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Sustainability of frankincense production in Tigray, Ethiopia: an emergy synthesis

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ABSTRACT

The frankincense from *Boswellia papyrifera* plays important roles in rural livelihoods and the national economy. On the other hand, *Boswellia papyrifera* is under threat of extinction. Nevertheless, little is known about the sustainability and fair-trade relationship of the current production system of the frankincense commodity. The current paper primarily analyzed sustainability of the production, processing, and exporting systems of frankincense production using the total emergy flows to the product. Data were primarily collected through key informant interviews and from secondary sources in the Tigray region, northern Ethiopia. An emergy synthesis method was used to assess the direct and indirect environmental energy requirements for the production, processing, and exporting of frankincense. The Emergy Sustainability Index (ESI), and Ratios were used as indicators of ecological sustainability. Whereas the Emergy Exchange Ratio (EER) was used to evaluate the level of fair trade of frankincense with importing countries. The average total emergy of the system was 50.14E+20sej/year, of which 3.92E+20sej are from local renewable, 45.20E+20sej from local nonrenewable and 1.02E+20sej from imported nonrenewable sources. The Percent Renewable (% Ren), Environmental Loading Ratio (ELR), Emergy Yield Ratio (EYR) and ESI were 7.82, 11.79, 49.50 and 4.19, respectively. The EER showed that the region exported 11.8 times more emergy in frankincense products than it received in the money paid for it in 2008/09, showing unfair trade between the exporting and importing countries. According to our results, it can be concluded that the current production, processing, and exporting of frankincense is not sustainable.

Keywords

emergy flow, energy, fair trade, frankincense, indices of sustainability

Citation

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INTRODUCTION

Boswellia papyrifera (*B. papyrifera*) (Del.) Hochst, also known as frankincense tree, is a deciduous dryland tree/shrub species belonging to the family Burseraceae, which is native to Ethiopia, Eritrea and Sudan (Oqbazgi 2001). It grows in marginal lands such as on steep and rocky mountains with shallow soils and low moisture (Esser et al. 2023; Davison et al. 2022; Tadesse et al. 2007). The species is multipurpose with great socio-economic, cultural, and environmental importance locally, nationally, and internationally (Eshete et al. 2012). *B. papyrifera* is widely known for its non-wood product, oleo-gum-resin, commonly known as frankincense, gum olibanum, or olibanum, which is obtained through incisions made in the trunks. The product, hereafter frankincense, belongs to a group of aromatic gums and resins which contain odiferous substances (Tolera et al. 2013).

Frankincense has been an important trade commodity for thousands of years. It is used as a raw material in a variety of industries, including in food (Lemenih and Teketay 2003), pharmaceutical (Khalifa et al. 2023; Hamidpour et al. 2016; Lemenih and Kassa 2011) perfumery (Lemenih and Teketay 2003; FAO 1995), adhesive (Gebrehiwot et al. 2002), and painting (Gebrehiwot et al. 2002; Murthy and Shiva 1977) industries. It is also used for ritual and church ceremonies, and traditional medicines all over the world (Lemenih et al. 2011). In Ethiopia, frankincense is a source of income for rural people and foreign currency for the country (Lemenih et al. 2012; Tilahun et al. 2011). The Tigray region is one of the largest frankincense producing regions in Ethiopia (Gebrehiwot et al. 2003). According to the data from the Revenue and Custom Authority (RCA) of the Tigray branch in Ethiopia, the region produced 21,889 tons and exported 9604 tons of frankincense over the period from 2008/09–2012/13 and earned a total of US$ 32.74 million. China, Germany, Greece, Tunisia, United Arab Emirates and Vietnam imported 81% of the total exports during that period.

Despite its significance, the species is under threat of extinction due to both natural and human-induced factors (Groenendijk et al. 2012; Gebrehiwot et al. 2002). Different studies indicate that Ethiopian *B. papyrifera* trees that produce much of the world's frankincense are declining dramatically and could decline by 90% in the next 50 years (Lemenih et al. 2011). A recent study also revealed that over 75% of studied populations lack young trees and projected the production of frankincense will be halved in 20 years unless intensive conservation and restoration efforts are urgently done to secure and sustain this product (Bongers et al. 2019).

Unsustainable utilization for subsistence and commercial purposes (Eshete et al. 2021; Lemenih et al. 2011), environmental degradation and human pressure (Gidey et al. 2020) are the most important reasons for the fast depletion and serious degradation of frankincense forest resources in Ethiopia. Although some studies show that managing dry forests for the production of frankincense is a competitive land use which yields higher returns than crop production options (e.g. Lemenih et al. 2012; Lemenih et al. 2011; Tilahun et al. 2007), their conversion to croplands and subsequent deforestation is also accelerating due to the anticipation of increased crop production returns (Dejene et al. 2013).

In this context, it is crucial to evaluate the sustainability of the current production system of the frankincense commodity. However, limited efforts have been made so far to understand the contribution of nature towards this commodity owing to lack of appropriate accounting tools. The sustainability and fair-trade relationship of production, processing and export (PPE) of frankincense therefore remain ambiguous.

Many tools for assessing the environmental benefits of commodities are available (Odum 1994), including Environmental Impact Assessment (EIA), Environmental Auditing (EA), Life Cycle Assessment (LCA) and Material Flow Analysis (MFA). However, they focus either on environmental impacts or economic bases. Emergy synthesis is an environmental accounting technique used to analyze ecological and economical return (Odum 1996). It provides a means for assessing the environmental resource base and economic flows for coupled human-environment systems using common biophysical units called solar emjoules (Odum 1996). Emergy is defined as "all the available energy that was used in the work of making a product and expressed in units of one type of energy" (Odum 1996). By expressing both economic and environmental components in common units, emergy permits meaningful comparison of the resource requirements for national economic processes, and consequently a means to monitor and compare sustainability. Moreover, it is one of the sustainability and fair-trades measuring methods. Importantly, the emergy synthesis technique accounts for the system's ecological and economic components, and it is essential to show real wealth, considering the work of nature and humans in production (Brown 2003).

Emergy has been used to evaluate national economies (e.g., Cuadra and Bjorklund 2007; Campbell et al. 2005; Abel 2004; Ulgiati et al. 1994), international trade (e.g. Brown 2003; Brown and Ulgiati 2001), various economic sectors such as forest, agriculture, and energy (e.g. Lu et al. 2006, 2009, 2010; Cuadra and Rydberg 2006; Bastianoni et al. 2005; Brown and Ulgiati 2002; Tilley and Swank 2003; Tilley 1999) and environmental services (e.g. Brown et al. 2009; Campbell 2008; Brown 2004; Brown and Ulgiati 1999). In all cases, the technique offers a useful complement to economic evaluation of costs and benefits by examining the environmental work embodied in goods and services. To our knowledge, the emergy synthesis was not considered yet, and little is known about the emergy synthesis method for evaluating the production, processing, and exporting of frankincense systems in Ethiopia. Therefore, this study was conducted to: (1) evaluate the system of production, processing and export of frankincense, considering its ecological and economic contribution to the system; (2) evaluate the sustainability of the production, processing and export of frankincense systems using emergy indices; and (3) synthesize the exchange of emergy in dollars equivalence and analyze the fair-trade export of frankincense between Ethiopia and major importing counties.

DATA AND METHODS

Description of the study area

Tigray is found in northern Ethiopia located at 12º16′38″–14º58′26″ N and 36º22′13″- 39º59′33″ E (Figure 1) and covers an area of 5.17 million hectares (Birhane et al. 2017). The climate of the region is primarily characterized by arid and semi-arid conditions with an annual rainfall of 450–980 mm (Birhane et al. 2017; Hadgu et al. 2015), mainly raining between June and September (Nyssen et al. 2006). The mean annual temperature ranges from 15 to 25°C (Birhane et al. 2011).

The major land use types are bush and shrub lands, cultivated and grass lands (BoARD 2013). Frankincense is among the primary sources of income in the region, contributing more than 6 million USD annually to the country (Lemenih et al. 2003). The region is also known for its export items of cotton, incense, sesame and minerals (CSA 2013). The production of frankincense is done in 15 of the 34 districts, and the product is processed in four towns of the region (Figure 1).

