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Emergy synthesis of dry afromontane forest ecosystem services in Tigray, Ethiopia

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Abstract

Dry forests play a significant role in carbon sequestration and storage, biodiversity conservation and soil moisture regulation. The indirect ecosystem services provided by the forests are often undervalued due to the lack of a proper valuation system. Traditionally, the economic valuation of forests has primarily focused on direct use values, which only represent a fraction of the real value of forest ecosystem services. This study aims to assess the values of woody species diversity, carbon stock, and soil moisture using emergy valuation method. In addition, it seeks to evaluate forest sustainability and compare emergy based values among the different forest types in Hugumbirda dry Afromontane Forest in Tigray, Ethiopia. The forest was stratified into Mixed Natural Forest (MNF), Mixed Plantation (MP), *Juniperus procera* Plantation (JP), and *Cupressus lusitanica* Plantation (CP) forest types. Then, data on woody species diversity and carbon stock estimation were collected from 60 randomly selected 20 m * 20 m plots. A total of 300 soil samples were collected from these plots for soil moisture content determination. Woody species richness was calculated using diversity indices, and carbon stock was estimated using an allometric equation specifically developed for dry Afromontane forests in the study region. Sustainability was assessed using emergy indices and ratios. The results showed significant differences ($P < 0.05$) in carbon stock, soil moisture content, and species richness emergy among the forest types. The MP forest type showed a significantly higher ($P < 0.05$) emergy of carbon stock compared to the other forest types. The MNF showed significantly higher ($P < 0.05$) emergy of moisture content than the MP and CP forest types. The emergy of species richness, cumulative emergy, and emdollars of the MNF were significantly higher than the other three forest types ($P < 0.05$). These findings highlight that MNF type demonstrates better tree species richness, indicating strong potential for their sustainability and ecological resilience. Therefore, conserving mixed natural forests is recommended to enhance biodiversity, ecosystem resilience, and sustainable resource value for long-term environmental and community benefits.

Keywords Diversity indices, Emergy method, Emdollars, Emergy sustainability index, Integrated reinforcement, Soil moisture content, Sustainable forest management tree diversity benefit



1 Introduction

Tropical forests harbor over half of the terrestrial biodiversity [51, 68] and sequester about 30% of the earth's terrestrial carbon [39]. Specifically, old-growth tropical forests exhibit low annual soil carbon efflux [71], contributing to their role as significant carbon sinks. These tropical forests also support the livelihoods of millions of people [51], providing essential ecosystem services and resources. However, widespread deforestation and forest degradation trigger environmental shifts that diminish ecosystem services and impact biodiversity from local to global scales [47].

In response to these factors, international conventions and national policies have been initiated to support biodiversity conservation and climate change mitigation [53]. For example, forest restoration has become a globally prioritized initiative to deal with the current global climate change [10], with more than two billion hectares of potential land identified for restoration globally [55]. Ethiopia is one of the countries responding to these global initiatives and planning to restore around 15 million hectares of land [44, 67]. The restoration efforts include afforestation and reforestation activities through the planting of both indigenous and exotic tree species [44]. In Ethiopia, *Cupressus lusitanica* and *Eucalyptus* species are among the most widely planted exotic tree species [78]. Some studies indicated that restoration efforts significantly enhanced carbon storage within forests. This is exemplified by findings from restored exclosure areas, which showed significantly higher carbon stock than adjacent grazing lands [34, 54]. Furthermore, Muluneh and Worku [56] reported that larger forest patches had significantly higher carbon stocks and sequestration potential, emphasizing the role of restoration in climate mitigation. A study result from Singapore also showed higher annual Soil Carbon efflux from secondary forest than old-growth forest [71]. Moreover, restoration of deforested and degraded lands often changes soil moisture content across different forest vegetation covers [40]. These findings highlight the need for a comprehensive evaluation of forest ecosystem services to ensure sustainability.

Different approaches are usually used to appraise forest ecosystem services. However, traditional accounting methods often focus on marketable goods and services while neglecting non-marketable ecosystem services like regulating services (e.g., climate regulation, water purification, flood control, pollination and disease regulation) and cultural services (e.g., spiritual and religious value, recreational and aesthetic appreciation values) provided by natural resources, leading to an incomplete valuation of forest ecosystems [62]. Traditional accounting methods often underestimate the real wealth of nature by excluding the significant contributions of free environmental resources [70]. These contributions, comprising both local renewable and non-renewable resources, provided substantial emergy value in systems such as frankincense production [77]. Likewise, a previous study revealed that environmental sources contributed significantly more emergy to the sustainability of forest ecosystems than economic feedback inputs [85]. This suggests the fact that the real value of nature is underestimated, leading to decisions being made based on incomplete and insufficient information [32]. These limitations highlight the need for an integrated approach that quantifies both the economic and environmental inputs holistically [50]. Such an approach would ensure that decision-making processes are informed by a more comprehensive understanding of ecosystem values.

In this context, emergy analysis emerges as comprehensive and robust approach for evaluating ecosystem goods and services [80]. Emergy refers to the total energy, directly and indirectly, used to produce a product or provide a service, expressed in terms of solar emjoules [65]. This emergy analysis or synthesis provides a thermodynamically grounded accounting system [65]. Unlike conventional economic valuation methods, emergy synthesis incorporates all forms of energy, from environmental inputs to human-driven processes, offering a more complete picture of resource use and value [65]. This approach effectively connects environmental and economic dimensions [36], and has been widely applied across diverse ecosystems, including industrial, agricultural, urban and wetland [4, 5, 28, 35, 86]. More recently, its application has expanded to forest ecosystems to assess the soil carbon efflux in tropical forests [71], evaluate the impacts of vegetation cover changes on resource conservation [38], quantify the global ecosystem structure and productivity [49], examine the sustainability of frankincense of *Boswellia papyrifera* [77], and predict urban ecosystem services [52].

Despite its potential, the application of emergy synthesis for evaluating the real value of forest ecosystem services remains limited. This study applies the concepts of emergy synthesis to evaluate and compare woody species diversity, carbon stock and soil moisture ecosystem services across four forest types in the Hugumbirda dry Afromontane Forest, located in northern Ethiopia. The primary objective of the study was to conduct an emergy evaluation of the four forest types and assess their ecosystem services in relation to carbon stock, soil moisture content, and woody species diversity, and overall ecological sustainability.

