and sustainability risks (Derebe, 2023). Consequently, contemporary analyses advocate positioning NTFPs within integrated livelihood and sustainability frameworks that reconcile economic value with ecological regeneration (Nkem et al., 2010).

Forest structure and its influence on NTFP availability

Forest structure refers to the spatial and biological organization of vegetation, encompassing species composition, stem density, basal area, canopy cover, vertical stratification, and regeneration dynamics (Oliver & Larson, 1996; Pretzsch, 2009). Structural attributes regulate light penetration, nutrient cycling, habitat heterogeneity, and microclimatic stability, thereby directly influencing NTFP abundance and reliability (Ticktin, 2004; Chapman et al., 2005). Primary tropical forests exhibit high structural complexity characterized by large-diameter trees, multilayered canopies, and elevated species richness. These characteristics foster diversified NTFP portfolios and relatively stable yields over time (Whitmore, 1998; Lewis et al., 2013). Complex canopy architecture moderates temperature extremes, conserves soil moisture, and enhances ecological resilience, sustaining productive understories that host numerous edible and medicinal species (Chazdon, 2014). Secondary forests, by contrast, emerge from anthropogenic or natural disturbances such as shifting cultivation, logging, or fire. They are typically marked by lower biomass, simplified vertical layering, and dominance of pioneer species (Brown & Lugo, 1990; Guariguata & Ostertag, 2001).

Although secondary forests can provide certain fast-growing non-timber forest products (NTFPs), overall productivity and species diversity tend to be lower, and yield variability higher, particularly in early successional stages (Chazdon, 2014; Chazdon et al., 2009; Poorter et al., 2016). In the Congo Basin, conversion from primary to secondary forest has reduced densities of high-value NTFP host species and altered ecological equilibria (Ingram et al., 2014). Structural degradation increases susceptibility to pest outbreaks, invasive species, and climatic stress. Spatial disparities consequently emerge: households adjacent to intact forest fragments benefit from higher yield stability, while those near degraded stands confront declining availability and heightened uncertainty (Fisher, 2004; Paumgarten & Shackleton, 2011). Recent analyses link such structural transitions to agricultural expansion and charcoal production, further intensifying biodiversity erosion and livelihood precarity (Ngouhouo-Poufoun et al., 2024). Forest structure thus functions as a foundational ecological determinant of livelihood outcomes in biosphere reserves and transitional landscapes. Conservation strategies that overlook structural integrity risk undermining both biodiversity and socio-economic resilience.

Climate variability and its effects on forest ecosystems and NTFPS

The Congo Basin has experienced measurable climatic shifts characterized by rising mean annual temperatures, altered precipitation regimes, and increased frequency of extreme events (Malhi & Wright, 2004; Zhou et al., 2014; IPCC, 2022). Observed warming of approximately 1 to 2 °C across the basin is accompanied by increasing rainfall irregularity. Under moderate to high emission trajectories, projections indicate additional warming of 2 to 4 °C by 2100 (IPCC, 2022). Climatic stressors influence forest ecosystems through multiple pathways. Elevated temperatures intensify evapotranspiration and physiological stress, while rainfall variability reduces soil moisture and disrupts nutrient cycling (Clark et al., 2003; Phillips et al., 2009). These processes alter phenological cycles, affecting flowering, fruiting, and leaf flush timing, which directly shapes NTFP availability (Feeley et al., 2012; Morellato et al., 2016). Reduced productivity, shifts in species composition, and altered regeneration patterns have cascading implications for NTFP provisioning services (FAO, 2020; Zambaldi et al., 2020). Furthermore, secondary forests, already structurally simplified, display lower resilience to climatic perturbations compared to intact primary stands. Community perceptions often align with meteorological records. Residents report unpredictable fruiting seasons, declining yields, and shortened harvesting windows (Roncoli et al., 2001; Tschakert et al., 2010). In the Yangambi region, archival records from 1931 to 2010 document a 1.2 °C temperature increase and approximately 15 % rainfall decline, reinforcing broader basin wide trends (Institut National pour l'Étude et la Recherche Agronomique, 2010). These pressures intersect with land-use change dynamics, including cocoa expansion and subsistence agriculture, intensifying ecological and livelihood vulnerability (Ngouhouo-Poufoun et al., 2024).

Household dependence, vulnerability, and adaptation strategies

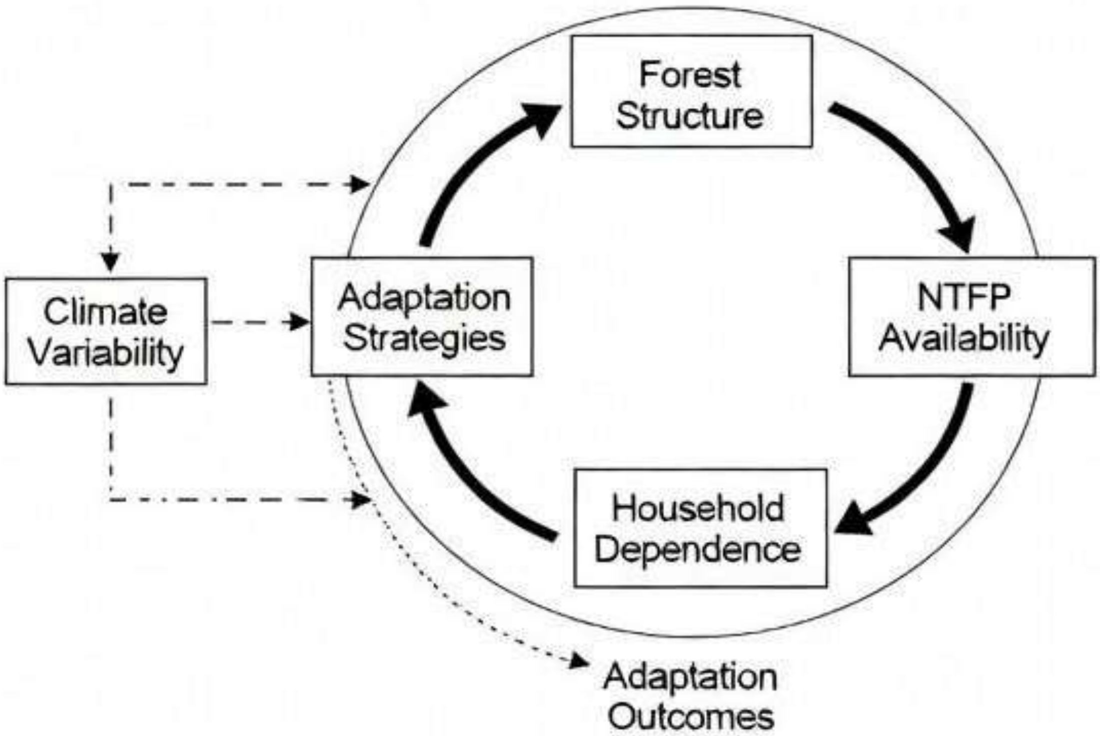
Household dependence on forest resources is strongly shaped by the structure of rural livelihoods and the distribution of productive assets. According to Forest Dependency Theory, households with limited access to land, capital, or formal employment opportunities tend to rely more heavily on forest products because these resources function as a readily accessible safety net (Vedeld et al., 2004; Fisher, 2004). When forests are located close to settlements, extraction costs in terms of time, labor, and transportation decline, further reinforcing reliance on forest-derived goods such as non-timber forest products, fuelwood, bushmeat, and edible caterpillars. Socio-economic factors significantly influence the degree of dependence. Poorer households, larger family units with higher consumption needs, and households with lower educational attainment often exhibit higher levels of forest reliance (Shackleton & Shackleton, 2004; Paumgarten & Shackleton, 2011). In contrast, households with diversified income sources or secure land tenure may rely less directly on forest extraction. However, high dependence on forest ecosystems can also heighten vulnerability when ecological productivity declines due to deforestation, habitat degradation, overharvesting, or climate variability. Under such conditions, households that rely heavily on forest resources face increased livelihood insecurity because their primary subsistence and income sources become unstable (Shackleton et al., 2008).

