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Quantifying firewood extraction and its socioecological drivers in the context of thirty year trends of Lake Malawi National Park

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Title

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Abstract

Firewood collection from protected areas hinders forest conservation efforts across Sub-Saharan Africa. In Lake Malawi National Park (LMNP), a World Heritage Site, this pressure has not been assessed for the past three decades. This study provides a direct quantification of extraction based on household surveys conducted in all 11 communities utilizing the park forest. We recorded the number of collectors and collection frequency to estimate extraction quantities, as well as socioeconomic factors, energy use, and collection sources to identify drivers. To calibrate these household survey-based estimates, we directly measured the weights of firewood bundles collected in the park. The results indicated a significant annual extraction of 16,947 megagrams within the park forest. Critically, our unique 30-year comparison reveals that aggregate extraction pressure increased nearly parallel to population growth (191.2% vs. 201.5%). This close coupling highlights a crucial "scale trap," as per-capita rates remained virtually unchanged (from approx. 1.44 to 1.39 kg person^{-1} day^{-1}) despite widespread charcoal adoption, thus masking escalating total pressure. A linear mixed-effects model identified household drivers such as access to off-park sources and confirmed that significant community-level variation remains after accounting for household factors. These findings demonstrate the limitations of standardized interventions within the park alone, implying the need for tailored community strategies and broader socio-ecological system (SES) approaches that promote off-park wood sources and address landscape-level demographic and energy dynamics. Our integrated methodology provides the essential foundation for robust "pressure-response" evaluations and transitioning to sustainable forest management.

Keywords

firewood, protected area, long-term change, scale trap, socio-ecological system (SES), World Heritage Site

1. Introduction

1.1. The Challenge of Firewood Extraction in Protected Areas

Sustainable management of natural resources fundamentally depends on understanding the balance between ecological supply (resource availability and regeneration) and human demand (extraction rates) (Daly 1990; Sheppard et al. 2020). Achieving this balance is a central challenge in conservation and development, particularly for resources like firewood that are essential for rural livelihoods.

Across Sub-Saharan Africa (SSA), this challenge is acute. Biomass fuels serve as the primary energy resource for households, with rural areas showing a reliance exceeding 90% (FAO 2017; IEA 2022). This utilization has become a principal driver of forest degradation, second only to commercial logging (Hosonuma et al. 2012; Lourenço et al. 2025). The increase in population size, together with limited access to other energy solutions, sustains this demand (Bamwesigye et al. 2020; IEA 2022), while forest habitats are designated as protected zones as deforestation spreads in neighboring landscapes (DeFries et al. 2005; Newmark 2008). Consequently, as alternative forest resources diminish outside the protected area boundaries, human pressure for resources like firewood becomes increasingly concentrated on these ecologically isolated reserves.

This concentrated pressure creates a profound structural dilemma. For local communities, these forests act as a vital safety net for daily survival (Ryan et al. 2016; Lhoest et al. 2020), yet securing these short-term necessities can degrade the ecosystem services, such as water regulation, on which their long-term well-being depends (Adams et al. 2004; Van

Wilgen and Mcgeoch 2015; Wei et al. 2018). In the specific context of protected zones, this manifests as a critical tension between the vital daily necessities of local communities and the overarching goal of conservation (Adams et al. 2004; Berkes 2007). To harmonize resource use with ecological protection and ensure sustainability, it is essential to first accurately investigate the quantity of resources extracted and the resulting pressure exerted on these protected ecosystems.

1.2. Needed Approach: Quantification, Drivers, and Trends

Addressing the challenge of resource management requires a robust, integrated approach that begins with reliable data on extraction. Previous attempts to assess wood fuel sustainability have often failed to provide reliable results due to a lack of accurate knowledge regarding demand and extraction rates (Masera et al. 2015). Within protected areas, understanding the extent of resource removal is essential for evaluating ecological performance (Van Wilgen and Mcgeoch 2015). Despite this necessity, a significant methodological challenge persists: many studies rely on household consumption data as a proxy for extraction (e.g., Banks 1996; Shankar et al. 1998; Bekele et al. 2013; Wessels et al. 2013). Using consumption as a proxy, however, can lead to estimates that drastically differ from actual extraction (Swemmer et al. 2019), potentially leading to misinformed management. Therefore, direct quantification, the empirical measurement of resource removal from the environment, is the essential baseline for establishing the reliable estimates required for future sustainability assessments (Sheppard et al. 2020). Furthermore, assessing extraction intensity (e.g., in Mg ha^{-1}) requires not only quantifying the total amount removed but also clearly defining the spatial area from which it is collected. This spatial context is essential for comparing extraction pressure against the ecosystem's supply. While

78 some studies have directly quantified extraction rates within well-defined collection areas (e.g., Rono et al. 2019; Lhoest
79 et al. 2020), this crucial link between amount and area is not always established.

80 While direct quantification provides the essential baseline, effective management depends on understanding the
81 factors driving this pressure. Quantitative data alone cannot explain why pressure varies across different segments of the
82 population. Research has shown that extraction is driven by a complex interplay between factors operating at multiple
83 levels (Brooks et al. 2012). At the household level, key determinants include household size, which affects energy
84 demand, and livelihood strategies, such as the reliance on forest resources versus off-farm employment (Masozera and
85 Alavalapati 2004; Zulu and Richardson 2013). Household wealth also influences the adoption of alternative fuels,
86 though this is often a complex "fuel stacking" process rather than a simple transition (Hiemstra-van der Horst and
87 Hovorka 2008; Zulu 2010). Furthermore, access to alternative wood sources outside the protected area can reduce the
88 need to collect from within (Cooke et al. 2008; Sassen et al. 2015). These household decisions are embedded within a
89 broader community context, shaped by factors such as the geographical availability of resources (Lhoest et al. 2020),
90 local economic structures including market access (Shankar et al. 1998), and the effectiveness of local governance (Tole
91 2010). However, analyses of these drivers have typically remained separate, often focusing on either household or
92 community-level factors in isolation (e.g., Jumbe and Angelsen 2007; Hermans-Neumann et al. 2016). More
93 importantly, these socioeconomic analyses are rarely linked directly to the physical quantity of extraction. Effectively
94 integrating robust quantification with sophisticated analysis of multi-scale drivers therefore remains a key challenge.

95 Furthermore, these dynamics must be understood over the long term. Extraction pressures are not static; they

fluctuate with socioeconomic changes such as population growth and shifting energy use patterns (Zulu 2010). As Lattimore et al. (2009) emphasize, capturing the dynamic nature of both the resource base and socioeconomic drivers through long-term data is essential for devising effective management strategies.

Consequently, an approach that integrates these three dimensions—direct quantification, driver analysis, and long-term trend evaluation—is required to accurately grasp and manage the changing pressure on the socio-ecological system (SES) of protected areas.

1.3. The Lake Malawi National Park Context

To address these interconnected gaps, this study focuses on Lake Malawi National Park (LMNP), a UNESCO World Heritage Site. The park provides an ideal setting for this research, distinguished by its unique history of integrating local communities. This context represents a long-standing implementation of Community-Based Natural Resource Management (CBNRM), a strategy widely adopted to reconcile conservation goals with local livelihood needs by allowing regulated resource use (DeGeorges and Reilly 2009; Foyet 2024).

When the park was established in 1980, residents of its enclave villages, settlements surrounded by the protected lake and forest, were not relocated. Because their livelihoods depended on park resources, the collection of essential firewood (deadwood) was permitted from the outset, with rules governing this practice formalized in the park's first management plan (Grenfell 1993). This long-standing effort to balance protection with resource use was the subject of a pioneering quantitative assessment of firewood collection three decades ago (Abbot and Homewood 1999). Crucially, the existence of this historical data provides the essential baseline required to evaluate the long-term dynamics of

114 extraction pressure. Building on this unique historical context, our study revisits a critical test case: if a sustainable
115 balance can be advanced in a World Heritage Site with a high conservation mandate, the lessons learned offer powerful
116 implications for other protected areas.