2 Methods

2.1 Study area

The study was conducted in the Hugumbirda dry Afromontane Forest, located in southern Tigray, Ethiopia (Fig. 1). It lies at 12°22' to 12°42' N and 39°28' to 39°40' E (Fig. 1). The altitude varies from 1560 to 2688 m above sea level [45]. The Hugumbirda Forest area is primarily characterized by highland and midland agroecologies [2]. Based on the boundary demarcation in 1993, this forest covers an area of 21,654.24 hectares where 97.5% comprises high natural forest, shrubs, bushes, agricultural lands and settlements, while the remaining 2.5% consists of plantation forest [2]. The topography of the study area is generally undulating, with some steep terrain features [7].

The forest area primarily comprises fragmented dry Afromontane forests [7], predominantly associated with the Dry *Weyna Dega* agro-ecological zone [13]. The rainfall pattern is bimodal, with peak precipitation occurring between June and September (Fig. 2). The monthly average minimum and maximum rainfall depths are 13.5 and 285.6 mm, respectively (Fig. 2) with the average annual precipitation ranging from 653 to 819 mm [3]. The monthly average minimum and maximum temperatures are 7.9 and 22.2 °C, respectively (Fig. 2). The dominant soil types in the study area are *Leptosols* and *Regosols*, typically found on slopes and valley bottoms, respectively [7]. Geologically, the area is composed of tertiary basalt, alkali-alluvial basalt, and tuff deposits [7]. The vegetation of the study area is characterized as dry Afromontane vegetation type, with dominant plant communities of *Juniperus. procera* – *Maythenus. senegalensis*, *Pterolobium stellatum* – *Ceitis africana* and *Codia purpurea* – *Opuntia ficus indica*. Exotic species such as *Cupressus lusitanica*, *Eucalyptus camaldulensis*, and *Acacia saligna* were primarily

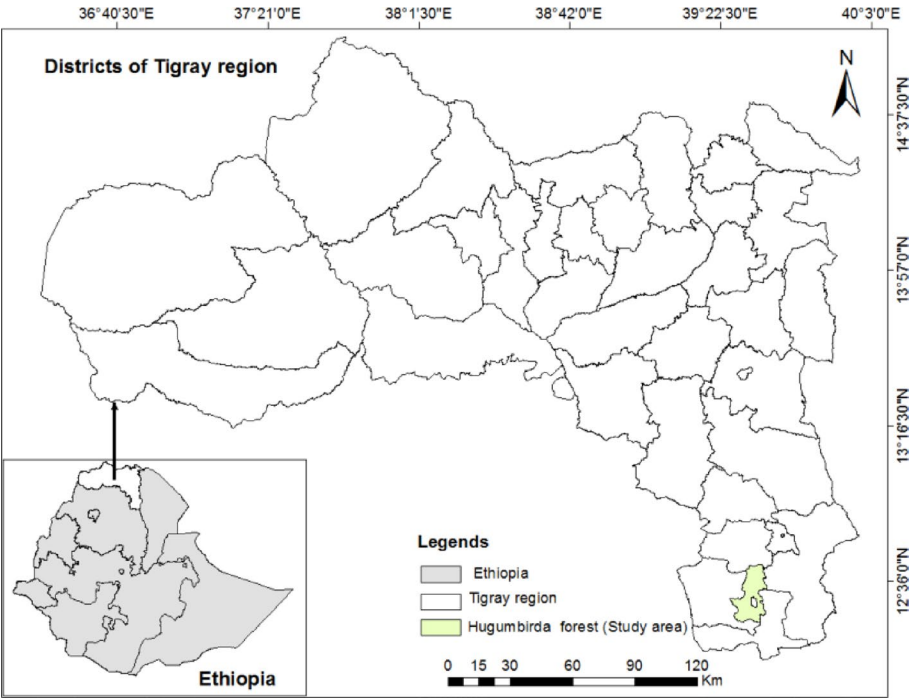


Fig. 1 Map of the study area showing the Hugumbirda forest in the Tigray region, Ethiopia

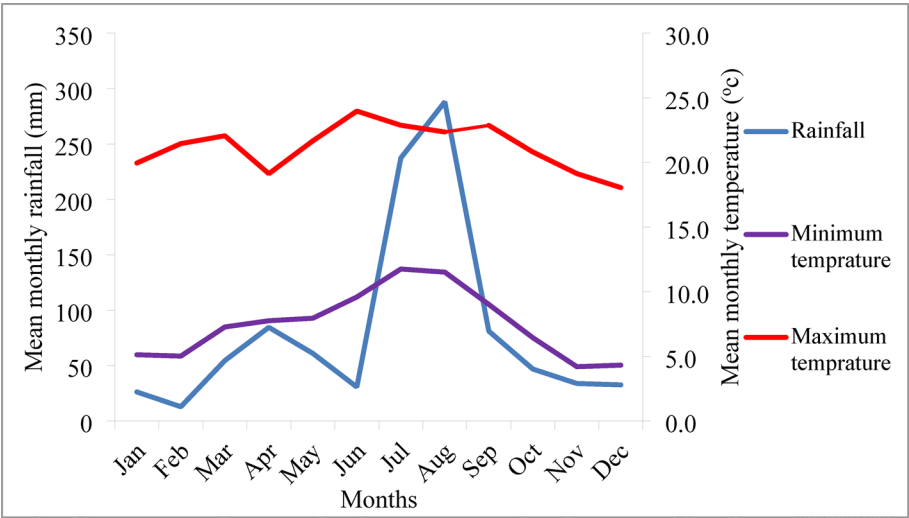


Fig. 2 Mean monthly climatic data of the research area from 1996 to 2016 G.C [61]

introduced into the natural forests [7]. These introductions may result in mixed forest stands, including combinations of *Cupressus lusitanica* with *Juniperus procera* and *Eucalyptus camaldulensis* with *Juniperus procera*. Local communities primarily depend on agriculture for their livelihoods. Mixed farming is common, with crops like teff, wheat, sorghum, barley, and maize, and livestock rearing [1, 75]. Local households near the forest rely heavily on its resources, particularly for fuelwood, construction timber and agricultural tools [46].