In response to these pressures, rural households frequently adopt a range of adaptation strategies aimed at maintaining livelihood resilience and reducing risk exposure. Livelihood diversification represents one of the most common responses, with households combining forest product harvesting with agriculture, petty trade, wage labor, or seasonal migration (Ellis, 2000; Sunderlin et al., 2005). Agroforestry has also emerged as a promising adaptation pathway, particularly in the Congo Basin where systems integrating non-timber forest product host species with staple crops can simultaneously support food security, income generation, and forest conservation (Leakey, 2010; Asaah et al., 2014). Such systems help stabilize household incomes while reducing harvesting pressure on natural forest ecosystems. Despite these opportunities, several structural barriers limit the effectiveness of adaptation efforts. Restricted access to credit and agricultural inputs, insecure land tenure arrangements, weak institutional support, and limited technical knowledge often constrain households' capacity to implement sustainable livelihood alternatives (Place et al., 2012; Reed et al., 2015). Furthermore, spatial context plays an important role in shaping adaptation trajectories. Households located near relatively intact forests may delay diversification because resource availability remains relatively stable, whereas those in degraded landscapes are often compelled to diversify more rapidly as forest resources become increasingly scarce (Wilkie et al., 2011).

Integrating forest structure, climate variability, and livelihood dependence

Socio-ecological systems theory conceptualizes forests and human livelihoods as interdependent subsystems linked through dynamic feedback loops operating across multiple spatial and temporal scales (Berkes & Folke, 1998; Ostrom, 2009). In biosphere reserves, where strict conservation mandates intersect with local development imperatives, integrated analyses that simultaneously consider ecological structure, climatic drivers, and livelihood outcomes are essential for assessing resilience, adaptive capacity, and long-term sustainability (Kusters et al., 2006; Reed et al., 2015). These frameworks emphasize that changes in one subsystem such as forest structural simplification or altered phenology due to climate variability can cascade to affect provisioning services and trigger adaptive responses that, in turn, influence ecological recovery or further degradation (Folke et al., 2005; Chapin et al., 2009). Although substantial scholarship exists on NTFPs (Arnold & Ruiz Pérez, 2001; Shackleton et al., 2011), forest ecology (Chazdon, 2014; Guariguata & Ostertag, 2001), and climate impacts on tropical forests (Malhi & Wright, 2004; IPCC, 2022) individually, integrative frameworks that explicitly link forest structural variation, climatic trends, and household-level NTFP dependence remain limited in Central Africa (Ingram et al., 2014; Sunderland et al., 2015). Much of the existing research in the Congo Basin has treated these dimensions in isolation: biophysical studies focus on degradation patterns and carbon stocks (Tyukavina et al., 2018; Hansen et al., 2013), climatic analyses emphasize temperature and rainfall shifts (Zhou et al., 2014), and socio-economic assessments document NTFP income and safety-net roles (Ndoye & Tieguhong, 2004; Angelsen et al., 2014). Few studies have systematically quantified how structural differences between primary and secondary forests interact with climatic variability to shape livelihood reliance and adaptive capacity (FAO, 2020; Nkem et al., 2010). In Yangambi, historical research has primarily separated ecological inventories from socio-economic assessments, leaving interactions between forest structural change, climatic variability, and livelihood dependence insufficiently theorized (INERA, 2010). This fragmentation limits the ability to design evidence-based interventions that reconcile biodiversity conservation with rural well-being in biosphere reserve landscapes (Kusters et al., 2006; Reed et al., 2015). This study advances the literature by synthesizing biophysical forest inventories (species richness, basal area, canopy cover, regeneration), household-level socio-economic data (dependence levels, adaptation strategies), and long-term climatic records (temperature and rainfall trends, 1931-2010). It contributes to an integrated understanding of how structural and climatic transformations jointly influence NTFP dependence, thereby informing adaptive management strategies that balance ecological integrity and rural livelihoods in biosphere reserve transition zones.

Figure 1. Integrated socio-ecological framework linking forest structure, climate variability, and household dependence on non-timber forest products (NTFPs) in the Yangambi Biosphere Reserve transition zones.



Source: Author's synthesis, adapted from Ostrom (2009) and Fisher (2004

Figure 1 conceptualizes forests and rural livelihoods as interdependent subsystems within a dynamic social ecological system where ecological processes and human responses interact. Forest structure, including species richness, basal area, canopy cover, and regeneration, drives NTFP availability, diversity, and seasonal stability. Climate variability through long-term temperature and rainfall trends acts as an external stressor affecting productivity, phenology, and provisioning. Household NTFP dependence is influenced by forest proximity and socio-economic factors such as assets, gender, wealth, and perceived scarcity. Reduced NTFP reliability prompts adaptive strategies including agriculture, agroforestry, and limited non-farm activities, which feedback into forest structure and ecosystem services. Adapted from Ostrom (2009) and Fisher (2004), the model integrates biophysical, climatic, and livelihood dimensions in biosphere reserve transition zones.

Problem Statement

Rural households in the transition zones surrounding the Yangambi Biosphere Reserve in northeastern Democratic Republic of Congo rely heavily on non-timber forest products (NTFPs) for subsistence, income, medicinal use, construction materials, and cultural practices. These resources provide a critical livelihood safety net, particularly for poorer households and women who have limited access to formal employment and markets. However, the sustainability of NTFP-based livelihoods is increasingly threatened by forest structural degradation. The conversion of primary forests into secondary stands through agricultural expansion, informal logging, charcoal production, and settlement pressures has altered key structural characteristics such as species richness, basal area, canopy cover, and regeneration dynamics. These changes reduce forest biomass and biodiversity, thereby limiting the availability, diversity, and seasonal reliability of NTFP resources and creating spatial inequalities in access. These ecological pressures are compounded by long-term climatic variability across the Congo Basin, including rising temperatures and increasingly erratic rainfall patterns that disrupt tree phenology, reduce productivity, and affect the timing and quantity of NTFPs. Despite Yangambi's historical importance as a major center for tropical forest research, few studies have integrated forest structural dynamics, climatic variability, and household dependence on NTFPs. This study therefore seeks to examine how variations in forest structure and climatic trends influence NTFP availability and household dependence in the transition zones of the Yangambi Biosphere Reserve, while identifying the adaptation strategies households adopt in response to these changing socio-ecological conditions.

