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The valuation of forest ecosystem services in Kenya: a comparative case study of Karura Forest Reserve and Kakamega National Forest Reserve

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CHAPTER 1: FRAMEWORK, RESEARCH DESIGN AND THESIS STRUCTURE

1.0 Background overview

Forests provide a wide range of ecosystem services (ES) which improve human wellbeing and support living components in the biosphere (Sangha et al., 2022). The quantity and quality of ES depend on the forest health resulting from consequential interactions with the biotic and abiotic factors (Brockerhoff et al., 2017). Nature and its processes are interconnected through various biogeochemical processes which maintain the flow of energy between the different biomes (Vanneste et al., 2024). Human interactions with nature are therefore unavoidable for purposes of sustenance and mutual dependence (Soga et al., 2021). These interactions define biodiversity at various tropic levels and are more visible within food webs and food chains (Schuldt et al., 2018). Globally, the widely accepted Common International Classification of Ecosystem Services (CICES) and Millennium Ecosystem Assessment (MEA) outline four major categories of ES i.e., provisioning, regulating, cultural and supporting (Haines et al., 2018). The most commonly recurring reference in research is provisioning ES, which infers an overreliance on tangible ES for industry, livelihoods and daily sustenance (Anand et al., 2020). Other intangible ES are also covered in research in the context of maintaining ecosystem health and building environmental resilience (regulatory ES), recreation and spiritual context (cultural ES), and sustenance of environmental productivity through nutrient cycling (supporting ES) (Mengist et al., 2020). The ecological importance of ES highlights the need for their valuation from an economic perspective to better contextualise their contribution to livelihoods (Quijas et al., 2013).

Natural resources, especially forest ecosystems in Africa are central to livelihoods at different socio economic levels (Osewe et al., 2024a), and they remain under threat of degradation and depletion from direct overreliance. Research has established the following main drivers exacerbating the depletion of forest resources in Africa: land use changes at forest edges for agricultural activities (Phiri et al., 2023), deforestation linked to logging and fuelwood provision activities (Abera et al., 2024), and climate change (Dessalegn et al., 2015). The conservation efforts in many African countries have been historically protection based approaches, such as the establishment of protected areas for biodiversity conservation (Imarhiagbe et al., 2022). In the last decades, sustainable forest management (SFM) principles have proven more effective particularly at the intersection of climate change mitigation and poverty alleviation for vulnerable rural communities (Tebkew et al., 2022). These contemporary approaches such as community based forestry, participatory forestry and payment for ecosystem schemes (PES) have shifted the narrative of values associated with forest ecosystems towards livelihood improvement (Charnley et al., 2022; Gasheye, 2024). The role and contribution that ES play in national economies towards human wellbeing are often undervalued and excluded in policy making which leads to high risk of overexploitation (Martinez et al., 2015). At a continental level, where many economies rely on natural resources (Mpuure et al., 2024), valuation of ES bridges the gap between ecological sustainability and the standardisation of comparable economic metrics for inclusion in national development priorities (Elbasit et al., 2021).

In Kenya, forest policy shifts and international climate change initiatives have been the main drivers toward changes in forest management practices over the last decade (Chisika et al., 2024). The Forest Conservation and Management Act of 2016 (Republic of Kenya, 2016), provides a framework for

community involvement in forest management by protecting ecosystems and guaranteeing economic and social benefits. Notably, it is through this legal provision that Community Forest Associations (CFAs) co-manage forests with state agencies and share benefits (Mutune & Lund, 2016). The global efforts to combat climate change through reduction of carbon emission programs like the Reducing Emissions from Deforestation and Forest Degradation program (REDD+) have also incentivised SFM practices (Atela et al., 2016). Therefore, valuation of ES would establish comparable economic metrics that can be used to assess national performance in climate mitigation efforts and forms baseline for carbon credit accounting (Enríquez et al., 2022; Kanyenji et al., 2020). These findings would also provide insights into the drivers of environmental degradation, which inform effective management practices through interventions within the national climate change action plans. Moreover, SFM ensures that forests remain attractive destinations for nature based tourism, which is a major revenue earner in Kenya (Ndivo et al., 2020). Establishing economic value of natural capital provides a nuanced perspective on benefits attributed to forests (Maingi, 2021), and supports objectives towards socio-economic development by integrating environmental sustainability into national economic planning (Milheiras et al., 2022).

1.1 Research problem and gap

Forests ecosystems in Kenya continue to face pressures from land use change, fragmentation, unsustainable resource extraction, and climate change (Mbuvi & Kungu, 2021; Rotich et al., 2025). Previous studies assessing the contribution of ES to livelihoods have primarily focused on homogenous forest ecosystems with similar management regimes to address the threats of deforestation (Kogo et al., 2019), forest degradation and climate change (Bamwesigye et al., 2020), often evaluating a limited range of ES (Okumu & Muchapondwa, 2022). For instance, the ES valuation of main water towers in Kenya was conducted in similar montane forest ecosystems such as Mau Forest complex in Central Kenya (Miller et al., 2021), Cherangani Hills and Mount Elgon in Western Kenya (Langat et al., 2018). Similarly, studies on urban forests in Nairobi (Karura Forest, Ngong Forest, Nairobi arboretum), Nyeri (Kabiruini Forest), and Nakuru (Menengai Forest) have largely emphasised their ecotourism benefits and biodiversity (Chisika et al., 2023; Oloo et al., 2020), with limited insights into the value of other ES and their comparability with classical economic metrics. This leaves a gap in understanding the valuation of diverse ES across different forest types and their economic implication to livelihood development.

Three interrelated limitations emerge from the body of existing literature on ES valuation in Kenya. (1) Few comparative analyses exists across different ecological structures like old-growth rainforest versus secondary urban forest, nor within dimensions of institutional arrangements like community co-management versus state led management (Mbuvi & Kungu, 2021). (2) Incomplete ES coverage, which prevents holistic natural capital accounting essential for policy integration (Akello et al., 2025; Weiskopf et al., 2022). (3) Fragmented disciplinary approaches in ES valuation research that disconnect socio-economic dependence, governance effects, and community livelihoods which are required for creating viable nature based finance pathways like PES (Chisika et al., 2024; Sapiains et al., 2021).

This research addresses these gaps by juxtaposing the valuation of the main ES from two distinct forest reserves: Kakamega National Forest Reserve (KNFR), an old growth tropical rainforest and Karura Forest Reserve (KFR), a secondary urban forest in the capital city of Nairobi (Osewe al., 2022). This contrast highlights differences in ES provision, effect of management strategies, and socio-economic contexts of surrounding forest communities. It quantifies the estimated economic contribution of the main ES to livelihoods and national development through the lenses of people centred forest management approaches. This research provides market pricing data on ES which is the economic baseline for establishing nature based finance initiatives in Sub Saharan Africa (SSA), a region which receives only 3% of global nature based financing (Gemayel et al., 2025).

1.2 Conceptual framework of research

This research is anchored in the interconnected relationship between forest structure, ES provision, socio-economic benefits and the implications of forest governance to livelihoods as summarised in Figure 1. This valuation approach centres on the forest composition and management regimes, which determine the nature and magnitude of provisioning, regulating, cultural, and supporting services. These ES mediate livelihoods, patterns of community dependence that are shaped by governance architectures and access rights. Valuation findings inform natural capital accounting frameworks and serve as market pricing baselines for mobilising nature-based finance. This research situates these dynamics within the global policy context of the Sustainable Development Goals (SDGs), REDD+, and the Convention on Biological Diversity (CBD) (Golub et al., 2025; Pistorius, 2012), which recognise people centred forest management approaches and instruments such as PES and Plantation Establishment and Livelihoods Improvement Scheme (PELIS) as viable pathways for integrating ES valuation into policy and financing mechanisms (Diafas et al., 2017; Waruingi et al., 2021).