117 **1.4. Study Objectives**

118 To address the gaps identified above, this study leverages the unique long-term context of LMNP as a model system
119 to evaluate resource sustainability. Specifically, we established three primary research objectives: (1) to quantify the
120 current extraction load and define the spatial extent of the collection area; (2) to elucidate the multi-level socioeconomic
121 drivers influencing these extraction patterns; and (3) to assess the long-term dynamics of extraction pressure by
122 comparing current data with the historical baseline established three decades ago (Abbot and Homewood 1999). By
123 addressing these interconnected objectives, we aim to provide the evidence required to determine whether current
124 conservation strategies can withstand the escalating pressures of a growing population, thereby offering broader insights
125 into the structural challenges of balancing conservation and rural livelihoods.

126 **2. Materials and methods**

127 **2.1. Study area**

128 LMNP is located at the southern tip of Lake Malawi on the Nankumba Peninsula in Mangochi District, southern
129 Malawi (14°02′S, 34°53′E). The park covers 9,410 ha, comprising 8,710 ha of land and 700 ha of lake. The Cape
130 Maclear Peninsula (CMP) area of LMNP, which is located at the northern end of the Nankumba Peninsula, forms the

largest terrestrial segment at 6,550 ha and was the primary focus of this study (Fig. 1).

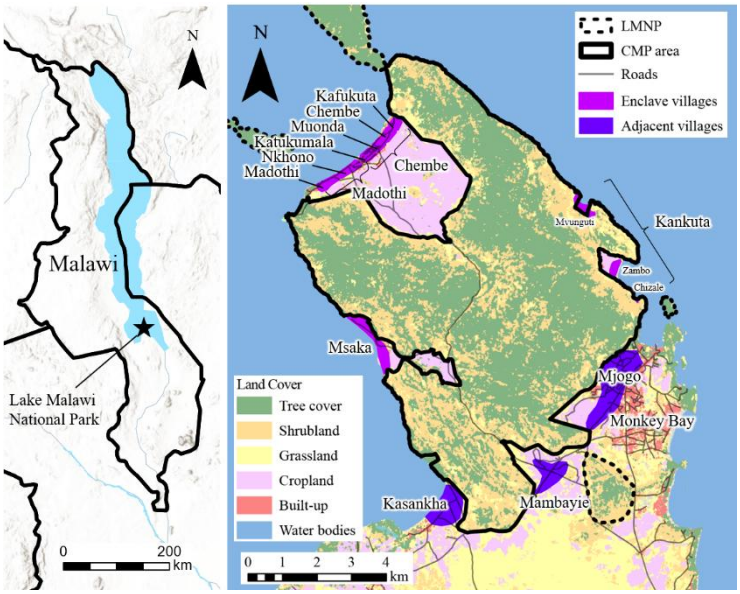


Fig. 1 Map of the study area showing the location of Lake Malawi National Park (LMNP) in Malawi (left panel) and the detailed land cover of the Cape Maclear Peninsula (CMP) area (right panel). The map indicates the boundaries of the park and the CMP, as well as the locations of the 11 surveyed enclave and adjacent villages. Land cover data is based on the ESA WorldCover 2021 dataset (Zanaga et al. 2022).

The landscape of the CMP area is characterized by rocky granite hills covered in miombo woodlands, with *Brachystegia microphylla* Harms as the dominant canopy species, along with dense tall grass cover. Its elevation ranges from 500 to 1,143 m above sea level. The region experiences unimodal rainfall pattern, with an average annual precipitation of 762 mm, with most falling between November and April, followed by an extended dry season from May to October.

Legally, the Department of National Parks and Wildlife of Malawi (DNPW) manages LMNP and operates the Resource Use Program, which permits communities to collect firewood and thatch grass under specific conditions (Department of National Parks and Wildlife 2019). Firewood collection is allowed only if it is carried out by female villagers on designated days (Tuesdays and Saturdays); a collection permit must be acquired; and the use of knives, axes, or similar tools is prohibited. Since the cutting of live trees is strictly forbidden, only deadwood can be collected. Charcoal production is not permitted within the LMNP. Based on our observations, no illegal charcoal production

occurs in the CMP area. All charcoal used in the area is transported from outside the area and sold in the local markets.

Outside the park boundaries, land suitable for housing and agriculture is already intensively used (Fig. 1). While some village commons exist in the form of small, rocky hills, they are predominantly covered in shrubs and do not function as a significant source of firewood. Although some trees are found sparsely within farmlands and a few households maintain private woodlots, opportunities to source firewood from outside the park are generally limited.

2.2. Target Communities

To evaluate forest resource use within the CMP area of LMNP, this study surveyed all communities known to collect resources from the CMP forest. In rural Malawi, 'communities' often correspond to villages governed by a Village Head or a Group Village Head who oversees several villages. Additionally, functional boundaries are formed based on physical geography and the jurisdiction of local governance structures such as the Village Natural Resources Committee.

Based on these considerations, we identified 11 distinct communities for household-level data collection (Table 1). Among these 11 communities, eight (e.g., Chembe, Madothi, Msaka, and Kankuta) are surrounded by the park and the lake (enclaves), whereas Kasankha, Mjogo, and Mambayie are adjacent to the park just outside. These communities differ in their dominant livelihood strategies (e.g., fishing, retail), household income sources, and opportunities to collect firewood from outside the park, all of which are potential drivers of firewood collection patterns.

Demographic trends highlight the increasing pressure on the CMP forest. Between 2008 and 2018, the population of

Table 1 Overview of communities targeted in the household survey. The table lists community names used in this paper, their administrative structure, relationship with Lake Malawi National Park (LMNP), and demographic data. Footnotes provide additional context on community definitions in relation to previous studies.

Area	Name of Group Village	Name of Village	Community names used in this paper	Connection with LMNP	No. of HHs in the community[c]	No. of HHs targeted	Population[c]
Cape Maclear[a]	Chembe	Chembe	Chembe	Enclaved	681	52	2,784
Cape Maclear[a]	Chembe	Kafukuta	Kafukuta	Enclaved	294	52	1,225
Cape Maclear[a]	Chembe	Katukumala	Katukumala	Enclaved	702	53	2,988
Cape Maclear[a]	Chembe	Muonda	Muonda	Enclaved	856	52	3,871
Cape Maclear[a]	Madothi	Madothi	Madothi	Enclaved	220	52	943
Cape Maclear[a]	Madothi	Nkhono	Nkhono	Enclaved	697	53	2,945
Kankhande	Chimphamba	Mambayie/Jonathan	Mambaiye	Adjacent	198	33	826
Msaka	Chimphamba	Msaka/Fulaide	Msaka	Enclaved	1253	33	6,418
Kasankha	Mbeya	Mbeya/Ntewa	Kasankha	Adjacent	457	36	2,368
Mjogo	Nsumbi	Mjogo	Mjogo	Adjacent	2546	36	11,777
Mvunguti[b]	Nsumbi	Kankuta	Kankuta	Enclaved	704	38	4,270
Total					8608	490	40,415

a: Some LMNP-related materials and Abbot & Homewood (1999) refer to the Cape Maclear area collectively as "Chembe".
b: Some LMNP-related materials and Abbot & Homewood (1999) treated Mvunguti, Zambo, and Chizale as independent enclave villages; in this study, they are consolidated as the Kankuta community.
c: Number of households and resident population (residing > 6 months) according to 2024 Health Surveillance Assistant (HSA) data.