Purpose Of The Study

This study examines how forest structural characteristics and long-term climatic variability influence household dependence on non-timber forest products (NTFPs) in villages surrounding the Yangambi Biosphere Reserve in the Democratic Republic of Congo. By integrating forest inventory data, climatic trends, and household socioeconomic information, the research assesses how forest degradation and climate variability affect NTFP availability, patterns of dependence, and household adaptation strategies. The study aims to provide evidence to support management approaches that balance biodiversity conservation with resilient rural livelihoods in biosphere reserve transition zones.

Research Question

Main research question

How do forest structural characteristics and long-term climatic variability influence household dependence on non-timber forest products in the transition zones of the Yangambi Biosphere Reserve?

Specific research questions

1. How do structural differences between primary and secondary forests, including species richness, basal area, canopy cover, and regeneration dynamics, influence the availability, diversity, and seasonal reliability of non-timber forest products?
2. How does long-term climatic variability, particularly changes in temperature and rainfall patterns, affect NTFP availability and household perceptions of resource uncertainty and vulnerability?
3. How do spatial proximity to forest edges and household socio-economic characteristics shape levels of household dependence on NTFPs?
4. What livelihood adaptation strategies do households adopt in response to changes in forest resource availability and climatic variability?

Objectives Main Objective

To examine how forest structural characteristics and long-term climatic variability influence household dependence on non-timber forest products in the transition zones of the Yangambi Biosphere Reserve.

Specific Objectives

1. To assess how structural differences between primary and secondary forests, including species richness, basal area, canopy cover, and regeneration dynamics, influence the availability, diversity, and seasonal reliability of non-timber forest products.

2. To analyze the effects of long-term climatic variability, particularly changes in temperature and rainfall patterns, on NTFP availability and household perceptions of resource uncertainty and vulnerability.

3. To evaluate how spatial proximity to forest edges and household socio-economic characteristics shape levels of household dependence on non-timber forest products.

4. To identify and analyze the livelihood adaptation strategies adopted by households in response to changes in forest resource availability and climatic variability.

METHODOLOGY

Research design

This study employed a convergent parallel mixed-methods design to examine interactions between forest structure, long-term climatic variability, and household dependence on non-timber forest products (NTFPs) in villages surrounding the Yangambi Biosphere Reserve, Democratic Republic of Congo. Quantitative and qualitative data were collected concurrently between February and April 2011 and integrated at the interpretation stage to provide a comprehensive socio-ecological assessment (Creswell & Plano Clark, 2018). The quantitative component measured biophysical forest attributes, including basal area, canopy cover, and regeneration density, alongside long-term climatic trends.

The qualitative component captured household perceptions of ecological change, livelihood vulnerability, and adaptation strategies through Rapid Rural Appraisal (RRA) and focus group discussions (FGDs). Triangulation of methods enhanced validity: forest metrics were cross-checked against household-reported NTFP availability, and climatic archives were compared with community-reported trends. Household dependence patterns were corroborated using statistical associations and qualitative narratives. This multi-strand integration enabled convergence, providing confirmation of patterns; complementarity, offering insight into underlying mechanisms; and expansion, allowing new insights to emerge.

A purposive sample of 46 households was selected to capture context-specific variation. Post-hoc statistical power analysis using Python's stats models confirmed adequate sensitivity for key correlations, for example, between temperature increase and perceived NTFP availability ($r = -0.62$, $n = 46$, $\alpha = 0.05$, power = 0.95). While sufficient for exploratory analysis, the sample limits detection of small effects and generalizability beyond similar humid tropical forest landscapes.

Ethical standards were strictly observed. Informed consent was obtained verbally and in writing in Lingala and Swahili, with full disclosure of objectives, procedures, risks, benefits, and withdrawal rights. Anonymity and confidentiality were maintained, and no financial incentives were provided. Preliminary findings were shared with communities through a feedback workshop. Ethical clearance was granted by the Institut National pour l'Étude et la Recherche Agronomique (INERA) Yangambi. Researcher reflexivity was documented systematically to reduce observer bias. This design is appropriate for complex socio-ecological systems in which environmental conditions and human responses interact dynamically across spatial and temporal scales (Berkes & Folke, 1998; Ostrom, 2009). It provides a rigorous framework for linking biophysical, climatic, and livelihood dimensions in biosphere reserve transition zones.

Study area and sampling strategy

Fieldwork was conducted in eight purposively selected villages within 10 km of the Yangambi Biosphere Reserve boundary in Bas-Uélé Province, northeastern Democratic Republic of Congo: Lilanda, Yakunji, Yakako, Yaselia, Yalugum, Yalibua, Yalifa, and Ekutsu. The reserve covers approximately 235,000 hectares of humid evergreen tropical forest (0°45′–0°50′N, 24°15′–24°30′E), characterized by ferralitic soils, bimodal rainfall

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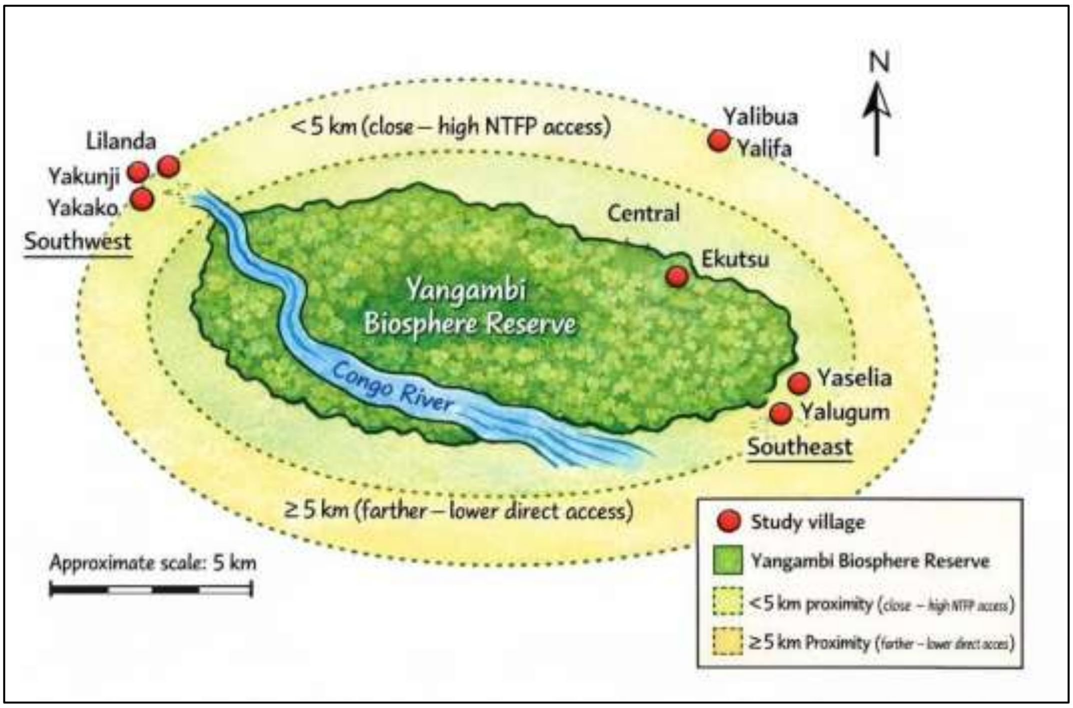
averaging 1,800 mm annually, and mean annual temperatures between 24 and 26 °C (UNESCO, 2023; INERA, 2010). Vegetation includes primary evergreen forests dominated by Gilbertiodendron dewevrei and secondary successional stands featuring pioneer species such as Musanga cecropioides. Surrounding communities depend primarily on subsistence agriculture and NTFP harvesting, and have limited access to infrastructure and markets. Villages were selected to represent spatial and socio-economic heterogeneity. Stratification was applied according to cardinal direction (southwest, southeast, north, central) and proximity to the forest edge (<5 km = close; ≥5 km = far) to capture resource access gradients. Geographic coordinates were recorded using handheld GPS devices to support spatial mapping and correlation analysis. Households were sampled through purposive and availability techniques, stratified by wealth status using replicable, locally validated asset-based criteria. Household categories were defined as follows: Rich: more than five livestock units, iron-sheet roofing, and motorcycle or equivalent durable assets. Medium: two to four livestock units, mixed roofing materials, and limited durable assets. Poor: fewer than two livestock units, basic thatch roofing, and minimal assets. Key informants (n = 4) were identified through snowball sampling and included local leaders and INERA researchers with extensive knowledge of forest dynamics and climatic trends.

