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Forest dependence is more than forest income: Development of a new index of forest product collection and livelihood resources

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ABSTRACT

Across the tropics, in both forested and agricultural landscapes, many households are highly dependent on forest resources. Small-holder farmers, many with few alternatives, collect fuelwood, building materials, wild foods, medicinal plants, and other forest products for subsistence or sale. Given continued tropical forest loss coupled with household forest dependence, quantifying levels of forest dependence is important for informing approaches to poverty alleviation and forest conservation. Forest dependence is largely measured using a relative forest income (RFI) approach, notably in the global analysis by the Poverty Environment Network of the Center for International Forestry Research. This approach ascribes monetary values to forest products, which may be unsuitable for contexts where households primarily consume rather than sell forest goods, and which does not address other burdens on households of relying on forest products (e.g., time use). In this paper, we introduce a new Forest Dependence Index (FDI), which measures (at the household level) forest products collected, effort involved in forest product collection, asset-based relative wealth, and non-forest livelihood strategies. Using a case study in Malawi, a country with high rates of poverty and forest ecosystem change, we: 1) demonstrate the FDI and its application; 2) compare the FDI to RFI; and 3) assess how the sub-indices contribute nuance to the FDI values. We calculate the FDI for agricultural communities in southern Malawi using household surveys that we conducted on income, assets and use of all forest products (e.g., amounts collected, walking time to collection sites). We show that the majority of households had intermediate FDI but low RFI values. We demonstrate how households can have the same RFI yet varying FDI values. Ultimately, we show that the FDI provides insight into multiple livelihood aspects of dependence and is a valuable addition to the RFI method for informing forest-based poverty alleviation strategies.

1. Introduction

Households in the global south depend on forests for numerous ecosystem services. Small-holder farmers living adjacent to forests collect multiple forest products for consumption and in some cases for sale, particularly fuelwood, building materials, wild foods and medicinal plants (e.g., Byron & Arnold, 1999; Vedeld, Angelsen, Bojö, Sjaastad, & Kobugabe Berg, 2007; Angelsen et al., 2014). In impoverished communities, household dependence on forests for provisioning ecosystem services may be high, especially in the absence of alternatives (Neumann & Hirsch, 2000, Angelsen & Wunder, 2003, Timko, Waeber, & Kozak, 2010). Forest-dependent households expend time and effort to harvest forest products, making it a labour-intensive livelihood strategy (Pattanayak & Sills, 2001; Fisher, Shively, & Buccola, 2005; Angelsen et al., 2014). When deforestation and forest degradation occur, it is often the forest-dependent poor who have the most to lose.

Poverty is interrelated with dependence on forests in multiple and potentially conflicting ways. On the one hand, high forest dependence together with poverty may indicate a lack of access to livelihood alternatives or even may be a cause of poverty as many forest products are economically marginal and have poor income generation potential (Angelsen & Wunder, 2003). On the other hand, forests act as safety nets for the rural poor in times of unexpected scarcity, or as gap fillers in times of regular seasonal shortfalls (Angelsen & Wunder, 2003; Shackleton & Shackleton, 2004; Paumgarten, 2005). In either case, impoverished households in areas with forest cover tend to be more dependent on forest

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products than the less impoverished, as they lack alternatives to supply their needs (Reyes, Nelson, & Zerriffi, 2018).

How we measure both poverty and forest dependence matters in assessments of the relationships between household well-being and forest resources. Poverty and forest dependence are typically measured using household income (Angelsen & Wunder, 2003; Vedeld et al., 2007; Angelsen et al., 2014), a point on which we will elaborate later. When discussing levels of poverty and forest dependence it is important to differentiate between the absolute and relative forest income (RFI) that is derived from forests: absolute forest income being the sum total of the monetary value of products harvested from the forest, and RFI being the proportion of household income comprised by forest income. Absolute forest income has been widely shown to increase as total household income increases (Vedeld et al., 2007; Nielsen, Pouliot, & Kim Bakkegaard, 2012; Córdova, Wunder, Smith-Hall, & Börner, 2013; Angelsen et al., 2014). Conversely, case studies (e.g., in Zimbabwe) have shown that relative forest income decreases as total household income increases (Cavendish, 2000; Campbell & Luckert, 2002), although this relationship did not hold in a large-scale study which compared multiple case studies from around the world (Angelsen et al., 2014). The use of forests for commercial purposes may increase relative forest income for wealthier households, and limited access to forests may decrease relative forest income for the less wealthy (Belcher, 2005; Timko et al., 2010; Angelsen et al., 2014). This varying evidence points to a complex and dynamic relationship between forests and livelihoods, requiring suitable metrics for evaluating household forest dependence.

Measurements of poverty beyond income-based measures, for instance using asset-based measures, show different trends than when considering income alone. For example, a case study in the Democratic Republic of Congo showed that households in intermediate wealth quintiles based on asset holdings had the highest relative forest income (rather than those with the lowest total income) and the highest absolute forest income (rather than those with the highest total income) (Nielsen et al., 2012). Measurements of income and assets together help to identify different types of poverty, including the chronic poor (low income, low assets), transient poor (low income, high assets), transient rich (high income, low assets), and chronic rich (high income, high assets) (Nielsen et al., 2012). The different groups depend on forests in different ways, for example with a higher proportion of transient and chronic rich households harvesting more valuable forest products (e.g. timber and poles) than poor households (Nielsen et al., 2012). Rural households with higher wealth generally have more options in preparing for and responding to shocks and thus may be less forest dependent (Dercon, 1998). In general, forests support the consumption needs of the chronic poor, act as a safety net for the transient poor, and may provide a pathway out of poverty for the transient rich (Nielsen et al., 2012; Reyes et al., 2018).

Given high rates of tropical deforestation and forest degradation in many regions where communities are highly dependent on forests, quantifying the extent of forest dependence is important for informing forest-based poverty alleviation strategies (Sunderlin, Angelsen, & Wunder, 2004). Existing methods of measuring forest dependence generally rely on converting forest products into monetary values and comparing to a household's overall income. This method does not incorporate the various burdens of forest collection or the factors that influence a household's economic vulnerability and adaptive capacity.

In this paper, we propose a new index of household forest dependence, henceforth called the Forest Dependence Index (FDI), that incorporates multiple livelihood dimensions involved in the collection of forest products as well as alternative livelihood resources. We address the following objectives and test the efficacy of the FDI, using a case study in Malawi, to:

Introduce the calculation of the FDI and to demonstrate its application.

Compare the FDI to the commonly used forest income method for measuring forest dependence.

Assess the construction of the index, and how the sub-indices and different aggregation methods can be used to provide information on forest dependence.

In the next section, we review the literature on forest dependence and introduce the use of indices. We then describe how we developed the FDI, tested it with data from the case study in Malawi and compared it to the forest income method. We present the findings and discuss the importance of the FDI.

1.1. Defining forest dependence

Forest dependence draws on the concepts of "forest use" and "forest reliance" yet is a distinct concept. Forest use includes: the practices involved in harvesting forest products, the use of other provisioning services from forests such as water, the use of forests as land for agriculture, and use for other cultural practices (Campbell, 2005; Sunderlin et al., 2005; Anthwal, Gupta, Sharma, Anthwal, & Kim, 2010). Forest reliance has been described as a form of economic insurance, support for consumption, and a means of poverty reduction (Pattanayak & Sills, 2001; Angelsen & Wunder, 2003; Fisher, 2004). Hence, forest use entails the interaction(s) with the forest, and reliance may be temporary or periodic, whereas dependence entails on-going livelihood strategies associated with forests. In this paper, we focus on the concept of dependence rather than use or reliance.

Several definitions of forest dependence have been discussed in the literature and their disparities affect approaches to quantification. Byron and Arnold (1999) discussed the multiplicity of notions of "forest dependent peoples" by identifying multiple groups with forest relationships (populations living within forests, farming communities, and commercial users) and by describing multiple reasons that households depend on forests, from a purposeful choice to a last resort. Relationships that communities have with forests range from those that are strictly economic to those with strong cultural and spiritual dimensions (Byron & Arnold, 1999; Youn, 2009). Sunderlin et al. (2005) described forest dependence in terms of reliance on ecosystem services, subsistence needs, safety nets, gap fillers and opportunities for poverty elimination from forest use. Angelsen and Wunder (2003) differentiated between two types of dependence: "a dominant source of subsistence and cash income" versus "supplementary way[s]," and described five aspects of forest benefits: different groups of beneficiaries; types of forest products and services; the role of forests in the household economy or livelihood strategy; the extent of forest resource management; and use of high versus low value forest products. Dubois (2003) described the contribution of forests for subsistence goods, goods for sale, income from employment, and indirect benefits (other ecosystem services) for dependent peoples. Newton, Miller, Byenkya, and Agrawal (2016) introduced a typology of definitions of "forest dependent peoples," based on a focus on dimensions of forests, dependence, or peoples, separately. Forest dimensions include a) products, and b) environmental services; dependence dimensions include a) livelihoods emphasis, and b) reliance emphasis; and people-centred dimensions focus on the spatial relationship communities have with forests (Newton et al., 2016). There may not exist a universally agreed upon definition of forest dependent peoples (Newton et al., 2016), thus when measuring forest dependence it is important to clarify the type of forest dependence being quantified and the relationship(s) the communities have with forests.

While we acknowledge that researchers conceive of forest dependence in a variety of ways, we have chosen to follow a definition of household forest dependence that incorporates the forest and the dependence dimensions articulated by Newton et al. (2016). Under the forest dimensions we emphasize forest products, and under the dependence dimensions we incorporate both livelihoods and reliance. We focus on measuring provisioning services provided by forests, as these are readily quantifiable and have been quantified in previous measurements of dependence (i.e. income from forest products). We nonetheless acknowledge the existence of numerous additional forest ecosystem services, including cultural, regulating and supporting services (Daily, 1997; Maass et al., 2005). Here, we conceptualize household forest dependence as the activities of forest product collection and consumption that constitute a key livelihood strategy used to meet household needs. We emphasize the direct extraction of products from forests for consumption, and the socio-economic characteristics of households that indicate whether or not they have alternatives to a forest-based livelihood.