Mangochi District grew at an annual average rate of 3.7%, a rate exceeding the national annual average of 3.0% for the same period (National Statistical Office 2018). The population density in 2018 was approximately 171 persons km^{-2} in Mangochi District and 186 persons per km^2 for Malawi as a whole.

This long-term growth is particularly pronounced within the park's enclave villages. A direct and robust comparison with historical data is possible, as our survey was designed to cover all areas investigated by Abbot and Homewood (1999) in their 1993–1994 research. For methodological clarity, it is important to note two differences in community definition. First, their study referred to six of the communities in our study (Chembe, Kafukuta, Katukumala, Muonda, Madothi, and Nkhono) collectively as ‘Chembe’. Second, three villages they treated independently (Mvunguti, Zambo, and Chizale) were aggregated into a single community, Kankuta, in our study, as they share a common village head and other local governance structures. The eighth community, Msaka, was defined consistently. The total population of this

176 eight-community area grew from 8,440 in 1994 (Abbot 1996) to 25,444 in 2024, which is a 201.5% increase over three
177 decades (Table 1). It should be noted that their 1993–1994 research focused exclusively on these enclave communities,
178 whereas our study also includes adjacent communities (Table 1) to capture the total current pressure. This carefully
179 matched comparison provides a robust foundation for the temporal analysis of firewood extraction presented in the
180 Discussion section.

181 **2.3. Data collection**

182 This study employed a household survey and direct field observations to quantitatively assess firewood extraction
183 and explore patterns of forest resource use across 11 communities around the CMP forest. The household survey
184 gathered socioeconomic and resource use data, while the field surveys involved direct measurement of firewood bundle
185 weights to calibrate the survey data.

186 2.3.1. Household Survey

187 The household survey was conducted between April and May 2023 using a semi-structured questionnaire. To
188 ensure comprehensiveness across the communities utilizing the CMP forest while accommodating logistical constraints,
189 we employed a geographically stratified sampling approach with fixed targets per community, rather than strictly
190 proportional sampling. The Cape Maclear area consists of enclave villages geographically bounded by the CMP forest
191 and the lake. Given this unique spatial constraint and the high concentration of the population within the enclave, we set
192 a higher target of approximately 50 households per community to ensure sufficient data resolution for this core area. For
193 the remaining communities, we established a baseline target of approximately 35 households. Within each community,

194 households were selected via simple random sampling using household registries maintained by local Health
195 Surveillance Assistants. If a selected household refused to cooperate or was unavailable, the next household on a pre-
196 generated randomized list was visited. This process was repeated until the target sample size was reached or the visit
197 period ended. In total, 490 households were surveyed, representing an overall sampling fraction of approximately 5.7%
198 of the total households across all selected communities (Table 1).

199 Trained enumerators conducted interviews with adult household members after obtaining verbal informed consent.
200 In this study, a "household" was defined as a group of individuals "eating from the same pot" on a daily basis. In 84% of
201 cases, interviews were conducted with household heads or their spouses, involving women in 78% and men in 32%
202 (including joint interviews), which reflects the gendered division of labor in firewood collection.

203 The survey covered the following topics: socioeconomic characteristics (e.g., household composition, income
204 sources, energy sources and cookstoves used); forest resource use (types of forest products collected, both from inside
205 and outside LMNP); and firewood collection patterns and use (number of collectors in the household, frequency of
206 collection trips, procurement methods and uses). These topics were investigated using structured questions with various
207 response formats appropriate to the data type (e.g., categorical choices [single/multiple] and proportional allocation for
208 income sources and firewood procurement).

209 Additionally, two key resource-related features at each household were recorded by enumerator observation: the
210 presence of live fences, which are commonly used for boundary demarcation of homestead and sometimes provide
211 edible leaves and firewood, and the number of fish-smoking ovens, which represent an important small-scale

commercial use of firewood (distinct from the daily cooking stoves reported in Table 4).

2.3.2. Firewood Bundle Weight Measurement

Field surveys to measure firewood bundle weights took place during both the dry season (August 2023, n=44 bundles) and the rainy season (March 2025, n=48 bundles). Measurements were conducted on multiple days along the main access road to the Cape Maclear area. Collectors encountered at this location were returning to the six communities: Chembe, Kafukuta, Katukumala, Muonda, Madothi, and Nkhono. Firewood collectors were weighed using a 150 kg-capacity digital scale, first while carrying the collected firewood bundle and then without it. The difference was recorded as the weight of the bundle.

These direct measurements helped us convert the number of firewood collection times from the household survey into monthly estimates of firewood collected per household in kg.

2.4. Data analysis

The socioeconomic characteristics of households, energy use, and forest resource collection patterns in the 11 communities surveyed were summarized by descriptive statistics. Note that the effective sample size (n) varies in certain analyses and tables depending on the specific subset of respondents (e.g., excluding non-firewood users) or instances where multiple responses were permitted. These specific sizes and conditions are detailed in the respective table captions.

2.4.1. Estimating Firewood Collection

First, firewood collection was estimated at the household level. To ensure statistical accuracy by accounting for

correlations between variables (e.g., that households with more collectors may also collect more frequently), we calculated the monthly firewood collection (in kg) for each surveyed household individually.

For each surveyed household *i* in community *j*, the estimated monthly firewood collection (F_{ij}) was calculated using the following formula:

$$F_{ij} = C_{ij} \times f_{ij} \times W \times B,$$

where, F_{ij} is the estimated monthly firewood collection (kg) for household *i* in community *j*, C_{ij} is the number of collectors in household *i* (obtained from the household survey), f_{ij} is the weekly collection frequency per collector for household *i* (obtained from the household survey), *W* is the average number of weeks per month (set at 4.345), and *B* is the average bundle weight (36.3 kg, obtained from direct field observations). For households reporting no firewood collectors, the collection quantity was set to zero. This calculation assumes that one collector brings back one bundle of firewood per collection trip, a premise we consider realistic given the labor and distances involved.

Second, these individual household-level estimates were aggregated to the community level. For each of the 11 communities, the mean monthly firewood collection per household ($\bar{x}_j$) was calculated from the surveyed households (n_j). This mean was then multiplied by the total number of households in the community (N_j) to estimate the total monthly firewood extraction for that community.

Finally, the overall annual extraction from the CMP forest was determined by summing the estimated monthly totals of all 11 communities and multiplying by 12. The 90% confidence interval (CI) for this overall annual estimate was calculated based on the principles of error propagation for sums of independent variables (additivity of variance). The

248 standard error for the aggregated monthly total ($SE_{monthly}$) and the annual total (SE_{annual}) were calculated as follows:

249 $$SE_{monthly} = \sqrt{\sum_{j=1}^{k}\left(\frac{N_j^2 s_j^2}{n_j}\right)}$$

250 $$SE_{annual} = 12 \times SE_{monthly}$$

251 Where, N_j is the total number of households in community *j*, n_j is the number of surveyed households in

252 community *j*, S_j^2 is the sample variance of household firewood collection in community *j*, and *k* is the number of

253 communities (i.e., 11). The 90% CI was then derived using SE_{annual} and the critical value from the t-distribution (*df* =

254 479).

255 To facilitate comparison with studies reporting volumetric data, weight-based estimates (Mg) were converted to

256 volume (m^3) using the mean wood density for tropical Africa (0.598 g cm^{-3}) reported by Chave et al. (2009).

257 Additionally, to enable direct comparison with the 1993–1994 study (Abbot and Homewood 1999), we calculated the

258 aggregated statistics specifically for the subset of eight communities covered in the historical survey.