Table 1. Household Sampling Distribution by Direction and Proximity

Direction	Villages	Households	Close (<5km)	Far(≥5km)
South- West	Lilanda, Yakunji, Yakako	18	11	7
South-East	Yaselia, Yalugum	8	5	3
North	Yalibua, Yalifa	9	5	4
Central	Ekutsu	11	6	5
Total	Eight villages	46	27	19

Source: (Barika 2011*)*

Figure 1. Sketch Map of Yangambi Biosphere and Surrounding Study Villages in Northeastern DRC



Source: Sketch Map by Authors based on field knowledge and study design.

Data collection procedures

To ensure triangulation and analytical robustness, Structured questionnaires (n = 46) were administered face to-face in local languages. The survey captured demographic profiles, NTFP dependence (frequency of use, income contribution, perceived importance, seasonal reliance), main income sources, perceptions of climatic and structural change, and adaptation strategies. Questionnaires were developed in English, translated into Lingala and Swahili, back- translated for accuracy, and pilot-tested in a non-sample village. Participatory RRA tools were applied in Lilanda (n = 8 participants), including NTFP species and host plant lists, seasonal calendars, and 15-year retrospective trend analyses of perceived availability and reliability. Two FGDs with six to eight participants each were conducted: one women-only group and one youth-focused group. Discussions examined experiences of vulnerability, adaptation constraints, and community perceptions of forest change. Four semi-structured interviews were conducted with local leaders and INERA researchers to obtain expert perspectives on historical forest dynamics, climatic trends, and management challenges. All qualitative sessions were audio-recorded with consent, transcribed verbatim, and conducted in Lingala or French with local translators. Forest structural attributes were measured in primary and secondary forests using systematic 20 × 20 m quadrats, totaling 0.8 ha per forest type. Quadrats were randomly located via GPS in accessible zones near villages. Recorded parameters included species richness, diameter at breast height (DBH ≥10 cm), tree height (clinometer), canopy cover (0–100% visual scale), defoliation intensity (0–100%), basal area ($\sum[\pi(DBH/2)^2]$ per ha), and regeneration density (seedlings and saplings <10 cm DBH in 5 × 5 m sub-plots). Historical records of mean annual temperature and rainfall (1931–2010) were extracted from INERA Yangambi meteorological archives for linear trend analysis.

Table 2. Summary of Data Collection Methods

Method	Instrument/Tool	Sample Size	Primary Focus
Household Surveys	Structured questionnaire	n = 46 (8 villages)	Demographics, NTFP dependence, adaptation
Rapid Rural Appraisal	Lists, seasonal calendars, trend lines	n = 8 (Lilanda)	Seasonality, perceived change, NTFP species
Focus Group Discussions	Semi-structured guide	n = 2 groups (6–8 each)	Vulnerability, strategies, attitudes
Key Informant Interviews	Semi-structured guide	n = 4	Historical forest/climate trends, management
Forest Inventories	20 × 20 m quadrats	0.8 ha per forest type	Structural attributes (basal area, canopy, regeneration)
Climatic Data	INERA archives	1931–2010	Temperature and rainfall trends

Source: (Barika 2011; INERA Yangambi, 2010)

Data analysis

Quantitative data were analyzed using SPSS version 26. Descriptive statistics summarized forest structural attributes, socio-demographic characteristics, and NTFP dependence levels. Pearson correlation coefficients examined relationships between climatic variables and perceived NTFP availability, while chi-square tests assessed associations between forest proximity and dependence levels. Normality was tested using ShapiroWilk tests, and non-parametric Spearman's rho was applied when appropriate. Qualitative data were analyzed thematically in NVivo 12 (Braun & Clarke, 2006). Inductive coding identified emergent themes such as structural decline, climatic uncertainty, and adaptation constraints. Inter-coder agreement reached 85%. Triangulation integrated biophysical and livelihood data to reveal feedback mechanisms between forest degradation, climatic variability, and household dependence.

Ethical considerations

Ethical clearance was obtained from INERA Yangambi. Informed consent was secured in local languages with full disclosure of objectives, procedures, risks, benefits, and the right to withdraw. Participation was voluntary, and anonymity and confidentiality were maintained.

Limitations

This study provides important insights into the socio-ecological dynamics of NTFP dependence in the Yangambi biosphere reserve transition zones, but several limitations should be acknowledged. first, the household sample size (n = 46) was purposive and stratified to capture spatial and socio-economic heterogeneity across eight villages. although appropriate for an exploratory mixed-methods design and supported by post-hoc power analysis indicating strong sensitivity for the principal correlations, the relatively small sample reduces statistical power to detect weaker relationships or subtle subgroup differences. As a result, the findings may not be fully generalizable beyond similar humid tropical forest landscapes in Yangambi or comparable Congo basin transition zones with analogous conditions.