It is important to define the term "forest products", and to specify the ecosystem from which forest products are collected. Forest products are all physical goods of biological origin – either plant, animal or fungi – derived from forests (Belcher, 2003). Given forest degradation and conversion of forests to other land use/land cover types, households in rural mosaic landscapes collect "forest products" from several ecosystem types, including non-forest ecosystems such as shrublands (Angelsen & Wunder, 2003). Forest products contribute to environmental income, that is, the income derived from all "non-cultivated sources," including forests and woodlands, wildlands (ex., savannahs and grasslands), bushlands, wetlands, fallows and wild (uncultivated or undomesticated) plants and animals harvested from croplands (Sjaastad, Angelsen, Vedeld, & Bojö, 2005; Angelsen et al., 2014). Forest environmental income is differentiated from non-forest environmental income, the former being the collection of forest products specifically from forest ecosystems. When measuring forest dependence, it is important to quantify forest products collected from forest ecosystems that follow standard forest definitions, including natural woodlands, because the attention is therefore on forests rather than other land cover/use types that may supply forest products.

1.2. Measuring forest dependence

Dependence on productive ecosystem services from forests has primarily been measured using forest income (discussed further below). There have been a few non-income based approaches to quantifying forest dependence, but none have seen widespread application. In a study on livelihood diversification and ecological conservation outcomes in Cameroon, Kimengsi, Pretzsch, Kechia, and Ongolo (2019) elicited household preferred livelihood strategies; a higher rank for forest-based strategies indicated a higher forest dependence. Ofoegbu, Chirwa, Francis, and Babalola (2017) asked households to rank (using a four-point scale from no contribution to a high contribution) the importance of forests for income, subsistence, livelihoods and resilience to climate change in South Africa. Similarly, in a study on household participation in forest management in Kenya, Wambugu, Obwoyere, and Kirui (2018) quantified forest dependence with respect to the degree of collection of forest products and other interactions with the forest such as livestock grazing, on a scale of: very low, low, moderate, high and very high.

The forest income approach focuses on economic dependence by eliciting the quantities of forest products collected by a household and the monetary value of the products, to quantify the income equivalent of harvested forest products (Cavendish, 2000). Early seminal studies by Cavendish (2000) and Campbell and Luckert (2002) on forest and environmental incomes inspired several further studies, including the Poverty and Environment Network (PEN) project (Angelsen et al., 2014; Wunder, Angelsen, & Belcher, 2014). Significant for its breadth of 24 countries and roughly 8000 surveys, the Center for International Forestry Research (CIFOR) led the PEN global comparative analysis using the forest income measurement (Angelsen et al., 2014). Forest income was determined to comprise on average 26.8%, 20.1% and 21.4% of rural household income in Latin America, Asia and Africa respectively (Angelsen et al., 2014).

The dominance of the forest income approach stems from the history of income quantification in household economics research and policy. Traditional notions of poverty were limited to income and material wealth, following classical economists such as Adam Smith and David Ricardo (Angelsen & Wunder, 2003; Sen, 2006; Wagle, 2008). Until the 1960s, policies on poverty alleviation emphasized increasing household income, but in recent decades the definition of poverty has been extended to include non-material aspects of well-being, such as health and education (Sen, 1992; Bossert, Chakravarty, & D'Ambrosio, 2013; King, Renó, & Novo, 2014). Measuring, describing and analyzing poverty have hence expanded to become more holistic, such as with the sustainable livelihoods framework which incorporates multiple forms of capital – natural, human, social, physical and financial – to reflect the multiple resources available for livelihoods (Scoones, 1998). In a similar vein, capturing the complex nature of forest dependence by going beyond income measurements may be beneficial for better understanding the livelihood implications of dependence, yet such approaches have not yet been attempted.

Measuring forest dependence using forest income has the key advantage of a common unit (income), yet the method has limitations. Household incomes fluctuate monthly, seasonally, and annually, and households may not keep rigorous accounts of their income flows, leading to decreased accuracy of income estimates through household surveys (Rutstein, 2008; Nielsen et al., 2012). Additionally, estimating forest income through amounts of forest products used does not account for the burden or inconvenience households face in the collection of forest products. The effort households undertake in the collection of forest products can be significant, especially for households with smaller farms and fewer trees to provide forest products, hence requiring household members to walk farther distances and carry heavier loads when collecting products (Heltberg, Arndt, & Sekhar, 2000). Here we assume forest product collection is perceived by households as a burden, although in some communities collection may not be perceived as such, where forest collection is undertaken as a part of life that contributes to customs and rituals such as in the harvesting of medicinal plants (e.g. Cunningham, 1993; Lebbie & Guries, 1995). Time poverty is also an issue for household members, especially for women who are responsible for much of household forest collection particularly in Africa (Sunderland et al., 2014), because their opportunities to engage in other aspects of the household economy or personal development are limited by the lack of time (Blackden, Wodon, & Shetty, 2006). Lastly, monetization of forest products is unrealistic in situations when households primarily consume rather than sell products. Given the limitations of the forest income method, and the additional factors involved in livelihood dependence for provisioning ecosystem services, we propose the FDI, a multi-variable index that is complementary to the forest income measurement.

1.3. Uses of indices

Indices, also called composite indicators, have been widely used in research and policy, particularly to assess economic development at the international level (Booysen, 2002). The Human Development Index and the new Multidimensional Poverty Index are examples. Indices are a valuable tool used to illustrate complex issues from a variety of disciplines with interpretable values (Nardo et al., 2005). Indices often evaluate and compare countries, but comparisons at the household level are also possible, such as with the Energy Poverty Index (Mirza & Szirmai, 2010). The FDI measures forest dependence at the household level.

The basic steps for constructing indices include selection, scaling, weighting and aggregation, and validation (Booysen, 2002). Selection involves the choice of relevant and measurable sub-indices and variables (Freudenberg, 2003). Scaling involves employing an approach to data normalization such as ranking, standardization or re-scaling so that data can be aggregated (Freudenberg, 2003; Nardo et al., 2005). Weighting is used to assign the relative importance of components, whether equal or not (Freudenberg, 2003). Aggregation combines components using one of multiple possible methods: linear or geometric, additive or multiplicative, or multivariate (Nardo et al., 2005). Lastly, the validation process tests for robustness of the index, such as through uncertainty and sensitivity analyses (Saisana & Tarantola, 2002). In the following section we will further discuss each of the steps with respect to the FDI.

A key advantage of using an index to measure forest dependence is the ability of indices to summarize complex issues into a single metric (Saisana & Tarantola, 2002). The FDI incorporates multiple livelihood aspects of forest dependence. In the next section, we outline the framework for the FDI and its application to a case study in southern Malawi.

2. Methods

2.1. Framework for the FDI

We have identified four key livelihood aspects of household dependence on forests for provisioning services that constitute the sub-indices of the FDI. The first two sub-indices relate to the collection of forest products, while the last two relate to household livelihoods in terms of economic adaptive capacity and alternatives to forest collection. The forest product sub-indices measure the diversity of forest products collected to meet household needs, the extent to which these products collected from forests are important, and the effort involved in collection, all of which indicate that harvesting products from forests entails an important livelihood strategy. The livelihoods sub-indices measure the alternatives that households have to harvesting products from forests, given levels of wealth and alternative livelihood strategies; dependence is lowered for households with more alternatives. Individually the sub-indices do not measure dependence, but when combined the sub-indices provide a comprehensive quantification of livelihood dependence on forests.

The first sub-index is *forest collection importance*, which captures the contribution of products collected from forests to supplying household needs. *Forest collection importance* measures the proportion of products collected from forests (Pimentel, McNair, Buck, Pimentel, & Kamil, 1997; Newton et al., 2016) compared to all sources of forest products used by a household, including those that are purchased or collected from non-forest locations such as trees on the homestead. Hence, the values indicate the degree to which households depend on the direct extraction of these products from forests for consumption (and potentially sale), rather than the derivation from other sources. While proximity to markets versus forests affects accessibility of product sources (Timko et al., 2010), if a household can afford to purchase products from the market rather than collecting them from forests, they can be considered less forest dependent. Conversely, dependence increases with increasing reliance on multiple products from forests to meet household needs (Shackleton, Delang, & Angelsen, 2011). The essential variables for the *forest collection importance* sub-index are the amounts of each product harvested from the forest and the amounts of each product from non-forest sources. The amount of a product from the forest is divided by the total amount from all sources, to yield a proportion value (similar to the RFI but not monetized).

The next sub-index is *effort*, measured in terms of the physical labour and time expended in the collection of forest products. This sub-index reflects the potential burden on a household of collecting forest products. With increasing labour (daily, weekly or monthly) spent on collecting forest products (Pattanayak & Sills, 2001), dependence increases. The essential variables in the *effort* sub-index include the amount (mass) of the forest product collected from the forest and the time spent walking to the collection site. Additional relevant variables that could be incorporated include the time spent collecting forest products (Brouwer, Hoorweg, & van Liere, 1997), frequency of collection (Liswanti, Sheil, Basuki, Padmanaba, & Mulcahy, 2011), number or proportion of household members who collect forest products, number of genders who collect (Sunderland et al., 2014), and number of age groups who collect (Paumgarten, 2005). The amount and walking time values for each forest product are aggregated in the construction of the FDI to account for the fact that households collect multiple products. While the amounts of forest products are also measured in the *forest collection importance* sub-index, the sub-indices are both mathematically distinct (proportion values versus aggregated values) and conceptually different (importance of forest products versus physical labour involved in collection).

The penultimate sub-index is *relative wealth*, measured using an asset-based approach. Using an asset as opposed to income measurement portrays long-term economic status more effectively, as assets are accumulated with savings over time (Filmer & Pritchett, 2001). Household wealth, accumulated over the long term, is an indicator of alternatives to forest product collection. With decreasing wealth, households lack alternatives to forest collection and dependence increases (Angelsen & Wunder, 2003). The essential variables are household asset holdings, which are used to construct a comparative wealth index. The methodology used here to calculate the wealth index follows that outlined and used extensively in the analysis of Demographic and Health Survey (DHS) data (Rutstein, 2008), as originally proposed by Filmer and Pritchett (2001).