2.2 Sampling technique and sample size

The Hugumbirda dry Afromontane Forest was stratified into (1) Mixed Natural Forest (MNF), (2) Mixed Plantation (MP) composed of a mixture of *Eucalyptus* and *Juniperus procera* forest, and (3) monoculture plantations planted with *Juniperus procera* (JP) and *Cupressus lusitanica* (CP) after reconnaissance survey. The areas of the MP, JP, CP, and MNF were 54.1, 147.9, 122.9, and 1511.2 hectares, respectively. Nested plots were established, comprising a 20 by 20 m main plot, 5 by 5 m and 1 by 1 m subplots. The subplots were established at the center of each main plot. The 20 by 20 m plot was used to measure the woody trees/shrubs, while the 5 by 5 m and 1 by 1 m subplots were used to measure the saplings and seedlings, respectively. A total of 60 plots were used to estimate the woody species diversity, tree biomass, and soil moisture contents, and compute their emergy values. The number of plots in each forest stratum was determined using the stratified sampling approach described by Assefa et al. [8]. The sample size was calculated using the following general formula: $n = \frac{(\sum N_h \times S_h)^2}{\frac{N^2 \times E^2}{t^2} + \sum N_h \times S_h^2}$, where n is the required number of sample plots, N_h is population size in stratum h , S_h is standard deviation in stratum h , N is total population size (sum of all N_h), E is desired margin of error (10%) and t is t -value from the t -distribution based on desired confidence level. Six preliminary sampling plots were randomly established for JP, CP, and MP forests, and ten plots for the MNF. In the preliminary sampling plots, the diameter at breast height (DBH) and height were recorded for all trees. From this initial dataset, the average carbon stock and its standard deviation were calculated for each forest type. The population size for each forest stratum (N_h) was estimated by dividing the total area of the stratum by the plot area (0.04 ha). Accordingly, based on the degree of homogeneity within each forest type in terms of carbon stock, 10 sample plots were allocated to each plantation type, while 30 plots were allocated to the MNF. Sample plots were laid out at 100 m intervals between plots and transects in the plantation forests, while 300 m intervals (between plots and between transects) were used in the MNF. The sample plots were randomly distributed in both MNF and plantation forests.

To collect data on purchased inputs, including labour, materials (goods), and services, and the average growth period (maturity) of each tree species, interviews were conducted with key informants comprising forestry experts ($n = 2$), forest guards ($n = 5$), and local elders ($n = 36$). These informants were purposively selected to ensure contextual relevance, with forest guards and local elders identified in collaboration with local leaders, forestry professionals, and extension experts familiar with the study area.

2.3 Data collections

Both primary and secondary data were used in this study. Primary data were collected from the four forest types to evaluate the emergy of carbon storage, soil moisture storage, and tree diversity through field measurements. The Diameter at Breast Height (DBH) and Height (Ht) of each tree (i.e., $DBH \geq 2.5$ cm and $Ht \geq 2$ m) were recorded within each plot to estimate the tree biomass, which was used to calculate the emergy associated with carbon stock for each forest type. To calculate the emergy of the soil moisture contents (SM), soil samples were collected from five subplots, one at the center and four at the corners of each sample plot using calibrated soil Auger. Soil samples were collected to a depth of 30 cm in each plot. A composite soil sample was obtained by

mixing soils from three layers (i.e., 0–10, 10–20 and 20–30 cm) for soil moisture analysis. In total, 300 soil samples were collected from 60 plots, with each sample weighing approximately 1.5 kg. To evaluate the emergy value of woody species richness, all tree and shrub species were identified and counted from the main plots, while saplings and seedlings of the woody plant species were recorded in 5 by 5 m and 1 by 1 m subplots, respectively.

Data on labour, purchased input materials (equipment) and services were primarily collected through interviews with forestry experts and local elders. All annual imported input data, including goods, labour, and services, used in the forest production system were recorded on a per hectare basis. All materials, equipment (e.g., tools), and vehicles (such as field cars, motorcycles) utilized in the forest production system were converted into annual flows (depreciation costs) based on their expected lifespans. The price of fuel and oil consumption data (ETB Litre⁻¹) were collected from the fuel station nearest to the forest area. Likewise, data on insolation (Kwh m⁻² day⁻¹), surface wind speed (m sec⁻¹), average heat flow (j m⁻²), albedo, and average elevation (m) were obtained from the NASA database [58]. The emergy per unit input (specific emergy for soil loss in Ethiopia, expressed in sej g⁻¹) and the emergy transformity values for labour, goods, and services were sourced from the National Environmental Accounting Database (NEAD), University of Florida, USA [64, 65]. Additional data were also sourced from research outputs, including erosion rate (g m⁻² yr⁻¹) [63], soil organic matter content (%) [66], the energy content of soil organic matter (kcal g⁻¹) [22], Gibbs free energy (j kg⁻¹) [65] and average runoff (m yr⁻¹) [76]. The area of each forest type (m²) was delineated through visual interpretation by analyzing satellite imagery of the Hugumbirda Forest area based on colour, texture, and spatial patterns. GIS expert manually traced boundaries in GIS software, guided by ecological knowledge, terrain data, and field validation. Annual rainfall (mm yr⁻¹) was obtained from climate data published by the National Meteorological Agency [61].

2.4 Emergy calculations

2.4.1 Emergy of carbon stock

Specific wood densities (g cm⁻³) for 40 woody plant species were obtained from secondary data sources, including the Global Wood Density Database, to estimate above-ground biomass (AGB). For tree species lacking density data in these sources, a default value of 0.6 g cm⁻³ was applied following the suggestion by Brown et al. [21]. The AGB was estimated using a general allometric equation proposed by Chave et al. [27] (Table S2, Eq. 1). Following Santantonio et al. [74], below-ground biomass (BGB) was approximated as 20% of the total AGB, using a conversion factor of 0.20 (Table S2, Eq. 3). Additionally, a conversion factor of 0.50 was used to estimate the carbon fractions of both AGB and BGB, represented as above-ground carbon (AGC) and below-ground carbon (BGC), respectively based on the recommendation by Brown et al. [21]. The carbon stock of trees and shrubs (kg per plot) was determined by summing the total carbon content (AGC + BGC) of all tree/shrub individuals within each plot. These values were then converted into grams per hectare (g ha⁻¹) for standardized reporting. The average growth period (i.e., the expected time to maturity) of each woody plant species was estimated through interviews with local people (elders), and forest guards, enabling calculation of annual total carbon accumulation (g ha⁻¹ yr⁻¹). Subsequently, the emergy of

carbon stock ($\text{sej ha}^{-1} \text{yr}^{-1}$) was estimated following the method of Campbell and Tilley [24] (Table S2, Eq. 4).

2.4.2 Emergy of soil moisture (storage)

The emergy of soil moisture (SM) was estimated using data obtained from laboratory analysis of collected soil samples. Soil moisture content was quantified via the gravimetric method following the procedures outlined by Johnson [42]. Wet soil samples were weighed using a digital balance and then oven-dried at 105 °C for 24 h. Moisture content was calculated as the difference between the average weight of the wet and dry soil samples. The average moisture content was expressed in both g cm^{-3} and g per plot. These values were subsequently converted into grams per hectare per year ($\text{g ha}^{-1} \text{yr}^{-1}$). Finally, the emergy of soil moisture ($\text{sej ha}^{-1} \text{yr}^{-1}$) was computed using allometric equations developed by Yan et al. [83] and Odum [65] (Table S2, Eq. 7).