259 2.4.2. Statistical Analyses

260 To compare the weights of firewood bundles collected during the dry and rainy seasons, Student's t test was

261 conducted.

262 For subsequent analyses involving collection amounts, the monthly household firewood collection (kg) was

263 log(x+1) transformed (where x is the collection amount) to handle zero-collection households and normalize the

264 distribution.

265 Differences in this transformed data between communities were assessed via one-way analysis of variance

(ANOVA). When the significance level of the ANOVA was less than 0.05, Tukey's HSD post hoc test was applied to pinpoint specific differences among the communities.

To analyze the multi-level drivers of firewood collection, we employed a linear mixed-effects model (LMM). This approach was chosen for its ability to account for the hierarchical data structure of our survey, with households nested within communities. The model was structured with this same log-transformed collection amount as the dependent variable. We included community as a random intercept to statistically account for unobserved variations specific to each community, such as differences in forest access, local norms, or governance effectiveness.

The explanatory variables, treated as fixed effects, were selected based on the theoretical drivers identified in the literature review (see Section 1.3). The initial full model encompassed variables representing: community location (enclave or adjacent), household demographics (household size, number of potential female collectors aged 10-64), firewood use patterns (for housework or small business), household assets and technology (live fence presence, fish smoking ovens, use of improved cookstoves, use of traditional three-stone fires), alternative firewood sourcing (off-park collection), as well as broader socioeconomic dimensions derived from income sources and energy use patterns. To handle potential multicollinearity and reduce dimensionality among the original variables representing these socioeconomic dimensions (i.e., multiple income and energy source types), we conducted principal component analyses (PCA) and included the resulting principal component scores as explanatory variables.

All continuous explanatory variables were standardized to have a mean of 0 and a standard deviation of 1 to improve model stability and allow for comparison of the effects. We started with a full model including all selected variables and

284 then performed model selection based on the Akaike Information Criterion (AIC) to identify the most parsimonious
285 model that best explained the data.

286 All analyses were performed in R (version 4.5.1) using the lme4 package to fit the LMM and the lmerTest package
287 to calculate p-values using Satterthwaite's method.

288 **3. Results**

289 **3.1. Socioeconomic Characteristics**

290 The average household size in the sample was 5.6 individuals (90% CI = ±0.17), with only slight differences among
291 communities. Among these individuals, females aged 10 to 64 years, who represent the primary potential firewood
292 collectors, averaged 2.1 individuals per household (90% CI = ±0.09).

293 Households reported various income sources, reflecting both land-based and aquatic livelihoods. These included
294 fishing; fish processing and trade; agriculture; retail; the sale of firewood, charcoal, and timber; tourism-related activities;
295 and various forms of piecework and formal employment (Table 2). Fishing and fish-related commerce were the most
296 important, accounting for an average of 37% (90% CI: 28–47%) of household income combined. These lake-based
297 livelihood activities were common in most communities but were notably absent in Mambayie, a village located inland

Table 2 Composition of household income sources by community and overall averages. Values for individual communities represent the community-level mean percentage of total income derived from each source ± standard error (SE), based on self-reported proportional contributions. Income source categories (1-8) are defined below the table. Three households (one in Kafukuta and two in Kankuta) were excluded from the analysis due to missing responses for specific income variables.

Community		Proportions of source of income (%)							
	n	1	2	3	4	5	6	7	8
Chembe	52	35.4 ± 5.7	10.1 ± 3.4	11.3 ± 3.2	8.7 ± 3.3	15.6 ± 3.9	2.7 ± 1.9	3.3 ± 1.6	13.0 ± 3.9
Kafukuta	51	39.1 ± 6.0	30.4 ± 5.5	0.6 ± 0.4	7.5 ± 3.3	4.9 ± 2.2	0.0 ± 0.0	9.5 ± 3.5	8.0 ± 3.5
Katukumala	53	20.5 ± 4.0	14.7 ± 3.5	25.4 ± 3.7	4.9 ± 2.0	13.7 ± 2.5	1.8 ± 1.3	12.9 ± 3.1	6.1 ± 2.7
Muonda	52	21.6 ± 4.9	19.7 ± 4.1	1.5 ± 1.4	15.5 ± 4.4	6.0 ± 2.3	3.3 ± 2.3	6.9 ± 2.7	25.5 ± 5.1
Madothi	52	8.8 ± 3.2	5.3 ± 2.5	19.8 ± 3.8	9.8 ± 3.5	4.2 ± 1.3	4.3 ± 1.8	37.1 ± 5.6	10.8 ± 3.5
Nkhono	53	11.9 ± 2.8	11.5 ± 3.2	10.0 ± 2.3	6.6 ± 2.2	13.2 ± 3.1	9.0 ± 3.2	20.1 ± 3.9	17.6 ± 4.0
Mambaiye	33	0.0 ± 0.0	0.0 ± 0.0	24.2 ± 4.2	24.5 ± 6.4	0.9 ± 0.7	0.0 ± 0.0	40.3 ± 6.4	10.1 ± 4.0
Msaka	33	33.2 ± 6.7	14.7 ± 4.6	21.8 ± 5.1	5.0 ± 1.9	7.3 ± 3.6	0.0 ± 0.0	8.8 ± 3.5	9.1 ± 4.4
Kasankha	36	28.3 ± 6.0	7.6 ± 3.3	15.2 ± 4.4	19.4 ± 5.3	7.2 ± 2.9	2.8 ± 2.8	7.6 ± 2.5	11.8 ± 4.1
Mjogo	36	4.2 ± 2.9	10.5 ± 4.2	13.3 ± 3.7	28.1 ± 6.1	1.1 ± 1.1	0.0 ± 0.0	14.0 ± 3.9	28.8 ± 5.8
Kankuta	36	34.1 ± 5.6	37.5 ± 5.4	4.9 ± 2.0	6.2 ± 2.7	3.5 ± 1.9	0.0 ± 0.0	1.4 ± 0.9	12.5 ± 4.3
All Communities	487	21.8 ± 1.5	14.9 ± 1.3	13.0 ± 1.0	11.6 ± 1.2	7.6 ± 0.8	2.5 ± 0.6	14.7 ± 1.2	13.9 ± 1.3

1: Fishing
2: Fish processing and trade
3: Agriculture
4: Retailing. Sales of food, commodities, meals, etc.
5: Sales of Firewood, Charcoal, and Timbers
6: Tourism. Tour guides, Lodge workers etc.
7: Piece work
8: Remittance, Working for a company or school, etc

and without direct access to Lake Malawi.

Agriculture is another important livelihood, but its contribution varies significantly among communities. For example, it accounted for approximately 25% of household income in Katukumala but only a minimum of 1% in Kafukuta. Similarly, income from selling forest products (firewood, charcoal, and timber) differed greatly: it contributed to an average of 16% of household income in Chembe, compared to just 1% in Mambayie and Mjogo (Table2).

Tourism-related income was observed only in the villages of GVH Chembe and GVH Madothi, as well as in the Kasankha community, where tourist accommodation is available. These economic patterns highlight the heterogeneous socioeconomic landscape in the CMP area.

3.2. Energy Use and Cooking Practices

Table 3 Household energy source usage by community and overall averages. Values for individual communities represent the percentage of surveyed households using each energy source. Multiple responses were permitted. Refer to Table 1 for the number of households surveyed (n) in each community.