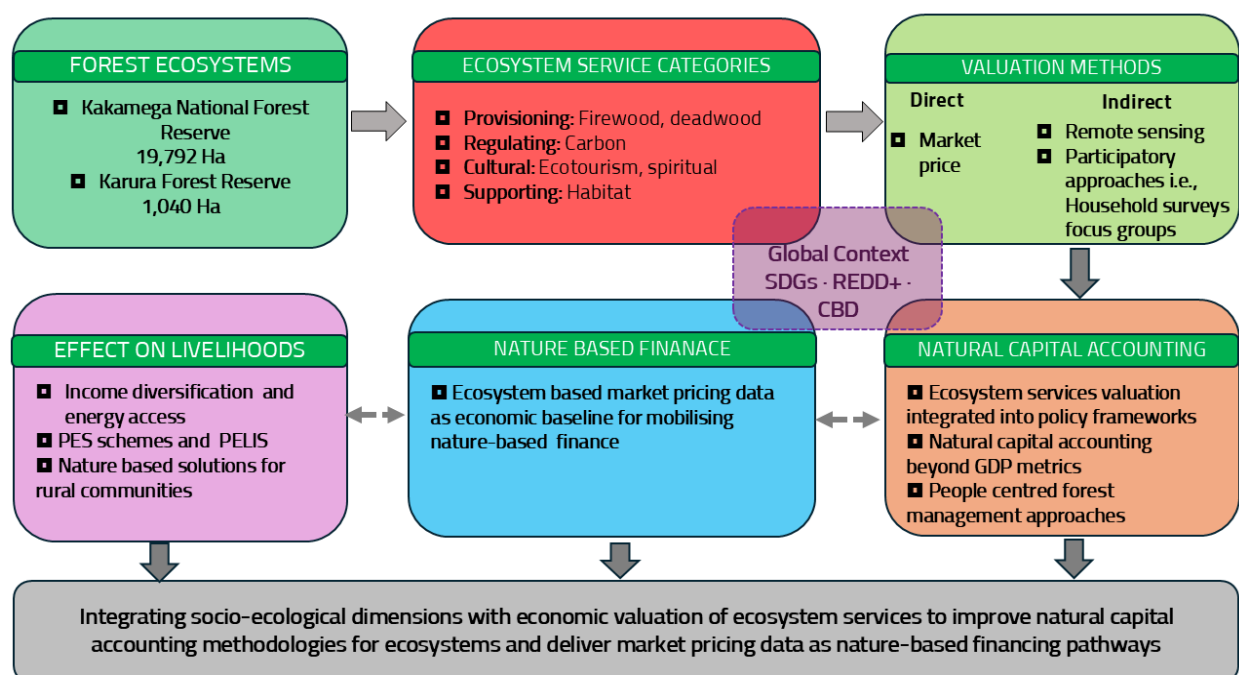


Figure 1. Conceptual framework for the integrated socio-ecological valuation of ES

1.3 Aim, objectives and rationale for research design

The aim of this doctoral research was to evaluate the main ES in two distinct forest reserves to establish comparable economic metrics for estimating their natural capital value. This research used interdisciplinary approaches (Figure 2) to address five objectives, with each objective forming the basis of a scientific publication in peer-reviewed journals (Figure 7). The mixed methods design integrated systematic literature review (Paper 1) for contextual framing, remote sensing and field measurements (Papers 2 and 5) for biophysical quantification, and household surveys (Papers 3 and 4) for socio-economic valuation. This ensured comprehensive coverage, methodological triangulation, and comparison across ecological, economic, and social dimensions. The objectives included:

- To review the impact of global and regional contextual factors on the valuation and perception of ES (**Paper 1**)
- To assess the ecological changes in forest structure, canopy cover and their implications on ES provision (**Paper 2**)
- To evaluate the main ES provided by KFR and their role in socio-economic wellbeing of surrounding communities (**Paper 3**)
- To evaluate the main ES provided by KNFR and socio-economic factors influencing the dependence of rural communities (**Paper 4**)
- To evaluate the performance of remote sensing techniques in estimating above ground biomass to determine carbon stock for managed (KFR) versus unmanaged (KNFR) forests in Kenya (**Paper 5**)

1.4 Material and methods

This research used ES indicators to simplify economic valuation of complex ecological functions by assigning comparable, quantifiable and measurable metrics for the various categories of ES (Albert et al., 2016). The interdisciplinary approaches revealed trade-offs and synergies that addresses gaps in natural capital accounting and provided holistic economic perspective as summarized in Figure 2 (Pouso et al., 2020). The main ES provided by respective forest reserves within the MEA and CICES categories were contextualised to highlight their role in local livelihoods and the interdependencies between forests and rural communities (Bisui et al., 2024; Mushi et al., 2020). The indicators used for the main ES in Table 1, captured a wide array of forest functions in economic terms, making the value of natural capital translatable to conventional economic systems (Brander et al., 2024; Pascual et al., 2023). The main ES utility combined with participatory approaches and ecosystem modelling methods provided a nuanced perspective of how forests contribute to both the environment and the socio-economic wellbeing of surrounding communities (Fischer et al., 2023). While KFR is completely fenced in an urban setting with sections of silvicultural treatments (Manji, 2017a), KNFR is fragmented ecosystem with sections of disturbance (Osewe et al., 2022). Therefore, comparable indicators for the main ES valuation were developed to suit unique contexts of each forest ecosystem. KFR had three main ES categories (provisioning, regulating and cultural services) evaluated, while KNFR had four main ES categories (provisioning, regulating, cultural and support service) evaluated. The interdisciplinary approaches in Table 1 were suited for capturing interconnected relationship between ecological health and forest community livelihoods.

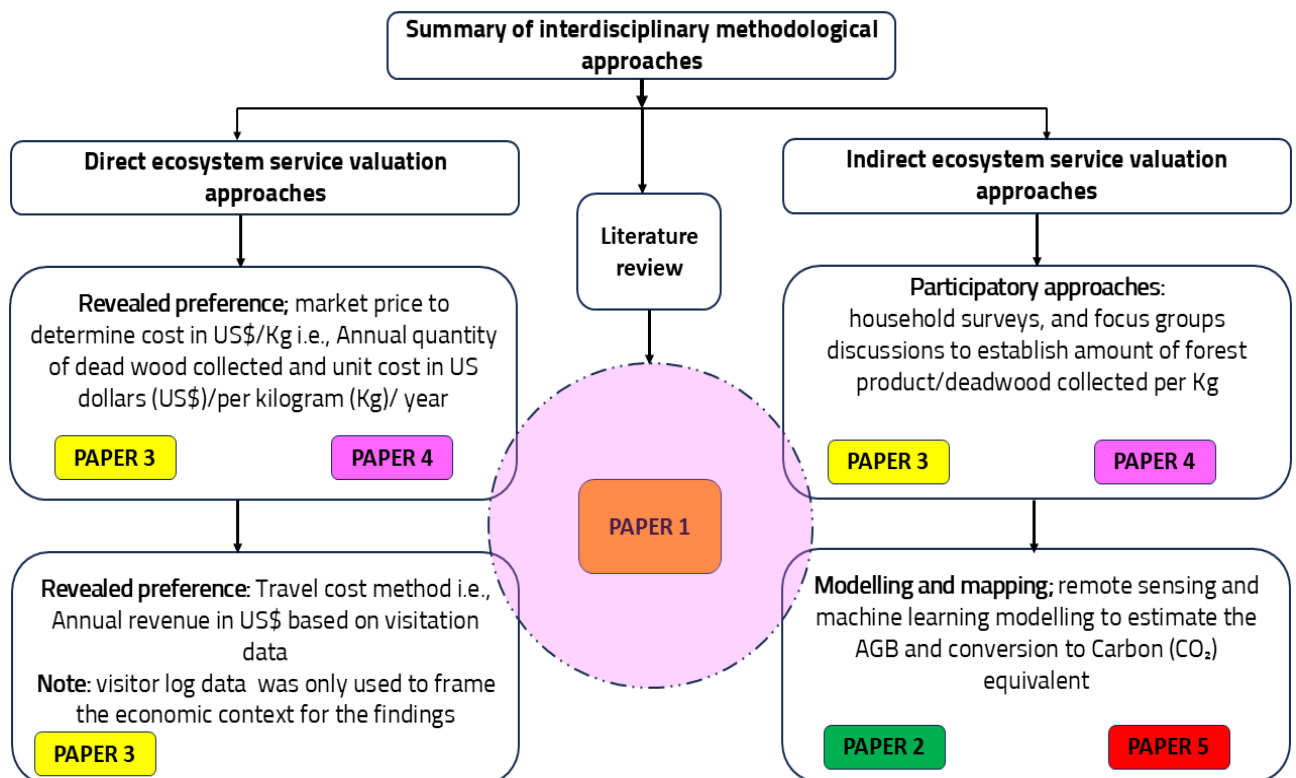


Figure 2. Summary of the interdisciplinary methodological approaches for valuation of ecosystem services

Table 1. categories of ES and evaluation approaches for KFR and KNFR

Study areas	Categories of main ES evaluated according to MEA and CICES	Indicators of ES Utility	Economic metrics for ES assessment	Methods and approaches used for ES valuation
KFR	Provisioning services	Deadwood (used as firewood)	Annual quantity of dead wood collected and unit cost in US dollars (US\$)/per kilogram (Kg)/ year	Participatory approaches: household surveys, and focus groups discussions to establish amount of deadwood collected per Kg Revealed preference; market price to determine cost in US\$/Kg
	Regulating services	Carbon storage	Carbon (CO ₂) equivalent in US\$ per metric/ton/year	Modelling and mapping; remote sensing and machine learning modelling to estimate the AGB and conversion to Carbon (CO ₂) equivalent
	Cultural services	Ecotourism	Annual revenue in US\$ based on visitation data	Revealed preference: Travel cost method Participatory approaches: questionnaires issued to key stakeholders
KNFR	Provisioning services	Forest products; firewood, vines, fruits, timber, mushrooms and medicinal plants	Annual quantity of forest products collected and unit cost (US\$/Kg/year)	Participatory approaches: focus groups and household surveys to establish amount of forest products collected per kilogram Revealed preference; market price to determine cost in US\$/Kg
	Regulating services	Carbon storage	Carbon (CO ₂) equivalent in US\$ per metric/ton /year	Modelling and mapping; remote sensing and machine learning modelling to estimate the AGB and conversion to Carbon (CO ₂) equivalent
	Cultural services	Spiritual values of sacred shrines	Willingness To Pay (WTP) within the price range in US\$	Participatory approaches; focus groups and household surveys
	Supporting service	Habitat connectivity	Area of forest cover in hectares (Ha) lost in two decades (20 years)/ equivalent Carbon (CO ₂) loss in US\$	Modelling and mapping; remote sensing and machine learning modelling

1.5 Study area

The study area consists of two distinct forest reserves in Kenya, both designated as protected areas (Kairu et al., 2024). KFR is in the capital city Nairobi as an urban forest with the size of 1,041 Ha (Manji, 2017b), while KNFR is situated in the rural Western region of the country as tropical rainforest with the size of 19,792.4 Ha (Osewe et al., 2022b), as detailed in Figure 3. This juxtaposition of the two forest reserves gives spatial context on the main ES values while referencing the influence of stand structure dynamics, tree species, management regimes, socio-economic factors and biodiversity ecosystem functions.