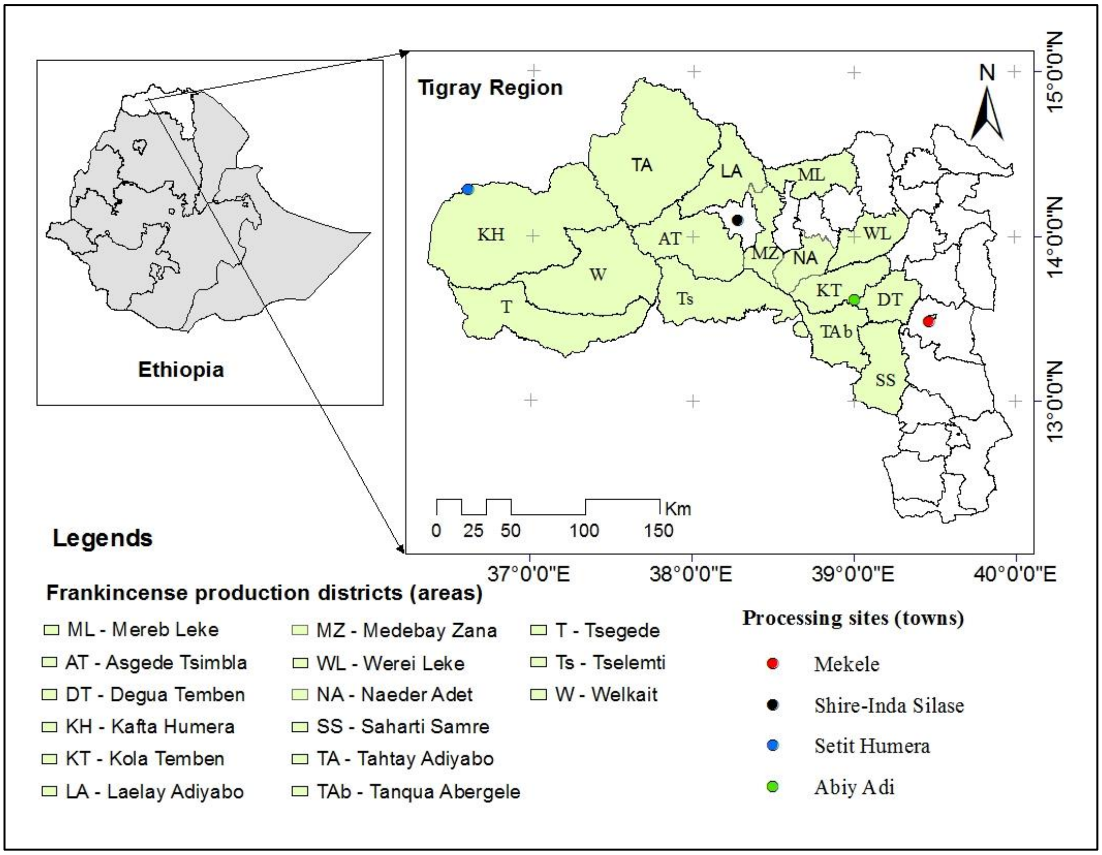

Figure 1. Location of the study areas (production districts and processing towns of Frankincense).

Sampling techniques and sample sizes

Sites for data collection were selected using a purposive sampling technique. Data were mainly collected from fifteen *B. papyrifera* growing districts and four frankincense processing towns (sites) in Tigray, Ethiopia (Figure 1). The system of production, processing and export of frankincense is characterized by a set of inputs, processes and outputs. To understand what inputs, outputs and processes were interacting in the system, identification and characterization of the main actors were done using the market chain framework (Figure 2). We listed 14 private trading companies, 13 cooperatives and 1 governmental enterprise as actors engaging in the production, processing and export systems of frankincense in the Tigray Region in consultation with the Tigray Bureau of Agriculture and Rural Development (BoANR). Besides, 45 key informant farmers were randomly included from the producer farmers in the three selected districts. Then, the actors were stratified into five groups based on their main involvement in the system of production, processing and export of frankincense. These were actors who were working in; (1) **all** producing, processing, and exporting stages of frankincense; (2) **only** producing and processing stages*;* (3) **only** processing and exporting stages; (4) **only** exporting stage and (5) **only** producing stage. One governmental enterprise and 11 cooperatives were purposely selected for the first and second stratum. For the third and fourth stratum, we also purposely selected only 1 and 13 private trading companies, respectively. For the last stratum, three districts were selected based on the distance to the processing sites and their production potentials. From each selected district, 15 key informants (frankincense producer farmers) were randomly selected. A total of 45 key informants (3 *15) were randomly chosen within this stratum for interviews. In general, a total of 71 respondents (26 private limited companies and 45 key informant farmers) were used for this study.

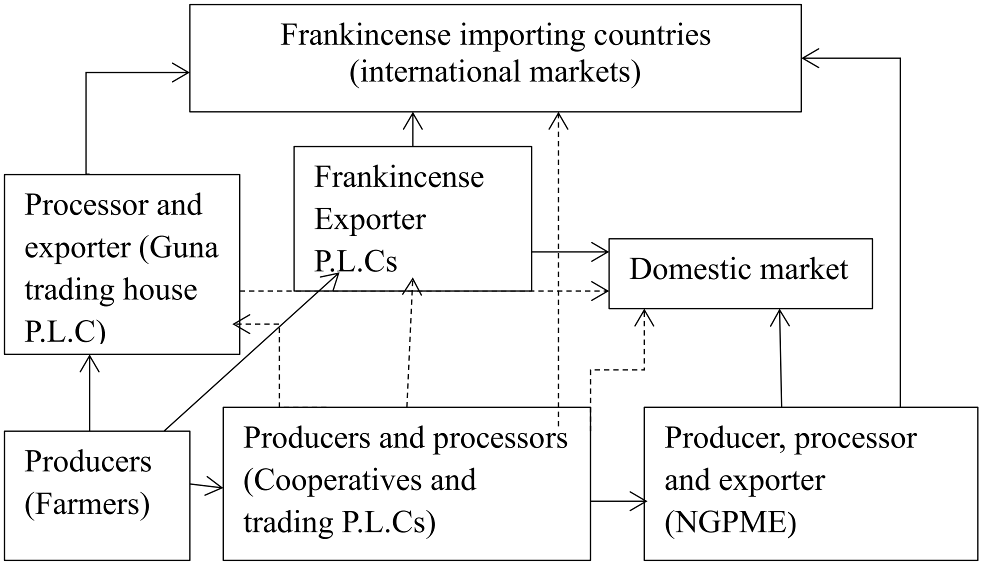

Figure 2. Schematic representation of market chain of production, processing and exporting system of frankincense in Tigray (Odum 1996). Private Limited Companies (P.L.Cs); Natural Gum Processing and Marketing Enterprise (NGPME).

Data collections

Both primary and secondary data were used in this study. Frankincense production data were obtained from governmental enterprise, cooperatives and producer farmers, while the processing data were gathered from the governmental enterprise as well as trading and cooperatives private companies.

Data on labor, purchased input materials, utilities (fuel and electricity) and services (i.e., guarding, shipping and insurance, and expert services) were collected primarily through key informant interviews with producers, processors and exporters. All input data (materials, labour and service) of the system were collected for five consecutive years (2008/09–2012/13). All materials, machines and buildings used in the system were changed to annual flows using their expected life services.

Data on the exported quantity of frankincense, currency gained (USD) and destinations of the products were collected from the Ethiopian Revenue and Custom Authority (RCA 2013), Ethiopia Natural Gum Processing and Marketing Enterprise (NGPME 2013) and Tigray Agricultural Marketing and Promotion Agency (TAMPA 2013). Similarly, data on insolation (Kwh/m^2/day), surface wind speed (m/sec), average heat flow (j/m^2), albedo, and average elevation (m) were collected from NASA website (accessed in 2013) as well as the emergy per unit input (specific emergy for Ethiopia soil loss) (sej/g) and emergy transformity values of (for example: educated and uneducated labour, goods and services) were collected from the National Environmental Accounting Database (NEAD), University of Florida, USA (Odum 1996 and 2000).

Data were also collected from research results such as erosion rate (g/m^2/year) (Nyssen et al. 2006), soil organic matter (%) (Pimentel et al. 1995), energy content of soil organic matter (kcal/g) (Campbell 2008), Gibbs free energy (j/kg) (Odum 1996) and average runoff (m/year) (Tadesse et al. 2009). We also gathered data from unpublished annual reports such as frankincense production (quintals), area of Boswellia lands (m^2) (BoARD 2013), and electricity utility **(**kwh/month) **(**EEPA 2013) and annual rainfall (m/year) (NMA 2013). Data on domestic marketing of frankincense, costs of different services and commodities were collected from the Central Statistical Authority (CSA 2013), NGPME (2013) and farmers (personal communication).