2.4.3 Emergy of species richness

The emergy value associated with woody plant species diversity protection was assessed based on species richness. Tree and shrub species identified across sampling plots were analyzed using the species richness index, computed with PAST Software. The emergy of woody plant species richness was then computed using the equation proposed by Bardi and Brown [9] (Table S2, Eq. 8).

2.5 Data analysis and statistical tests

Emergy synthesis methods and descriptive statistics were used to analyze the collected data.

2.5.1 Emergy synthesis

Emergy values of selected ecosystem services (ES) across different forest types were synthesized following the Odum [64] and [65] procedures (Fig. 3). First, a detailed energy system diagram was developed to represent the selected ecosystem of each forest type (Fig. 4). Second, a detailed diagram of the ecosystem services was subsequently transformed into more general and aggregated tables (Table S4). Third, the pathways represented in the aggregated diagram were described, quantified using appropriate metrics, and converted into emergy values through the application of transformity units [9, 59, 64, 65]. In the fourth step, emdollars were computed by dividing the emergy values by the Ethiopia's emergy-to-GDP ratio (i.e., $7.20\text{E}+12$), as recommended by Coscieme et

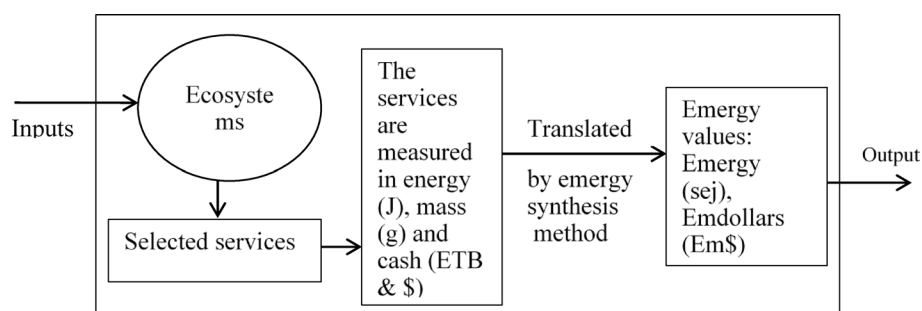


Fig. 3 Schematic diagram illustrating emergy synthesis evaluation of selected ecosystem services, adapted from Pulselli et al. [69]

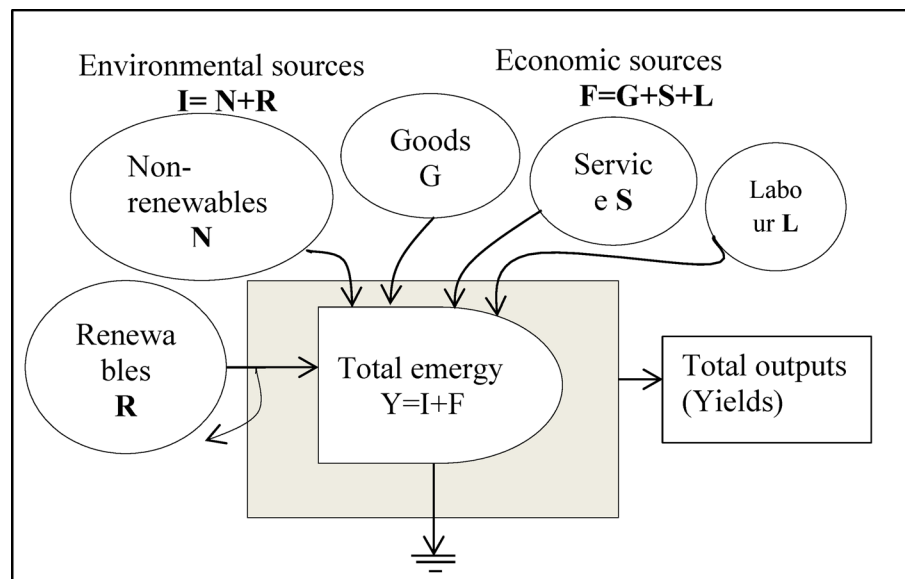


Fig. 4 Aggregated energy diagram illustrating the yield of selected ecosystem services of the Hugumbirda Dry Afromontane Forest

al. [30]. Subsequently, the annual energy yield for each selected ecosystem service ($\text{sej ha}^{-1} \text{yr}^{-1}$) was summarized in tables on a per hectare basis (Table S4). In the fifth step, energy-based sustainability indices and ratios were calculated using the formulae provided by Cohen et al. [29], and presented in Table S4.

2.5.2 Left–right energy language system: diagramming

Inputs were broadly categorized into environmental sources (I), including local renewables (R) and non-renewables (N), and economic sources (F) which include purchased non-renewables such as goods (G), Labour (L) and services (S) (Fig. 4). The system diagram has system boundaries and energy sources that drive the ecosystem processes (Fig. 4). The major environmental renewable sources consist of solar radiation, wind kinetic energy, rain-chemical, rain-geo-potential and earth cycle energies. In contrast, non-renewable inputs are represented by locally sourced materials such as topsoil and soil carbon losses, reflecting depletion of soil storage. The economic sources are purchased non-renewables, including purchased energies (fuels and oils), labour (L), goods (G), and services (S). Labour (mostly untrained) represents human power used as an input in the forest production system. It was mainly used as an input to perform different activities in the forest production process such as micro basin and infrastructure (roads and housing) construction, seedling raising, pitting, seedling planting, beating up, weeding and cleaning, and fire break construction. Goods refer to materials utilized in forest production systems, including traditional equipment such as digging implements, pruners/secateurs, scissors, spades, shovels, rakes, and wheelbarrows, as well as transport vehicles, including motorcycles and field cars. Moreover, services are categorized as non-renewable inputs from the economic system. These include vehicle repair and maintenance, as well as forest guarding services (Table S4 and Fig. 4).

2.5.3 Emergy table

Odum [65] described the emergy analysis table as structured template designed to compute the emergy of both energy storage and mass flows. These resources are first converted into energy equivalents, then further transformed into emergy units and emdollars following the Brown [15] procedures. The table comprises six columns [22], with each column defined based on Odum's framework [65] and presented in Table S1.

2.5.4 Transformity

Transformity refers to the process of transforming a specific quantity of energy or mass into emergy [88]. In this study, the energy inputs associated with the various forest production systems were calculated using the emergy databases developed by NEAD [59], Odum [64] and [65].