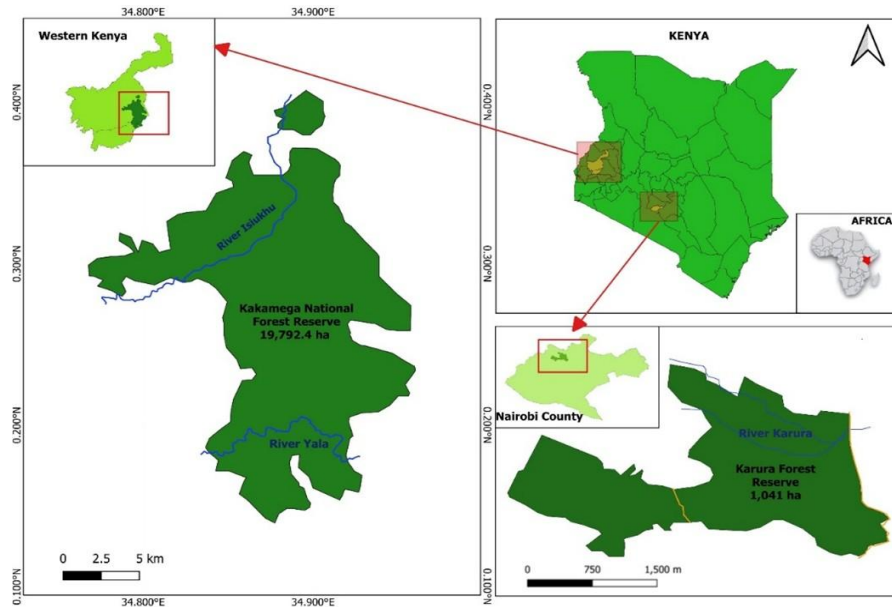


Figure 3. Map of study areas

KFR is classified as secondary forest with silvicultural treatments, comprising of both exotic and indigenous tree species, and replanted areas under various regimes (Osewe et al., 2025). It is co-managed by the Friends of Karura Community Forest Association (FKF-CFA) and the Kenya Forest Service (KFS) (Njeru, 2012). In contrast, KNFR is a fragmented tropical ecosystem, comprising three national reserves and two nature reserves (Osewe et al., 2022c). Its forest core comprises predominantly mature, undisturbed old growth stands of indigenous tree species. It is co-managed by the KFS, the Kenya Wildlife Service (KWS), and various CFAs within each Sub-county in Kakamega County (Bleher et al., 2006).

1.6 Data overview

Primary data for analysis was collected through fieldwork activities conducted in KNFR and KFR, which involved plot measurements (Figure 6), surveys and questionnaires (Table 2, Table 4 and Table 5). These surveys gathered responses from CFAs, the Kenya Forest Research Institute (KEFRI), and forest adjacent communities to provide socio-economic context on the role of ES in their livelihoods. Plot measurements were conducted using a handheld LiDAR device with installed Arboreal application (Lindberg, 2020), following a sampling regime coinciding with the Global Ecosystem Dynamics Investigation (GEDi) instrument path (Blair et al., 2021). Secondary data was sourced from the Web of Science platform to conduct a systematic review of ES valuation methods in East Africa using the Reporting standard for Systematic Evidence Syntheses (ROSES) framework (Osewe et al., 2024a). Tourist visitor log records were also obtained from FKF-CFA from 2020 to 2023 and only used to provide economic context of the findings framed in the valuation of main ES for KFR.

1.6.1 Questionnaire design and stakeholder survey plan

The main stakeholders identified for the survey in KFR included: (i) FKF-CFA, (ii) Karura Forest Environmental Education Trust (KFEET), (iii) Huruma community based organization (CBO), and (iv) KFS. A total of 36 members from Huruma CBO and 50 representatives from FKF-CFA, KFEET, and KFS participated in the survey. The questionnaires focused on stakeholder's perceptions on ES and the

impact of periodic deadwood removal carried out by the Huruma CBO, as detailed in Table 2. These responses were captured to evaluate perceptions of the felt benefits, as well as the direct and indirect values of the main ES.

Table 2. Summary of the questionnaires issued to the main stakeholders in KFR

Questionnaires	Topics discussed
Perceived benefits to stakeholders; (i) FKF-CFA, (ii) KFEET, and (iii) KFS	Q.1. Age Q.2. Gender Q.3. Employment category Q.4. Period of employment Q.5. Frequency of work in Karura Forest Reserve Q.6. Type of work provided Q.7. Range of monthly earnings Q.8. Wages satisfaction level Q.9. Perceptions regarding (a) employment, (b) wage, (c) skills, (d) financial needs and (e) sense of belonging
Benefits associated with removal of deadwood by Huruma CBO	Q.1. Community/Association name Q.2. Participation in deadwood removal activities Q.3. Sources of information about deadwood removal activities Q.4. Quantities collected Q.5. Benefits of removing dead wood Q.6. Perceived effects of dead wood removals on adjacent communities Q.7. Level of satisfaction with dead wood extraction activities

In Kakamega county, a sampling technique was used with the Sub-counties as strata, as detailed in Table 3. Preference was given to households that fell within the livelihood dependence zone, i.e., 5-10 km from the officially gazetted boundary of KNFR. For better representativeness of each stratum, the increased sample size was to reach a minimum of 100 respondents in each stratum, while preserving the proportionality and stratified structure of the sample size.

Table 3. Survey sample size for each administrative unit bordering KNFR

Sub-counties where Kakamega Forest Ecosystem lies	Targeted sample size with confidence level 95%, Margin of error 5%, population proportion of 50%.	Increased sample size for strata (n)	Number of Households per Sub- County (H)	Interval Number for household survey along road/ street/ pathways <i>Interval number (i) = $(H)/(n)$</i>
Lurambi Sub-County	94	154	52,015	337
Shinyalu Sub-County	93	153	39,589	258
Malava Sub-County	68	112	26,049	232
Navakholo Sub-County	68	112	27,671	247
Hamisi Sub-County	61	100	26,964	269
Total number of targeted households for survey		631		

Two questionnaires were issued to local communities within the forest dependence zone of KNFR to capture detailed insights of their reliance on the main forest ES. The first questionnaire focused on the use of tangible forest products such as fuel, food, and other resources essential for their livelihoods as detailed in Table 4. The second questionnaire concentrated on their perceptions and attitudes toward cultural ES as summarized in Table 5.