Community	Energy source used in the household (%)							
	Firewood	Charcoal	Electricity[a]	Solar	Maize cob[b]	Briquette	Fossil fuels[c]	Other[d]
Chembe	81	56	19	2	2	0	0	2
Kafukuta	88	52	10	10	0	0	0	0
Katukumala	89	64	19	0	23	0	0	15
Muonda	83	90	35	8	2	0	2	0
Madothi	87	48	21	15	0	2	2	12
Nkhono	85	66	21	11	6	0	0	8
Mambayie	97	58	0	18	6	3	0	18
Msaka	85	64	12	6	6	0	0	18
Kasankha	97	44	3	8	3	0	0	8
Mjogo	86	78	19	17	3	0	0	6
Kankuta	92	58	5	13	3	3	3	26
All communities (n=490)	88	62	16	9	5	1	1	9

a: Electricity supplied by the power company
b: Maize cobs left after the crop has been harvested.
c: Gas Petrol diesel paraffin
d: Batteries, torches, etc

Across the study area, households predominantly use traditional biomass fuels. Firewood remains the primary energy source, used by an average of 88% of households, while charcoal use is also widespread at 62% (Table 3). However, charcoal utilization varied significantly, from a high of 90% in Muonda to a low of

Table 4 Cook stove usage by community and overall averages. Values for individual communities represent the percentage of surveyed households using each stove type. Multiple responses were permitted. The categories for stove types (1-5) are defined below the table. Refer to Table 1 for the number of households surveyed (n) in each community.

Community	Cook stove used in the household (%)				
	1	2	3	4	5
Chembe	75	52	12	2	2
Kafukuta	40	52	6	0	4
Katukumala	70	57	28	0	0
Muonda	63	87	6	4	4
Madothi	81	52	8	6	0
Nkhono	60	68	17	4	4
Mambayie	73	52	33	0	6
Msaka	64	64	21	0	3
Kasankha	67	44	31	0	6
Mjogo	75	83	8	0	6
Kankuta	92	55	11	0	0
All communities (n=490)	68	61	16	2	3

1: Three stones, a traditional method of burning firewood using three stones placed on the ground as a stand for the pot.
2: Charcoal brazier
3: Improved cooking stove
4: Electric/Gas stove
5: Other

44% in Kasankha, indicating different local energy dynamics. Access to modern energy is minimal; electricity use averaged only 16%, and no households in Mambayie reported access.

Cooking technologies mirror this pattern. Traditional three-stone fires (68%) and charcoal braziers (61%) are the dominant methods (Table 4). Although improved cookstoves have been promoted in the area since 2017 (Department of National Parks and Wildlife 2019), their adoption remains low at just 16% overall. These findings underscore the continued high use of traditional biomass and inefficient cooking technologies.

3.3. Firewood Procurement and Use

Firewood procurement patterns across the communities are characterized by a high degree of direct collection from natural sources. Overall, 78% of the firewood used by the surveyed households was gathered directly from the park and within the village itself (Table 5). In contrast, firewood from private woodlots made up only approx. 5% of

Table 5 Firewood procurement methods for firewood-using households and overall averages. The analysis includes only households that reported using firewood. Values for individual communities represent the community-level mean percentage for each procurement method ± standard error (SE). The analysis is based on self-reported data where households allocated proportions of their firewood supply to sum to 100%. See footnotes for definitions of the procurement methods.

Community	n	Collection[a]	Production[b]	Purchase	Gifted[c]
Chembe	42	92.9 ± 4.0	2.4 ± 2.4	2.9 ± 2.4	1.9 ± 1.9
Kafukuta	46	73.9 ± 5.6	2.5 ± 2.1	21.9 ± 5.5	1.7 ± 0.9
Katukumala	47	86.0 ± 3.8	2.2 ± 1.3	4.7 ± 2.6	7.1 ± 2.8
Muonda	43	61.9 ± 6.9	14.7 ± 5.2	23.5 ± 6.1	0.0 ± 0.0
Madothi	45	89.0 ± 4.3	0.7 ± 0.5	4.9 ± 3.1	5.4 ± 3.1
Nkhono	45	79.6 ± 5.2	8.0 ± 3.3	5.5 ± 2.7	6.9 ± 3.1
Mambaiye	32	84.8 ± 5.7	0.3 ± 0.3	10.8 ± 5.0	4.1 ± 3.2
Msaka	28	60.7 ± 8.7	2.5 ± 2.5	25.0 ± 7.6	11.4 ± 5.9
Kasankha	35	88.6 ± 4.5	5.6 ± 3.8	4.7 ± 2.5	1.1 ± 0.5
Mjogo	31	47.1 ± 8.6	10.3 ± 5.4	39.4 ± 8.6	3.2 ± 2.9
Kankuta	35	80.0 ± 5.8	0.0 ± 0.0	15.7 ± 5.2	4.0 ± 2.9
All Communities	429	77.8 ± 1.8	4.5 ± 0.9	13.5 ± 1.5	4.1 ± 0.8

a: Collected from the park and in the village by themselves.
b: Obtained from privately owned plantations, etc.
c: Received from neighbours or relatives, etc.

procurement methods. However, there was significant variation at the community level. Chembe showed the highest rate of direct collection (93%), indicating heavy use of nearby forest resources. Conversely, Muonda had the highest rate of firewood production from private land (15%), suggesting some diversification of sources. In Mjogo, a relatively high proportion of firewood was bought (39%), whereas in Msaka, gifting between households played a more notable role, accounting for 11% of firewood access.

Regarding firewood use, 85% of households reported using it for domestic purposes, with cooking being its universal function across all communities (Table 6). Additionally, 17% of households used firewood for small-scale economic activities, such as preparing snacks for sale, smoking fish, brewing, or selling firewood itself. Community-level differences were notable in that whereas 97% of households in Kasankha used firewood for cooking, only 73% in Muonda did so, suggesting some reliance on alternative fuels. Conversely, Muonda had one of the highest proportions of firewood use for

Table 6 Reported uses of firewood by community and overall averages. Values for individual communities represent the percentage of surveyed households that use firewood for the specified purpose. Refer to Table 1 for the number of households surveyed (n). Footnote 1 provides examples of activities included in 'Small businesses'.

Community	for Housework	for Small businesses[a]
Chembe	81	15
Kafukuta	81	13
Katukumala	89	15
Muonda	73	25
Madothi	85	17
Nkhono	85	17
Mambayie	94	18
Msaka	85	24
Kasankha	97	8
Mjogo	86	17
Kankuta	92	13
All communities (n=490)	85	17

a: Small businesses include fish smoking, selling firewood and producing snacks and beverages.

Table 7 Household engagement with various forest resources by community and overall averages. Values for individual communities represent the percentage of surveyed households engaging with each resource. Data on forest resource collection are based on self-reports, while the presence of a live fence was directly observed by enumerators. Refer to Table 1 for the number of households surveyed (n). Footnotes provide definitions and context for specific categories.

Community	Inside LMNP									Outside LMNP[d]	Live fence[f]
	Fire-wood	Thatching grass	Grass for tools[a]	Medicinal plants	Edible plants	Branches for fences	Animals[b]	Mush-room	Other[c]	Firewood[e]	
Chembe	81	48	6	13	8	4	4	0	0	8	8
Kafukuta	60	48	0	0	0	0	0	0	2	62	35
Katukumala	85	66	11	4	6	2	13	4	4	28	4
Muonda	54	60	10	12	2	12	0	0	0	19	17
Madothi	87	75	23	10	0	13	2	0	15	42	31
Nkhono	85	75	2	11	6	13	11	2	6	26	55
Mambayie	85	67	0	0	0	0	0	0	0	45	0
Msaka	58	64	6	3	3	9	3	3	3	27	21
Kasankha	56	47	17	0	0	8	0	0	6	61	17
Mjogo	36	33	0	3	0	3	3	0	0	42	19
Kankuta	71	58	0	8	5	3	5	3	3	32	21
All communities (n=490)	70	59	7	6	3	6	4	1	4	35	22

a: Grass for mat, broom, fence
b: Mammal, Insect, Honey
c: Timber, Dirt, Stone
d: 'Outside the LMNP' includes private land such as homesteads and farmland, as well as common land belonging to the village.
e: Other types of forest resources are also collected outside LMNP, but in this report we only be discuss about the firewood.
f: Enumerators observed the state of the fence when they visited the household.

small-scale businesses (25%), whereas Kasankha had the remarkably low (8%).