Statistical analysis

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

Emergy synthesis

Synthesis is the act of combining elements into a coherent whole in the system (Brown and Ulgiati 2004). Five steps were used to complete an emergy synthesis of the system of production, processing, and export of frankincense (Odum 1996 and 2000). First, a detailed energy system diagram was constructed for the system of production, processing, and export of frankincense (Figure 3). Second, a detailed diagram of the frankincense production, processing and export system was transformed into a more general and aggregated table (Appendix 2). Third, pathways of the aggregated diagram were described; metrics quantifying the flows between components were converted to emergy values using transformity rates (NEAD 2008; Odum 2000; Odum 1996). In the fourth step, the raw data (quantified in traditional metrics) were used to estimate the emergy exchanges, while the emergy indices were calculated, and estimates of system sustainability were also made based on concepts of "maximum empowerment" (Lu et al. 2009; Odum 1996) in the fifth step.

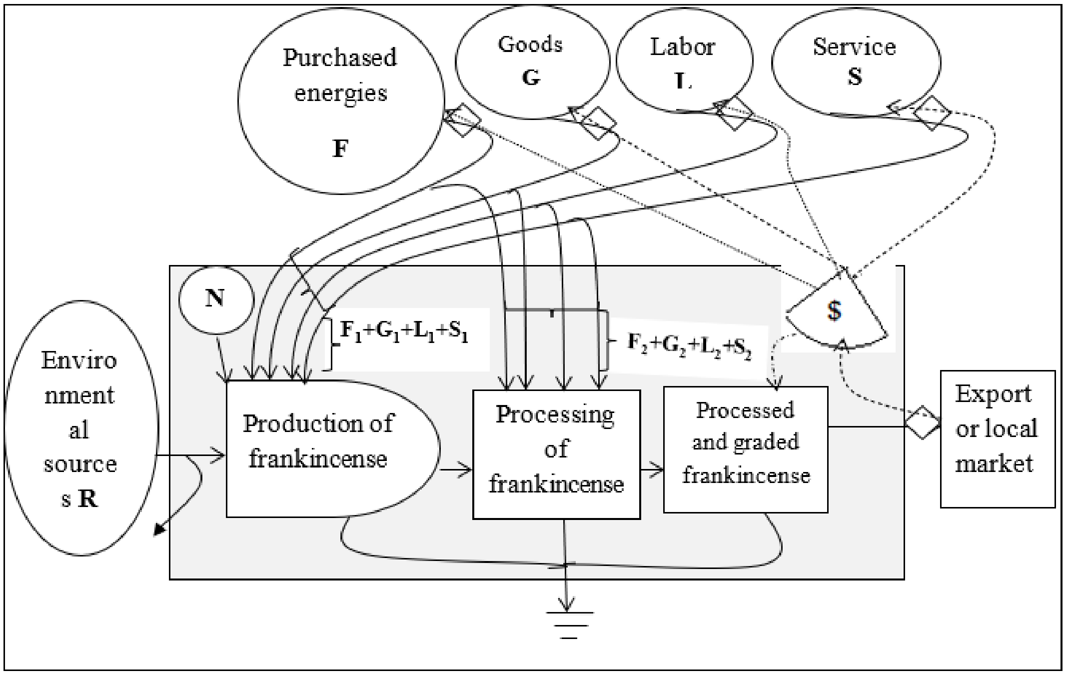

*Figure 3. Aggregated energy diagram of system of production, processing and export of frankincense in Tigray. Note: **R**= renewables resources; N= nonrenewable resources; F= Purchased energies; G= goods; L= labours and **S**=Services.*

Left-right energy language system: diagramming

Inputs were generally aggregated into local renewables (environmental energies), local non-renewables and purchased non-renewables (Figure 3). The system diagram shows the system boundaries and main energy sources driving the processes (Figure 3). The main environmental energies are solar, wind, precipitation (in chemical and geo-potential forms) and earth cycle energies, while the non-renewable inputs are local non-renewable inputs (soil storage). The purchased non-renewables include purchased energies (fuels and electricity), goods (G), Labour (L) and services (S). Goods are materials used in the production and processing steps. Labour is also used in the production and processing steps (Appendix 2 and Figure 3). The imported external inputs are generally used in the production (F_1, G_1, L_1 and S_1) and processing (F_2, G_2, L_2 and S_2) steps (Figure 3). In order to avoid double counting of emergy in planetary processes, the highest emergy of all environmental energy sources (i.e., rain-chemical energy) was considered following the suggestion of Odum (1996).

Emergy table

The emergy analysis table provides a template for the calculation of the emergy values for energy storages and flows (Odum 1996). The mass flows and storage reserves were converted to energy, and then to emergy units and emdollars following the methods of Brown (2003). This emergy evaluation table has six columns (Campbell 2008). The columns are defined according to Odum (1996) (Appendix 1).

Transformity

The transformity enables to convert a given amount of energy or mass into emergy (Zhao and Wu 2013). The transformities are determined through the analysis of production processes (Odum 1996). For example, global production processes determine the transformities of planetary products like wind, rain, snow, and waves (Brown 2004; Odum 2000; Odum 1996). Energy inputs for the system of production, processing and export of frankincense were computed using the emergy data bases of NEAD (2013), Odum (1996) and Odum (2000). Transformities for natural processes before 2000 were multiplied by 1.68 according to Brown (2004) and Odum (2000).

Flow summary and calculation of indices

Emergy income statements often report the annual flow of mass and/or dollars. The dollar flows are converted into an average emergy by multiplying the dollar amount by the emergy to dollar ratio (Odum 1996). Finally, the emergy accounting system combines the information of the income statement with summary variables to compute the emergy indices (Brown 2004; Odum 2000; Odum 1996). When evaluating the system, emergy flows of renewable (R) and nonrenewable resources within the system (N) as well as imported or purchased resources outside the system (F) were recognized (Figure 3). These summary variables were shown on the aggregate diagram and provide an overview of the emergy and dollar flows of the system (Figure 3). The emergy indices and ratios were calculated from the emergy analysis tables (Appendix 2) and the aggregated diagram (Figure 3) (Brown et al. 2000; Odum 1996). Some basic emergy performance indices or indicators were used.

These are:

$$\% \, Renewability \; (\% \, Ren) = \frac{R}{(R + N + F)}$$

It is the ratio of renewable emergy to total emergy used. A high percent renewable process is sustainable in the long run (Brown 2004; Odum 1996).

$$Emergy \; Yield \; Ratio \; (EYR) = \frac{Y}{F}$$

It is the ratio of the emergy output divided by the emergy input as feedback from the outside economy.

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

It is the ratio of the total emergy of the non-renewable inputs to the emergy of the total renewable inputs. The lower the ratio shows the lower the stress to the environment.

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

It is the ratio of the emergy yield ratio to the environmental loading ratio. The larger the ESI indicates the higher the sustainability of a system.

$$Emergy\ Exchange\ Ratio\ (EER) = \frac{Emergy\ in\ product}{(Price\ in\ USD\ x\ emergy/USD\ ratio\ for\ the\ country)}$$

This index measures the relative advantage in trade of one partner over the other.

RESULTS AND DISCUSSIONS

General characteristics of key informants

The respondents were trading companies, cooperatives, enterprises and producer farmers, representing 19.7, 15.5, 1.4 and 63.4% respectively. The majority (63%) of the respondents were frankincense producers (farmers), while the remaining (37%) of the respondents were private and state-owned companies, and cooperatives. In terms of the quantity of frankincense exported, the Ethiopian Natural Gum Processing and Marketing Enterprise (NGPME) was a major exporter in 2008/09, exporting about 70.1% of the total export. The second and third exporters were Guna Trading House PLC (15.5%) and Derar Trading PLC (9.8%), while the remaining (4.6%) was exported by other trading PLCs. Moreover, the NGPME and Guna Trading House were the major exporters of frankincense products for the fiscal years of 2009/10‒2012/13, representing 68% and 23.1% on average of the total export of frankincense, respectively.

Emergy synthesis of the system

The system diagram of the production, processing and export of frankincense shows the main driving energies were the various local renewable and imported non-renewable inputs of frankincense in Tigray (Figure 3). The average emergy which supports the system of production, processing, and export of frankincense was about 5.014E+21±4.00E+18sej for the years 2008/09‒2012/13 (Table 1). The local non-renewable inputs contributed 90.2% of the total emergy of the system. This is followed by local renewables, which accounted for 7.8% of the total emergy support required (Table 1). The purchased non-renewables from outside (fuels and electricity, goods, labour and services) accounted for 2.0% of the total emergy of the system of production, processing and export of frankincense (Table 1).