Table 4. Summary of questionnaire issued to local communities around KNFR

QUESTIONS	POSSIBLE RESPONSES					
	a	b	C	d	e	f
Gender	Female	Male	Other	I rather not say		
Occupation or work	Farmer	Civil servant	Retired	Self-employment		
How often do you use forest products	Daily	Weekly	Monthly	At least once in within 12 months (a year)	Never	
What Forest products do you use most frequently?	Firewood	Fruits (<i>Persea americana</i>)	Vines (<i>Mondia whitei</i>)	Timber	Medicinal plants (<i>Azadirachta indica</i>)	Others (mushrooms) (<i>Auricularia auricula-judae</i>)
Quantity of forest product used in kilograms	Under 20kg	21 kg to 50 kg	51 kg to 80kg	81 kg to 110 kg	Over 111kg	
Main use for forest products?	To sell and make profit (commercial)	For household use (subsistence)	Mixed use/ Commercial & subsistence			

Table 5. Summary of questionnaire assessing perceptions and attitudes toward cultural ES

QUESTIONS	POSSIBLE RESPONSES					
	a	b	C	d	e	f
Gender	Female	Male	Other	Prefer not to say		
Education level	None	Primary school	Secondary school	Tertiary education level/University	Specialised schools	
Do you have a religious affiliation	Yes	No	I don't know	Prefer not to say		
Would you pay if entrance was fee based	Yes	No	I don't know	Prefer not to say		
If the entrance was fee based, how much would you be willing to pay (select a price range that you would be most comfortable playing without straining)	less than Ksh 75 (0.54US\$)	Ksh 76 (0.55US\$) to Ksh 150 (1.09US\$)	Ksh 151 (1.10US\$) to Ksh 300 (2.17US\$)	Ksh 301 (2.18US\$) to Ksh 600 (4.34US\$)	Ksh 601 (4.35US\$) to Ksh 900 (6.52US\$)	Ksh 901 (6.53US\$) to Ksh 1200 (8.69US\$)
Have you experienced a sense of peace or tranquillity at the sacred groves	Yes	No	I don't know	Prefer not to say		
Have you had any physical sensations like tingling at sacred groves	Yes	No	I don't know	Prefer not to say		
Any spiritual experience at sacred groves	Yes	No	I don't know	Prefer not to say		
Have your visits improved your spiritual or religious life	Yes	No	I don't know	Prefer not to say		
Did you feel connected to a higher power	Yes	No	I don't know	Prefer not to say		
Would you recommend others to visit the sacred groves	Yes	No	I don't know	Prefer not to say		

The questionnaires were issued at household level and selection of the households was carried out by applying an interval number from a convergence point such as markets or road junctions as shown in Figure 4. For the Tiriki sacred groves which are locally known as the “*Ikavakava shrines*”, data was collected using the various sacred groves as the central convergence points.

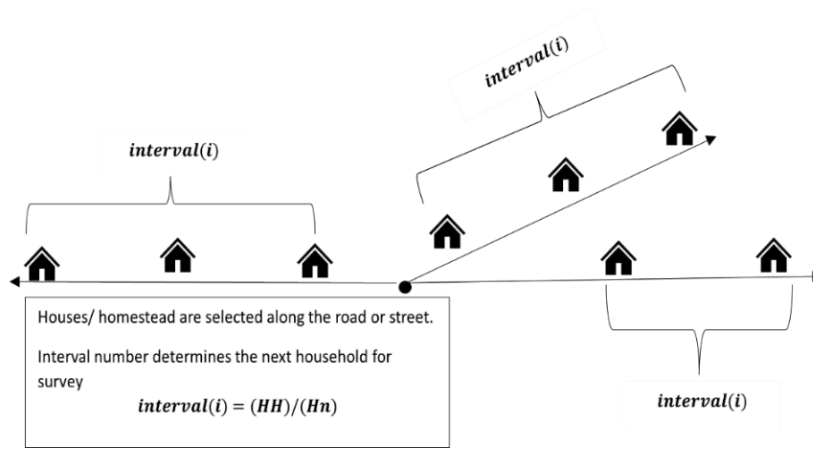


Figure 4. Diagrammatic frame for household selection during field survey in Kakamega County

1.7 Data collection

Data collection involved the integration of remote sensing and field measurements in both KNFR and the KFR. Remote sensed data was obtained from the following sources: Hansen product, Sentinel-2, Landsat 8, and GEDI. Field measurements were conducted using a systematic plot sampling regime correlated with GEDI path in both study areas.

1.7.1 Remote sensed data

Remote sensed data was obtained from the Hansen product (Pillay et al., 2022), which is an open access online database that quantifies global forest changes within the timeframe of 2000 to 2020. Hansen et al., (2019) demonstrated the suitability of this dataset for assessing changes in tropical rainforest ecosystems. The dataset was accessed from the repository with permanent link: <https://glad.earthengine.app/view/global-forest-change>. Further, the data used for image composite classification to compare the canopy cover changes from Hansen products were obtained from Sentinel-2 and Landsat 7, within the Google Earth Engine platform (GEE) (Zhang et al., 2021a).

Other remote sensed data obtained included GEDI data to estimate the AGB for carbon stock assessment in KNFR and KFR. The downloaded spatial point data provided detailed vegetation profiles and biophysical variables (Dixon et al., 2025; Fareed et al., 2025). GEDI is a full waveform LiDAR instrument that uses laser light pulses to capture physical and natural characteristics of the earth with relatively high precision as detailed in Figure 5. Its signals are recorded in nanosecond intervals and results in a waveform that reveals canopy height, vertical structure, canopy cover and topography. GEDI's wide spatial coverage, spanning 51.6° N to 51.6° S, makes it suitable for tropical and subtropical regions, providing valuable insights for forest monitoring and carbon stock assessments for both study areas.

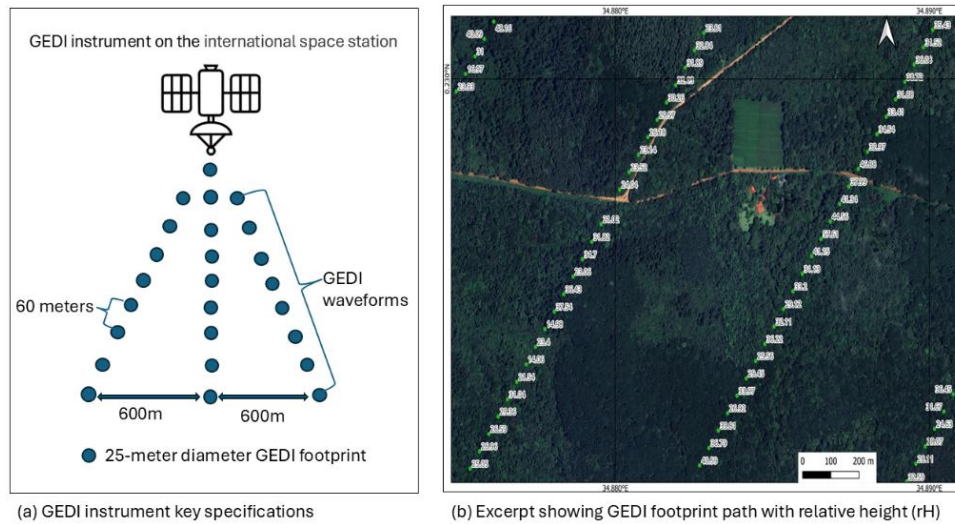


Figure 5. GEDI instrument specification and footprint in study area (KNFR excerpt)

GEDI data were converted to a spatial points data frame. These variables were subsequently exported as shapefiles and overlaid onto the study areas to establish a georeferenced plot sampling regime. The field plots were coincided with GEDI beams for comparison to assess variability and bias in AGB estimates as illustrated in (Paper 5)

1.7.2 Field measured data

Circular plots with an area of 500 m² were delineated within the GEDI footprint detailed in Figure 6. In both forest ecosystems, tree species were individually identified and their Diameter at Breast Height (DBH) ≥ 10 cm was measured by handheld LiDAR device and the average tree height for each plot was estimated using the Arboreal application within a real-world environment through an augmented reality (AR) (Lindberg, 2020; Sandim et al., 2023). The Arboreal application digitally tagged measured trees within the AR environment to avoid duplication in measurements. The plots were established at different sections coinciding with the GEDI footprint to capture variations of three treatments i.e., undisturbed indigenous sections, planted sections which were cleared and replanted under various regimes and undisturbed old growth forest sections in both ecosystems.

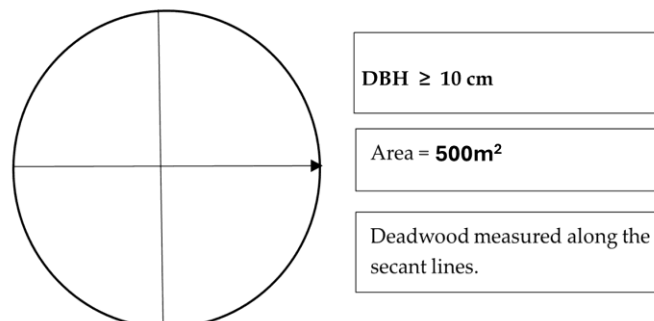


Figure 6. Size and shape of field plots used for measurements

1.8 Workflow of field measurements and survey activities

Field plot measurements in KFR were conducted on weekdays. During the field measurements, tree species were identified by an assigned taxonomist from KEFRI together with a scout ranger from FKF-CFA. Plot measurement activities were excluded on Tuesdays and Fridays, which were designated days for deadwood collection by local CBOs from the Huruma community, under the supervision of KFS and FKF-CFA. On these designated days, focus group discussions were held with the CBOs. In KNFR, plot measurement activities and household surveys were separated because of its extensive area and fragmented nature. A minimum of three plots were measured each day. At the plot level, tree species were identified by an assigned taxonomist from KEFRI in collaboration with KFS rangers from the Shinyalu Sub-station.