The types of forest products collected from LMNP reflect the multipurpose value of the park's ecosystems (Table 7). Firewood was the most collected resource, with over half of the households in all the communities except Mjogo reporting collection. In Mjogo, only 36% of households collected firewood from the park, likely because of access constraints or alternative sourcing strategies. Thatching grass also featured prominently, collected by most households in most communities, although Mjogo again showed the lowest proportion at 33%.

Other resources collected from LMNP include grass for making tools (mats, brooms, fences), medicinal plants, edible wild plants, fencing branches, mushrooms, honey, and small amounts of timber, soil, and stones. These uses vary by community. While the percentage of households collecting any single one of these other resources was low, the variety of products collected underscores the broad subsistence role of the park's forests beyond just energy needs.

While some households collect firewood from outside LMNP, this practice varies unevenly across communities. In Kafukuta and Kasankha, over 61% of households accessed off-park firewood sources, whereas fewer than 8% in Chembe. Live fences, a potential source of supplementary firewood, were also unevenly distributed. For example, more than half of the households in Nkhono had live fences, whereas none were recorded in Mambayie.

3.4. Collection Quantities and Extraction Pressure

To convert firewood collection frequency into a weight-based estimate, we first measured a total of 92 firewood bundles. The mean bundle weight was 37.8 kg (90% CI = ± 3.1) in the dry season and 35.0 kg (90% CI = ± 2.6) in the rainy season. A t-test revealed no statistically significant seasonal difference ($t = 1.08$, df = 87.79, $p = 0.2852$). As this numerical difference was not statistically significant, seasonal variations in bundle weight were considered negligible. Therefore, an overall average bundle weight of 36.3 kg (90% CI = ± 2.0) was used for all subsequent calculations.

Across all communities, the average number of firewood collectors per household was 0.83 (90% CI = ± 0.06), and each collector made an average of 0.88 (90% CI = ± 0.07) collection trips per week. While the average frequency was less than one trip per week, our survey data revealed a wide range among households. A small number of households across several communities reported exceptionally high collection frequencies of 3 to 6 times per week. These variations

in collection behavior between communities are detailed in Table 8. Based on these figures, the total monthly firewood collected across all 11 communities was estimated at approximately 1,412 megagrams (Mg) (Table 8), which corresponds to an annual extraction of 16,947 Mg (90% CI: 14,859–19,035 Mg) from the CMP forest. Given the CMP forest area of 6,550 ha and a community population of 40,415, this results in a per capita firewood collection rate of approximately 1.15 kg per day and a per hectare extraction pressure of 2.59 Mg ha^{-1} yr^{-1} (90% CI = ± 0.32). This weight-based estimate corresponds to an approximate volumetric extraction rate of 4.33 m^3 ha^{-1} yr^{-1} when converted using the mean wood density for tropical Africa (0.598 g cm^{-3}; Chave et al. 2009). This integrated estimate establishes a critical baseline for evaluating the sustainability of firewood extraction from the CMP forest and for comparison with other contemporary protected areas.

Table 8 Firewood collection parameters by community and overall estimates. Values for individual communities are presented as the community-level mean ± 90% confidence interval (CI).

Community	No. of FW collector per HH	No of FW collection per week[a]	Monthly weight (Mg) of collection
Chembe	1.00 ± 0.20	0.90 ± 0.18	146.67 ± 40.31
Kafukuta	0.38 ± 0.16	0.47 ± 0.19	28.74 ± 12.92
Katukumala	1.08 ± 0.23	1.29 ± 0.41	157.63 ± 37.42
Muonda	0.85 ± 0.26	0.78 ± 0.33	153.20 ± 45.65
Madothi	0.94 ± 0.20	1.05 ± 0.18	46.05 ± 8.69
Nkhono	0.96 ± 0.15	1.13 ± 0.17	151.66 ± 37.71
Mambayie	1.15 ± 0.20	1.14 ± 0.22	47.31 ± 11.59
Msaka	0.70 ± 0.26	0.37 ± 0.18	210.96 ± 68.92
Kasankha	0.56 ± 0.21	0.84 ± 0.25	76.09 ± 39.51
Mjogo	0.50 ± 0.21	0.71 ± 0.18	212.95 ± 118.99
Kankuta	0.92 ± 0.17	1.04 ± 0.21	181.02 ± 52.80
Overall Mean[b]	0.83 ± 0.06	0.88 ± 0.07	
Total[c]			1412.27 ± 174.02

a: Number of collections per week per collector. FW:Firewood, HH: Household
b: Average calculated across all 490 surveyed households.
c: Sum of the estimated monthly collection weights for the 11 communities.

To facilitate a direct comparison with historical data from Abbot and Homewood (1999), we calculated a partial total for the eight communities included in their study (Chembe, Kafukuta, Katukumala, Muonda, Madothi, Nkhono, Msaka, and Kankuta).

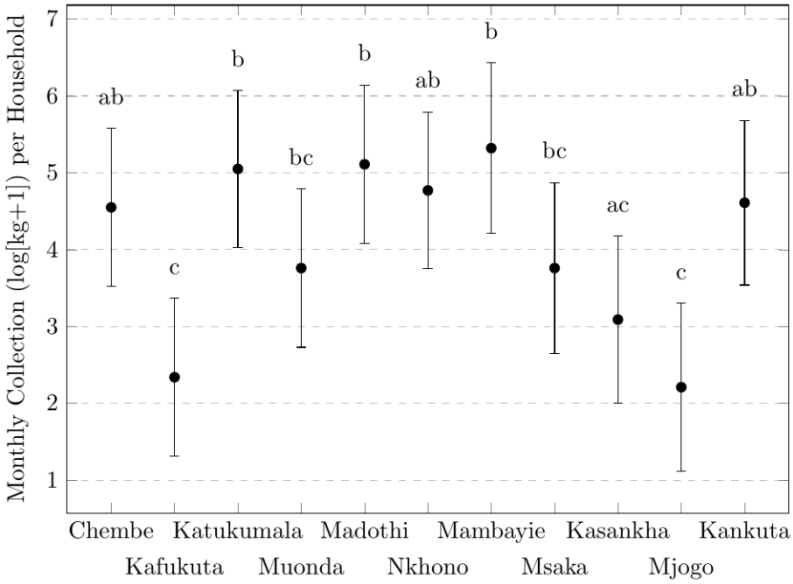


Fig. 2 Community-level differences in monthly firewood collection per household. The y-axis represents the community mean of log(x+1) transformed monthly household firewood collection (kg), where x is the collection amount. Points represent the mean, and error bars represent 90% confidence intervals. Communities not sharing a common letter are significantly different at $p < 0.05$ based on Tukey's HSD test.

The total annual firewood collection from these specific communities was 12,911 Mg (90% CI: 11,473–14,349 Mg), corresponding to a per-capita collection rate of 1.39 kg person^{-1} day^{-1}. This sub-total provides the basis for the 30-year temporal analysis presented in the Discussion.

3.5. Community-level Variation

A one-way ANOVA on the log-transformed data revealed significant differences in the average amount of firewood collected per household across the 11 communities ($F(10, 479) = 8.10, p < 0.001$). A post hoc Tukey's HSD test identified several distinct groups of communities (Fig. 2). For instance, communities such as Katukumala, Madothi, and Mambayie showed significantly higher collection rates than Kafukuta and Mjogo.