2.5.5 Flow summary

Raw data on mass flows and storage resources were converted into energy equivalents and subsequently transformed into emergy units (sej) and emdollars (\$), as presented in Table S4 and Fig. 3. These quantified values are essential for constructing emergy income statements, which are useful for comparative assessments, and providing information for policy decision-makers [15]. An emergy income statement typically presents annual mass flows and/or associated dollar values. To facilitate emergy accounting, the energy content of mass flow and storage must first be converted into emergy units. The dollar flows of the imported goods and services are transformed into emergy by multiplying their monetary value by the appropriate emergy-to-dollar ratio for the specified year and item [65]. Finally, the emergy accounting system integrates the data from the emergy income statement with summary variables to calculate the emergy sustainability indices and ratios [18, 64, 65]. In evaluating the forest production system, we considered the emergy flows from renewable (R) and non-renewable resources within the system (N) and imported resources from outside the system (F) (see Fig. 4 and Table S4). The emergy sustainability index (ESI) and related ratios (Table S3), which link environmental and economic resource flows, were derived from the data compiled in the emergy synthesis table (see Table S4A-D) following the methods of Brown et al. [19] and Odum [65]. These indices and ratios were computed using key emergy variables: renewable emergy (R), non-renewable emergy (N), imported emergy (F), and the average emergy yield of a system (Y) [23, 29]. Forest-type-specific ESI values and associated ratios were calculated using the specified system variables, with results presented in Table S4E.

Some basic emergy indices and ratios were used as performance indicators of long-term ecological sustainability, economic efficiency and system processes [17]. These include:

$$\% \text{Renewability } (\%Ren) = \frac{R}{R + N + F} * 100$$

It is the ratio of renewable emergy to total emergy used within a system. Processes characterized by a high proportion or percentage of renewable emergy are considered more sustainable over the long run [18, 65].

$$\text{Emergy Yield Ratio (EYR)} = \frac{Y}{F} = \frac{R + N + F}{F}$$

It is the ratio of the emergy outcome divided by the emergy input from the outside economy. A high EYR reflects a system's ability to generate substantial emergy outputs relative to what it consumes from external sources.

$$\text{Environmental Loading Ratio (ELR)} = \frac{F + N}{R}$$

It is the ratio of non-renewable and imported emergy use to renewable emergy use. A lower ELR signifies reduced pressure on the environment or lower ecological loading, thereby indicating a more sustainable and resilient system.

$$\text{Emergy Sustainability Index (ESI)} = \frac{\text{EYR}}{\text{ELR}}$$

It is a ratio of the emergy yield ratio to the environmental loading ratio. A higher ESI value indicates greater sustainability within a production system, reflecting both efficient resource use and reduced environmental pressure

$$\text{Emergy Investment Ratio (EIR)} = \frac{F}{R + N}$$

This index represents the ratio of the purchased emergy, originating from economic inputs, to the total emergy derived from both renewable and non-renewable environmental sources. It shows the relationship between the emergy of economic inputs and that of environmental inputs (R and N).

2.6 Statistical analysis

Data analysis was performed using SPSS software (version 20) and PAST software. A one-way Analysis of Variance (ANOVA) was applied to examine mean differences in annual emergy, cumulative emergy and corresponding emdollars of the three selected ecosystem services within four distinct forest types. Tukey's post-hoc test was employed following one-way ANOVA to perform multiple comparisons and identify statistically significant differences among group means. To meet the assumptions of normality and homogeneity of variance, emergy values for carbon stock and species richness were transformed using a double squared root transformation, while cumulative emergy and emdollar values for each selected ecosystem service underwent logarithmic transformation before statistical analysis.

3 Results

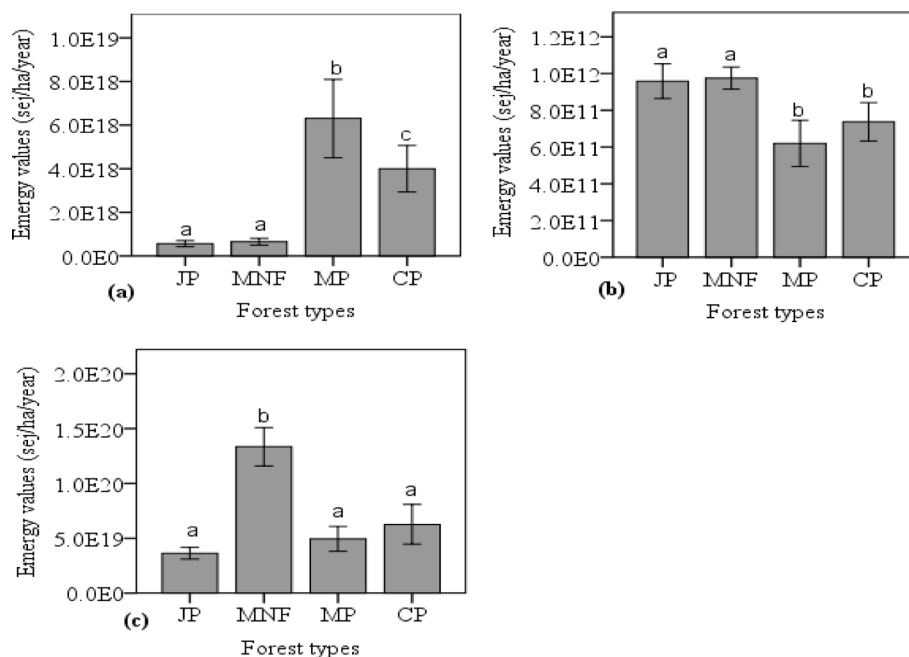
3.1 Emergy of carbon stock, soil moisture and woody species richness

The diameter and height of 2946 trees and shrubs were measured across all sample plots to compute the emergy associated with carbon stock. The highest emergy value for carbon stock per plot was recorded in the Mixed Plantation (MP), composed of a mixture of *Eucalyptus* and *Juniperus procera* species ($1.19\text{E}+19 \text{ sej ha}^{-1} \text{ yr}^{-1}$). Conversely, the lowest value was observed in the Mixed Natural Forest (MNF), with $6.49\text{E}+16 \text{ sej ha}^{-1} \text{ yr}^{-1}$ (Table 1a). Results from the one-way ANOVA revealed statistically significant differences in carbon stock emergy values among the four forest types (Fig. 5a). The MP exhibited significantly higher emergy value for carbon stock ($p=0.0001$) compared to *Juniperus procera* (JP), MNF, and *Cupressus lusitanica* (CP) forests (Fig. 5a).