The final sub-index is *non-forest livelihood strategies*. Rural households tend to diversify their livelihoods to enhance income sources and reduce risk (Sunderlin et al., 2005). The number of livelihood strategies indicates economic standing in the short to medium term (Barrett, Reardon, & Webb, 2001), as well as alternatives to forest dependence. A decreasing number of non-forest income sources, hence a less diversified livelihood, means that household dependence on the forest increases because the household has fewer livelihood alternatives to adapt and respond to shocks (Ellis, 1999; Wunder, Börner, Shively, & Wyman, 2014). The variable in this sub-index is the number of livelihood strategies that provide income or subsistence production (i.e., farming). Agriculture, wage labour, and businesses are examples, as well as remittances and cash allowances from governments or NGOs. To calculate the sub-index, the number of strategies a household employs is simply summed. *Relative wealth* is differentiated from *non-forest livelihood strategies* as the former indicates long-term wealth while the latter indicates economic status over a shorter term, and the former quantifies wealth while the latter measures the strategies that contribute to the household economy.

While several methods of combining the sub-indices to form the FDI are possible, we recommend one method and also mention alternatives. Note that the variables for each sub-index must be measured using a common unit for all forest products and all households. All sub-indices are standardized across the households in the sample in their calculation (Fig. 1). The proposed aggregation method uses an additive approach that occurs at the forest product level, meaning that the *forest collection importance* and *effort* sub-index values are summed first per forest product, and then the values for all forest products per household are summed. Weights could be assigned to forest products depending on their comparative value to a household. One could also assign weights to the sum of the two sub-indices that capture information on forest products (*forest collection importance* and *effort*) and the sum of the two sub-indices that capture information on livelihoods (*relative wealth* and *non-forest livelihood strategies*). An alternative aggregation approach would be to aggregate at the sub-index level, where each sub-index would be calculated separately at first, then all sub-indices would be combined. The sub-indices could therefore be weighted individually, if some were deemed more important than others in contributing conceptually to forest dependence. Such a method would, however, separate the *forest collection importance* and *effort* values for individual forest products. One negative consequence of this approach would be the loss of information on a forest product collected in a smaller volume by a household, such as medicinal plants as opposed to fuelwood. To overcome this, identical weights could be assigned to the forest product in question (e.g. medicinal plants) in both the *forest collection importance* and *effort* sub-indices, to raise the value for said product.

The additive aggregation method is used in cases where data are in a partially or fully comparable interval scale; if the interval scales are not comparable, a geometric weighting scheme must be applied (Ebert & Welsch, 2004; Nardo et al., 2005). Standardization of the household values of the variables ensures that the data are in a comparable interval scale. Another aggregation method, the multi-criteria or multivariate approach can be used when index components have varying significance and require different weights (Nardo et al., 2005). An additive approach also implies full compensability, where low performance in some variables can be overcome by higher performance in others, whereas a multi-criteria approach implies non-compensability, and a geometric approach falls in between the two (Nardo et al., 2005). For the purposes of this paper (a proof of principle for the FDI) we do not take a stand on the compensability of the metrics chosen but use the additive approach for its simplicity to demonstrate the method.

In the application of the FDI values, it is important to recognize their relative nature. The FDI values are similar to the DHS wealth index scores in that they can be compared within the sample used to create it but should not be compared across samples. This is because the scores have been constructed based on the sample population's data range and context (Howe, Hargreaves, & Huttly, 2008). The relativity of the FDI values stems from the incorporation of the DHS wealth index, and from the standardization of the data across the sample population. Therefore, the FDI values cannot be directly compared across samples, but the distributions of values and the importance of different sub-indices could be compared to assess dependence across samples. Such comparisons could only be conducted if the data have been collected in the same way, the variables and aggregation methods are the same, and the social-ecological contexts are similar. Additionally, we will demonstrate a method of pooling the data from multiple sites to be able to analyze the FDI values across samples.

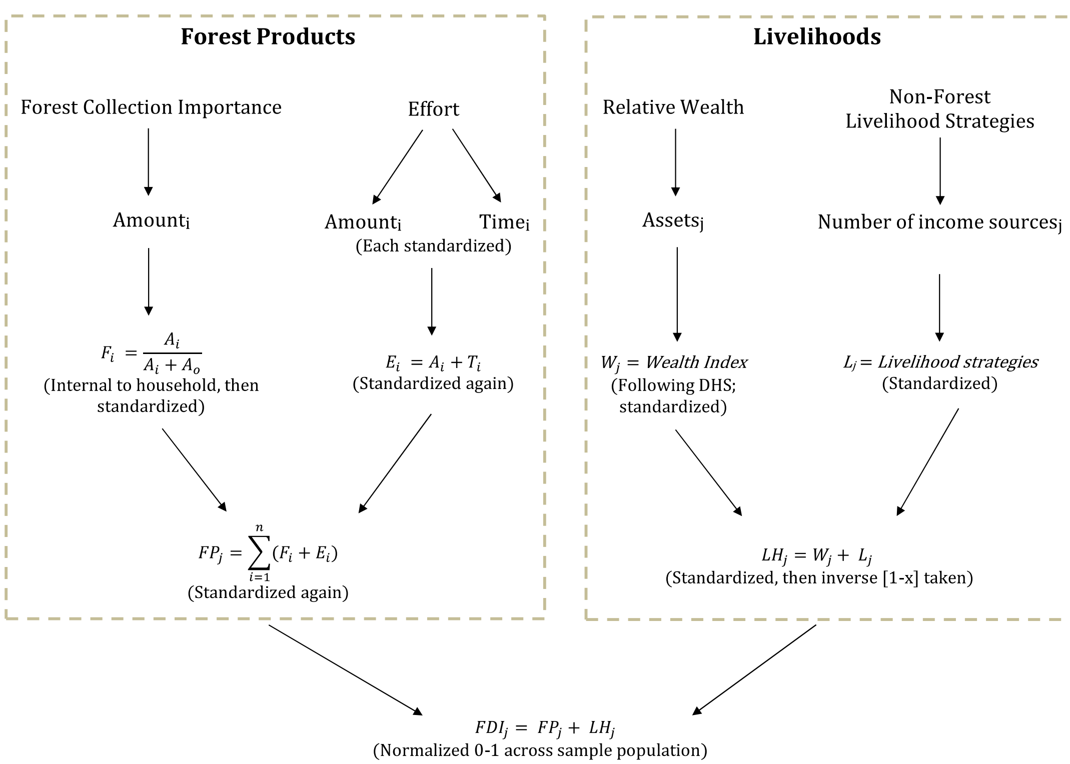

Fig. 1. Flowchart showing the steps involved in calculating the Forest Dependence Index (FDI). Aggregation is additive and occurs at the forest product level, meaning that *forest collection importance* and *effort* values are combined per forest product first, then summed over all products at the household level. Dashed line boxes are shown for emphasis of the aggregation of the forest products and livelihoods sub-indices. Abbreviations are as follows: F = *forest collection importance*, E = *effort*, W = *relative wealth*, L = *non-forest livelihood strategies*, FP = forest product sub-indices combined, LH = livelihoods sub-indices combined, A = amount, T = time, n = total number of forest products. Subscripts are as follows: i = forest product level, j = household level, o = other source. The z-scores standardization method is used across the sample population for all intermediate steps, and the re-scaling normalization method is used in the final calculation of the FDI.

2.2. Case study in southern Malawi

To assess the efficacy of the proposed FDI, we applied it to data from a case study in southern Malawi. Malawi is an ideal location in which to study levels of forest dependence given the use of various forest products by a population that is low income. Among the most impoverished countries in the world, Malawi had the sixth lowest per capita purchasing power parity (PPP) in 2017 (IMF, 2017; UN, 2017). It is densely populated (152 people per km^2), with 68% of rural women and 52% of rural men engaged in agricultural production (NSO, 2017). Less than 10% of the population have access to electricity, and all households use firewood or charcoal for fuel, either as a primary or secondary energy source (Zulu, 2008; Dasappa, 2011). Rural households burn on average 5 kg of fuelwood per day at our study site (Nerfa and Rhemtulla, *unpublished data*). Deforestation rates are high at 0.6 to 1.0% forest cover loss per annum from 1990 to 2015; forest degradation rates are similar if not higher (Kamanga, Vedeld, & Sjaastad, 2009; FAO, 2015). The main proximate causes of forest loss and degradation are land clearing for agriculture and charcoal production (Fisher, 2004; Zulu, 2008). Agricultural communities in Malawi collect fuelwood and other products from nearby forests, such as village forests on communal lands, state-owned forest reserves, and private woodlots (Zulu, 2010). Harvesting of certain products is permitted in forest reserves, including dry wood, thatch, fodder, medicinal plants, fruits and wild foods (Kamanga et al., 2009). Households also collect forest products from other land use/land cover types with tree cover such as farms and homesteads (i.e. agroforests) (Kuyah, Sileshi, Njoloma, & Mng'omba, S., & Neufeldt, H. , 2014).

Household surveys (n = 157) were conducted from June to July in 2016 to quantify how forest products contribute to household livelihoods. We focused on measuring the collection of forest products, hence provisioning ecosystem services, and did not investigate additional ecosystem services or cultural forest use. The study boundary encompassed nine villages in one water catchment adjacent to the Zomba-Malosa forest reserve in the Zomba district of southern Malawi. Our local collaborator facilitated initial meetings with village heads to request permission to conduct the research. We randomly selected households to survey by identifying and tagging rooftops in Google Earth Pro© then used a random number algorithm to select the houses to visit (Google, 2013). The final sample comprised approximately 30% of households per village.