The household surveys were conducted in Kakamega County and parts of Vihiga County in areas where the southern tip of the KNFR extended. The surveyed households were distributed along the forest edge covering the Sub-counties of Lurambi, Shinyalu, Navakholo, Malava and Hamisi. To achieve the targeted minimum of 100 responses per Sub-county, five enumerators organized four hour focus group workshops with at least five CFA leaders in each of the five Sub-counties prior to questionnaire distribution. These interactive sessions were conducted to identify utility preferences for the main ES. Questionnaires were distributed with a minimum target of administering 25 questionnaires per day in each Sub-county.

1.9 Data processing and analysis

Remote sensing data were processed using a series of steps. Hansen product images with less than 10% cloud cover were filtered to create composites for further analysis in GEE and QGIS software (Ma et al., 2023; Seidler, 2017). Satellite imagery from Sentinel-2 and Landsat 7, covering the period from 2000 to 2020, were reclassified to generate composites for forest area density analysis (FAD) and morphological spatial pattern analysis (MSPA) using Guidos software (Vogt et al., 2017). GEDI waveforms with fidelity greater than 0.95 were selected and filtered by applying a maximum allowable difference of 50 meters between the lowest elevation detected by GEDI and the actual terrain elevation. The filtered data was used to estimate AGB for KFR and KNFR. The AGB estimates were converted to Carbon equivalent providing estimates of carbon storage in both forest ecosystems.

A structured analysis of survey responses was conducted in RStudio (Nguyen et al., 2022a), to evaluate the socio-economic impact of ES provided by KFR and KNFR, as well as the perceptions of surrounding communities. For KFR, data collected from FKF-CFA and Huruma CBOs were categorized and numerically coded for descriptive statistical analysis (Saginova et al., 2020). For KNFR, datasets from Lurambi, Shinyalu, Navakholo, and Malava Sub-counties were merged into a single numerical column dataset which focused on analysis of tangible ES. The dataset for assessing cultural ES from Hamisi Sub-county was analysed separately using similar descriptive statistical tools (Romanazzi et al., 2023).

1.9.1 Analysis of remote sensed data

The data analysis for forest canopy cover changes used Hansen product as input and processed it on the GEE platform (Zhang et al., 2021b). First, machine learning algorithms were applied to identify and

reclassify pixels into "*gain*" and "*loss*" categories. The reclassified pixels were aggregated to produce a statistical summary, quantifying the extent of forest cover loss for two decades (2000 to 2020) in KNFR. The Hansen dataset was reclassified to produce a binary raster map for a MSPA analysis which assigned differentiated density values to forested and non-forested areas within the study area (Soille et al., 2022). This facilitated the analysis of forest fragmentation and habitat change in KNFR (Ye et al., 2020).

To estimate AGB, data from the selected GEDI waveforms with fidelity greater than 0.95 were downloaded, extracted, and processed in RStudio (Kellner et al., 2023). This workflow produced spatial point data frame variables, which were reclassified for further analysis in QGIS to establish positions of coinciding field plots. Predictors were derived by filtering Sentinel-2 imagery to develop a machine learning model using the Random Forest (RF) algorithm (Nieto et al., 2024). The variability and bias were assessed using the relative difference between AGB estimates from the field measurements of plots coinciding with the GEDI path relative to estimates from the integrated GEDI-RF.

1.9.2 Analysis of field measured data and interview data

In both study areas, the collected survey data were converted into a single column numeric format, with questionnaire prompts reclassified into coded categories and responses represented as numerical values (Nguyen et al., 2022b). The dataset for the KFR was converted to a delimited text format and analysed in RStudio. Descriptive statistical analysis was conducted to examine the perceptions of FKF-CFA members on ES derived from KFR (Krause et al., 2020). Further, a Fishers exact test (Jeff et al., 2012), was carried out to evaluate differences in satisfaction levels across work categories among FKF-CFA members as an indicator of direct benefit from KFR.

For KNFR, the four datasets on tangible ES were merged into a single numerical column dataset, while the dataset on intangible ES was analysed separately. Both datasets were reclassified into coded categories, with responses represented as numerical values, and then converted into a delimited text format for analysis in RStudio. Descriptive statistical analysis was conducted using the weighted median per category of forest products collected, to estimate the amount collected in Kg per year. These amounts were subsequently multiplied by market prices to estimate their economic value. Data were tested for normality using the Shapiro-Wilk test to determine the appropriate parametric or non-parametric statistical approach; where parametric assumptions were met, an analysis of variance (ANOVA) was performed to assess differences in the means of forest products collected across socio-economic categories such as work, gender, and utility (Kim, 2014). For the dataset on intangible ES, the WTP was analysed based on the price amounts selected by respondents in the questionnaire (Pedroso et al., 2019). An ANOVA test was also conducted to determine the influence of main drivers such as religion and literacy levels on the cultural ES of sacred shrines.

In both ecosystems, the field-measured plot dataset included plot coordinates, the number of trees measured per plot, tree species within the plots, the DBH of each tree, and the average height of trees in the plot per specie. Each plot was assigned to a unique ID within the dataset. Descriptive statistical analysis in RStudio, based on site-specific and species-specific allometric equations, was used to calculate biomass for each species. The aggregated biomass per plot was subsequently used to

compare AGB estimates derived from GEDI-RF model. To estimate carbon storage for each ecosystem, biomass was converted into carbon equivalents (CO₂) using the Intergovernmental Panel on Climate Change (IPCC) conversion factor (Clarke, 2023). The monetary value of carbon was then calculated in US\$ per metric ton of CO₂ equivalent, based on the pricing outlined in the EU Emissions Trading Scheme (ETS) (EU, 2024).

1.10 Summary of research design and workflow

This doctoral research synthesizes five peer-reviewed publications into a coherent analysis linking ES provision, forest governance architecture, stakeholder perspectives and nature based finance as detailed in Figure 7. The design selects managed (KFR) versus unmanaged (KNFR) ecosystems to compare institutional ecological contexts, to reveal determinants of ES delivery and natural capital value. The sequence from Chapters 2 to 6 builds cumulatively from **Paper 1** which frames regional ES gaps, then **Paper 2** which establishes ecological state in terms of structure forest cover. **Paper 3** and **Paper 4** deliver socio-ecological valuations of the main ES within dimensions of an urban wellbeing versus rural setup. **Paper 5** tests methodological robustness of remote sensing techniques using GEDI to estimate AGB for carbon stock calculation. The chapters are organized as follows:

- Chapter 1: Conceptual framework, research design and thesis structure
- Chapter 2: Reviewing the impact of global and regional contextual factors on the valuation and perception of ES. (**Paper 1**)
- Chapter 3: Assessing the ecological changes in forest structure, canopy cover and their implications on of ES provision. (**Paper 2**)
- Chapter 4: Evaluating the main ES provided by KFR and their role in socio-economic wellbeing of surrounding communities. (**Paper 3**)
- Chapter 5: Evaluating the main ES provided by KNFR and socio-economic factors influencing the forest resource dependency amongst rural communities. (**Paper 4**)
- Chapter 6: To assess performance of remote sensing techniques in estimating AGB to determine carbon stock for managed (KFR) versus unmanaged (KNFR) forest in Kenya. (**Paper 5**)
- Chapter 7: Comparative analysis of research findings
- Chapter 8: Original research contributions
- Chapter 9: Conclusions and future research implications