Table 1 Annual emergy values for carbon stock (a) and soil moisture contents (b) across different forest types in the Hugumbirda Dry Afromontane Forest, Southern Tigray, Ethiopia

Forest types (strata)	Emergy values (sej ha ⁻¹ yr ⁻¹)		
	Minimum	Maximum	Mean ± SD
<i>a</i>			
<i>J. procera</i> plantation (JP)	3.00E+17	8.53E+17	5.63E+17 ± 1.93E+17
Mixed natural forest (MNF)	6.49E+16	1.67E+18	6.52E+17 ± 4.08E+17
Mixed plantation (MP)	3.17E+18	1.19E+19	6.30E+18 ± 2.51E+18
<i>C. lusitana</i> plantation (CP)	1.96E+18	6.68E+18	4.00E+18 ± 1.49E+18
<i>b</i>			
<i>J. procera</i> plantation (JP)	7.24E+11	1.14E+12	9.59E+11 ± 1.31E+11
Mixed natural forest (MNF)	6.24E+11	1.42E+12	9.75E+11 ± 1.61E+11
Mixed plantation (MP)	2.72E+11	7.96E+11	6.20E+11 ± 1.75E+11
<i>C. lusitana</i> plantation (CP)	5.00E+11	1.01E+12	7.37E+11 ± 1.47E+11

Note that E stands for the exponential symbol ($\times 10^n$)

**Fig. 5** Emergy values of carbon stock (a), soil moisture content (b) and species richness (c) across different forest types in the Hugumbirda dry Afromontane Forest. Bars marked with different letters are statistically significant at $p < 0.05$, as determined by one-way ANOVA. Note that E stands for the exponential symbol ($\times 10^n$)

However, the emergy of carbon stock did not differ significantly between MNF and JP forests (Fig. 5a). In contrast, the carbon stock emergy of the MP was markedly higher by approximately 11 and 10 times than that of JP and MNF, respectively. Additionally, the emergy value of carbon stock in the MP was approximately twice that of the CP forest (Table 1a).

In contrast to the carbon stock emergy results, the highest emergy for soil moisture content per plot was observed in the MNF, at $1.42\text{E}+12 \text{ sej ha}^{-1} \text{ yr}^{-1}$. Conversely, the lowest value was recorded in the MP forest, with $2.72\text{E}+11 \text{ sej ha}^{-1} \text{ yr}^{-1}$ (Table 1b). Results from one-way ANOVA showed that the emergy values of soil moisture in the MNF and JP forests were significantly higher ($P < 0.05$) than those in the MP and CP forests (Fig. 5b).

Table 2 Emergy values for species richness across different forest types in the Hugumbirda Dry Afromontane Forests, Southern Tigray, Ethiopia

Forest types	Emergy values (sej ha ⁻¹ yr ⁻¹)		
	Minimum	Maximum	Mean ± SD
<i>J. procera</i> plantation (JP)	2.20E + 19	4.40E + 19	3.63E + 19 ± 7.42E + 18
Mixed natural forest (MNF)	5.50E + 19	2.53E + 20	1.33E + 20 ± 4.67E + 19
Mixed plantation (MP)	2.20E + 19	7.70E + 19	4.95E + 19 ± 1.58E + 19
<i>C. lusitanica</i> plantation (CP)	1.10E + 19	9.90E + 19	6.27E + 19 ± 2.54E + 19

Note that E stands for the exponential symbol (× 10ⁿ)

Table 3 Cumulative emergy (sej ha⁻¹ yr⁻¹) (a) and emdollars (sej/\$) (b) values for the selected ecosystem services in the Hugumbirda Dry Afromontane Forests, Southern Tigray, Ethiopia

Forest types	Minimum	Maximum	Mean ± SD
<i>a</i>			
<i>J. procera</i> plantation (JP)	2.28E + 19	4.49E + 19	3.69E + 19 ± 7.39E + 18
Mixed natural forest (MNF)	5.52E + 19	2.53E + 20	1.34E + 20 ± 4.68E + 19
Mixed plantantion (MP)	3.39E + 19	8.16E + 19	5.58E + 19 ± 1.37E + 19
<i>C. lusitanica</i> plantation (CP)	1.69E + 19	1.03E + 20	6.67E + 19 ± 2.45E + 19
<i>b</i>			
<i>J. procera</i> plantation (JP)	3.16E + 6	6.23E + 6	5.12E + 6 ± 1.03E + 6
Mixed natural forest (MNF)	7.66E + 6	3.53E + 7	1.86E + 7 ± 6.50E + 6
Mixed plantation (MP)	4.70E + 6	1.13E + 7	7.75E + 6 ± 1.91E + 6
<i>C. lusitanica</i> plantation (CP)	2.35E + 6	1.43E + 7	9.26E + 6 ± 3.40E + 6

Note that E stands for the exponential symbol (× 10ⁿ)

The highest emergy value for species richness was recorded in the MNF, reaching 2.53E + 20 sej ha⁻¹yr⁻¹, while the lowest value was recorded in the CP forest, at 1.10E + 19 sej ha⁻¹yr⁻¹ (Table 2). The mean emergy value for species richness in MNF was approximately 3.7, 2.7, and 2 times greater than those of JP, MP, and CP forests, respectively (Table 2). Results from the one-way ANOVA confirmed that MNF had significantly higher species richness emergy value ($p < 0.05$) compared to MP, CP, and JP forest types (Fig. 5c).

3.2 Cumulative emergy and emdollar values

The cumulative emergy value of the three selected forest ecosystem services per plot was highest in the MNF, and lowest in the JP forest (Table 3a). One-way ANOVA results revealed that cumulative emergy in the MNF was significantly higher ($p < 0.05$) than in the other three forest types (Fig. 5a). However, the cumulative emergy values were not statistically significantly different between the MP and CP forests (Fig. 5a). Similarly, no significant differences were observed in the cumulative emergy associated with carbon stock, soil moisture, and species richness between the MP and CP forest types (Fig. 6a). The emdollar value was significantly higher ($p < 0.05$) in the MNF, reaching 18.6 million US dollars and lower in the JP, at 5.12 million US dollars (Table 3b and Fig. 6b). However, emdollar values did not differ significantly between MP and CP forest ecosystem services (Fig. 6b).