The household survey was adapted from the PEN prototype questionnaire (CIFOR, 2008). The surveys were conducted in the local language Chichewa by research assistants hired as translators and informed consent was obtained from all participants. The survey questions focused on household demographics, assets, income and production, and collection of forest products. Note that the FDI was developed after the design and execution of the household surveys. Assets included buildings owned, valuable items owned, savings and land holdings. Income and production included all sources in the last year: agriculture, livestock, animal products, wage income, business, and other sources (ex. remittances), as well as the associated input costs (where applicable). Agricultural crops, livestock and animal products that generated income or that were used for subsistence purposes were included. Forest product categories included fuelwood, timber, wild food (ex. fruit, honey, mushrooms), wood for crafts, medicinal plants, fodder, and animals hunted. Forest product collection locations included forest reserves, village forests, private woodlots, homesteads, and the household's own farm. For each forest product, the households were asked where they collected the product, how much they collected in the past month and how long it took to walk to the collection site on a typical trip.

2.3. Calculating the FDI using the Malawi data

The FDI was calculated using only fuelwood and wild foods, since all of the essential variables were available for these products, but not for timber, craft wood, medicinal plants, fodder, and animals. We did not collect data on other sources of these forest products. Multiple meta-analyses, however, have found that fuelwood and wild foods were the two most important forest products in economic forest dependence (Vedeld et al., 2007; Angelsen et al., 2014). We treated the forest products equally, although weights could be assigned. We included fuelwood and wild foods collected from all forest ecosystems (village forests, forest reserves and private woodlots). We used the z-scores standardization technique across the sample population throughout the FDI calculation which results in a mean of 0 and standard deviation of 1, until the final step at which time we normalized the final FDI value using rescaling across the sample population, resulting in a range of 0 to 1.

For the *forest collection importance* sub-index, we determined the average amount of fuelwood and wild food collected from forests and the amount acquired from all other sources in the past month, in kilograms, for each household. 'Other sources' of fuelwood included amounts collected from the homestead and farm, and the amount purchased in Malawi Kwacha (MWK). We converted the monetary value in MWK to a kilogram value using the market value of 35 Kwacha per kilogram, as informed by our local community contact. 'Other sources' of wild foods were the amounts collected from the homestead and farm, wild foods purchased (only three households reported this), and the household's crop production in the past month, where we divided the annual amount in kilograms of all crops produced by 12. The monthly crop estimate has two caveats: that households may not consume the entirety of their crop production and that crop production is not distributed evenly throughout the year. We used this calculation, however, as an estimate in the absence of data on amounts of foods consumed. For each forest product, we divided the amount collected from the forest by the sum of the amount collected from the forest and the amounts acquired from other sources. We then standardized the values using z-scores.

To calculate the *effort* sub-index, we standardized the amounts of fuelwood and wild food in kilograms collected over the past month, and standardized the walking times to the collection sites in minutes. We took the average amount and walking time across all harvesting locations for each product per household, then standardized across all households. We then aggregated the amount and walking time per product, and standardized again.

To calculate the *relative wealth* sub-index, we calculated the wealth index following the DHS method (Rutstein, 2008). We conducted principal components analysis (PCA) on all assets reported for each household using SPSS (IBM Corp. Released, 2016). We used mean substitution for the imputation of missing values for area of buildings owned and number of buildings with the different materials of walls, roofs, windows and doors. All variables were individually standardized across all households prior to conducting the PCA. The final assets included are shown in Table 1.

For the *non-forest livelihood strategies* sub-index, we counted the number of non-forest livelihood sources from which households had derived income or produced for subsistence use in the past year. Possible types were: agriculture (crops produced for income or subsistence use), livestock sold, animal products sold, wage income, businesses owned, land rented out, remittances and social assistance. The last category included social cash transfers, farming input vouchers and hunger relief vouchers from the government, as well as cash support from NGOs. We determined the total number of strategies per household, then standardized the values across the sample population.

Table 1
Household assets used in the principal components analysis (PCA) in the construction of the household wealth index for the *relative wealth* sub-index of the FDI, including whether their values were continuous or binary.

Asset	Continuous	Binary
Use of a community tap water source		✓
Use of a river water source		✓
Land area of buildings owned	✓	
Number of buildings with brick walls	✓	
Number of buildings with a natural roof	✓	
Number of buildings with a metal roof	✓	
Number of buildings with glass windows	✓	
Number of buildings with a solid door	✓	
Area of total land holdings	✓	
Access to irrigation		✓
Number of chickens owned	✓	
Number of ducks owned	✓	
Number of bicycles owned	✓	
Cell phone ownership		✓
Radio ownership		✓

To aggregate the sub-indices, we first summed the standardized *forest collection importance* and *effort* values per product then took the sum over all products for each household and standardized again. We took the sum of the wealth index and the livelihood strategies sub-indices, standardized the value, and took the inverse (1 minus x), to reflect a greater forest dependence for those households with lower wealth and fewer livelihood strategies. We took the sum of the combined *forest collection importance* and *effort* values and the combined (inverse) *relative wealth* and *non-forest livelihood strategies* values. Lastly, we normalized the FDI values across the sample population using re-scaling.

2.4. Comparison of the FDI to the RFI approach

To compare the FDI to the relative forest income (RFI) method of measuring forest dependence, we used the household survey data to also calculate the relative forest income and total income for all households. We converted the amounts of forest products collected into forest income using the average local market values in MWK (informed by our local contact). For fuelwood, we multiplied the monthly amount by 12 to give an annual estimate. For wild foods, we multiplied the monthly amount by six to account for the six-month dry season and six-month wet season which affects the availability of plant products. Annual forest income was estimated from amounts collected from village forests, forest reserves and private woodlots. We added the monetary values of amounts collected from the homestead and own farm to the total non-forest income. We summed all annual income estimates of forest products. To estimate total household income in the past year, we summed all forest and non-forest income sources, and subtracted the input costs to non-forest income sources as applicable. For agriculture, the average local market value in MWK was applied to the total amount of each crop produced and the sum taken. For livestock and animal products, the sum of the income from sales in MWK was taken. If total income from non-forest sources was negative, due to higher input costs than income, the value was set to zero. Lastly, we calculated RFI by dividing forest income by total household income.

One challenge in comparing the FDI with the RFI method is that the former is a relative index that can only be used to compare households within the sample, whereas the latter produces an absolute value for a given household. Thus, we standardized the final FDI values across the households rather than normalizing, and we standardized the RFI values across households, then compared the values. We compared the two metrics using the Kolmogorov-Smirnov test. We tested whether individual households with the same RFI have divergent FDI values by comparing the underlying values for the sub-indices for households with different FDI values but with approximately equal RFI values. This was done by comparing three households (differing FDI) for three categories of RFI: low (approximately 0.2), moderate (approximately 0.6) and high (approximately 1), for a total of nine households.

2.5. Assessment of the construction of the FDI

We assessed the distributions of the sub-indices and observed which sub-index was most similar to the FDI distribution. We tested the internal consistency of the FDI by computing Cronbach's alpha. An alpha value of 0.8 is typically used as evidence that multiple values measure the same essential construct; lower alpha values, however, indicate that the data are multidimensional (Saisana & Tarantola, 2002). We did not perform uncertainty or sensitivity analyses following standard methods for indices because the FDI calculation did not have variation in the typical sources of uncertainty, including data imputation, normalization, weighting, and aggregation methods (Nardo et al., 2005). We used only one method for imputation of missing data (mean substitution), one normalization technique (standardization) other than the rescaling of the final value, one method of aggregation (linear, additive), and did not apply weighting. This was done as it is the first example of the FDI and the goal of this paper is to present the concept in as simple a manner as possible. If future users of the FDI wish to use multiple methods of the above steps, uncertainty and sensitivity analyses should be performed. The design choices we made in constructing the FDI (e.g., standardization technique, aggregation method) will affect the output values of the FDI, thus we were not seeking robustness in the traditional sense for indices. Lastly, because the index measures at the household level rather than at the national level and we do not aggregate the average values of variables within sub-indices across multiple households, we do not need to account for the distributions of the variables in such a way.

We assessed the effects of pooling the data (combining multiple data sub-sets) on the values and distribution of the FDI. We expected that combining versus separating the data into sub-sets would affect the FDI values due to the standardization process, and we aimed to show the importance of pooling the data in order to allow comparisons of sub-sets. Using multiple calculations, we compared the FDI values for two groups of villages: the group that is closer to the Zomba-Malosa forest reserve and the group that is farther away from the forest reserve. Proximity to the forest is expected to affect household forest dependence levels as the *effort* values will be greater for households living farther away from the forest product collection sites. We calculated the FDI in a total of three ways (Fig. 2):

- Pooled – all households in the sample were used to construct the FDI (n = 157), as described above
- Pooled-Separated – all households in the sample were used to construct the FDI, and it was split after construction into two sub-samples:
  - o Four villages closer to the forest reserve (n = 58)
  - o Five villages farther from the forest reserve (n = 99)
- Clustered – the sample was separated by proximity to the forest reserve first, then the FDI was calculated separately for the closer villages and farther villages

We compared the pooled-separated to the clustered subsets by proximity to the forest reserve, and conducted Kolmogorov-Smirnov tests and paired t-tests to check for differences in the distributions and means. We also compared the mean values for close

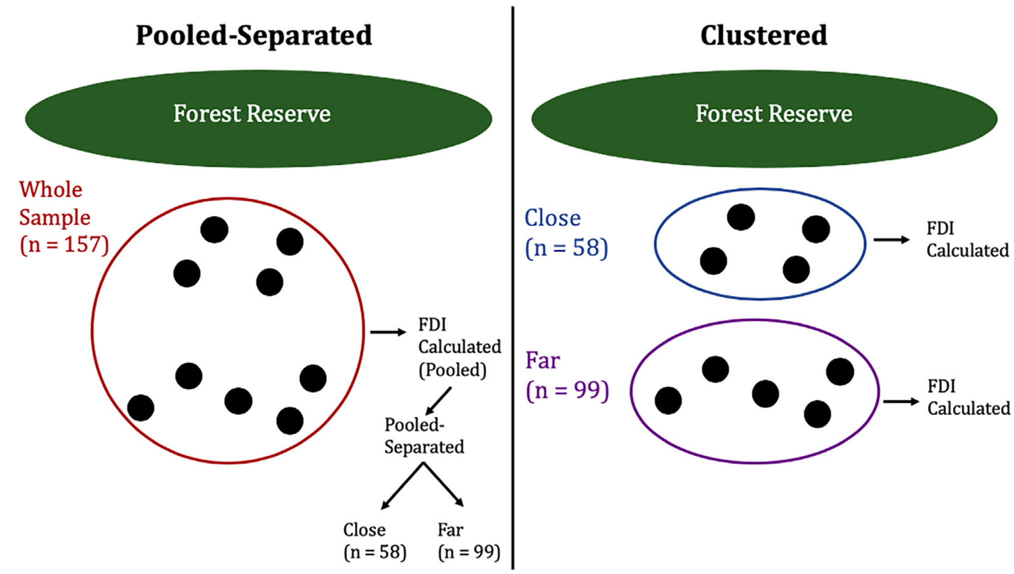

Fig. 2. Diagram showing the analysis of the Forest Dependence Index (FDI) used to investigate the effect of data pooling, which involved three calculations. The first was pooled, where the FDI values were calculated for the whole sample (n = 157). The second was pooled-separated (on left) where pooled values were divided into the two groups: villages closer to the forest reserve (n = 58), and villages farther from the forest reserve (n = 99). The third was clustered (on right), where the sample was divided into the close and far groups initially then the FDI was calculated for each group separately. Locations of villages are not exact but are meant to demonstrate stratification by proximity to the forest.

versus far villages for the pooled-separated method using an independent sample *t*-test.