The emergy flow of local non-renewable inputs was highly influenced by the amount of organic matter of the top soil loss of the system under study (4.52E+21sej) (Appendix 3). This indicates that the higher soil loss (organic matter) of the system triggers high emergy flows through local non-renewable inputs. The average emergy flow of the renewable inputs to the system was 3.92E+20sej (Table 1). This renewable emergy is derived from the rain-chemical energy source, which is the highest emergy of all energy sources supplied by planetary processes (Appendix 3).

Table 1. Descriptive statistics of emegry (sej) of production, processing, and export system of frankincense from 2008/09–2012/13 in Tigray, Ethiopia.

Emegry sources	Minimum	Maximum	Mean±SE
Renewables (R)	**3.92E+20**	**3.92E+20**	**3.92E+20±0.00**
Non Renewable within(N)	**4.52E+21**	**4.52E+21**	**4.52E+21±0.00**
Non renewables from outside (F)			
Purchased energies	2.21E+18	2.22E+18	2.22E+18±2.00E+15
Goods (G)	8.98E+19	1.14E+20	9.89E+19±4.04E+18
Labours (L)	3.60E+17	4.50E+17	3.93E+17±1.51E+16
Services (S)	4.72E+17	7.49E+17	5.87E+17±5.24E+16
Total feedbacks (F)	**9.33E+19**	**1.18E+20**	**1.02E+20±4.25E18**
Total emergy of the system	**5.005E+21**	**5.03E+21**	**5.014E+21±4.00E+18**

Emergy and frankincense production

The local renewable and non-renewable emergy flows of the system were unchanged with the level of frankincense production across the production years (Figure 4). This might be due to the constant physical area and major weather patterns of the system of production, processing, and export of frankincense during the study were similar. Consequently, the emergy flow of imported non-renewables has increased with increasing frankincense production (Figure 4). This shows that the emergy flow of the system relied on imported non-renewable resources. This result agreed with Cuadra and Rydberg (2006) and Siracusa et al. (2007) who stated that systems are supported by either renewable or non-renewable sources, however, those systems which are supported by non-renewable inputs can result in unsustainability of production systems.

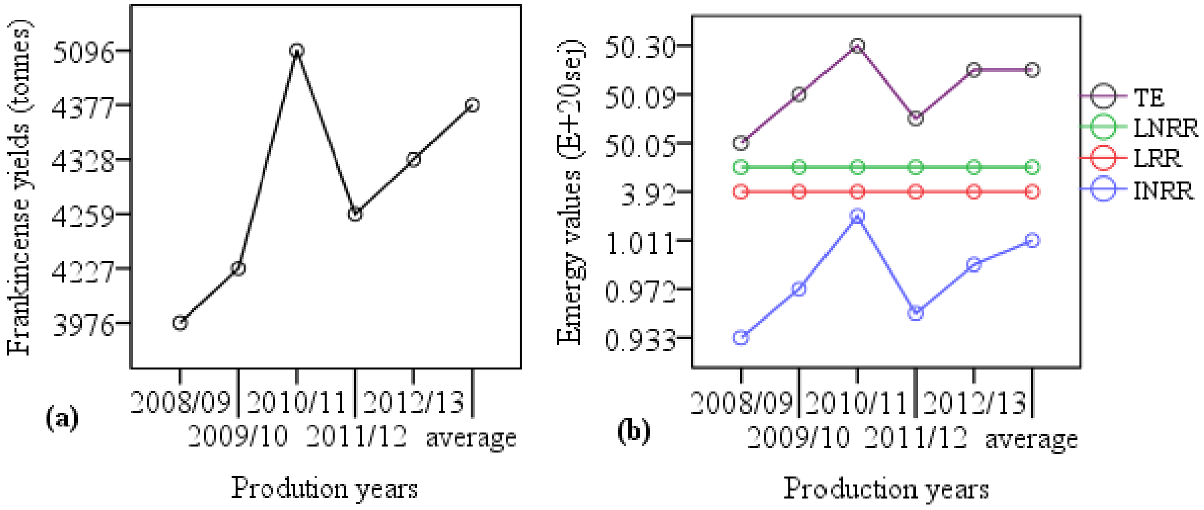

Figure 4. Relationships between frankincense production (a) and emergy (total emegry (TE), local nonrenewable resources (LNRR), local renewable resources (LRR) and imported nonrenewable resources (INNR) (b) of the system of PPE of frankincense in Tigray, Ethiopia.

Frankincense production and emdollars

The highest frankincense yield was gained in 2010/11 from the system, while the lowest was recorded in 2008/09 (Table 2). The quantity of frankincense was considerably high in 2010/11 due to the high demand for frankincense in the domestic market (Table 2). In 2008/09, around 3,976 tons of frankincense were produced, of which 40% was exported, and the remaining (60%) was locally sold (Table 2). On average, around 4,378 tons of frankincense were annually produced within five years, of which 44% was annually exported and the rest 56% was sold in the domestic markets. This showed that less than half of the produced yearly frankincense was exported to the international market (Table 2).

Table 2. Production, export and local sale of frankincense from 2008/09–2012/13 in Tigray, Ethiopia

Frankincense (tons)	Production years						
	2008/09	2009/10	2010/11	2011/12	2012/13	Average	Total
Total production	3,976	4227	5,097	4,260	4,329	4,378	21,889
Exported quantity	1,590	1,953	2,000	2,013	2,049	1,921	9,605
Domestic marketing	2,386	2,274	3,097	2,489	2,420	2,533	12,666

The emdollars values generally increased from 2008/09 up to 2011/12 and declined (Figure 5b). Similarly, the actual receivable US dollar (foreign currency gained) shows an increasing trend up to 2011/12 and then declined (Figure 5a). In 2008/09, the emdollar value of the system of PPE of frankincense was 57.30E+06USD (Figure 5b), while the actual dollar earned was 4.86E+06USD (Figure 5a). This indicates that Ethiopia has lost around 11.8 times more of its environmental resources (frankincense). In other words, when Ethiopia considers nature works on the exported frankincense product, the country should gain 57.3 million USD, but it earns practically 4.86 million USD (Figure 5b and a). On average, Ethiopia has lost above 10 times its emergy value in the product of frankincense from 2008/09–2012/13 (Figure 5). This kind of trading mainly favored importing countries rather than exporting country (Ethiopia). This result is not in line with the trade convention of a fair price for international marketing (Brown 2003).

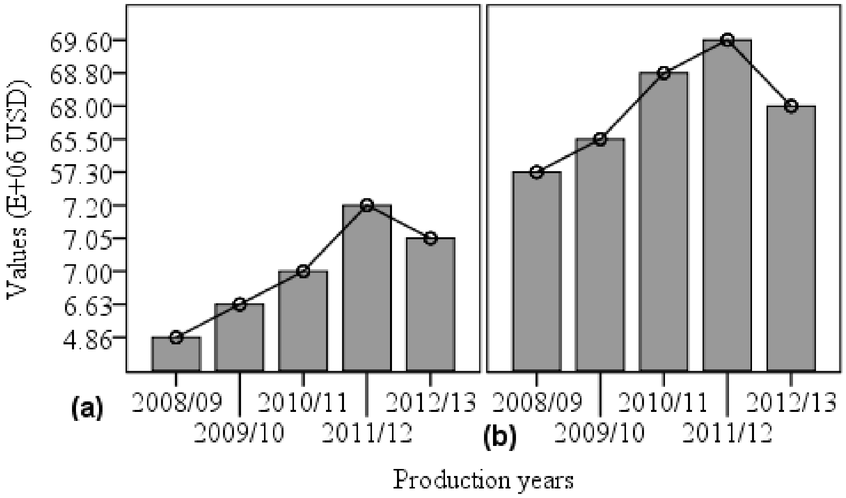

Figure 5. Total received US dollars from exports (a) and emdollar values (b) of frankincense in Tigray, Ethiopia

Emergy indices of sustainability

In emergy language, sustainability is considered a function of the emergy yielded by the process to the economy, the degree to which the process relies on renewable emergy flows, and the overall load of the process on the environment (Brown and Ulgiati 2004). In the long run, processes with a high percentage of renewable emergy are likely more sustainable than those with a high proportion of non-renewable emergy (Campbell 2008).