3.3 Emergy sustainability evaluation of the four forest types

The result of renewable emergy (ratio) indicated that the rate of renewable energy involved in the process was 100%. This result revealed that all forest types exhibited a 100% renewable energy contribution, indicating that their ecological processes are fully

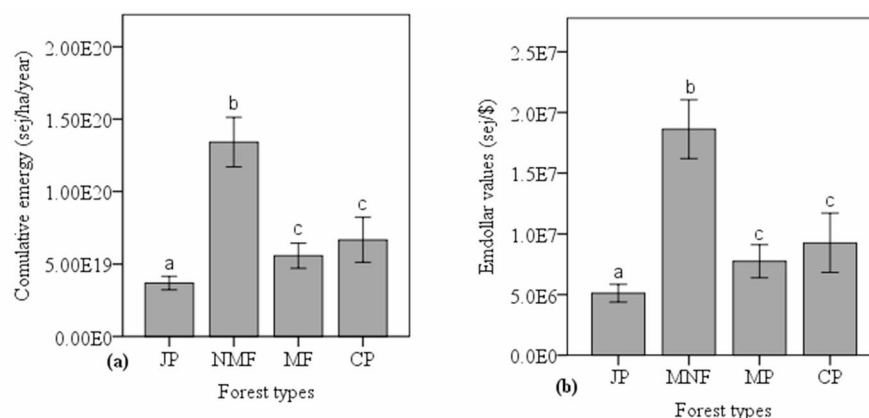


Fig. 6 Cumulative energy (a) and emdollar (b) values for the selected ecosystem services for the different forest types in the Hugumbirda Dry Afromontane Forest. Bars marked with different letters are statistically significant at $p < 0.05$, as determined by one-way ANOVA. Note that E stands for the exponential symbol ($\times 10^n$)

Table 4 Emergy sustainability indices and ratio results for mixed natural forest (MNF), mixed plantation (MP), *J. procera* Plantation (JP), and *C. lusitanica* Plantation (CP) forest types, adopted from Brown [18], Odum [64] and [65]

Emergy index and ratios	Different forest strata			
	MNF	MP	JP	CP
%Renew = $R/(R + N + F)$	1.00E + 00	1.00E + 00	1.00E + 00	1.00E + 00
Non-renewable to renewable ratio = $(N + F)/R$	2.88E-06	4.02E-06	4.02E-06	4.02E-06
Emergy yield ratio (EYR) = Y/F	2.49E + 05	3.91E + 04	2.60E + 04	4.69E + 04
Emergy investment ratio (EIR) = $F/(R + N)$	7.00E-07	1.84E-06	1.84E-06	1.84E-06
Environmental loading ratio (ELR) = $(F + N)/R$	2.88E-06	4.02E-06	4.02E-06	4.02E-06
Emergy sustainability index = EYR/ELR	6.18E + 10	9.73E + 9	6.46E + 09	1.17E + 10

Note that E stands for the exponential symbol ($\times 10^n$)

supported by renewable energy flows (e.g., sunlight, and rainfall etc.), rather than non-renewable or purchased energy inputs. This finding indicated that the forest management strategies implemented across these forest types are environmentally friendly and restorative approaches (Table 4). Furthermore, the Emergy Yield Ratio (EYR) was highest in the MNF, followed by CP, MP, and JP forest types, respectively (Table 4). Relatively lower EYR values in JP and MP suggest reduced efficiency in converting local renewable inputs into ecosystem service outputs per unit of external investment, highlighting their limited capacity to concentrate emergy from the surrounding environment. Likewise, the Environmental Loading Ratio (ELR) of the MNF was approximately 1.4 times lower than that of the plantation forests (MP, JP, and CP) (Table 4). This lower ELR value suggests that MNF imposes less environmental stress due to its reliance on renewable rather than non-renewable inputs. The Emergy Investment Ratio (EIR) of the MNF was nearly threefold lower compared to MP, JP, and CP forests, indicating greater efficiency in harnessing local resources with minimal external investment (Table 4). The Emergy Sustainability Index (ESI) value of the MNF, at $6.18E + 10$, was approximately 10, 6, and 5 times greater than those of the JP, MP, and CP forest types, respectively. This finding demonstrates that MNF exhibits greater long-term sustainability than both mixed and mono plantations, highlighting the ecological balance and resilience of native species assemblages (Table 4). In contrast, MP and CP plantations often reduce soil moisture and species richness (Figs. 5b and c), resulting in lower ESI values ($9.73E + 09$ and $1.17E + 10$,

respectively). Likewise, the JP plantation recorded a low ESI value ($6.46\text{E} + 09$) (Table 4), attributed to diminished species richness (Fig. 5c). Despite these negative effects on soil moisture and above-ground species richness, MP and CP plantations significantly enhanced carbon storage (Fig. 5a).

4 Discussions

4.1 Emergy of carbon stock

The emergy value of carbon stock was significantly higher in the MP forest, while the lowest emergy value was found in the MNF. This finding is partially consistent with the results of Ence [33], who reported that eucalyptus captures large amounts of CO_2 , fixes carbon, and releases oxygen. The present finding agrees with a study result reported by Zerga [84], who mentioned that farmers have to intercrop indigenous trees like *J. procera* within *Eucalyptus* woodlots since such trees can compete and survive well. Similarly, although water-related service values declined due to trade-offs, vegetation-related ecosystem services substantially increased, following the conversion of desert shrublands into plantation systems in the arid regions of northwestern China [82]. Also, Xu et al. [82] reported that the emergy for carbon storage increased by nearly 13-fold in plantation systems compared to desert shrublands.

4.2 Emergy of soil moisture

The emergy values for the soil moisture content were significantly higher in the MNF and JP as compared to the MP (*Eucalyptus* and *J. procera*) and CP forests. This variation may be attributed to species-specific influences on forest soils [14] and structural differences in canopy architecture among the tree species [25]. These findings suggest that the CP and MP forests are characterized by relatively lower canopy cover, while the MNF and JP forests exhibit higher canopy cover, which likely contributes to enhanced soil moisture retention. Previous studies have also shown that *Eucalyptus* plantations exhibit high water-use competition [26] and exert substantial influence on the water resources of catchment areas [43]. Additionally, eucalyptus plantations have been shown to suppress herbaceous species and growth [12, 31], which are vital components for soil carbon accumulation, erosion control, and moisture retention. Zhang and Fu [87] also demonstrated allelopathic inhibition of seed germination and seedling growth. Supporting this, a study conducted in Ethiopia by Chanie et al. [26] reported reduced soil moisture and biodiversity in areas adjacent to *Eucalyptus* stands.

4.3 Emergy of species richness

The mean emergy value for species richness was significantly higher in the MNF than in JP, MP, and CP forests. However, no statistically significant difference was observed among the plantation forests (i.e., MP, CP, and JP). This result was consistent with the findings of Romane et al. [73], who reported no statistically significant difference in the plant species richness between plantations composed of native and introduced trees. This result indicates that the emergy value associated with tree species richness was not generally dependent on tree species. These results imply that if forest managers want to increase tree species richness, they should prioritize planting diverse mixtures of species, rather than concentrating on a limited number of similar taxa within the same stand at the same time. For example, Bayle [11] reported several adverse effects

of eucalyptus plantations, including soil nutrient depletion, reduced crop yields, and the release of allelochemicals that suppress the growth of neighbouring crops, thereby diminishing agricultural productivity and soil health. Similarly, Amsalu [6] highlighted the negative influence of eucalyptus plantations on the physico-chemical properties of soil. Moreover, the cumulative emergy of the MNF was significantly higher than that of the three plantation forests, supporting the recommendation by Rad et al. [72] that forest managers should prioritize the natural composition of forest communities.