3. Results

3.1. Forest dependence in southern Malawi

The distribution of the FDI was approximately normal (mean = 0.45, standard deviation = 0.13, n = 157), which suggests that the majority of households had intermediate levels of dependence (Fig. 3). While a roughly normal distribution makes sense following the central limit theorem, given that we added independent variables and normalized the sum, the distribution of the FDI values was not perfectly normal because the distributions of values for the variables in the sub-indices varied.

3.2. FDI versus RFI

Household incomes in the study area in Malawi were low; 97% of households were below the poverty line of $1.90 USD per person per day (Roser & Ortiz-Ospina, 2017). Agriculture was the most important income source for households, followed by wage income and income from businesses owned (Supplementary Materials Table 1). The mean household forest income was 12% of the mean non-forest income, and 9% of the mean total income (Table 2).

The FDI values differed greatly from those derived from the RFI method (Fig. 4). The distributions were significantly different (Kolmogorov-Smirnov D value = 0.21, p = 0.00097). The RFI distribution was right skewed, whereas the FDI had roughly a normal distribution. As the two metrics were both standardized, the mean values were both 0 and the standard deviation values were both 1. For RFI, the majority of households had low values, whereas for the FDI the majority of households had intermediate values. Considering individual households, 81 households (52% of the sample) had lower standardized RFI values than FDI values, while 76 households (48%) had lower standardized FDI values than RFI values.

A comparison of nine households (three for each of low, medium and high RFI values), showed that the FDI distinguished households in a different manner than RFI (Table 3). The varying walking times, amounts of forest products collected, *forest collection importance* values, number of non-forest livelihood strategies and wealth index values differentiated the households into distinctive FDI values despite their similar RFI values. For example, looking at two households with a medium RFI of approximately 0.6: the first (FDI = 0.66) had high fuelwood walking times and amounts,

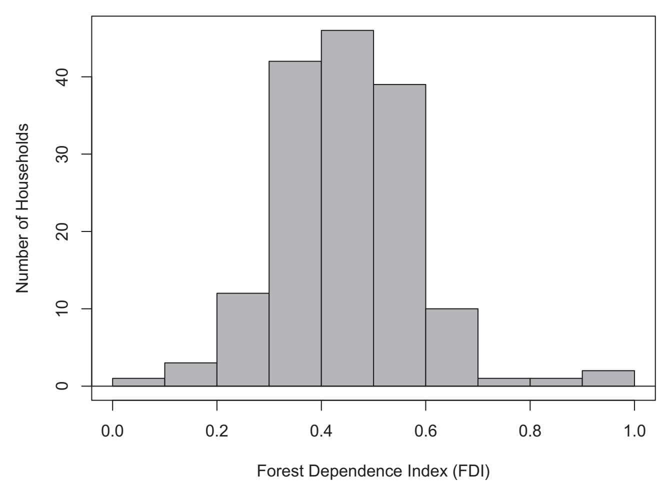

Fig. 3. Histogram of household values for the Forest Dependence Index (FDI) (mean = 0.45, SD = 0.13) for the study area in southern Malawi (n = 157).

Table 2
Annual forest, non-forest, and total household income in U.S. Dollars (1 MWK = 0.0014 USD in 2018), for the study area in southern Malawi (n = 157). The income from fuelwood and wild foods collected from homesteads and farms was added to the total income. All minimum values were 0.

	Mean (USD)	Max (USD)	SD
Forest income	57	1274	127
Non-forest income	481	5507	741
Total household income	637	5540	844

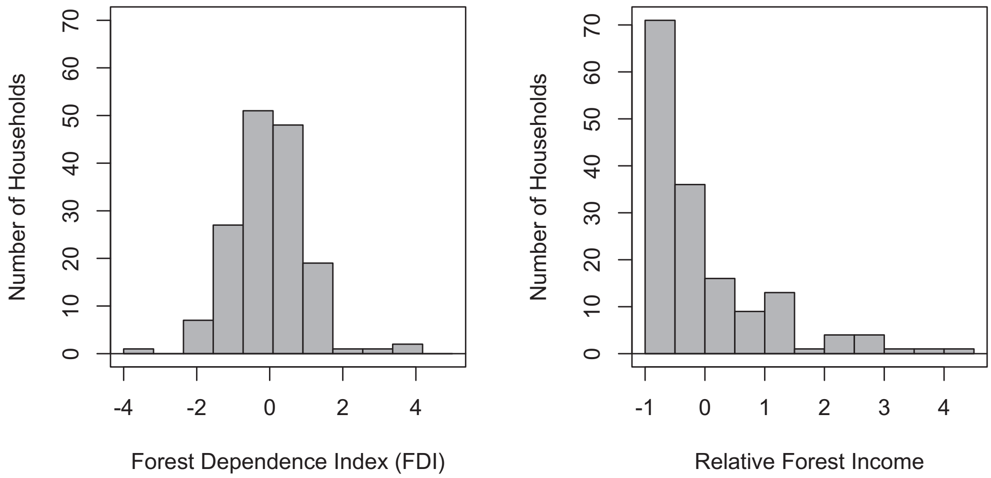

Fig. 4. Histograms of household values in the study area in southern Malawi (n = 157) for forest dependence as measured using relative forest income (RFI), the proportion of total household income comprised by forest income, compared to the Forest Dependence Index (FDI), both standardized using z-scores. Monetary values of forest products collected from homesteads and farms were added to the total non-forest income. Both mean values are 0 and both standard deviation values are 1.

Table 3
Comparison of three households each with low (~0.2), medium (~0.6) and high (~1) relative forest income (RFI) values and divergent Forest Dependence Index (FDI) values. Individual households are labelled HH1 to HH9. Checkmarks indicate whether households collected forest products from the forest reserve, village forest, or both. Values for fuelwood walking time and amount separated by commas correspond respectively with the locations listed (forest reserve and village forest).

	Relative Forest Income (Approx. 0.2)			Relative Forest Income (Approx. 0.6)			Relative Forest Income (Approx. 0.1)		
	HH1	HH2	HH3	HH4	HH5	HH6	HH7	HH8	HH9
Forest Dependence Index (FDI)	0.55	0.39	0.26	0.86	0.53	0.33	1	0.59	0.43
Relative forest income	0.19	0.19	0.27	0.68	0.58	0.6	0.9	1	1
Non-forest income (USD)	671	152	205	265	67	8	25	0	0
Non-forest livelihood strategies	3	3	4	3	3	3	1	2	2
Wealth index	−0.8	0.02	1.82	0.12	−0.65	0.58	−0.13	−0.99	0.47
Fuelwood walking time (mins)	30	420	120	120, 30	120	30	200	180	180
Fuelwood amount (kg)	270	16	126	300, 300	160	21	240	24	1.5
Forest reserve	✓	✓	✓	✓	✓	✓	✓	✓	✓
Village forest				✓					
Fuelwood forest collection importance	1	0	1	0.86	0.53	0.33	1	0.67	0.33
Wild foods walking time (mins)	140	9	30	120	0	0	45	0	240
Wild foods amount (kg)	0	4	0	35	0	0	15	0	0
Forest reserve	✓	✓	✓				✓	✓	✓
Village forest				✓					
Wild foods forest collection importance	0	0.02	0	0.24	0	0	0.54	0	0

collected from both the forest reserve and village forest, and collected wild foods from the village forest; the second (FDI = 0.31) had a relatively low walking time and amount for fuelwood and did not collect wild foods. These two households had the same number of non-forest livelihoods but the latter household had a higher wealth index which contributed to the lower FDI value.

3.3. FDI construction assessment

The distributions of the sub-indices varied, and each provided a different contribution to the final distribution of the aggregated FDI values. Within the forest product sub-indices, the range of the wild foods *forest collection importance* was larger than that of fuelwood *forest collection importance* (Supplementary Materials Fig. 1). The vast majority of households had low wild foods *forest collection importance* values, while fuelwood *forest collection importance* values tended to be either high or low. Most households had intermediate values of fuelwood *effort* while most households had low values of wild foods *effort*. Within the livelihoods sub-indices, the majority of households had low wealth index values and intermediate numbers of livelihood strategies (Supplementary Materials Fig. 2). The *relative wealth* values were not correlated with the *non-forest livelihood strategies* values, indicating the distinction between these two sub-indices. The distribution of the final FDI values appears most similar to the inverse of the *relative wealth* and *non-forest livelihood strategies* sub-indices combined (Fig. 5).

The Cronbach alpha value was 0.22, indicating relatively low internal consistency. This is reasonable as forest dependence is not a unidimensional construct, and there are conceptual differences between the four sub-indices, where *forest collection importance* and *effort* pertain to the collection of forest products while *relative wealth* and *non-forest livelihood strategies* pertain to adaptability of the household economy.