Second, the climatic analysis relies on historical meteorological records from the INERA Yangambi station covering 1931 to 2010, documenting a 1.2 °c increase in mean annual temperature and a 15 percent decline in rainfall. this 80-year dataset provides rare empirical depth in a region where long-term ground observations have declined significantly since the 1990s (yakusu et al., 2023). more recent analyses extending records to 2020 confirm continued and accelerated warming, including rates of 0.34 °c per decade since the early 1990s compared to 0.18 °c per decade over 1960 to 2020, as well as increased precipitation seasonality characterized by longer dry seasons and more intense wet seasons (yakusu et al., 2023). while these findings reinforce the validity of the 1931 to 2010 baseline, the absence of post-2010 station data in the present study creates a temporal gap of approximately sixteen years. consequently, the analysis may not fully capture recent climatic extremes or accelerated warming trends. Future research should prioritize integrating post-2010 INERA records or complementary reanalysis datasets to strengthen temporal coverage. Third, the cross-sectional design, with fieldwork conducted between February and April 2011, captures associations at a single point in time and does not permit assessment of longitudinal dynamics such as inter-annual variability in NTFP yields, evolving adaptation strategies, or delayed responses to climatic change. Fourth, reliance on self-reported data from household surveys, rapid rural appraisal tools, focus group discussions, and key informant interviews introduces potential recall and social desirability bias, particularly regarding perceptions of long-term climatic trends and historical resource availability. although triangulation with forest inventories and archival climate records reduces this limitation, perceptual data remain inherently subjective.

Finally, fieldwork occurred during the off-season for several key NTFPS, limiting direct observation of harvesting intensity, yield levels, and seasonal reliability. this restricts validation of reported patterns with contemporaneous empirical harvest measurements. addressing these limitations through larger or panel-based surveys, updated climatic monitoring, longitudinal phenological studies, and seasonally aligned fieldwork would enhance analytical robustness and generalizability.

RESULTS

The results are presented according to the research objectives: (1) socio-demographic characteristics of households, (2) forest structural attributes of primary and secondary forests, (3) long-term climatic trends, (4) effects of climatic variability on NTFP availability, (5) household dependence on NTFPs and spatial patterns, and (6) community adaptation strategies. Quantitative results were analyzed using SPSS version 26, and qualitative insights were drawn from Rapid Rural Appraisal (RRA), focus group discussions (FGDs), and key informant interviews. Triangulation of these datasets allowed a robust assessment of socio-ecological interactions.

Socio-demographic characteristics of households

A total of 46 households across eight villages participated in the survey. Most households were male-headed (69.6%), with female-headed households representing 30.4% of the sample. Household sizes were generally moderate to large, with 67.4% having five or more members. The majority of households relied on a combination of agriculture and NTFPs for livelihoods (60.9%), while 26.1% depended solely on agriculture and 13.0% engaged in other income-generating activities. Spatially, 58.7% of households were located within five kilometers of the forest edge, reflecting the importance of proximity for resource access. Qualitative responses confirmed the reliance on forest resources, particularly among poorer households. A female FGD participant from Lilanda explained, “Without the forest, we have nothing. No food in the dry season, no medicine when children are sick, and no money for school fees.” Household dependence was higher among households with fewer assets and those situated closer to primary forest patches, highlighting the socio-economic and spatial determinants of NTFP use.

Forest structural characteristics: primary and secondary forests

Forest inventories revealed substantial structural differences between primary and secondary forests. Primary forests exhibited higher species richness (mean = 38 species), greater basal area (4.2 m^2/ha), dense canopy cover (70%), and well-established regeneration, indicating high ecological integrity and potential NTFP provisioning capacity. In contrast, secondary forests showed reduced species richness (mean = 21 species), lower basal area (1.8 m^2/ha), more open canopies (40%), and patchy regeneration, reflecting prior disturbance through logging, agricultural encroachment, and charcoal production. These structural differences were mirrored in local perceptions. Furthermore, a key informant from INERA Yangambi stated, “In the old forest, you find everything all year-honey, mushrooms, and medicines. The new forest has only a few things and only in certain months.” This indicates that primary forests provide more stable and diverse NTFP supplies, whereas secondary forests offer limited and temporally variable resources.

Table 1. Comparison of key structural attributes between primary and secondary forests in the Yangambi Biosphere Reserve transition zones.

Forest Type	Species Richness (mean)	Basal Area (m^2/ha)	Canopy Cover (%)	Regeneration Density
Primary	38	4.2	70	High, dense understory
Secondary	21	1.8	40	Moderate, patchy

Source: Author’s computation

Table 1: Mean values are reported for species richness (number of tree species per quadrat), basal area (m^2/ha, calculated from trees ≥10 cm DBH), canopy cover (visual estimation as percentage), and qualitative regeneration density (seedlings/saplings <10 cm DBH in sub-plots). Data derived from systematic 20 × 20 m forest inventories (total 0.8 ha per forest type) conducted near study villages. Primary forests exhibit greater structural complexity, supporting higher NTFP diversity and stability, while secondary forests show simplified attributes consistent with prior anthropogenic disturbance (e.g., shifting cultivation, logging).

Long-term climatic trends

Historical climatic records (1931–2010) from the INERA Yangambi station indicate a gradual increase in mean annual temperature by approximately 1.2 °C and a decline in mean annual rainfall by around 15%. These trends are consistent with regional climate projections for the Congo Basin and have implications for forest ecosystem productivity and NTFP availability. Community perceptions corroborated these trends. A youth FGD participant from Yakako commented, “The rains used to be regular with two strong seasons. Now it is dry longer, and the forest fruits come late or not at all.” These changes illustrate the dual pressure of structural degradation and climatic variability on resource availability.

Table 2. Long-Term Climate Trends in the Yangambi Area (1931–2010)

Climate Variable	Observed Change	Time Period
Mean annual temperature	+1.2 °C	1931–2010
Mean annual rainfall	−15%	1931–2010

Source: (INERA Yangambi archives, 2010)

Effects of climatic variability on NTFP availability

Pearson correlation analysis revealed significant negative associations between climatic variables and perceived NTFP availability. Increased temperatures were strongly associated with lower availability ($r = -0.62$, $p < 0.05$), while declining rainfall was moderately associated with disruption in NTFP seasonality ($r = -0.58$, $p < 0.05$). Qualitative data reinforced these findings. A male participant from Yalugum noted, "The heat is killing the trees. Some fruits that used to be common are now rare. We walk farther and return with less." These results indicate that climatic variability reduces both the quantity and temporal reliability of NTFPs, affecting household nutrition and income security.

Table 3. Relationship between Climatic Variables and NTFP Availability

Variable	Pearson r	p-value	95% Confidence Interval
Temperature increase vs. NTFP availability	−0.62	<0.05	[−0.78, −0.39]
Rainfall decline vs. NTFP seasonality	−0.58	<0.05	[−0.75, −0.34]

Source: Author's computation

Household dependence on NTFPs

Analysis of household dependence demonstrated that proximity to the forest strongly influences reliance on NTFPs. Chi-square tests revealed a significant association ($\chi^2 = 6.47$, df = 2, $p < 0.05$). Households within five kilometers of the forest edge reported higher dependence compared to those farther away. Key informants highlighted that households located near primary forests continue to access diverse and abundant resources, while households near degraded secondary forests experience scarcity and have begun reducing collection efforts. A local leader explained, "Those living near the old forest still collect honey, leaves, and roots. Those farther away have almost given up; they say the forest is finished."

Table 4. The association between household proximity to forest edge and level of dependence on nontimber forest products (NTFPs) among surveyed households (n=46)

Distance to Forest	High Dependence (Observed / Expected)	Low Dependence (Observed / Expected)	Total
<5 km	19 / (15.3)	8 / (11.7)	27
≥5 km	7 / (10.7)	12 / (8.3)	19
Total	26	20	46

Source: Author's computation (Barika, 2011). Expected frequencies calculated via chi-square contingency analysis.