4.4 Cumulative emergy and emdollars

The cumulative emergy of MNF was significantly higher than that of the plantation forests. Likewise, the corresponding emdollar value, reached approximately 18.6 million US dollars, was significantly higher than the plantation forest types. This elevated value primarily reflects the high emergy contribution from tree species richness inherent to the natural forest. Supporting this finding, natural forests exhibit higher native species abundance and greater understory species richness compared to plantation forests [60] and relatively provide enhanced ecosystem service benefits [41]. The findings of this study indicate that the values derived through emergy synthesis were comparable to those obtained through economic analysis, particularly for services and natural storage elements that exist outside economic markets like clean water and biodiversity [22]. However, the substantial value emphasizes an urgent need to safeguard the integrity of these natural systems, ensuring that future generations can continue to benefit from the vital environmental services and biodiversity they provide [22].

4.5 Emergy sustainability evaluations

The result of renewable emergy (%) was approximately 100%, signifying a complete reliance on renewable energy sources within the production system. This large proportion of renewable resources entering the production system indicates its long-term sustainability, as ecosystems that depend minimally on non-renewable or external resources are better positioned to maintain ecological balance and resilience over time [48]. According to the World Energy Council [81], Africa's renewable energy share reached approximately 18.9% in 2015. In comparison, the renewable emergy percentage of the present study was above 18.9% across all forest types, indicating that all the restoration strategies are environmentally friendly and contribute positively to sustainable resource use. In contrast to our finding, a low share of renewable energy (7.82%) was reported in the frankincense production and exporting system [77], indicating a heavy reliance on non-renewable energy. The EYR was higher by 5–9 fold in the MNF than in the CP, MP, and JP forests. This revealed that the MNF exhibited higher efficiency in integrating dispersed local inputs into the production system for each unit of external emergy invested. In contrast, the plantation forests (i.e., MP, JP and CP) exhibited relatively lower EYRs, indicating a reduced efficiency in utilizing dispersed local inputs per unit of external input within their production systems. This means that the MNF production system relied more heavily on environmental resources than on imported (purchased) inputs [28]. A higher EYR signifies greater system output per unit of input emergy, reflecting the process's ability to utilize locally available resources [16], implying greater system sustainability in the natural forest compared to the plantation forests.

The MNF showed a lower ELR than the plantation forests, likely due to its minimal reliance on purchased inputs within the production process. This low ELR value of the natural forest signified the lower stress imposed on the environment [17]. This result was also consistent with Cohen et al. [29], who reported that most of Sub-Saharan African countries exhibited a low environmental loading ratio ($ELR < 1$), except Botswana, South Africa, and Kenya. The Non-renewable to Renewable Ratio of the MNF was lower by 1.4 times compared to the plantation forests (i.e., MP, JP, and CP), highlighting its superior reliance on renewable resources and reduced environmental stress.

Moreover, the ESI value of the MNF was significantly higher than that of the plantation forests (i.e., JP, MP, and CP). This was the result of aggregated measures of system yield and environmental loading [20], which assumes sustainability as a function of productivity, renewability and environmental impact [16]. In this framework, Ulgiati and Brown [79] emphasized that achieving high production yields with minimal environmental loading is indicative of greater sustainability. Thus, the emergy sustainability index indicated the greater sustainability of ecosystem service provisions of the mixed natural forest compared to the plantation forests. Supporting this result, Muys et al. [57] emphasized the use of multiple criteria in forest management decision-making, including wood and non-wood products, soil and water conservation, and biodiversity protection. All the forest types exhibited ESI values of greater than 10, showing that the processes are underdeveloped [37, 79]. This high ESI value indicates a high EYR, minimal environmental stress, strong reliance on renewable local resources, and robust ecological resilience within the forest production system.

5 Conclusions

Our findings show that the cumulative emergy and emdollar values of the mixed natural forest are significantly higher than those of the plantation forests. This is due to the high emergy value obtained from the tree diversity in the mixed natural forest type. This finding highlights the significant advantages of natural forest development over plantation forests, particularly in mitigating climate change through enhanced carbon stock, safeguarding tree diversity, and conserving soil moisture. In addition, the mixed natural forest exhibits lower ELR and EIR, as well as higher EYR and ESI values, as compared to the plantation forests. The MNF has higher efficiency, lower environmental stress, and high environmental sustainability. This higher environmental sustainability reflects its ecological capacity to boost carbon storage, support biodiversity, and strengthen resilience, offering crucial services for climate mitigation and long-term ecosystem stability. Traditional accounting methods often emphasize marketable goods and services, while overlooking the value of the non-marketable ecosystem services. In contrast, the emergy synthesis approach offers a robust and integrative framework for assessing forest ecosystem services by holistically incorporating both economic and ecological attributes within a system. For sound and sustainable forest management, forests must be supported by both economic and ecological systems. and the findings of this study provide valuable insights for guiding the sustainable management of dry Afromontane forests, particularly in Ethiopia and, more broadly, across tropical dry forest regions.

Therefore, we recommend that policymakers adopt emergy synthesis as a comprehensive valuation framework to account for both economic and ecological forest services, thereby promoting sustainable forest management. Future research should focus on

refining energy indicators, exploring their relationship with ecological resilience, and integrating remote sensing technologies to enable scalable, holistic assessment and conservation across tropical dry forest ecosystems.

Supplementary Information

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Supplementary material 1.

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Author contributions

Abadi Tsfay: Conceptualization, Validation, Formal analysis, Methodology, Writing—original draft, Writing—review and editing. Emiru Birhane: Conceptualization, Funding acquisition, Project administration, Resources, Writing—review and editing. Getachew Nega: Formal analysis, Investigation, Validation, Writing—original draft. Nigussie Abadi: Methodology, Writing—original draft, Writing—review and editing. Mebrahtu Brhan: Methodology, Writing—original draft, Writing—review and editing. Meley Mekonen Rannestad: Conceptualization, Funding acquisition, Project administration (NORGLOBAL 2), Investigation, Methodology, Writing—review and editing.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval

The protocol was reviewed and approved by the Institute of Climate and Society Institutional Review Board (ICS-IRB) Committee of Mekelle University (Reference No.: MU/ICS/2237/2022), in accordance with the institutional guidelines for research involving human participants.

Informed consent to participate

All participants provided informed consent to participate and voluntarily agreed to participate after being fully informed about the research study. The privacy and anonymity of all participants were rigorously protected throughout the research process.

Consent to publish

Not Applicable.

Competing interest

The authors declare no competing interests.

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