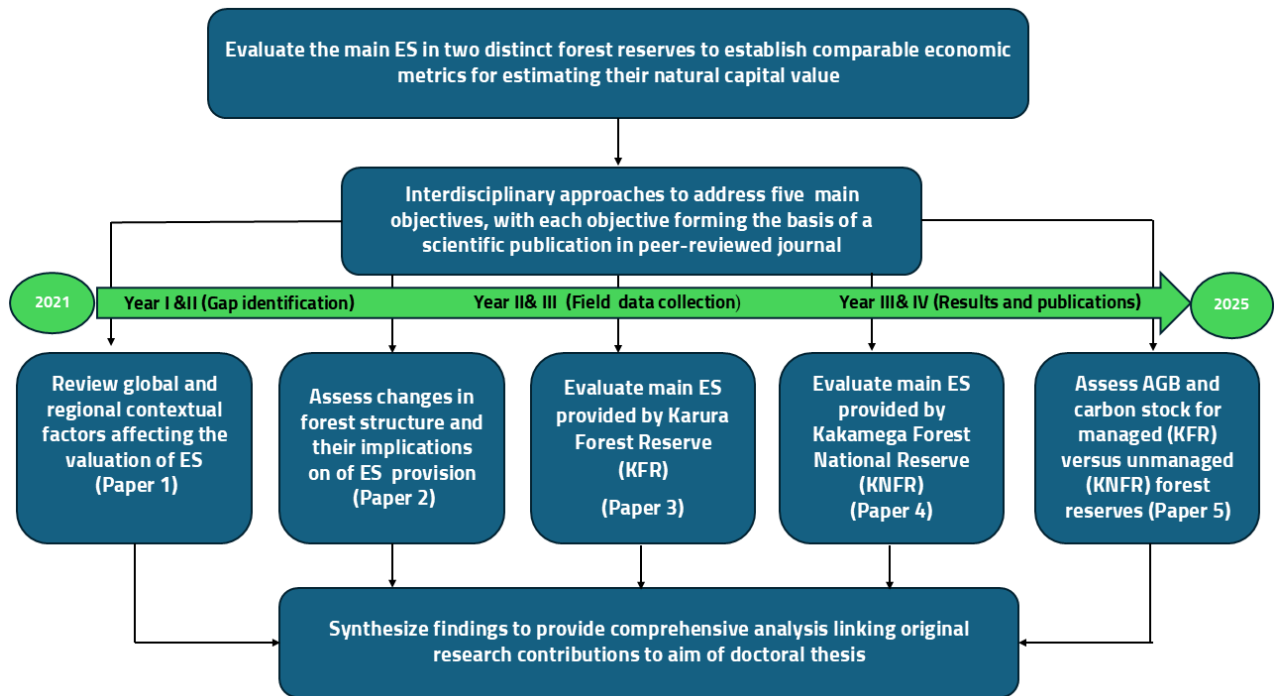


Figure 7. Workflow of doctoral research

1.11 Research limitations

The following limitations are acknowledged in this research: (1) The socio-economic data were collected during a single fieldwork period, which is consistent with standard cross-sectional ES valuation practice, though longitudinal studies would further strengthen the temporal findings of annual economic estimates derived from weighted medians. (2) Provisioning ES values were derived from local market prices at the time of fieldwork, which are subject to seasonal and inflationary variation; however, market price methods remain the most transparent and widely applied approach for provisioning ES valuation. (3) Cultural ES valuations reflect respondent perceptions captured through structured questionnaires rather than longitudinal or ethnographic assessments, which may not fully capture the relational and intergenerational dimensions of spiritual values associated with "*Ikavakava*" shrines; however, the mixed-methods design integrating focus group discussions alongside questionnaires mitigated this constraint. (4) Plot size of 500 m² may underrepresent spatial variability and species composition in the heterogeneous multilayered canopy of KNFR; however, this plot size is consistent with tropical forest inventory approaches for plot level validation of spaceborne lidar instruments correlated with GEDI beam paths. (5) Absence of individual tree height measurements at plot level introduced bias in AGB and carbon stock estimation, especially in plots outside the GEDI path; however, this threshold is consistent with standard tropical forest inventory protocols, and the heteroskedasticity analysis quantified the resultant model variability and bias across both forest ecosystems.

CHAPTER 2: REVIEW OF GLOBAL AND REGIONAL FACTORS AFFECTING THE VALUATION OF ECOSYSTEM SERVICES. (PAPER 1)

Osewe, E. O., Popa, B., Vacik, H., Osewe, I., & Abrudan, I. V. (2024). Review of forest ecosystem services evaluation studies in East Africa. *Frontiers in Ecology and Evolution*, 12.

<https://doi.org/10.3389/fevo.2024.1385351>

This Chapter contextualised ES valuation trends, methodological preferences, and socio-economic influences on ES perception at a regional scale. This contributed to the doctoral research by providing a meta-analysis on comparative metrics of economic valuation for natural capital. It identified the most used ES valuation methods in East Africa: market price methods at 14.9% for provisioning services and travel cost methods at 10.4% for cultural services. It established that remote sensing approaches at 14.7% were preferred for tropical forest ecosystems and household interviews at 11.8% preferred amongst the participatory approaches. This Chapter finds that provisioning services were the most assessed at 55%, followed by regulating services at 30%, supporting services at 8.6%, and cultural services at 6.4%. This demonstrated how communities prioritized ES differently based on economic dependencies and ecological conditions. It also reflected a methodological preference toward economically observable and technically measurable ES. This chapter highlighted the systematic undervaluation of intangible ES in East African valuation literature and recommend stakeholder engagement at local levels, integrating ES valuation into policy frameworks for sustainable resource management.

CHAPTER 3: ECOLOGICAL CHANGES IN FOREST STRUCTURE, CANOPY COVER AND THEIR IMPLICATIONS ON ECOSYSTEM SERVICE PROVISION. (PAPER 2)

Osewe, E. O., Ni ã, M. D., & Abrudan, I. V. (2022). Assessing the Fragmentation, Canopy Loss and Spatial Distribution of Forest Cover in Kakamega National Forest Reserve, Western Kenya. *Forests*, 13(12). <https://doi.org/10.3390/f13122127>

This Chapter addressed fragmentation and canopy loss, linking the ecological changes in forest structure to quantity and quality of ES provided in KNFR. It provided the detailed fragmentation analysis which quantitatively estimated forest cover loss at 826.60 hectares over a 20 year period (2000 to 2020) in KNFR. The findings highlighted how fragmentation and canopy loss altered species interactions, leading to habitat loss with an increase in the dominant layer by 8.5% and a 2.5% decrease in the interior layer. Agricultural expansion was the principal anthropogenic driver of fragmentation, reflecting the unresolved livelihood dependency of forest-adjacent communities illustrated by a change in the core layer of 96% and a 14% increase in the openings class layer. Fragmentation impacted ES such as carbon storage, with an equivalent of 123,494 megagrams of carbon emitted due to forest cover loss. This Chapter recommends community based forest conservation policies, including

community centred resource management, and alternative livelihood programs to avert livelihood dependency of forest-adjacent communities.

CHAPTER 4: EVALUATING THE MAIN ECOSYSTEM SERVICES PROVIDED BY KARURA FOREST RESERVE AND THEIR ROLE IN WELLBEING OF SURROUNDING COMMUNITIES. (PAPER 3)

Osewe, E. O., Popa, B., Kagombe, J. K., Osewe, I., & Abrudan, I. V. (2025). Ecosystem services values for local people in participatory forestry context: The case of Karura urban forest reserve. *Trees, Forests and People*, 100834. <https://doi.org/10.1016/j.tfp.2025.100834>

This Chapter provided insights on the impact of participatory forest management approaches to urban forestry in the global South. It evaluated the ES in KFR vis-à-vis perspectives drawn from FKF-CFA staff and Huruma CBOs. It estimated the economic value of direct and indirect ES from KFR at \$526,027 annually. This included wages for FKF-CFA staff, revenue from visitor entrance fees, and monetary valuation of deadwood collected. The direct ES benefits to FKF-CFA staff had an annual value of US\$ 91,656. This highlighted the importance of participatory forest management and demonstrated how community engagement in employment, deadwood collection, and conservation efforts contribute to both ecological benefits and livelihood improvement. 58% of the total FKF-CFA staff were casual labourers who were mainly from the surrounding local community. Therefore, participatory urban forestry approach provided additional source of household income. KFR proved financially sustainable due to consistent revenue from ecotourism estimated at US\$ 412,414 per annum vis-à-vis salary obligations to the FKF-CFA staff estimated at US\$ 91,656 per annum. These findings demonstrated the fiscal viability of participatory co-management at KFR and provided measurable livelihood benefits for adjacent communities. By linking ES with economic metrics, the management approach for KFR showed a positive impact for livelihood improvement and potential for scalability, making it a suitable model for replication to other urban forest in Kenya.

CHAPTER 5: EVALUATING THE MAIN ECOSYSTEM SERVICES PROVIDED BY KAKAMEGA NATIONAL FOREST RESERVE AND SOCIO-ECONOMIC FACTORS INFLUENCING FOREST DEPENDENCY. (PAPER 4)

Osewe, E. O., Popa, B., Vacik, H., Kagombe, J. K., Osewe, I., & Abrudan, I. V. (2025). Unlocking pathways to livelihood improvement through valuation of ecosystem services in Kakamega Forest, Kenya. *Trees, Forests and People*, 101031. <https://doi.org/10.1016/j.tfp.2025.101031>

This Chapter addressed the socio-economic factors affecting forest resource dependency for rural communities around KNFR in Western Kenya. It evaluated the ES provided by KNFR and the socio-economic factors influencing extent of forest resource dependence by rural communities. It estimated

the total annual valuation for tangible ES at US\$ 283,362, which comprised of vines (*Mondia whitei*) at US\$ 74,786, firewood at US\$ 73,513, fruits (*Persea americana*) at US\$ 72,860, medicinal plants US\$ 39,320, timber US\$ 12,801, and mushrooms (*Auricularia auricula-judae*) at US\$ 8,015. For the intangible ES, 93% of the respondents showed WTP within the price range of US\$ 0.55 to US\$ 2.17 for spiritual ES. This Chapter established that forest fringe communities had a strong preference for tangible ES; firewood at 49% was the most frequently used forest product of the total foraged products. Socio-demographic factors influenced livelihood dependence on forest resources such as gender, occupation, and forest product utility. 66% of the total forest products foraged were by women compared to the 33% by men, while only 9% had formal employment as civil servants compared to the 90% who were either farmers (43%), self-employed (45%) or retired (2%). Moreover, 68% of foraged products were for subsistence while 30% were for commercial use. Consequently, few respondents had additional household income from sale of foraged products and limited access to alternative energy sources to biofuels. PES schemes were proposed to reduce dependence on forest ES by providing diversified income streams through forest based enterprises like beekeeping and value addition for *Mondia whitei* and *Auricularia auricula-judae*. This Chapter gave a holistic and nuanced perspective on the interlinkages between resource use and rural communities. It highlighted the importance of people centred forest management approaches through ES valuation, offering insights on the long term effectiveness of nature based solutions that are locally grounded.