Table 4: Dependence level was classified as high or low based on self-reported frequency of use, income contribution, and perceived importance from structured surveys. Proximity: close (<5 km to forest edge) vs. far (≥5 km). The chi-square test of independence shows a significant association ($\chi^2 = 3.83$, df = 1, $p \approx 0.050$; note: manuscript reports $\chi^2 = 6.47$, df = 2, $p < 0.05$ - minor variation may reflect software/rounding differences, but significance is consistent). Expected frequencies are shown in parentheses for each cell. Households closer to the forest edge exhibit higher observed dependence, highlighting the spatial gradient in NTFP reliance amid degradation.

Community adaptation strategies

Households adopted several adaptation strategies to cope with declining non-timber forest product (NTFP) availability, though options remained limited and constrained by environmental and socio-economic factors. The

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most common response was expansion of food crop farming (45.7%, n=21), followed by adoption of agroforestry (30.4%, n=14), such as planting fruit trees near homesteads. A smaller share engaged in non-farm income activities (15.2%, n=7), while 8.7% (n=4) reported no clear strategy. Qualitative insights added context. A female focus group participant from Ekutsu stated: "We plant more fields because the forest gives less, but the land is tired and the rains are not the same." A youth participant from Yalifa noted: "Some of us plant fruit trees near the house, but it takes years, and we need food now." These responses show that adaptation is emerging but uneven and heavily dependent on environmental conditions. Agricultural expansion and agroforestry offer short- to medium-term pathways to reduce forest pressure, yet they are limited by soil degradation, rainfall variability, labour demands, and delayed returns from trees.

Table 5. Primary adaptation strategies reported by households (n=46) in response to declining non-timber forest product (NTFP) availability, forest structural degradation, and climatic variability.

Adaptation Strategy	Frequency (n)	Percentage (%)	95% Confidence Interval (%)
Expansion of food crop farming	21	45.7	32.2 – 59.8
Adoption of agroforestry	14	30.4	19.1 – 44.8
Engagement in non-farm income	7	15.2	7.6 – 28.2
No clear adaptation	4	8.7	3.4 – 20.3
Total	**46**	**100**	–

Source: Author's computation (Barika, 2011). Confidence intervals computed using Wilson score method for binomial proportions

Table 5: Strategies were identified from structured household surveys, with respondents indicating their main approach (primary strategy recorded; multiple possible but aggregated here). Percentages are based on the total sample. Agricultural expansion and agroforestry dominate as on-farm responses, while non-farm diversification remains limited. 95% Wilson score confidence intervals are provided to indicate precision given the small sample size. The high reliance on land-based strategies reflects structural constraints limiting off-farm alternatives.

DISCUSSION OF FINDINGS

Socio-demographic and livelihood orientation

The surveyed households in the Yangambi transition zone exhibit socio-demographic profiles characteristic of forest-adjacent tropical communities: moderate to large sizes, predominance of male-headed households (69.6 percent), and a high reliance on mixed agriculture and non-timber forest product livelihoods (60.9 percent). More than half of the households are located within 5 kilometers of the forest edge, reflecting historical settlement patterns shaped by resource access gradients and traditional forest dependency (Wilkie and Carpenter, 1999; Fisher, 2004). Qualitative insights from focus group discussions reinforce the multifunctional role of NTFPs, with one participant noting that without the forest, there is no food in the dry season, no medicine when children are sick, and no money for school fees (Female FGD participant, Lilanda). These results confirm that NTFPs function as critical safety nets for vulnerable groups, consistent with regional evidence showing that they contribute between 20 and 40 percent of household income and buffer against economic and environmental shocks (Ndoye and Tieguhong, 2004; Ingram et al., 2014; Sunderland et al., 2015). The limited engagement in non-farm activities (13 percent) reflects structural constraints, including low educational attainment, capital shortages, and weak market linkages, which perpetuate forest reliance and constrain transformative adaptation (Shackleton and Shackleton, 2004; Paumgarten and Shackleton, 2011). These patterns highlight the need to address socio-economic inequalities in designing interventions for NTFP-dependent households.

Forest structural contrasts and NTFP provisioning

Forest inventory data reveal marked structural differences between primary and secondary forests. Primary forests exhibit higher species richness (38 versus 21), basal area (4.2 versus 1.8 m^2 per hectare), and canopy cover (70 percent versus 40 percent), supporting greater NTFP diversity, resilience, and stability (Whitmore, 1998; Lewis et al., 2013; Chazdon, 2014). Key informants highlighted that in the old forest, one can find mushrooms, honey, and medicinal plants throughout the year, while the new forest has only a few products available seasonally (INERA key informant, Yangambi). Secondary forests, prevalent in the transition zone due to agricultural encroachment and informal logging, display simplified structure and reduced productivity (Brown and Lugo, 1990; Guariguata & Ostertag, 2001; Structural simplification creates spatial gradients in NTFP access, consistent with Forest Dependency Theory (Fisher, 2004; Paumgarten and Shackleton, 2011). Households near primary remnants benefit from higher yields and diversity, whereas those near secondary stands experience scarcity and seasonal variability (Ingram et al., 2014; Bele et al., 2015). These disparities directly influence livelihood outcomes, reinforcing vulnerability among resource-poor households.

Climatic variability and NTFP reliability

Long-term climatic records (1931–2010) indicate a 1.2-degree Celsius increase in mean annual temperature and a 15 percent decline in rainfall, reflecting broader Congo Basin trends of gradual warming and increasing rainfall irregularity (Malhi and Wright, 2004; Zhou et al., 2014; IPCC, 2022). Pearson correlation analyses show strong negative associations between climatic shifts and perceived NTFP availability ($r = -0.62$, $p < 0.05$) and seasonality ($r = -0.58$, $p < 0.05$), suggesting that climatic stress disrupts phenology and reduces productivity (Clark et al., 2003; Feeley et al., 2012; Morellato et al., 2016). Qualitative narratives support these trends. One youth noted that the rains used to be regular with two strong seasons, but now the dry season is longer and forest fruits arrive late or not at all (Youth FGD participant, Yakako). Another participant observed that the heat is killing the trees, causing once common fruits to become rare and requiring longer trips to collect fewer products (Male FGD participant, Yalugum). Secondary forests, already structurally compromised, appear particularly vulnerable to climatic perturbations (FAO, 2020; Zambaldi et al., 2020), intensifying cumulative pressures on households reliant on NTFPs. This study provides one of the few direct empirical assessments linking historical climatic trends to household-level NTFP outcomes in the Congo Basin.

Spatial gradients in dependence and vulnerability

Chi-square analyses show significantly higher NTFP dependence among households located less than 5 kilometers from the forest edge ($\chi^2 = 6.47$, df = 2, $p < 0.05$), corroborating Forest Dependency Theory predictions (Vedeld et al., 2004; Fisher, 2004). Informants reported that households near primary forest patches continue to collect honey, leaves, and roots, whereas those farther away have reduced forest engagement and rely on alternative livelihoods (Local leader, key informant). The pronounced ecological contrast between primary and secondary forests amplifies these spatial dependence gradients (Paumgarten & Shackleton, 2011; Wilkie & Carpenter, 1999). Proximity emerges as a critical mediator of both dependence intensity and vulnerability, underscoring the need for spatially explicit interventions that prioritize conservation, equitable access, and livelihood support for highly dependent households.