3.6. Drivers of Household Collection

409 Before constructing the model, we conducted a principal component analysis (PCA) to reduce the dimensionality of

410 variables related to income sources and household energy use. The PCA of income sources identified four principal

411 components that together explained 84% of the total variance (Table S1 in Online Resource 1). Similarly, the PCA of

412 energy use revealed three principal components that explained 78% of the variance (Table S2 in Online Resource 1).

413 The final linear mixed-effects model, selected based on AIC, identified several significant predictors of the monthly

414 household firewood collection volume (Table 9). Household size and the use of firewood for housework were both

415 significantly and positively correlated with the amount of firewood collected. In contrast, households that also collected

416 firewood from sources outside the national park collected significantly less firewood.

Table 9 Results of the linear mixed effects model explaining the monthly firewood collection amount (log(x+1) transformed, where x is the collection amount in kg).

Predictor	Estimate	Std. Error	*t* value	*p*-value
Fixed Effects				
Intercept	0.99	0.39	2.56	0.015 *
Household size (members)	0.38	0.10	3.68	< 0.001 ***
Firewood for housework (Yes)	3.16	0.30	10.64	< 0.001 ***
Collection from outside park (Yes)	-1.04	0.23	-4.58	< 0.001 ***
Random Effects				
τ_{00} (Community Intercept)	0.83			
σ^2 (Residual)	5.01			
Model Fit Statistics				
Observations	490			
Number of groups (Community)	11			
AIC	2215.1			
BIC	2240.3			

Note: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05.
The dependent variable is the natural logarithm of the monthly firewood collection amount (kg).
Variables were standardized before analysis where appropriate.
'Firewood for housework (Yes)' and 'Collection from outside park (Yes)' are dummy variables, with 'No' as the reference category.

The model's explanatory power was assessed using R-squared values for mixed-effects models. The marginal R-squared, which

420 represents the variance explained by the fixed effects alone, was 0.211. The conditional R-squared, representing the

421 variance explained by both fixed and random effects, was 0.323.

422 The random effects component of the model revealed significant variation among communities (Variance = 0.83),
423 indicating that there are baseline differences in firewood collection levels across the communities that are not explained
424 by the socioeconomic factors included in our model (Fig. S1 in Online Resource 2). In this figure, the points represent
425 each community's specific effect on firewood collection after accounting for household-level factors. Communities
426 whose 95% confidence intervals (error bars) do not cross the zero line have a collection level that is significantly
427 different from the overall average.

428 **4. Discussion**

429 By providing a direct quantification of firewood extraction in a World Heritage Site with a long history of
430 community-based management, this study establishes an empirical foundation for addressing the challenge of balancing
431 local livelihoods and conservation. Our analysis confirms that firewood collection is influenced by universal drivers such
432 as access to off-park wood sources; however, standard explanatory variables alone are insufficient to capture the full
433 variation, highlighting the critical influence of community-specific dynamics.

434 **4.1. Extraction Pressure in Context**

435 Firewood collection in the CMP forest is rooted in its widespread use for daily life. On average, 88% of households
436 in our study reported using firewood, and 78% collected it directly, primarily from the park forest (Table 5). These
437 figures are consistent with the broader context, aligning with reports that over 90% of rural households in SSA use solid
438 biomass fuels (Zulu and Richardson 2013; FAO 2017) and that 91% of rural Malawian households use firewood
439 (World Bank Group 2022). This widespread use translates into quantifiable extraction pressure. Our estimate of annual

extraction within this specific management unit (the 6,550 ha CMP forest) is 16,947 Mg (90% CI: 14,859–19,035 Mg). This corresponds to a per-capita collection rate of 1.15 kg day^{-1} across the current population of 40,415, and a per-hectare extraction intensity of 2.59 ± 0.32 Mg ha^{-1} yr^{-1} (or 4.33 m^3 ha^{-1} yr^{-1}). Quantifying pressure at this operational scale provides park managers and communities with a direct metric for evaluating sustainability against the forest's carrying capacity. Furthermore, although seasonal differences in bundle weights were not statistically significant in our sample, this core conclusion regarding extraction rates would remain fundamentally unchanged even if such minor seasonal variations were factored into the total extraction estimates.

This extraction rate falls within the broad range documented in the scarce literature on quantitative, area-based assessments, particularly in high-dependency regions. Our rate of 2.59 Mg ha^{-1} yr^{-1} is substantially greater than the ~0.20 Mg ha^{-1} yr^{-1} reported in South Africa (Swemmer et al. 2019), the 0.20–0.69 Mg ha^{-1} yr^{-1} in south-eastern Cameroon (Lhoest et al. 2020), and markedly higher than the 0.25 m^3 ha^{-1} yr^{-1} in Kenya's Koibatek Forest Zone (Rono et al. 2019). However, it is lower than the intense pressures reported from a forest reserve in Nigeria (~5.5 Mg ha^{-1} yr^{-1}; Adewuyi and Olofin 2014) and is comparable to rates in heavily used forests in the Sikkim Himalaya, where rates ranged from 2.8 to 7.8 Mg ha^{-1} yr^{-1} depending on the forest type (Chettri et al. 2002). This variation highlights that extraction pressure is context-dependent, yet our findings confirm that the pressure on LMNP is significant. This pressure is likely a direct consequence of land use in the surrounding landscape (Fig. 1), where the scarcity of alternative forest patches, particularly for enclave villages, leads the national park to function as the primary firewood source for a large population. This reflects the trend of protected areas becoming isolated forested islands (DeFries et al. 2005; Newmark 2008;

458 Gondwe et al. 2021).

459 Beyond simply highlighting the intense local pressure, this rigorous, area-based quantification (2.59 Mg ha^{-1} yr^{-1})

460 contributes critical data essential for understanding resource dynamics across different contexts. The broader

461 methodological implications of employing such a quantitative approach for evaluating sustainability are discussed

462 further in Section 4.4.

463 **4.2. Household and Community Drivers**

464 Our analysis reveals distinct drivers of firewood collection at both the household and community levels. At the

465 household level, the LMM identified that access to firewood sources outside the national park significantly reduced

466 collection within the park (Table 9). This finding provides a direct, evidence-based rationale for strategies focused on

467 increasing off-park wood availability, such as promoting agroforestry.

468 However, the LMM also highlighted that the household-level variables included in our model alone cannot fully

469 explain extraction patterns. Significant variation was observed at the community level (random effects accounting for

470 ~11% of total variance), indicating the critical influence of unmeasured community contexts. Our qualitative

471 observations suggest potential contributing factors include local economic structures and geographical access. For

472 example, Mjogo, whose households exhibit a significantly lower intrinsic tendency to collect firewood compared to the

473 average (Fig. S1 in Online Resource 2), is the region's commercial and transport hub, potentially providing more diverse

474 income opportunities that reduce reliance on collected firewood (Hiemstra-van der Horst and Hovorka 2008; Zulu

475 2010). Conversely, tourism centers like Madothi and Nkhono show significantly higher intrinsic collection per

household (Fig. S1 in Online Resource 2), suggesting that the economic benefits from tourism may not be sufficient to shift community-wide energy use away from collected firewood. Other unmeasured factors, such as local governance and internal community heterogeneity, also likely contribute to the observed community-level variation. For example, rule enforcement may be weaker in more geographically isolated communities, a common challenge for protected areas globally (Nolte 2016; Bowker et al. 2017).