Table 3. Sustainability ratios of emergy synthesis of production, processing and export of frankincense in Tigray, Ethiopia

Indices	2008/09	2009/10	2010/11	2011/12	2012/13	Average
% Ren	7.83	7.83	7.79	7.83	7.82	7.82
ELR	11.77	11.78	11.83	11.79	11.79	11.79
EYR	53.60	51.50	42.70	50.20	49.58	49.52
ESI	4.50	4.37	3.61	4.25	4.20	4.19

%Ren=Percent renewable; ELR=Environmental loading ratio; EYR=Emergy yield ratio; ESI=Emergy sustainability index

Percent renewable (%)

There is a clear tendency for a decrease in the percent renewable for the increased volume of frankincense production (Figure 6). A high percentage of renewable (7.83%) was obtained in the lower quantities of frankincense in 2008/09, 2009/10 and 2011/12, while the lowest % renewable (7.79%) was recorded in 2010/11 (Table 3). This indicates that as we exploit the natural resource base of the system in the form of frankincense at an increased volume of production, then the % Ren decreases (Figure 6). Thus, in order to support the system's production potential at an increased level, the system needs more local and imported non-renewable emergy flows (as the local renewable emergy is constant). This highlighted that more emergy flows are required to support the system to produce more frankincense yield. As this emergy was sourced from non-renewable inputs (local and imported), only system processes with high renewability percentage could be sustainable in the long run (Brown and Ulgiati 2004). Consequently, the production, processing and export system of frankincense could be unsustainable in the long run.

Besides this, the average result of renewable emergy (%) was about 7.82%, which signified that the rate of renewable energy in the process was lower (Table 3). Incomparable to this result, the World Energy Council (2016) reported a high renewable energy share (appr. 18.9%) in Africa until 2015. Thus, the average result of the renewable energy (%) of producing, processing and exporting frankincense was below 18.9%, indicating the system's unsustainability.

Environmental loading ratio

The lowest ELR was obtained in 2008/09, while the highest was recorded in 2010/2011 (Figure 6). The ELR generally increased with an increase in frankincense production, particularly from

2008/09 to 2010/11, while it also showed a decreasing trend with a reduction in frankincense production (Figure 6). In general, the ELR values are greater than ten (ELR > 10) across all the study years (Figure 6), indicating a larger distance of development from the process of a system (Brown 2004). This high ELR could be due to the higher consumption of non-renewable resources (goods and labour) used to support the system. This might result in heavier stress on the environment (Brown and Ulgiati 2005) and disturbance of the ecological functions of a system (Brown and Ulgiati 1997). Our result disagreed with UNEP (2012) which reported a lower environmental loading ratio (ELR < 1) for most of Sub-Saharan Africa, except Botswana, South Africa and Kenya. The high ELR might indicate local environmental disturbance, which is caused by the developmental process from outside (Brown and Ulgiati 1997 and 2004), high reliance from outside sources (Cuadra and Rydberg 2006), and ecosystem stress due to production (Brown 2003).

Emergy yield ratio

The maximum EYR was recorded in 2008/09, while the minimum EYR for the system was obtained in 2010/11 (Figure 6). In comparison, the highest EYR value (53.6) represented a higher yield of the system per input of emergy than the lowest EYR value (42.7) (Table 3 and Figure 6). As utilizing the local resources in the system, a unit of external investment enhances the system process by roughly 1.3 times more in 2008/09 and 2010/11 (Table 3 and Figure 6). For the system of production, processing and export of frankincense, the average EYR over five consecutive years was approximately 49.6 (Table 3). This higher index value indicated that a greater benefit was made per unit of invested emergy in the system.

Emergy sustainability index

The ESI of the frankincense of the PPE system ranged from 3.61 to 4.50, with an average value of 4.19 over five consecutive years (Table 3 and Figure 6). As frankincense production levels increased, the ESI values generally decreased (Figure 6). According to Ulgiati and Brown (1998), the ESI score that ranges from 1 to 10 denotes a growing economy. The average ESI value of this study falls between 1 and 10, and reveals a moderate sustainability of the system. However, it does not have any guarantee to withstand continual exploitation and maintain its sustainability in the long term. This is because the sustainability of a production system depends on the input emergy of either renewable or non-renewable resources (Brown and Ulgiati 1997 and 2004; Cuadra and Rydberg 2006).

Furthermore, since the ESI combines the EYR and ELR indices, the ESI value can be easily influenced by these indices. For example, if the ecology of frankincense tree production is disturbed (i.e., due to soil losses), the emergy of imported inputs to the process from outside increases to support the system. This can result in a low ESI value in the long-run. Moreover, as frankincense production increases, its EYR decreases, thereby the ELR increases, creating stress on the environment (Figure 6), which results in the unsustainability of the system of the PPE of frankincense. In line with this result, Eshete et al. (2012), Kassa et al. (2011), Gebrehiwot et al. (2002) and Tadesse et al. (2007) showed that the population pressure (settlement) and intensive production of frankincense caused unsustainability of frankincense production. These factors cause ecological disturbance mainly due to topsoil erosion, resulting in deterioration of the frankincense production system.

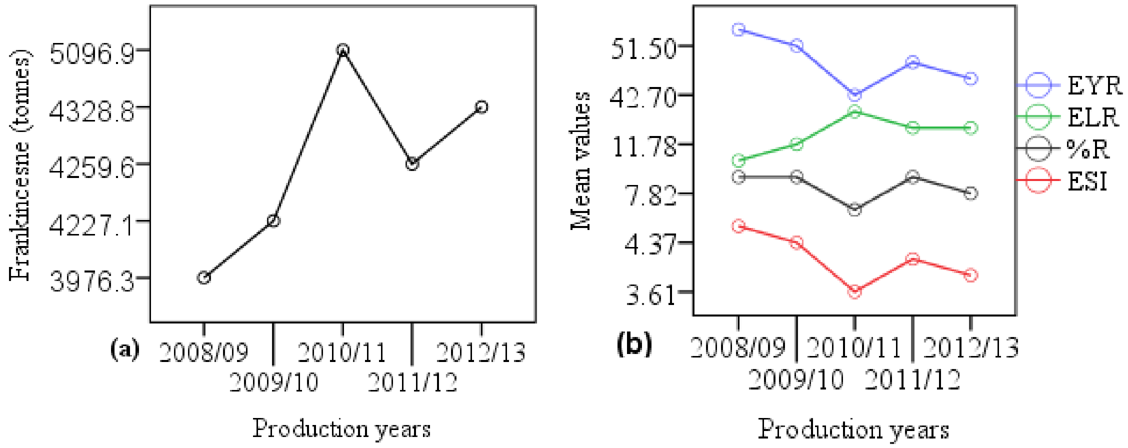

Figure 6: *Relationships between the frankincense production **(a)** and emergy sustainability ratios **(b)**; %R=Percent renewable; ELR=Environmental loading ratio; EYR=Emergy yield ratio; ESI=Emergy sustainability index in Tigray, Ethiopia.*

Emergy exchange ratios (EER)

Denmark had the highest EER of all importing countries (49.8), followed by Germany (21.7) and the Netherlands (17.0). The rest of the importing countries had less than 10 EER values (Figure 7). The differences in EER among the importing countries might be due to the inequality in trade among the countries. Highly developed countries purchase a large supply of raw materials compared to economically less developed countries (Brown 2003; Odum 2000). Similarly, Cuadra and Rydberg (2006) stated that Nicaragua traded coffee products with Australia, Denmark, Italy, Sweden, Switzerland, and the USA. Of which, Italy, Sweden, Switzerland, and USA had greater than one EER value (i.e., 1.92, 2.17, 3.08 and 2.78, respectively), showing that the emergy advantage of the importer countries and emergy disadvantage of the exporter country.

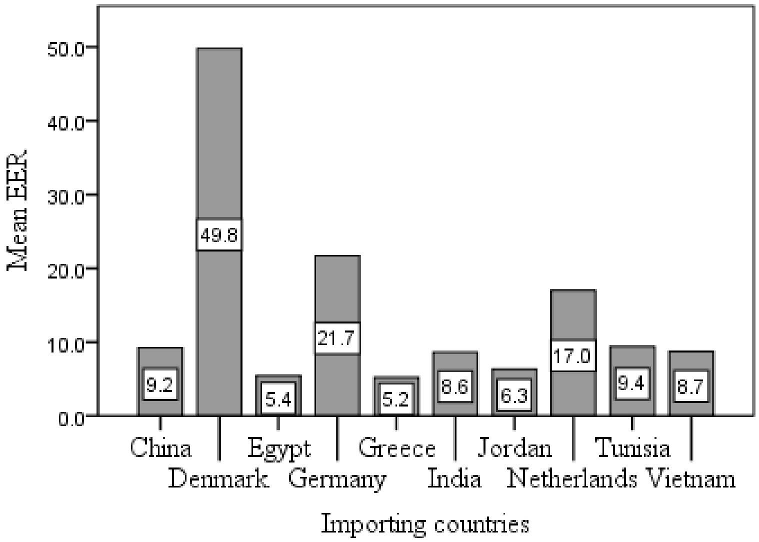

Figure 7: Emergy exchange ratio: Ethiopia with frankincense importing countries

CONCLUSIONS

The total emergy flow supporting the production, processing, and export system was directly proportional to the quantity of frankincense produced and highly dependent on local non-renewable inputs. The results of emergy sustainability indices showed that non-renewable resources highly supported the system.