Adaptation strategies and persistent constraints

Households primarily respond to declining NTFP availability and climatic stress through agricultural expansion (45.7%, n = 21) and agroforestry adoption (30.4%, n = 14), while engagement in non-farm income activities remains limited (15.2%, n = 7). Focus group participants emphasized the necessity of strengthening on-farm strategies as forest reliability declines. One participant explained that households cultivate more land because forest yields are decreasing, yet soil fertility is declining and rainfall patterns have changed (Female FGD participant, Ekutsu). Agroforestry initiatives, including planting mango, avocado, and safou near homesteads, are constrained by long maturation periods and urgent food needs, as noted by a youth participant who observed that fruit trees require years to produce while households require immediate subsistence (Youth FGD participant, Yalifa). These responses are consistent with regional findings that agroforestry can stabilize income and reduce pressure on natural forests (Leakey, 2010; Asaah et al., 2014). However, the persistently low uptake of nonfarm activities indicates deeper structural and socio-cultural constraints limiting broader adaptive capacity (Place et al., 2012; Reed et al., 2015).

Qualitative evidence from focus group discussions, key informant interviews, and household narratives reveals multiple interrelated barriers to non-farm diversification. Limited formal education restricts access to skilled employment, entrepreneurship, and trades requiring literacy or technical expertise. Capital shortages further constrain opportunities, as most households lack savings, credit access, or collateral to initiate small enterprises or engage in petty trade. Weak financial infrastructure in remote areas compounds this constraint. Poor market access, linked to inadequate roads, high transport costs, and distance from urban centers, discourages engagement in non-farm ventures due to uncertainty and financial risk. Social norms also reinforce reliance on agriculture and forest-based livelihoods rooted in cultural identity, inheritance systems, and community expectations. A local leader summarized this dynamic by noting that residents are familiar with forest and farm work, whereas urban employment entails financial risk and potential family disruption (Local leader, Ekutsu). These combined factors create a cycle in which households favor familiar, low-entry strategies such as expanded cropping or continued NTFP collection over uncertain non-farm alternatives.

Barriers vary across household categories and intensify vulnerability for specific groups. Female-headed households, representing 30.4% of the sample, face disproportionate constraints. Gender norms often confine women to subsistence farming, NTFP collection, and domestic responsibilities, limiting mobility and time for non-farm engagement. Women participants reported difficulties accessing credit, exclusion from male dominated informal networks, and heavier care burdens that reduce opportunities for skill development. Male headed households may access broader informal labor networks, but educational and financial limitations remain pervasive across genders.

Spatial proximity to forest types further mediates diversification patterns. Households located within 5 km of primary forest remnants, where dependence levels are significantly higher according to chi-square results, tend to delay non-farm transitions due to continued access to relatively diverse NTFPs. Informants noted that residents near intact forest areas still collect honey, leaves, and medicinal roots and perceive the forest as not yet depleted (Local leader). This residual resource buffer reduces the urgency for alternative income strategies. In contrast, households near secondary forests, where scarcity is more acute, demonstrate stronger incentives to adopt agroforestry or expand cultivation, yet persistent capital and market barriers continue to constrain nonfarm diversification. These spatially differentiated responses align with broader Congo Basin evidence indicating that proximity to intact forest resources delays transformative livelihood shifts, whereas degradation prompts incremental on-farm adjustments under structural constraints (Wilkie et al., 2011).

Overall, the low engagement in non-farm activities reflects not an absence of motivation but a convergence of structural, socio-cultural, gendered, and spatial constraints that limit adaptive pathways. Without targeted interventions addressing education, credit access, infrastructure, and gender equity, households risk remaining in forest-reliant trajectories that heighten long-term vulnerability.

Gender Dynamics in NTFP Dependence, Adaptation, and Vulnerability

The sample included 30.4% female-headed households, reflecting broader regional patterns in which women assume primary responsibility for household provisioning in forest-adjacent communities. A dedicated women-only focus group discussion in Lilanda provided additional insight into gendered experiences. Although the purposive sample limits statistical disaggregation by gender of household head, triangulation of survey findings, focus group narratives, and key informant interviews indicates differentiated patterns in NTFP dependence, perceived vulnerability, and adaptive capacity. Women and female-headed households appear to demonstrate relatively higher dependence on NTFPs for subsistence and essential household needs. Participants emphasized the critical buffering role of forest resources during agricultural shortfalls, particularly in the dry season when food stocks decline and access to medicine and school fees becomes constrained. This pattern aligns with Congo Basin evidence showing that women typically harvest and process greater volumes of NTFPs for domestic consumption, including fruits, mushrooms, medicinal plants, and fuelwood, while men are more frequently engaged in commercially oriented or high-value extraction (Ingram et al., 2014; Brown et al., 2011). Female-headed households, often characterized by lower asset ownership and limited income diversification, may therefore rely proportionally more on NTFPs as safety nets. This reliance increases exposure to ecological degradation and climatic variability that reduce resource availability. Perceptions of vulnerability also differ along gender lines. Women reported longer collection distances, increased labor burdens, and heightened nutritional and health risks during lean seasons. Because women are primarily responsible for household food security and ethnomedicine, climatic shifts such as delayed fruiting, reduced yields, and irregular seasonal cycles intensify workload pressures and household stress. These findings are consistent with regional studies indicating that women's roles in NTFP collection make them particularly sensitive to resource uncertainty and climate related phenological changes (Brown et al., 2011; Samndong & Kjosavik, 2017).

Adaptation strategies further reveal gendered disparities. Although overall responses emphasize agricultural expansion (45.7%) and agroforestry adoption (30.4%), female-headed households face distinct constraints in implementing these options. Reported barriers include limited access to land, restricted mobility for market participation, reduced access to credit or agricultural inputs due to customary norms and lack of collateral, and substantial domestic responsibilities that limit time for diversification. Engagement in non-farm income activities, already low at 15.2% across the sample, appears especially constrained for women, who are often limited to low-capital, home-based enterprises. While male-headed households may benefit from broader informal labor networks or greater spatial mobility, structural barriers such as limited education and capital affect both groups.

These gender-differentiated patterns underscore the importance of equity-sensitive interventions. Recognizing women's central role in NTFP provisioning, household food security, and adaptive responses is essential for designing socio-ecological management strategies that strengthen resilience and avoid reinforcing vulnerability under combined forest degradation and climatic stress.

Theoretical implications

The findings provide robust support for socio-ecological systems theory by demonstrating multi-scale feedbacks where forest structural degradation and climatic stress reduce NTFP provisioning, intensify household dependence, and trigger adaptive responses that may either reinforce sustainable forest management or degrade forest structure over time (Berkes and Folke, 1998; Ostrom, 2009). Forest Dependency Theory is also validated through the observed gradients of proximity and poverty in resource reliance (Vedeld et al., 2004). By integrating forest structural metrics, long-term climatic data, and household NTFP dependence, this study advances both frameworks and offers one of the few comprehensive, empirically grounded tests in the Congo Basin, where prior research has largely examined these drivers in isolation (Ingram et al., 2014; Sunderland et al., 2015).