When the pooled-separated subsets were compared with the clustered subsets, by village proximity to the forest reserve, the distributions and means were significantly different for villages farther from the forest, and the means were significantly different for villages closer to the forest reserve (Fig. 6). For farther villages, the pooled-separated values were shifted higher and the mean was higher than for the clustered sub-set (pooled-separated mean = 0.46, clustered mean = 0.39; *t*-test p-value less than 2.03e^{-09}; K-S D value = 0.32, p-value = 3.22e^{-05}). For the closer villages, the mean of the clustered values (0.45) was higher than that of the pooled-separated values (0.41; p-value = 0.045).

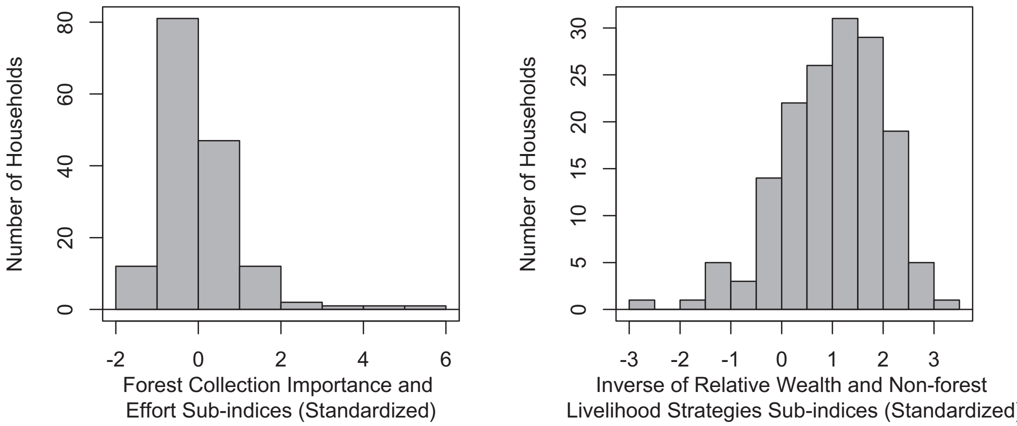

Fig. 5. Histograms of household values (standardized using z-scores) for the *forest collection importance* and *effort* sub-indices combined and the inverse of the *relative wealth* and *non-forest livelihood strategies* sub-indices combined, for the study area in southern Malawi (n = 157).

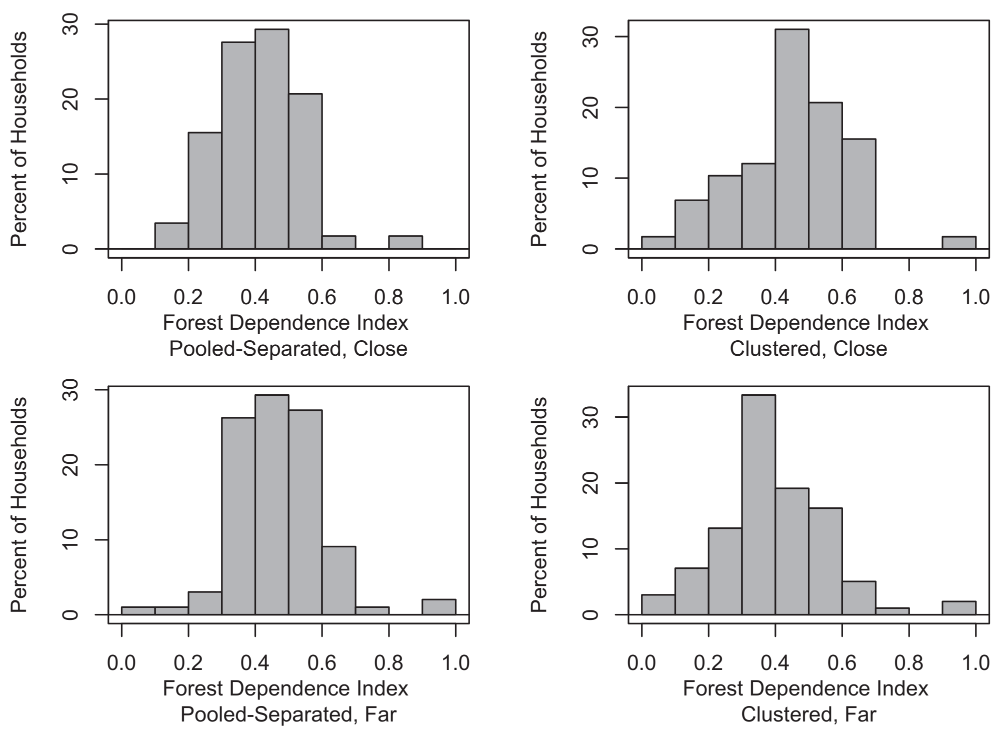

Fig. 6. Forest Dependence Index (FDI) calculated for all households in the sample (n = 157) subsequently separated by proximity to the forest reserve ("pooled-separated"), and FDI calculated individually for the two groups separated by proximity to the forest reserve ("clustered"). FDI for villages closer to the forest reserve shown above (n = 58; pooled-separated, close mean = 0.41, SD = 0.12; clustered, close mean = 0.45, SD = 0.17) and for villages farther from the forest reserve shown below (n = 99; pooled-separated far mean = 0.46, SD = 0.14; clustered, far mean = 0.39, SD = 0.16).

The distributions were not significantly different (K-S D = value 0.21, p-value = 0.083), though it appears that fewer households had low values in the clustered sub-set. For the pooled-separated villages, the villages farther from the forest reserve had a larger mean FDI (0.46) than villages closer to the forest reserve (0.41; p = 0.016).

4. Discussion

Incorporating additional livelihood variables to measure forest dependence is important because RFI may underestimate dependence when compared to the FDI, as shown in the Malawi case study. The FDI provides a more comprehensive view of how dependence manifests in the livelihoods of small-holder farmers and forest dependent peoples in general. Accounting for the diversity of forest products that contribute to household needs, the effort involved in collecting forest products, relative wealth and number of non-forest livelihood strategies sheds light on the extent to which multiple livelihood factors contribute to forest dependence. Including the time and physical effort of harvesting forest products, in addition to accounting for the amounts of forest products collected (which the RFI method also does), contributed to the increase in the forest dependence values for households who expend more effort than others. Without accounting for time and labour, the effects of forest product collection on household livelihoods is less apparent. Of course, for some households whose time and effort are comparatively lower, their forest dependence values will be reduced in the FDI. Including the degree to which households are dependent on forest products in the *forest collection importance* sub-index also contributes to the increase in dependence for households whose needs are primarily met from forest collection, and the reduction for others who have more alternative sources of forest products. The RFI method does not account for other sources of forest products. The *relative wealth* sub-index using the asset-based wealth index also affects the forest dependence values, similar to the study by Nielsen et al. (2012) where amounts of forest products collected showed a different trend with respect to asset as opposed to income-based measures of household wealth. Incorporating the number of alternative livelihood strategies is also important for quantifying the extent to which households have alternatives to depending on forests. The RFI method can be used to address alternative livelihood strategies if the constituent values of total household income are determined to compare non-forest sources to forest sources. Vedeld et al. (2007) compared the proportion of forest income to total household income using a diversification index based on Simpson's index, which measured the inverse sum of the proportion of total income comprised by each livelihood activity. Their results showed an increase in the diversification index with increasing RFI values until 0.30, at which time the diversification index decreased with increasing RFI. This finding accords with the incorporation of the *non-forest livelihood strategies* sub-index since at higher levels of forest dependence, livelihood diversification is decreased.

The FDI has the advantage of directly incorporating the number of alternative livelihood strategies into determining dependence on forests. The FDI also has the benefit of the calculation of sub-indices so that one can observe the sub-index values for households for a more nuanced differentiation between households regarding levels of dependence. By examining the sub-indices individually, one can analyze how the different sub-indices contribute to the final index values. To investigate local levels of forest dependence, additional questions could be explored with respect to the sub-indices, such as: why do some households expend greater or less labour and effort than others on the collection of forest products (e.g., Pattanayak & Sills, 2001); what socio-economic factors affect the non-forest livelihood strategies undertaken by households (e.g., Babulo et al., 2008)? Socio-economic factors associated with dependence – such as household size, age of household head, length of residence in the village – have been assessed with respect to the RFI (e.g., Masozera and Alavalapati, 2004; Tieguhong & Nkamgnia, 2012; Ofoegbu et al., 2017), and could also be analyzed for the FDI. While it is not possible to examine causal relationships between the socio-economic variables internal to the FDI (asset-based wealth and livelihood diversity) and forest dependence, which can be done for RFI, the FDI takes an alternative approach by including the additional livelihood variables in the multi-dimensional measurement of dependence.

For researchers and practitioners interested to apply a forest dependence metric, we encourage the use of the FDI we have described or a variant thereof that maintains the overall FDI principles. We would like to emphasize that we are proposing *a* version of an index to measure forest dependence, rather than suggesting that this should be *the* definitive index to measure forest dependence. The FDI must capture the variability of forest dependence in the sample population, reflect the diversity of forest products used to meet household needs, reflect the relative burden of the collection of forest products for households, and reflect how wealth and livelihood strategies affect levels of forest dependence. The FDI may reflect the importance of different forest products with respect to one another, and account for the relative importance of the sub-indices, although we did not do so here. The use of the additive, product-level weighting approach can be employed as in the Malawi case study. Variants could also be applied, in terms of aggregation techniques and selection of variables within the sub-indices. Additional variables could be incorporated in the *effort* sub-index – for instance the number of household members who collect forest products – to increase the level of information on factors that influence levels of forest dependence. A sub-index level aggregation approach could also be taken by calculating each sub-index separately then aggregating the sub-indices, which would be useful where there is differential conceptual importance of the sub-indices for determining household forest dependence. Lastly, we have focused on forest provisioning ecosystem services, but an additional sub-index on other ecosystem services could potentially be incorporated if these were quantified.