The EYR, %Ren and ESI values generally decreased with increasing frankincense production, while the ELR increased with increasing frankincense production, indicating a high stress on the environment. Although this system provides a remarkable output for the economy using little resources from outside of the system, the environment is unable to withstand the pressure loaded by the system of production, processing, and export of frankincense in the long run. This system might be unsustainable. Moreover, the emergy product of the output of the system (considering only the exported quantity) showed that Ethiopia had lost above ten times more emergy values, which could have been earned from its environment during the transaction. On the contrary, countries importing frankincense from Ethiopia benefited ten times more emergy from which they paid for the frankincense product. Our finding highlights that successful production, processing, and export of frankincense would be attained when inputs of the system depend on local renewable resources, and local non-renewable resources should be used up to the tolerable level of the environment.

The findings of this paper have implications for sustainable business model of frankincense production system that incorporates the economic, environmental, and social issues.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

REFERENCES CITED

Abel T. 2004. Systems diagrams for visualizing macroeconomics. Ecological Modelling: 178, 189□194. https://doi:10.1016/j.ecolmodel.2003.12.035

Bastianoni S, Campbell D, Susani L, Tiezzi E. 2005. The Solar transformity of oil and petroleum natural gas. Ecological Modelling: 186, 212□220. https://doi.org/10.1016/j.ecolmodel.2005.01.015

Birhane B, Aynekulu E, Mekuria W, Endale D. 2011. Management, use and ecology of medicinal plants in the degraded drylands of Tigray, Northern Ethiopia. Journal of Horticulture and Forestry Vol. 3(2), 32□41.

Birhane E, Mengistu T, Seyoum Y, Hagazi N, Putzel L, Mekonnen Rannestad M. 2017. Exclosures as forest and landscape restoration tools: lessons from Tigray Region, Ethiopia. 19(4): 37□50. https://doi.org/10.1505/146554817822330498

BoARD. 2013. Bureau of Agriculture and Rural Development, annual reports of 2008/09-2012/13. Tigray regional state, Mekelle, Ethiopia.

Bongers F, Groenendijk P, Bekele T, Birhane E, Damtew A, Decuyper M, Eshete A, Gezahgne A, Girma A, Khamis MA, Lemenih M, Mengistu T, Ogbazghi W, Sass-Klaassen U, Tadesse W, Teshome M, Tolera M, Sterck FJ, Zuidema PA. 2019. Frankincense in peril. Nature Sustainability, 2(7), 602–610. https://doi.org/10.1038/s41893-019-0322-2

Brown M. 2003. Resource imperialism. Emergy perspectives on sustainability, international trade and balancing the welfare of nations. In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A., Mayumi, K. (Eds.), Book of proceedings of the International Workshop “Advances in energy studies. Reconsidering the importance of energy”, Porto Venere, Italy, 24–28 September 2002, SGE Publisher Padova, Italy, p. 135–149.

Brown M, 2004. A picture is worth thousand words: energy system language and simulation. Ecological Modelling: 178, 83-100. https://doi.org/10.1016/j.ecolmodel.2003.12.008

Brown M, Brandt-Williams S, Tilley D, Ulgiati S. 2000. Emergy synthesis: theory and applications of the emergy methodology, University of Florida, Center for Environmental Policy, Gainesville, USA, p. 328.

Brown M, Cohen J, Sweeney S. 2009. Predicting national sustainability: the convergence of energetic, economic and environmental realities. Ecological Modelling: 220, 3424□3438. https://doi.org/10.1016/j.ecolmodel.2009.08.023

Brown M, Ulgiati S. 1997. Emergy based indices and ratios to evaluate sustainability: monitoring economics and technology towards environmentally sound innovation. Ecological Engineering: 9, 51□69. https://doi.org/10.1016/S0925-8574(97)00033-5

Brown M, Ulgiati S. 1999. Emergy evaluation of the biosphere and natural capital. Amibo: 28(6), 486□492.

Brown M, Ulgiati S. 2001. Emergy measures of carrying capacity to evaluate economic investments. Population and Environment: 22 (5), 471□501. https://doi.org/10.1023/A:1010756704612

Brown M, Ulgiati S. 2002. Emergy evaluations and environmental loading of electricity production systems. Journal of Cleaner Production: 10, 321□334.

Brown M, Ulgiati S. 2004. Emergy analysis and environmental accounting. Encyclopedia of emergy. Elsevier, 2, 329□325. https://doi.org/10.1016/S0959-6526(01)00043-9

Brown M, Ulgiati S. 2005. Emergy, transformity and ecosystem health. In. Jorgensen et al.(eds). Handbook of ecological indicators for assessment of ecosystem health.

Campbell D. 2008. Environmental accounting of natural capital and environmental services of the US national forest system. Msc thesis, University of Florida, USA.

Campbell D, Brandt-Williams S, Meisch M. 2005. Environmental accounting using emergy: evaluation of the State of West Virginia. USEPA. Office of Research and Development, Washington, DC. 116.

CSA. 2013. Central Statistical Agency report on population census of Ethiopia, as of 2007. Addis Ababa, Ethiopia.

Cuadra M, Bjorklunds J. 2007. Assessment of economic and ecological carrying capacity of agricultural crops in Nicaragua. Ecological Indicators: 7, 133□149. https://doi.org/10.1016/j.ecolind.2005.11.003

Cuadra M, Rydberg T. 2006. Emergy evaluation on production, processing and export of coffee in Nicaragua. Ecological Modelling: 196, 421□433. https://doi.org/10.1016/j.ecolmodel.2006.02.010

Davison C, Bongers F, Phillips D. 2022. The future of Frankincense: Understanding the plant's diversity is key to its conservation. The Journal of the American Botanical Council, 133, 40–59. Available at: https://www.herbalgram.org/media/17303/hg133-frankincense.pdf

Dejene T, Lemenih M, Bongers F. 2013. Manage or convert Boswellia woodlands? Can frankincense production payoff? Journal of Arid Environments, 89□ 77□83. https://doi.org/10.1016/j.jaridenv.2012.09.010

EEPA. 2013. Ethiopian Electric Power Authority, annual reports of 2008/09-2012/13, Mekelle, Tigray Ethiopia.

Eshete, A. Kassa, H, Livingstone, J. 2021. Inclusive frankincense value chain development in Ethiopia. A historical perspective on forest governance and reforms for better livelihoods and conservation outcomes. PENHA, Addis Ababa, Ethiopia and Tropenbos International, Ede, the Netherlands.

Eshete A, Teketay D, Lemenih M, Bongers F. 2012. Effects of resin tapping and tree size on the purity, germination and storage behavior of Boswellia papyrifera (Del.) Hochst. Seeds from Metema District, North Western Ethiopia. Forest Ecology and Management, 206, 31□36. https://doi.org/10.1016/j.foreco.2011.12.049

Esser L, Weldemariam E. 2023. Climate changes could jeopardize a main source of livelihood in Africa's drylands, Journal for Nature Conservation, Volume 71, 1617□1381. https://doi.org/10.1016/j.jnc.2022.126319

FAO. 1995. Flavours and fragrances of plant Origin. Non-wood forest products 1. Food and Agricultural Organization (FAO), Rome. https://www.fao.org/3/v5350e/v5350e.pdf

Gebrehiwot G, Muys B, Mitiku H, Mitloehner R. 2002. Boswellia papyrifera (Del.) Hochst: a tropical key species in northern Ethiopia. George-August University of Goettingen, institute of tropical silviculture Goettingen, Germany.