CHAPTER 6: LIMITATIONS OF REMOTE SENSING TECHNIQUES IN ESTIMATING ABOVE GROUND BIOMASS TO DETERMINE CARBON STOCK FOR MANAGED VERSUS UNMANAGED FOREST RESERVES IN KENYA. (PAPER 5)

Osewe, E. O., Daniel Niță, M., Islam Keskes, M., Osewe, I., & Vasile Abrudan, I. (2025). Assessing spatial dynamics of GEDI biomass prediction in managed versus unmanaged tropical forest ecosystems in Kenya. *Annals of Forest Research*, 68(2), 97–116.

<https://doi.org/10.15287/afr.2025.4245>

This Chapter assessed the performance of remote sensing techniques in estimating AGB to determine carbon stock for managed (KFR) versus unmanaged (KNFR). It provided a measure on the limitation of using the GEDI-RF model relative to field-measured models in two plot coinciding scenarios under different forest stand structures (managed versus unmanaged) in Kenya. The integrated GEDI-RF model improved the AGB estimation accuracy by filling gaps within gridded areas where GEDI footprint was absent and provided continuous spatial coverage. The GEDI-RF model had high variability and low precision in KNFR (p-value of 0.005 for heteroskedasticity) due to the dense, old-growth canopy structures, whereas it demonstrated low variability and high precision in KFR (p-value of 0.195 for heteroskedasticity). 55% of plots which coincided with GEDI had less than 10% relative difference in

AGB estimates between models. In both forest ecosystems, the GEDI-RF model overestimated values $\leq 100 \text{ Mg ha}^{-1}$ and underestimated $\geq 200 \text{ Mg ha}^{-1}$. The comparative assessment across managed (KFR) versus unmanaged (KNFR) forest ecosystems, revealed variability in model performance between different stand structures and offered a practical methodology in resource constrained tropical contexts of the Global South. This Chapter puts forward a replicable, cost effective, and scalable remote sensing approach that used GEDI to improve the accuracy of AGB and carbon stock estimation in tropical forests where NFI data are lacking or limited.

CHAPTER 7: COMPARATIVE ANALYSIS OF RESEARCH FINDINGS

This chapter examines the trade-offs and synergies across the main ES categories and domains, makes the connections between the empirical findings from the five studies and the theoretical, policy, and governance perspectives. It therefore addresses what becomes analytically visible when ecological, socio-economic, and geospatial analysis are interpreted in combination.

7.1 Cross cutting synthesis of ecosystem service provision and valuation in Kakamega National Forest Reserve and Karura Forest Reserve

The management regime, socio-economic profile of adjacent communities and spatial configuration of each forest reserve interact to determine both the nature and the magnitude of the main ES delivery across all four main ES categories. Table 6 presents this comparison across KFR and KNFR, disaggregating the differences in provision, valuation, and governance context.

Table 6. Comparative ES provision, valuation and governance context across KFR and KNFR

ES category	Dimension	KFR (urban / managed)	KNFR (rural / unmanaged)
Provisioning	Principal use	Deadwood collection by Huruma CBO members on designated days; access strictly supervised by FKF-CFA and KFS	Firewood, <i>Mondia whitei</i> , medicinal plants (<i>Azadirachta indica</i>), <i>Persea americana</i> , timber, and <i>Auricularia auricula-judae</i> ; access is unsupervised
	Annual value	US\$ 21,957 (from deadwood collection)	US\$ 283,362 (total provisioning portfolio)
	Extraction driver	Middle-income urban households with access to alternative energy; low structural dependence	Subsistence livelihoods (90% of surveyed households); no viable alternative energy sources
Regulating	Carbon stock	AGB density of 177 Mg ha ⁻¹ , with CO ₂ e worth (US\$ 3.2 million)	AGB density of 106 Mg ha ⁻¹ , with CO ₂ e worth (US\$ 123 million)
	AGB model performance	P value of 0.195 for heteroskedasticity, low variability with high precision in managed, urban forest ecosystem	P value of 0.005 for heteroskedasticity, high variability with low precision in unmanaged, old-growth tropical rainforest
Cultural	Primary service	Ecotourism; recreational use by urban visitor base	Spiritual services centred on Tiriki “ <i>Ikavakava</i> ” sacred shrines; ecotourism constrained by fragmentation
	Economic valuation metric	US\$ 412,414 per annum (ecotourism revenue; revealed preference method)	93% of respondents WTP the price range of KES 76 (0.55US\$) to KES 300 (2.17US\$); WTP not significantly related to religious affiliation (ANOVA P= 0.5152)
	Valuation challenge	Market-proximate; readily captured by conventional methods	Value constitutive of cultural identity; partially captured by WTP elicitation but not fully commensurable with monetary metrics
Supporting	Habitat connectivity	Silvicultural treatments maintain habitat for ecotourism-relevant species; biodiversity conservation driven by revenue dependency	826.60 ha lost over 20 years; pollinator and seed-disperser networks disrupted; progressive biodiversity decline
	Governance response	Full perimeter fencing and monitored access points prevent further encroachment	Legal protection without enforcement infrastructure has not halted fragmentation; absent landscape-level connectivity measures

This research revealed differences between the natural capital value and governance architecture in both forest reserves. For instance, KNFR holds a carbon stock approximately 38 times larger than that of KFR, sustains a provisioning economy valued at US\$ 283,362 per annum and encompasses culturally significant sacred shrines with a demonstrated WTP. It lost 826.60 Ha of forest cover over two decades, the equivalent of releasing 123,494 Mg CO₂e. KFR, by comparison holds a stock of 53,724 Mg CO₂e with negligible habitat loss. This asymmetry reflected differences in size, governance architecture, stakeholder influence and local forest community pressures rather than ecological endowment. The FKF-CFA co-management model at KFR, combining perimeter fencing, monitored access points, CBO income linkages and an ecotourism revenue stream of US\$ 412,414 per annum, converted a secondary urban forest into a stable, self-financing conservation unit. Although KNFR holds the larger ecological asset, it lacks a comparable governance architecture to effectively conserve it. This pattern is consistent with adaptive co-management theory (Demie & Tufa, 2025; Laichena, 2021), which holds that governance capacity rather than legal designation determines conservation outcomes. These findings suggest that scaling natural capital accounting and nature-based financing in Kenya's forest sector requires institutional design capable of translating ES value into durable incentive structures for community stewardship.

A second significant difference identified was the extractive value forest-adjacent communities derive from KNFR and the regulating ES that extraction progressively depleted. In KNFR, high AGB supports elevated carbon stocks which are both eroded by extractive pressure from subsistence households. This provisioning and regulating trade-off stems from absent economic alternatives for adjacent communities. 9% of surveyed respondents around KNFR had formal employment as civil servants while a cumulative 90% were either retired at 2%, self-employed at 45% or farmers at 43%. In contrast, the median wage for 34% of FKF-CFA workers in KFR was above KES 29,530 which categorises them as middle-income group for households in Nairobi. Therefore, forest extraction constituted rational response to structural poverty rather than irrational behaviour. Interventions addressing ecological symptoms alone, without addressing underlying livelihood conditions would fail to alter fragmentation trajectory in KNFR. Habitat loss at KFR remained negligible because forest-adjacent communities had a financial stake in the forest's continuity rather than in its depletion. KFR illustrated what becomes possible when a co-management model like FKF-CFA creates an income structure through employment within the conservation system, which replaced the need for extraction. This research contributes an empirical dimension to the limitations of TEV literature acknowledged in context of SSA. The TEV framework (Djenontin et al., 2024; Jagger et al., 2022), captures the extractive dimension what communities derive from forest ecosystems and the ecological cost of that extraction but cannot account for the structural livelihood constraints that drive it.

A third difference this research identified was in the commensurability of cultural ES within standard valuation frameworks. The East African meta-analysis identified spiritual services in only 13% of cultural assessments, compared to 44% for ecotourism revenues. This disparity does not reflect the relative importance of these ES to communities, rather it reflected the structural bias of revealed preference methods toward ES values that provide observable market transactions. In KNFR, Tiriki "*Ikavakava*" shrines constituted core elements of community identity and forest relationships, not

peripheral cultural attributes. 93% of respondents expressed WTP between KES 76 (US\$0.55) and KES 300 (US\$2.17) specifically for shrine access. This WTP showed no significant correlation with religious affiliation which indicated broad cultural attachment that transcended denominational boundaries. The findings highlighted how standard frameworks systematically undervalue such constitutive spiritual values, which have implications for REDD+ co-benefit design and participatory forest management negotiations. This research establishes that spiritual service monetisation require deliberate integration beyond market-based metrics to ensure equitable benefit sharing. This finding exposed a recognised limit of monetary commensuration in socio-ecological systems (Gunton et al., 2022; Pascual et al., 2017) and supports the case for pluralistic valuation approaches.