We encourage researchers interested in measuring forest dependence in an expanded way to calculate the FDI with existing datasets where possible, and to collect the data in future household surveys so as to be able to calculate the index. Most PEN-type household surveys may include the majority of the data needed to calculate the FDI, including the amounts of forest products collected, household assets and alternative livelihood strategies. Country-level implementation of the new FAO Forestry modules (Bakkegaard et al., 2016), in conjunction with LSMS survey-type data, could also allow the calculation of the FDI at broader scales. The data that are less likely to be available from existing household surveys are the walking distances or collection times, and the alternative sources of the forest products. We encourage researchers to collect data on the distance to collection sites and times spent harvesting forest products so that effort can be estimated. We acknowledge that forest products may not be collected separately on individual trips; therefore, a distance or time to the general collection site or collection time could be averaged across products. We also encourage the collection of data on the extent to which forest products contribute to livelihood needs for the *forest collection importance* sub-index. While amounts (kg) of other sources of forest products would be ideal, if this is not possible, eliciting an estimation of the importance of products from forests to a household's livelihood would also be viable. For instance, a Likert scale from 0 to 4 on the importance of the forest for providing the product could be converted into a proportion value (i.e. 0 = not important, 1 = somewhat unimportant, 2 = somewhat important, 3 = important, 4 = extremely important). An alternative would be to elicit the proportion collected from the forest: e.g., 0%, 25%, 50%, 75%, or 100%.

The FDI can be calculated in cases when data are not available for some forest product types collected by households. In the Malawi case we used fuelwood and wild foods because we could determine the importance of these products for the *forest collection importance* sub-index. Although this is an incomplete picture of all of the forest products collected by households in the study area in Malawi, here we demonstrated how researchers can work with the available data on forest products used by households. We acknowledge that complete information on every forest product collected by households will in most cases not be available, thus the FDI should be used to capture as much information on the importance of multiple forest products as possible.

The FDI and RFI differ both conceptually and mathematically. Conceptually, the FDI focuses on measuring the consumption of forest products, whereas the RFI method measures the income production from forest products. Mathematically, the FDI values are relative to other households in the study area, given the standardization of values throughout the calculation and normalization of values in the final step. The RFI values, on the other hand, are absolute in the sense that they are not calculated relative to other households – rather, they reflect the relative amount of forest income to total income for an individual household. The FDI should be considered complementary to RFI because of the relative nature of the former and the absolute nature of the latter. We standardized both metrics across the study population to be able to compare the resulting distributions even though we could not compare the values. In the Malawi case study, the majority of households had low RFI values while the majority of households had intermediate FDI values. A higher number of households had lower RFI values than FDI values.

We compared villages that were close and far from forests in two ways – pooled (where we standardized across the whole dataset) and clustered (where we standardized within each group). The results differed, highlighting the important message that comparisons are only valid when the FDI is constructed by standardizing across the entire dataset. We saw a significant difference in the FDI mean values and distributions between the pooled-separated and clustered methods for villages farther away from the forest reserve, and a difference in the mean values but not distributions for the two methods for villages closer to the forest reserve. Within the pooled-separated method, we saw that farther villages had a higher mean FDI than closer villages, which we would expect due to the longer walking times hence greater effort expended in product collection. Here, we also showed that despite a roughly normal distribution of the FDI values, the values may be shifted to indicate lower or higher levels of forest dependence in different study areas.

We acknowledge the limitation of the FDI values being relative to other households in the study sample, hence the inability to directly compare FDI values across samples constructed separately. In response to this limitation, the pooling method can be used to allow direct comparison across samples. Such work has been conducted with other indices such as the DHS wealth index; when assessing the effects of protected areas on community health and material living standards in developing countries, Naidoo et al. (2019) used DHS asset data from 34 developing countries to construct and compare wealth scores. If the data from multiple study sites could not be combined to reconstruct the index, for example due to disparate available data, the trends in the FDI values across study sites could nevertheless be compared.

The FDI can assist in assessing levels of forest dependence and poverty through the additional livelihood information that it incorporates. Policies and management interventions can be developed to address local livelihood conditions towards poverty alleviation by incorporating the importance of forest products to household needs, the effort involved in collection, household relative wealth and the number of non-forest livelihood strategies, as measured in the FDI. Strategies for poverty mitigation and reduction can be designed and implemented by understanding which households depend more heavily on forest products, and which households have limited livelihood opportunities. In order to enhance poverty mitigation potential, households need a sustained supply of forest products, for daily and emergency consumption (Arnold & Perez, 2001; Shackleton & Shackleton, 2004; Belcher, 2005), and the burden of collecting a diversity of products should be reduced. Increasing opportunities in the production, processing and marketing of forest products can enhance sources of income to target poverty reduction (Belcher, 2005; Shackleton, Campbell, Lotz-Sisitka, & Shackleton, 2008). Increasing commercialization of forest products may, however, increase harvesting practices that are detrimental to plant species and communities, thus strategies for joint conservation and development must be carefully implemented (Arnold & Perez, 2001).

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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References

Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N. J., Bauch, S., ... Wunder, S. (2014). Environmental income and rural livelihoods: a global-comparative analysis. *World Development, 64*(S1), S12–S28.

Angelsen, A., & Wunder, S. (2003). Exploring the forest–poverty link: Key concepts, issues and research implications. *Economist, 40*, 68.

Anthwal, A., Gupta, N., Sharma, A., Anthwal, S., & Kim, K. H. (2010). Conserving biodiversity through traditional beliefs in sacred groves in Uttarakhand Himalaya, India. *Resources, Conservation and Recycling, 54*(11), 962–971.

Arnold, J. E. M., & Perez, M. R. (2001). Can non-timber forest products match tropical forest conservation and development objectives?. *Ecological Economics, 39*, 437–447.

Babulo, B., Muys, B., Nega, F., Tollens, E., Nyssen, J., Deckers, J., & Mathijs, E. (2008). Household livelihood strategies and forest dependence in the highlands of Tigray, Northern Ethiopia. *Agricultural Systems, 98*(2), 147–155.

Bakkegaard, R. K., Agrawal, A., Animon, I., Hogarth, N., Miller, D., Persha, L., ... Zezza, A. (2016). *National socioeconomic surveys in forestry*. Rome: FAO.

Barrett, C. B., Reardon, T., & Webb, P. (2001). Nonfarm income diversification and household livelihood strategies in rural Africa: Concepts, dynamics, and policy implications. *Food Policy, 26*(4), 315–331.

Belcher, B. (2005). Forest product markets, forests and poverty reduction. *International Forestry Review, 7*(2), 82–89.

Belcher, B. M. (2003). What isn't an NTFP? *International Forestry Review, 5*(2), 161–168.

Blackden, C. M., Wodon, Q., & Shetty, S. (2006). Gender, time use, and poverty in Sub-Saharan Africa: Foreword. World Bank Working Paper, (73).

Booysen, F. (2002). An overview and evaluation of composite indices of development. *Social Indicators Research, 59*(2), 115–151.

Bossert, W., Chakravarty, S. R., & D'Ambrosio, C. (2013). Multidimensional poverty and material deprivation with discrete data. *Review of Income and Wealth, 59*(1), 29–43.

Brouwer, I. D., Hoorweg, J. C., & van Liere, M. J. (1997). When households run out of fuel: Responses of rural households to decreasing fuelwood availability, Ntcheu District, Malawi. *World Development, 25*(2), 255–266.

Byron, N., & Arnold, M. (1999). What futures for the people of the tropical forests?. *World Development, 27*(5), 789–805.

Campbell, B., & Luckert, M. (2002). *Uncovering the Hidden Harvest: Valuation methods for woodland & forest resources*. Valuation Methods for Woodlands and Forest Resources: London; Sterling, VA; Earthscan Publications.

Campbell, M. O. N. (2005). Sacred groves for forest conservation in Ghana's coastal savannas: Assessing ecological and social dimensions. *Singapore Journal of Tropical Geography, 26*(2), 151–169.

Cavendish, W. (2000). Empirical regularities in the poverty-environment relationship of rural households: Evidence from Zimbabwe. *World Development, 28*(11), 1979–2003.

Center for International Forestry Research (CIFOR). (2008). PEN Prototype Questionnaire, Version 4.4 September 2008. Retrieved from: http://www.cifor.org/fileadmin/fileupload/PEN/pubs/pdf_files/PEN_Prototype_Questionnaire_-_version_4-4_-_September_2008.pdf

Córdova, J. P. P., Wunder, S., Smith-Hall, C., & Börner, J. (2013). Rural income and forest reliance in highland Guatemala. *Environmental management, 51*(5), 1034–1043.

Cunningham, A. B. (1993). African medical plants: Setting priorities at the interface between conservation and primary healthcare. *People and Plants Working Paper, 1*, 50.

Daily, G. C. (1997). *Nature's services: Societal dependence on natural ecosystems*. Washington, DC: Island Press.

Dasappa, S. (2011). Potential of biomass energy for electricity generation in sub-Saharan Africa. *Energy for Sustainable Development, 15*(3), 203–213.

Dercon, S. (1998). Wealth, risk and activity choice: Cattle in Western Tanzania. *Journal of Development Economics, 55*(1), 1–42.

Dubois, O. (2003). Forest-based poverty reduction: A brief review of facts, figures, challenges and possible ways forward. In *Forests in Poverty Reduction Strategies: Capturing the Potential* (pp. 65–86). Torikatu: European Forest Institute.

Ebert, U., & Welsch, H. (2004). Meaningful environmental indices: A social choice approach. *Journal of Environmental Economics and Management, 47*(2), 270–283.

Ellis, F. (1999). Rural livelihood diversity in developing countries: evidence and policy implications. *Diversity, 40*(40), 1–10.

Filmer, D., & Pritchett, L. (2001). Estimating wealth effects without expenditure data–or tears: an application to educational enrollments in states of India. *Demography, 38*(1), 115–132.

Fisher, M. (2004). Household welfare and forest dependence in Southern Malawi. *Environment and Development Economics, 9*(2), 135–154.