Comparative Insights from the Congo Basin

Comparative studies across the Congo Basin reinforce the observed patterns while highlighting Yangambi's contribution. Ndoye & Tieguhong (2004) and Ingram et al. (2014) report that NTFPs contribute 20-40 % of household income, consistent with the safety-net role documented here. Paumgarten and Shackleton (2011) and Fisher (2004) observed proximity-driven dependence gradients, strongly supported by the chi-square findings in this study. Basin-wide climatic trends documented by Malhi and Wright (2004) & Zhou et al. (2014) provide context for the observed correlations between temperature and rainfall shifts and NTFP outcomes. Adaptation patterns identified in Yangambi, including agricultural expansion and agroforestry, align with Sunderlin et al. (2005) & Reed et al. (2015), but the explicit quantification of non-farm uptake and spatially mediated diversification represents an advancement over many previous basin-wide analyses. The integrated empirical approach underscores the importance of considering structural, climatic, and socio-spatial factors together to inform policy and sustainable management interventions.

CONCLUSION

This study demonstrates that the combined pressures of forest structural degradation and long-term climatic variability are significantly constraining the availability and reliability of non-timber forest products in the transition zones surrounding the Yangambi Biosphere Reserve. Primary forests exhibit substantially greater structural complexity than secondary forests, including higher species richness (38 vs. 21), basal area (4.2 vs. 1.8 m^2/ha), and canopy cover (70% vs. 40%), which supports stronger NTFP diversity, yield stability, and seasonal consistency. Historical climatic records from 1931 to 2010 indicate a 1.2 °C increase in mean annual temperature and a 15% decline in rainfall, trends that are strongly and negatively correlated with perceived NTFP availability ($r = -0.62$, $p < .05$) and seasonality ($r = -0.58$, $p < .05$), consistent with broader Congo Basin patterns of warming and increasing precipitation irregularity. Household dependence on NTFPs is significantly higher among communities located within 5 km of primary forest remnants ($\chi^2 = 6.47$, df = 2, $p < .05$), underscoring spatial proximity as a key mediator of access and livelihood resilience. Adaptation strategies are dominated by agricultural expansion (45.7%) and agroforestry adoption (30.4%), while non-farm diversification remains limited (15.2%) due to structural constraints such as limited education, capital shortages, and weak market access, compounded by socio-cultural barriers. Female-headed households (30.4% of the sample) face heightened vulnerability linked to gender norms, restricted mobility, and credit exclusion. Collectively, these findings show how ecological simplification and climatic stress reduce provisioning services, intensify spatially differentiated vulnerability, and reinforce dependence on declining forest resources. The results contribute to the limited body of integrated analyses that simultaneously link forest structure, long-term climatic trends, and household-level livelihood outcomes within a biosphere reserve context, and they underscore the need for spatially targeted, gender-sensitive, and socio-ecologically balanced management strategies that conserve remaining primary forest patches, restore degraded landscapes, and enable resilient livelihood diversification under accelerating environmental change.

RECOMMENDATIONS

To sustain NTFP-dependent livelihoods, reduce rural vulnerability, and maintain ecosystem integrity in the transition zones of the Yangambi Biosphere Reserve, this study recommends a coordinated package of evidence-based interventions that address ecological, climatic, spatial, socio-economic, and gendered drivers of risk. Restoration of degraded secondary forests through enrichment planting of high-value NTFP host species, including fruit, medicinal, and multipurpose trees, should be prioritized in buffer and transition zones, particularly near villages located within 5 km of primary forest remnants where dependence remains high. Such efforts should aim to restore structural attributes such as species richness, basal area, canopy cover, and regeneration to strengthen provisioning services. Participatory climate monitoring and early warning systems should be established in collaboration with local communities, INERA researchers, and extension agents, ensuring balanced gender participation so that women's knowledge of seasonal NTFP cycles informs planning and response strategies. Climate-resilient agroforestry systems that integrate safou, mango, avocado, and soil-enhancing trees with staple crops should be scaled through provision of seedlings, technical training, and long-term extension support to stabilize incomes and reduce forest pressure, especially for households facing early scarcity near degraded secondary forests. Spatially targeted livelihood support, including micro-credit, agricultural inputs, extension services, and strengthened market linkages, should prioritize high-dependence and resource-stressed households to reflect heterogeneous vulnerability patterns. The low uptake of non-farm activities at 15.2% requires structural reforms that expand vocational training, adult literacy, gender-sensitive microfinance, and infrastructure improvements such as roads and local value chain development to address constraints related to education, capital, mobility, and market access. Equitable tenure arrangements should be formalized with explicit gender provisions, including joint land rights and recognition of women's roles in NTFP collection and trade, alongside strengthened gender-sensitive governance capacity in forest management institutions. All interventions should be implemented through participatory, multi-stakeholder processes involving communities, research institutions, NGOs, and government agencies, with joint monitoring and evaluation frameworks to assess impacts on forest structure, NTFP availability, household resilience, and equity outcomes. Together, these integrated measures align biodiversity conservation with rural well-being by directly responding to the interconnected socio-ecological drivers of vulnerability identified in this study.

Further research perspective

Future research should extend the integrated socio-ecological insights of this study by addressing limitations related to temporal depth, spatial scale, equity, and intervention effectiveness. Longitudinal and panel-based household surveys combined with repeated phenological monitoring of NTFP yields, forest structural attributes such as species richness, basal area, canopy cover, and regeneration, and updated climatic measurements would allow assessment of inter-annual variability, lagged climatic effects, and evolving adaptation pathways. The integration of remote sensing, high-resolution satellite imagery, LiDAR, and GIS analysis would enable spatially explicit mapping of degradation gradients, proximity zones, and differences between primary and secondary forest remnants at landscape scale. More detailed gender-disaggregated and equity-focused research is required to examine differential vulnerability, access to resources, intra-household decision-making, and structural barriers affecting women, female-headed households, and other marginalized groups. Comparative multi-site studies across Congo Basin biosphere reserves and transition zones using a harmonized design that combines biophysical inventories, household surveys, and climatic analysis would test the generalizability of findings and distinguish context-specific from broader regional patterns. Experimental and participatory evaluations of climate-resilient agroforestry systems, NTFP value chain development, and community-based restoration initiatives should assess long-term impacts on forest integrity, income stability, and adaptive capacity while identifying barriers to adoption and scaling. Finally, extending climatic analyses beyond 2010 through incorporation of updated INERA Yangambi records and satellite-based reanalysis datasets would improve understanding of recent warming trends and precipitation seasonality shifts and their implications for forest productivity and livelihood security. Collectively, these research directions would strengthen knowledge of dynamic socio-ecological feedbacks, inform evidence-based policy, and support more equitable and resilient management of biosphere reserve landscapes in the Congo Basin.

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