7.2 Synergies from the Integrated analysis approach in ecosystem services valuation for Kakamega National Forest Reserve and Karura Forest Reserve

Each data layer in this research had a defensible but partial conclusion when examined in isolation, and the three conclusions pointed in different directions. Ecological data from Chapters 3 and 6 inferred a defensible and internally consistent conclusion i.e., KNFR stored more carbon, with a higher AGB density of 177 Mg ha⁻¹ compared to KFR at 106 Mg ha⁻¹, consistent with the higher carbon storage capacity characteristic of old growth forests. However, active carbon sequestration rates in old growth forests are lower than in secondary managed forests such as KFR, where net biomass accumulation remains positive (Heinrich et al., 2021; Robinson et al., 2025). On ecological grounds, KNFR stood out as a more significant conservation site compared to KFR. Socio-economic data from Chapters 4 and 5 established a different institutional picture entirely. KFR generated sustainable livelihood support for adjacent communities through ecotourism revenue, CBO income streams, and employment-driven income diversification. In contrast, communities in KNFR remained structurally dependent on forest extraction without a clear institutional pathway out of that dependence. Geospatial analysis from Chapter 6 produced a third conclusion. KFR was the more technically tractable site compared to KNFR for satellite based carbon accounting due to differences in stand structure between managed secondary forest (KFR) versus unmanaged old growth tropical forest (KNFR), that affect signal penetration when using of remote sensing techniques. Therefore, KFR was more immediately eligible candidate for voluntary carbon market certification.

Each conclusion was coherent on its own terms, but if taken alone as the basis for policy, would have produced a different and partially misleading response. The ecological conclusion could justify REDD+ project development in KNFR on the basis of carbon stock estimates by the GEDI remote sensing techniques. The socio-economic conclusion could underpin PES scheme and PELIS design focused on product substitution whilst leaving unaddressed the governance deficit that makes compliance with any conservation agreement difficult to enforce. The geospatial analysis conclusion could support carbon credit certification in KFR whilst directing nature based financing away from KNFR, the site where conservation need and ecological value are both greater.

What the integration of all three layers revealed was a self-reinforcing feedback loop that no single analytical source could have exposed independently. Rural poverty increased extractive pressure on KNFR, while the extraction drove fragmentation and the fragmentation diminished the carbon stock. The progressive erosion of that stock degraded the ecological asset whose climate value, if credibly

quantified through improved Measurement, Reporting, and Verification (MRV), could initiate the nature-based finance needed to support the livelihood alternatives that would reduce extraction pressure in the first place. Breaking this feedback loop requires simultaneous engagement with governance capacity, income diversification, and technical MRV infrastructure such as GEDI.

The implication of this research extends beyond the specific context of the two study sites. The integrated analysis approach in ES valuation by combining field measured data, socio-economic participatory assessment, and earth observation data within a unified MEA and CICES classification, addressed a methodological gap that the regional meta-analysis in Chapter 2 identified as persistent across East Africa. Supporting services appeared in 6.42% of ES valuation studies across the region, revealed preference methods dominated to the near exclusion of relational and cultural valuation approaches, and earth observation data were routinely analysed without field-based validation in structurally complex forests. Against that backdrop, this integrated approach offered a replicable model that is both more technically rigorous and more socially comprehensive than the methods currently prevalent in ES valuation literature for SSA.

CHAPTER 8: ORIGINAL RESEARCH CONTRIBUTIONS

This research presents four categories of original contributions: methodological, empirical, conceptual, and policy contributions to ES valuation across two different forest reserves. The central finding was that the differences in governance architecture, local stakeholder priorities, forest community perspectives and utility preferences on the main ES evaluated were the main determinants of natural capital value for both KFR and KNFR.

8.1 Methodological contribution

This study puts forward a replicable, cost effective, and scalable remote sensing approach that used GEDI to improve the accuracy of AGB and carbon stock estimation in tropical forests where NFI data are lacking or limited. The comparative assessment across managed (KFR) versus unmanaged (KNFR) forest ecosystems, revealed variability in model performance between different stand structures and offered a practical methodology in resource constrained tropical contexts of the Global South where it is most needed for Article 6 of the Paris Agreement (Bouwer, 2025; Cook et al., 2024), on carbon markets for certification standards in tropical rainforests.

This research conducted a comprehensive meta-analysis (Chapter 2), of ES valuation in East Africa that mapped methodological preferences in ES prioritisation, and socio-economic influences across the region. This analytical framework provided country specific ES valuation trends and tied these patterns to broader socio-economic contexts like poverty and subsistence reliance. The analysis highlighted existing gaps in ES valuation approaches and gave guidance for future studies on integrating ES valuation methods for the East African region.

8.2 Empirical contribution

This study provided an integrated economic valuation with stakeholder perspectives to estimate both direct and indirect ES benefits for KFR, quantifying the natural capital value of forest reserves through primary socio-economic data collected from forest-dependent communities (Chapter 4). The empirical

data demonstrated that urban forest conservation under participatory management generates measurable and sustainable revenue streams, improves household livelihoods, and supports ecological conservation goals. Offering data for a replicable model in urban forest management across other African cities.

This research provided a community centred perspective of rural forest dependence patterns in Western Kenya by providing the economic value of tangible and intangible ES from KNFR and statistically linking this to the main socio-economic drivers like gender, occupation, and energy access (Chapter 5). This nuanced integration of ecological economics with socio-demographic factors gave practical insights for designing targeted PES schemes and sustainable income alternatives aimed at reducing pressure on natural resources.

8.3 Conceptual contribution

This study demonstrated that legal designation does not predict carbon stock stability because both forests share national reserve status yet diverge due to differences stakeholders and local forest community utility preferences. It showed ecological richness does not guarantee nature based finance access because MRV precision depends on silviculture history rather than biomass volume. It also confirmed that monetary valuation cannot fully capture cultural services because Tiriki shrine WTP demonstrated innate community attachment independent of religious affiliation, level of education or socio-demographics. These findings established governance as an endogenous variable rather than contextual background. This study puts forward pluralistic valuation methods and co-management regimes as essential tools for delivering ES benefits equitably to forest-dependent communities.

8.4 Policy contribution

This research positioned ES based market data as a viable instrument for closing the nature-based financing gap in SSA. It addressed the absence of credible, site specific economic baselines that satisfy the due diligence requirements of private capital and multilateral climate funds. By anchoring ES valuation in two contrasting forest reserves, this research furnished comparable pricing data that nature-based finance instruments require to move from policy aspiration to investable propositions. This contribution sits at the intersection of ecological economics and nature finance architecture for the SSA context.

This study reconstituted governance architecture as a diagnostic and measurable policy variable in forest ES assessment. Existing nature based finance readiness frameworks treat governance as a precondition to be assumed or improved. The comparative findings across KFR and KNFR demonstrated that governance capacity operates as the operative determinant of whether a legally designated forest reserves can deliver ES irrespective of its ecological endowment or formal protection status. This reframing has implications for how nature based financing eligibility is assessed, shifting the locus of policy intervention from ecological criteria toward local communities and institutional diagnostics.

CHAPTER 9: CONCLUSIONS AND FUTURE RESEARCH IMPLICATIONS

This doctoral study demonstrated how forest management, socio-economic dynamics, and ecological conditions shaped the utility and perception of ES. By contrasting KFR with KNFR, this research highlighted the differences in ES values for provisioning, regulating, cultural, and support services. KNFR had high levels of provisioning ES dependence, driven by rural livelihood subsistence and limited biofuel alternatives, whereas KFR had controlled access within an urban context which reduced direct extraction while supporting ecotourism and recreational services. Regulating ES, like amount of carbon storage was more in KNFR compared to KFR due to its old growth forest structure despite degradation from fragmentation. The stand structure, management approaches and urban proximity of KFR facilitated consistent delivery of cultural services.

This research improved and put forward practical, replicable and scalable methodologies for ES assessment in tropical forests of the Global South where data limitations persist. It demonstrated the potential of integrated remote sensing approaches in forest carbon monitoring, while emphasizing the socio-economic realities that influence forest use and conservation. It underscored the importance of integrating ecological, economic, and community dimensions in forest policy and PES design. This research contributed toward improving methodologies in natural capital accounting for forest ecosystems in diverse contexts and presents practical frameworks that could improve ES valuation, forest monitoring, and the inclusion of natural capital to nature based financing through PES and PELIS. It recommends common approaches in ES valuation and integration of natural capital accounts into national policy frameworks, to enable mobilisation of nature based finance interventions that recognise both ecological conditions and local community needs. Future studies should explore innovative nature based finance instruments towards climate mitigation and adaptation by leveraging on ES based market data for assessing fiscal risks and mobilisation of private capital in nature based finance strategies.

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