Fisher, M., Shively, G. E., & Buccola, S. (2005). Activity choice, labor allocation, and forest use in Malawi. *Land economics, 81*(4), 503–517.

Food and Agriculture Organization of the United Nations (FAO). (2015). Global Forest Resources Assessment 2015. FAO Forestry. Retrieved from: http://www.fao.org/forest-resources-assessment/current-assessment/en/

Freudenberg, M. (2003). Composite indicators of country performance: a critical assessment. OECD Science, Technology and Industry Working Papers, 16, 35.

Google. Google Earth Pro, release 7.1.2.2041 2013 Santa Clara, CA.

Heltberg, R., Arndt, T. C., & Sekhar, N. U. (2000). Fuelwood consumption and forest degradation: A household model for domestic energy substitution in rural India. *Land Economics, 76*(2), 213.

Howe, L. D., Hargreaves, J. R., & Huttly, S. R. A. (2008). Issues in the construction of wealth indices for the measurement of socio-economic position in low-income countries. *Emerging Themes in Epidemiology, 5*(1), 3.

IBM Corp. Released. (2016). IBM SPSS Statistics for Windows, Version 24.0. 2016.

International Monetary Fund (IMF). (2017). International Monetary Fund World Economic Outlook Database, April 2017. Retrieved from: https://www.imf.org/external/pubs/ft/weo/2017/01/weodata/index.aspx

Kamanga, P., Vedeld, P., & Sjaastad, E. (2009). Forest incomes and rural livelihoods in Chiradzulu District, Malawi. *Ecological Economics, 68*(3), 613–624.

Kimengsi, J. N., Pretzsch, J., Kechia, M. A., & Ongolo, S. (2019). Measuring livelihood diversification and forest conservation choices: Insights from rural Cameroon. *Forests, 10*(2), 81.

King, M. F., Renó, V. F., & Novo, E. M. (2014). The concept, dimensions and methods of assessment of human well-being within a socioecological context: A literature review. *Social Indicators Research, 116*(3), 681–698.

Kuyah, S., Sileshi, G. W., Njoloma, J., Mng'omba, S., & Neufeldt, H. (2014). Estimating aboveground tree biomass in three different miombo woodlands and associated land use systems in Malawi. *Biomass and Bioenergy, 66*, 214–222.

Lebbie, A. R., & Guries, R. P. (1995). Ethnobotanical value and conservation of sacred groves of the Kpaa Mende in Sierra Leone. *Economic Botany, 49*(3), 297–308.

Liswanti, N., Sheil, D., Basuki, I., Padmanaba, M., & Mulcahy, G. (2011). Falling back on forests: How forest-dwelling people cope with catastrophe in a changing landscape. *International Forestry Review, 13*(4), 442–455.

Maass, J. M., Balvanera, P., Castillo, A., Daily, G. C., Mooney, H. A., Ehrlich, P., ... Ayala, R. (2005). Ecosystem services of tropical dry forests: Insights from long-term ecological and social research on the pacific coast of Mexico. *Ecology and Society, 10*(1), 17.

Masozera, M. K., & Alavalapati, J. R. (2004). Forest dependency and its implications for protected areas management: A case study from the Nyungwe Forest Reserve, Rwanda. *Scandinavian Journal of Forest Research, 19*(S4), 85–92.

Mirza, B., & Szirmai, A. (2010). Towards a new measurement of energy poverty: A cross-community analysis of rural Pakistan. *UNU-MERIT Working Papers*.

Naidoo, R., Gerkey, D., Hole, D., Pfaff, A., Ellis, A. M., Golden, C. D., ... Fisher, B. (2019). Evaluating the impacts of protected areas on human well-being across the developing world. *Science Advances, 5*(4).

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2005). Handbook on constructing composite indicators. *OECD Statistics Working Papers*.

National Statistical Office (NSO). (2017). Malawi Demographic and Health Survey 2015-2016.

Neumann, R. P., & Hirsch, E. (2000). *Commercialisation of Non-Timber Forest Products: Review and Analysis of Research*. Bogor, Indonesia: Center for International Forestry Research. Rome: FAO.

Newton, P., Miller, D. C., Byenkya, M. A. A., & Agrawal, A. (2016). Who are forest-dependent people? A taxonomy to aid livelihood and land use decision-making in forested regions. *Land Use Policy, 57*, 388–395.

Nielsen, M. R., Pouliot, M., & Kim Bakkegaard, R. (2012). Combining income and assets measures to include the transitory nature of poverty in assessments of forest dependence: Evidence from the Democratic Republic of Congo. *Ecological Economics, 78*, 37–46.

Ofoegbu, C., Chirwa, P. W., Francis, J., & Babalola, F. D. (2017). Socio-economic factors influencing household dependence on forests and its implication for forest-based climate change interventions. *Southern Forests: A Journal of Forest Science, 79*(2), 109–116.

Pattanayak, S. K., & Sills, E. O. (2001). Do tropical forests provide natural insurance? The microeconomics of non-timber forest product collection in the Brazilian Amazon. *Land Economics, 77*(4), 595–612.

Paumgarten, F. (2005). The role of non-timber forest products as safety-nets: A review of evidence with a focus on South Africa. *GeoJournal, 64*(3), 189–197.

Pimentel, D., McNair, M., Buck, L., Pimentel, M., & Kamil, J. (1997). The value of forests to world food security. *Human Ecology, 25*(1), 91–120.

Reyes, René, Nelson, Harry, & Zerriffi, Hisham (2018). Firewood: Cause or consequence? Underlying drivers of firewood production in the South of Chile. *Energy for Sustainable Development*.

Roser, M., & Ortiz-Ospina, E. (2017). Global Extreme Poverty. OurWorldInData.Org, 1. Retrieved from: https://ourworldindata.org/extreme-poverty/

Rutstein, S. O. (2008).). The DHS Wealth Index: Approaches for rural and urban areas. *Demographic and Health Research, 60*.

Saisana, M., & Tarantola, S. (2002). *State-of-the-art report on current methodologies and practices for composite indicator development*. Italy: Joint Research Center. European Commission.

Scoones, I. (1998). Sustainable rural livelihoods a framework for analysis. *Analysis, 72*, 1–22.

Sen, A. (1992). *Inequality reexamined*. New York; Cambridge, Mass: Russell Sage Foundation.

Sen, A. (2006). Conceptualizing and measuring poverty. In D. Grusky, S. Kanbur, & A. Sen (Eds.), *Poverty and inequality*. California: Stanford University Press.

Shackleton, C., & Shackleton, S. (2004). The importance of non-timber forest products in rural livelihood security and as safety nets: A review of evidence from South Africa. *South African Journal of Science, 100*(11), 658–664.

Shackleton, S., Campbell, B., Lotz-Sisitka, H., & Shackleton, C. (2008). Links between the local trade in natural products, livelihoods and poverty alleviation in a semi-arid region of South Africa. *World Development, 36*(3), 505–526.

Shackleton, S., Delang, C. O., & Angelsen, A. (2011). Non-Timber Forest Products in the Global Context. *Non-Timber Forest Products in the Global Context, 7*, 55–81.

Sjaastad, E., Angelsen, A., Vedeld, P., & Bojö, J. (2005). What is environmental income? *Ecological Economics, 55*(1), 37–46.

Sunderland, T., Achdiawan, R., Angelsen, A., Babigumira, R., Ickowitz, A., Paumgarten, F., ... Shively, G. (2014). Challenging perceptions about men, women, and forest product use: A global comparative study. *World Development, 64*(S1), S56–S66.

Sunderlin, William D., Angelsen, Arild, & Wunder, S. (2004). Forests and poverty alleviation. *State of the World's Forests, 2003*, 10.

Sunderlin, W. D., Belcher, B., Santoso, L., Angelsen, A., Burgers, P., Nasi, R., & Wunder, S. (2005). Livelihoods, forests, and conservation in developing countries: An overview. *World Development, 33*(9 SPEC. ISS), 1383–1402.

Timko, J. A., Waeber, P. O., & Kozak, R. A. (2010). The socio-economic contribution of non-timber forest products to rural livelihoods in Sub-Saharan Africa: Knowledge gaps and new directions. *International Forestry Review, 12*(3), 284–294.

Tieguhong, J. C., & Nkamgnia, E. M. (2012). Household dependence on forests around lobeke National Park, Cameroon. *International Forestry Review, 14*(2), 196–212.

United Nations (UN) (2017). List of Least Developed Countries Retrieved from: http://unctad.org/en/PublicationsLibrary/ldcr2017_en.pdf.

Vedeld, P., Angelsen, A., Bojö, J., Sjaastad, E., & Kobugabe Berg, G. (2007). Forest environmental incomes and the rural poor. *Forest Policy and Economics, 9*(7), 869–879.

Wagle, U. (2008). Three related concepts of poverty. *Multidimensional poverty measurement. Economic studies in inequality, social exclusion and well-being*. New York, NY: Springer.

Wambugu, E. W., Obwoyere, G. O., & Kirui, B. K. (2018). Effect of forest management approach on household economy and community participation in conservation: A case of Aberdare Forest Ecosystem, Kenya. *International Journal of Biodiversity and Conservation, 10*(4), 172–184.

Wunder, S., Angelsen, A., & Belcher, B. (2014). Forests, livelihoods, and conservation: Broadening the empirical base. *World Development, 64*(S1), S1–S11.

Wunder, S., Börner, J., Shively, G., & Wyman, M. (2014). Safety nets, gap filling and forests: A global-comparative perspective. *World Development, 64*(S1), S29–S42.

Youn, Y. C. (2009). Use of forest resources, traditional forest-related knowledge and livelihood of forest dependent communities: Cases in South Korea. *Forest Ecology and Management, 257*(10), 2027–2034.

Zulu, L. C. (2010). The forbidden fuel: Charcoal, urban woodfuel demand and supply dynamics, community forest management and woodfuel policy in Malawi. *Energy Policy, 38*(7), 3717–3730.

Zulu, L. E. O. C. (2008). Community forest management in southern Malawi: Solution or part of the problem?. *Society and Natural Resources, 21*(8), 687–703.