Gebrehiwot G, Muys B, Mitiku H, Mitloehner R. 2003. Introducing Boswellia papyrifera (Del.) Hochst and its non-timber forest product, frankincense. International Forestry Review: 5, 348–353. : https://doi.org/10.1505/IFOR.5.4.348.22661

Gidey T, Hagos D, Juhar HM, Solomon N, Negussie A, Crous-Duran J, Oliveira TS, Abiyu A, Palma JH. 2020. Population status of Boswellia papyrifera woodland and prioritizing its conservation interventions using multi-criteria decision model in northern Ethiopia. Heliyon, 6(10), e05139. https://doi.org/10.1016/j.heliyon.2020.e05139

Groenendijk P, Eshete A, Sterck FJ, Zuidema PA, Bongers F, 2012. Limitations to sustainable frankincense production: blocked regeneration, high adult mortality and declining populations. Journal of Applied Ecology, 49: 164□173. https://doi.org/10.1111/j.1365-2664.2011.02078.x

Hamidpour R, Hamidpour S, Hamidpour M, Hamidpour R. 2016. Frankincense (Boswellia Species): The novel phytotherapy for drug targeting in cancer. iMedPub Journals, Vol. 4 No. 1:46. Available at: http://www.imedpub.com

Kassa H, Tefera B, Fitwi G. 2011. Preliminary value chain analysis of gum and resin marketing in Ethiopia. CIFOR, Bogar, Indonesia.

Khalifa SAM, Kotb SM, El-Seedi SH, Nahar L, Sarker SD, Guo Z, Zou X, Musharraf SG, Jassbi, AR, Du M, Hesham R, El-Seedi HR. 2023. Frankincense of Boswellia sacra: Traditional and modern applied uses, pharmacological activities, and clinical trials. Industrial Crops and Products, Volume 203, 117106, ISSN 0926-6690. https://doi.org/10.1016/j.indcrop.2023.117106

Hadgu G, Tesfaye K, Mamo G, Kassa B, 2015. Farmers’ climate change adaptation options and their determinants in Tigray Region, Northern Ethiopia. African Journal of Agricultural Research, 10 (9), 956□964. Doi.org/10.5897/AJAR2014.9146.

Lemenih M, Abebe T, Olsson M. 2003. Gum and resin resources from some acacia, Boswellia and commiphora species and their economic contributions in Liban, South-East Ethiopia J. Arid Environ.55 (3)□ 465□482. DOI:10.1016/S0140-1963(03)00053-3

Lemenih M, Kassa H. 2011. Opportunities and challenges for sustainable production and marketing of gums and resins in Ethiopia, CIFOR, Bogor, Indonesia.

Lemenih M, Kassa H, Kassie GT, Abebaw D, Teka W. 2012. Resettlement and woodland management problems and options: a case study from a resettlement district in north-western Ethiopia. Land Degrad. Develop.25, 305–318 (2014). https://doi.org/10.1002/ldr.2136

Lemenih M, Teketay D. 2003. Frankincense and myrrh resources of Ethiopia: II. medicinal and industrial uses. SINET: Ethiop. J. Sci., 26 (2): 161–172. DOI: 10.4314/sinet.v26i2.18213

Lemenih M, Wiersum F, Woldeamanuel T, Bongers F. 2011. Diversity and dynamics of management of gum and resin producing woodlands in Ethiopia: a trade-off between degradation and domestication. Land Degrad. Develop.25, 130–142 (2014). https://doi.org/10.1002/ldr.1153

Lu H, Bay Y, Ren H, Campbell D. 2010. Integrated emergy, energy and economic evaluation of rice and vegetable production systems in alluvial paddy fields: implications for agricultural policy in China. Environmental Management: 91, 2727□2735. https://doi.org/10.1016/j.jenvman.2010.07.025

Lu H, Campbell D, Li Z, Ren H. 2006. Emergy synthesis of an agro-forestry restoration system in lower sub-tropical China. Ecological Engineering: 27, 175□192. https://doi.org/10.1016/j.ecoleng.2005.12.002

Lu H, Kang L, Campbell D, Ren H, Tan Y, Feng R, Luo J, Chan F. 2009. Emergy and economic evaluation of four production systems on reclaimed wet lands surrounding the pearl river Estuary, China. Ecological Engineering: 35, 1743□1757. https://doi.org/10.1016/j.ecoleng.2009.08.001

Murthy TK, Shiva MP. 1977. Salai guggul from Boswellia serrata Roxb-Its exploitation and utilization. Indian Forester 103:466□474

NASA. 2013. The National Aeronautics and Space Administration (NASA). Accessed in 2013: https://www.nasa.gov/.

NEAD (National Environmental Accounting Data base). 2013. Emergy system database by country for 2008. Center for environmental policy, University of Florida; USA.

NGPME. 2013. Natural gum processing and marketing enterprise export report of frankincense from Tigray in 2008-2012. Mekelle, Ethiopia.

NMA. 2013. National Metrological Agency Climatic report from 2003-2013 for Tigray stations, Mekelle; Ethiopia.

Nyssen J, Descheemaeker K, Haregeweyn N, Haile M, Deckers J, Poesen J. 2006. Lessons learnt from 10 years research on soil erosion and soil and water conservation in Tigray. Tigray Livelihood Papers No. 7, Mekelle: Zala-Daget Project, Mekelle University, K.U.Leuven, Relief Society of Tigray, Africa museum and Tigray Bureau of Agriculture and Rural Development, p.53.

Odum H. 1994. The emergy of natural capital. In: Jansson, A., Hammer, M., Folke, C. & Costanza, R., Investing in natural capital. Island Press, Covelo, CA, 200-214.

Odum H. 1996. Environmental accounting: emergy and environmental decision making. John Wiley & Sons, Inc. USA. p.370.

Odum H. 2000. Handbook of emergy evaluation: emergy of global processes, University of Florida, Center for Environmental Policy, Gainesville, p.22.

Oqbazgi W. 2001. The distribution and regeneration of Boswellia papyrifera (Del.) Hochst. in Eritrea. PhD Dissertation, Wageningen University, Wageningen, Netherlands. Available at: https://edepot.wur.nl/194745

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kuiz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri L, Blair R. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science, New Series, Vol. 267, No. 5201□1117□1123. https://www.jstor.org/stable/2886079

RCA. 2013. Revenue and Custom Authority Export report of agricultural commodities with their destinations from Tigray from 2008/09□2012/13, Mekelle, Ethiopia.

Siracusa G, LaRosa D, Palma P, Lamola E. 2007. Emergy evaluation of an eco-village: new frontiers for sustainability. Environment, Development and Sustainability: 10, 845-855. https://doi.org/10.1007/s10668-007-9087-2

Tadesse N, Bheemalingeswara K, Berhane A. 2009. Groundwater suitability for irrigation: a case study from Debre Kidane watershed, eastern Tigray, Ethiopia. Momona Ethiopian Journal of Science (MEJS), Vol. 1 (1): 36 – 58. DOI:10.4314/mejs.v1i1.46040

Tadesse W, Desalegn G, Alila R. 2007. Natural gum and resin bearing species of Ethiopia and their potential applications. Arid Environment: 16(3), 211□221. DOI: https://doi.org/10.5424/srf/2007163-01010

TAMPA. 2013. Tigray agricultural marketing and promotion, agency agricultural commodities export report from Tigray, 2008/09-2012/13. Mekelle, Ethiopia.

Tilahun M, Muys B, Mathijs E, Kleinn C, Olschewski R, Gebrehiwot K. 2011. Frankincense yield assessment and modeling in closed and grazed Boswellia papyrifera woodlands of Tigray, Northern Ethiopia. Journal of Arid Environments, 75(8), 695–702. https://doi.org/10.1016/j.jaridenv.2011.03.005

Tilahun T, Vranken L, Muys B, Deckers J, Kidanemariam G, Kindeya G, Bauer H, and Mathijs E. 2007. Valuing dry land forest ecosystem services: a case of rural households' willingness to pay and contribute labor for frankincense forest conservation in Ethiopia. Division Agricultural and Food Economics, K.U.Leuven, Celestijnenlaan 200E box 2411, BE-3001 Leuven, Belgium.

Tilley D. 1999. Emergy basis of forest systems. PhD Dissertation, University of Florida, UMI Dissertation Services, Ann Arbor MI, p.296.