Any variation not explained by the LMM analysis is likely attributable to other unmeasured factors. These may include disposable household income, specific cultural cooking preferences, the detailed structure and effectiveness of local governance (e.g., Village Natural Resource Committee‘s functioning), and fine-scale geographical access constraints (Cooper et al. 2018). Internal heterogeneity within communities also plays a critical role. As noted in the results (Section 3.4), a small number of households reported exceptionally high collection frequencies (3-6 times/week, exceeding the permitted frequency), suggesting that a community’s overall collection rate could be disproportionately influenced by a few high-intensity collectors.

Some variables initially considered based on theory were excluded during model selection (AIC-based), suggesting their independent effects were not statistically significant after accounting for other factors. For example, the effect of cooking technology might be obscured by limitations in our data (e.g., capturing stove use as binary variables rather than proportional usage time) or by usage patterns (e.g., the low adoption rate of improved cook stove (16%) and the widespread use of traditional three-stone fires (68%). Understanding these deeper contextual factors, spanning household economics, cultural norms, governance, geography, resource availability, and collection practices, is essential for

494 creating effective policies (Hiemstra-van der Horst and Hovorka 2008). Therefore, future research should complement
495 large-scale surveys with in-depth qualitative and quantitative investigations (e.g., detailed energy diaries) to truly balance
496 conservation with local livelihood needs.

497 Collectively, these findings, including the specific household drivers, the significant community-level variation, and
498 the internal heterogeneity, demonstrate why standardized, top-down approaches are ineffective. Effective management
499 requires combining interventions targeting household drivers (e.g., agroforestry) with tailored strategies that address the
500 specific economic and governance contexts of each community.

501 **4.3. Long-Term Dynamics and Landscape Scale**

502 The 30-year temporal comparison offers crucial insights into the long-term effectiveness of conservation
503 interventions. By quantitatively comparing current extraction pressure with data from the same eight communities
504 surveyed three decades ago (Abbot and Homewood 1999), we can benchmark the macro-level impact of intervening
505 changes. Our analysis reveals a clear finding: while population grew by 201.5% (from 8,440 to 25,444), total annual
506 firewood collection increased by a nearly parallel 191.2% (from 4,433 to 12,911 Mg). This close tracking is explained
507 by the fact that the per-capita collection rate remained virtually unchanged, moving from approximately 1.44 kg person^{-1}
508 day^{-1} in 1994 to 1.39 kg person^{-1} day^{-1} in 2023. This finding highlights a critical "scale trap" for conservation
509 management: focusing solely on per-capita metrics—which stabilized in this case—can mask a drastic escalation in the
510 aggregate extraction pressure on the ecosystem driven by population scale.

511 This lack of reduction in per-capita firewood use is particularly striking given the significant energy transition in the

region. The absence of charcoal in earlier literature (Grenfell 1993; Abbot 1996; Abbot and Homewood 1999) combined with local accounts suggests that charcoal use was negligible in these communities in the early 1990s. In contrast, our current data show that 62% of households now use charcoal (Table 3). However, the expected reduction in firewood pressure from this shift did not occur. We suggest that this is due to the "offsetting" effects of fuel stacking and economic diversification. First, our data show that while charcoal is widely adopted, it has not replaced firewood, which is still used by 88% of households (Table 3). This specifically implies that most households use charcoal alongside, rather than instead of firewood. Second, the region's population growth has been accompanied by economic diversification. The significant use of firewood for small-scale businesses, such as fish smoking, reported by 17% of households, likely represents a demand layer that has expanded with the population over three decades. These factors effectively offset the potential savings from charcoal adoption.

Consequently, the adoption of charcoal has not relieved the pressure on the park but rather added a new layer of pressure on the broader landscape. As all charcoal is imported into the CMP area, reportedly primarily from other areas within Mangochi District via bicycle or vehicle transport, this local change in energy use represents a "leakage" or displacement of deforestation pressure to other regions, a classic environmental problem (Pfeifer et al. 2012; Albers and Robinson 2013). This finding demonstrates that the park is not a closed system; the SES now faces a dual burden of sustained internal pressure and expanding pressure on the surrounding landscape. We discuss the implications of this broader landscape of pressures in Section 4.4. Further investigation into these supply chains and their ecological impacts is needed.

4.4. Broader Implications and Conclusion

The parallel growth of extraction pressure and population growth, revealed by our 30-year comparison, highlights a critical "scale trap" for conservation management. Focusing only on per-capita metrics risks a severe misinterpretation of sustainability. This close coupling, despite three decades of interventions including the current CBNRM approach, demonstrates precisely why interventions focused solely within the park are insufficient and underscores the urgent need for a broader SES approach.

An SES approach is needed because drivers operate across scales, extending beyond the park boundaries where communities and current CBNRM frameworks primarily operate. While community-focused interventions (including CBNRM and tailored strategies addressing local drivers identified in Section 4.2) remain essential for promoting stewardship, our findings on scale dynamics (Section 4.3) show they are insufficient alone to counter broader landscape dynamics like population growth and leakage. Therefore, sustainable solutions require integrating these community-level efforts with coordinated action among external actors operating at a larger scale. This includes partnerships between conservation authorities, local government (responsible for development and land use planning), and energy sector stakeholders to address factors like immigration linked to regional economic opportunities (tourism, fishing) and wood fuel supply chains extending beyond the park, as well as crucial collaboration with traditional leadership structures that influence community settlement patterns and local resource access norms.

Beyond the specific findings for LMNP, our integrated methodological approach provides a valuable template for assessing extraction pressures elsewhere. It combines the quantification of "how much" pressure is applied (extraction

548 load), the spatial definition of "where" it occurs (within a clearly defined collection area), and a nuanced understanding
549 of "who" is driving it (household and community factors). Crucially, quantifying pressure within a defined spatial
550 boundary provides the essential foundation for robust "pressure-response" evaluations, enabling future research to
551 correlate extraction levels with ecological outcomes (e.g., forest degradation). The accumulation of such spatially explicit
552 studies is necessary for meta-analyses aimed at identifying generalizable patterns and estimating sustainable harvesting
553 thresholds, thereby offering guidance even for data-poor contexts where detailed local studies are unfeasible.
554 In conclusion, this research quantifies firewood extraction pressure in LMNP, dissects its multi-scale drivers, and
555 reveals a persistent coupling between aggregate extraction and population growth via a unique 30-year comparison. We
556 demonstrate the limitations of park-focused management and the critical need for integrated SES approaches operating
557 at a landscape scale. Effective management requires combining tailored, community-specific interventions with these
558 broader landscape strategies. Our methodology provides a pathway for the evidence-based assessments needed to design
559 and monitor such integrated solutions, contributing to the global challenge of balancing conservation and livelihoods.
560

5. Statements and Declarations

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Conceptualization: TH; Methodology: TH, JB, PC, MC, YK, JM, PM, SY; Data collection: TH, JB, YK, NM, JM; Analysis: TH, HM; Writing – original draft: TH; Writing – review & editing: All authors

Data Availability

The datasets generated during the current study are not publicly available due to ethical restrictions and agreements with local communities but may be available from the corresponding author on reasonable request.

Ethical Approval and accordance

This study received ethical approval from the University of Malawi Research Ethics Committee (UNIMAREC) (reference number P.05/23/248). All research procedures were performed in accordance with the ethical guidelines and

regulations of the University of Malawi and the principles outlined in the Declaration of Helsinki.

Field permission

Permission to conduct fieldwork in Lake Malawi National Park and surrounding communities was obtained from the Department of National Parks and Wildlife (DNPW) and the relevant Traditional Authorities prior to data collection.

Consent to participate

Verbal informed consent was obtained from all participants prior to the interviews.

Consent to publish

Informed consent regarding participation and publication was obtained from all participants.

Clinical trial number

Not applicable.

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