Tilley D, Swank W. 2003. Emergy-based environmental systems assessments of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. Environmental Management: 69, 213–227. https://doi.org/10.1016/j.jenvman.2003.08.002

Tolera M, Sass-Klaassen U, Eshete E, Bongers F, Sterck F. 2013. Frankincense tree recruitment failed over the past half century. Forest Ecology and management: 304, 65□72. https://doi.org/10.1016/j.foreco.2013.04.036

Ulgiati S, Brown M. 1998. Monitoring patterns of sustainability in natural and man-made ecosystems. Ecological Modelling: 108, 23–36. https://doi.org/10.1016/S0304-3800(98)00016-7

Ulgiati S, Odum H, Bastianoni S. 1994. Emergy use, environmental loading and sustainability. An emergy synthesis of Italy. Ecological Modelling: 73, 215-268. https://doi.org/10.1016/0304-3800(94)90064-7

UNEP. 2012. Environmental accounting of national economic systems: an analysis of west african dry land countries within a global context. United Nations Environment Programme, Nairobi.

World Energy Council (WEC). 2016. World energy resources. ISBN: 978 0 946121 58 8. pp1–33. London EC3V 3NH, United Kingdom. Available at: https://www.worldenergy.org/assets/images/imported/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf

Zhao S, Wu C. 2013.Valuation of mangrove ecosystem services based on emergy: a case study in China. Int. J. Environ. Sci. Technol. (2015) 12:967–974. DOI 10.1007/s13762-013-0458-y

APPENDIX 1 – EMERGY TABLE DEMONSTRATION

Note	Item	Input Data and Units	Unit Solar Emergy (sej/unit)	Solar Emergy	Em$ value ($)

Column 1: Note. The line numbers for the item evaluated were listed, which corresponds to a footnote where raw data sources were cited and calculations shown.

Column 2: Item. The names of the items were listed.

Column 3: Data. For each line item the raw data were given in joules, grams and US dollars.

Column 4: Solar Emergy per Unit. For many items the solar emergy per unit (transformities where the unit is energy) has already been calculated in previous studies and some were also taken from NEAD database.

Column 5: Solar Emergy. The solar emergy was calculated from the product of columns three and four

Column 6: Emdollars (Em$). This number was obtained by dividing the emergy in column 5 by the emergy/dollar ratio in the specified years.

APPENDIX 2 – EMERGY SYNTHESIS TABLE OF THE SYSTEM FOR 2008/2009 (2001 ETHIOPIAN FISCAL YEAR).

Note	Item	Input data and units	Unit solar emergy (sej/unit)	Solar emergy	Em$ value ($)
Renewable resources					
1	Sun light	2.44E+19J	1.00sej/j	2.44E+19sej	3.39E+06
2	Wind	1.48E+14J	1.58E+03sej/j	2.34E+17sej	3.25E+04
3	Rain geo-potential	5.20E+15J	1.05E+04sej/j	5.47E+19sej	7.60E+06
4	Rain- chemical	1.28E+16J	3.05E+04sej/j	3.92E+20sej	5.44E+07
5	Earth cycle	8.92E+15J	3.40E+04sej/j	3.00E+20sej	4.17E+07
Non-renewable inputs					
6	Top soil loss	1.51E+16J	3.00E+05sej/j	4.52E+21sej	6.28E+08
Purchased inputs					
7	Fuel	3.35E+13J	6.60E+04sej/j	2.21E+18sej	3.07E+05
8	Electricity	1.51E+10J	1.60E+05sej/j	2.42E+15sej	28.00
Production goods					
9	Wood	1.21E+15J	6.89E+04sej/j	8.34E+19sej	1.16E+07
10	Tapping axe	7.67E+05g	1.90E+11sej/g	1.46E+17sej	2.03E+04
11	Dirrat	399.34 USD	7.20E+12sej/USD	2.88E+15sej	400.00
12	Collection basket	6988.47USD	7.20E+12sej/USD	5.03E+16sej	7.00E+03
13	Bucket	1747.12USD	7.20E+12sej/USD	1.26E+16sej	1.75E+03
14	Axe	998.35 USD	7.20E+12sej/USD	7.19E+15sej	1.00E+03
15	Medicine	27454.7USD	7.20E+12sej/USD	1.98E+17sej	2.74E+04
Labour					
16	Labour for tapping	9.13E+12J	2.62E+04sej/j	2.392E+17sej	3.32E+04
17	Nursery laborer	1.69E+10J	2.62E+04sej/j	4.422E+14sej	61.39
Services					
18	Expert service	2.64E+10j	1.2E+05sej/j	3.165E+15sej	4.39E+02

Note	Item	Input data and units	Unit solar emergy (sej/unit)	Solar emergy	Em$ value ($)
19	Guarding in site	73195.6USD	7.20E+12sej/USD	5.27E+17sej	7.22E+04
Processing goods					
20	Wood	3.09E+13j	6.89E+04sej/j	2.13E+18sej	2.96E+05
21	Cement	6.67E+09g	2.90E+05sej/g	1.94E+15sej	27
22	Steel sheet	3.28E+05g	9.17E+08sej/g	3.01E+14sej	42
23	Metal	2.18E+05g	1.90E+11sej/j	4.14E+16sej	5.69E+04
24	Soap	1.12E+04USD	7.20E+12sej/USD	8.05E+16sej	1.12E+04
25	Cloth	2.91E+04USD	7.20E+12sej/USD	2.10E+17sej	2.91E+04
26	Collection sack	1.74E+04USD	7.20E+12sej/USD	1.26E+17sej	1.74E+04
27	Shipping & insurance	469846.9USD	7.20E+12sej/USD	3.383E+18sej	4.70E+05
Labour					
27	Uneducated (cons.)	2.63E+10j	2.62E+04sej/j	6.88E+14sej	95
28	Cleaning, sorting	3.20E+12j	2.62E+04sej/j	8.37E+16sej	1.15E+04
29	Educated (const.)	1.17E+08j	1.20E+05sej/j	1.41E+13sej	1.94
Services					
30	Expert service	2.60E+11J	1.20E+05sej/j	3.12E+16sej	4.32E+03
31	Lifting	2.80E+04USD	7.20E+12sej/USD	2.02E+17sej	2.80E+04
32	Guarding	2.46E+03USD	7.20E+12sej/USD	1.77E+16sej	2.46E+03

APPENDIX 3 – AGGREGATED EMERGY SYNTHESIS TABLE (2008/2009) FOR PRODUCTION, PROCESSING AND EXPORTING OF FRANKINCENSE IN TIGRAY, ETHIOPIA.

Note	Item	Input data and units	Unit solar emergy (sej/unit)	Solar emergy	Em$ value ($)
Renewable resources					
1	Sun light	2.44E+19J	1.00sej/j	2.44E+19sej	3.39E+06
2	Wind	1.48E+14J	1.58E+03sej/j	2.34E+17sej	3.25E+04
3	Rain-geo potential	5.20E+15J	1.05E+04sej/j	5.47E+19sej	7.60E+06
4	Rain- chemical	1.28E+16J	3.05E+04sej/j	3.92E+20sej	5.44E+07
5	Earth cycle	8.92E+15J	3.40E+04sej/j	3.00E+20sej	4.17E+07
Total renewables (R)		**3.92E+20sej**			
Nonrenewable inputs					
6	Top soil loss	1.51E+16J	3.00E+05sej/j	4.52E+21sej	6.28E+08
Total local non renewable		**4.52E+21sej**			
Purchased inputs					
7	Fuel	3.35E+13J	6.60E+04sej/j	2.21E+18sej	3.07E+05
8	Electricity	1.51E+09J	1.60E+05sej/j	2.42E+15sej	3.36E+02
Total purchased non renewable		**2.22E+18sej**			
Goods					
9	Wood	1.241E+15J	6.89E+04sej/j	8.553E+19sej	1.19E+07
10	Cement	6.67E+09g	2.90E+05sej/g	1.94E+15sej	27
11	Steel sheet	3.28E+05g	9.17E+08sej/g	3.01E+14sej	42
12	Metal materials	9.85E+05g	1.90E+11sej/g	1.87E+17sej	2.61E+04
13	Other materials	5.65E+05USD	7.20E+12sej/USD	4.07E+18sej	5.65E+05
Total goods		**8.98E+19sej**			
Labour					
16	Uneducated	1.24E+13J	2.62E+04sej/j	3.25E+17sej	4.51E+04
17	Educated	2.87E+11j	1.20E+05sej/j	3.45E+16sej	4.79E+03

Note	Item	Input data and units	Unit solar emergy (sej/unit)	Solar emergy	Em$ value ($)
Total labour		**3.60E+17sej**			
Services					
18	Lifting & Guarding	1.04E+05USD	7.20E+12sej/USD	7.49E+17sej	3.05E+04
Total services		**7.49E+17sej**			
Total F		**9.33E+19sej**			
Total emergy of the system		**5.005E+21sej**			