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# Rooting the Future; On-Farm Trees' Contribution to Household Energy Security and Asset Creation as a Resilient Development Pathway—Evidence from a 20-Year Panel in Rural Ethiopia

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**Abstract:** Most rural people globally cook with firewood or other sources of biomass. When biomass that has more productive uses is instead burnt, it is a sign of household level energy insecurity. Burning crop residue and dung for fuel reduces the availability of fertilizer and fodder, as well as directly contributes to poor health outcomes. Ethiopia is largely deforested, and now many of Ethiopia's trees are on farms rather than in forests. The objective of this research is to investigate the relationship of on-farm trees to household-level energy security, rural livelihoods, and wellbeing. Using an econometric model with 20-year panel data from rural Ethiopia, we find on-farm trees contribute to building the household's most valuable asset: their home. By contributing to household-level energy security, we find on-farm trees increase crop residue availability for maintaining the rural household's second most valuable asset: their livestock. Large development efforts, including integrated water management projects and investment programs from the World Bank, are increasingly recognizing contributions of trees on farms, and environmental quality in general, as important contributing factors to meeting sustainable development outcomes. Asset creation related to on-farm trees and improved home biomass management provides a compelling pathway for building resilience, maintaining wellbeing, and reinforcing the foundation of rural livelihoods.

**Keywords:** Africa; rural livelihoods; wellbeing outcomes; on-farm trees; resilience pathways

## 1. Introduction

Firewood, twigs, leaves, crop residue, and dung are the primary sources of solid biomass energy used for cooking by over 2.5 billion people [1]. Lack of access to electricity and use of modern cooking solutions are widely-used indicators of energy poverty and the focus of global efforts, such as the United Nations' Sustainable Development Goal target 7.1 [2,3]. National-level energy security policy and research are increasingly aligned with sustainable development concepts, including diversification, resilience, and environmental/climate friendliness [4,5]. Key issues for developing country energy security are unequal access and risks, including volatility of international markets [6]. With less than one percent of the population with access to electricity during the early 1990s, Ethiopia has dramatically improved access to electricity to over 40% [7]. Like many developing countries, the improvement has

been uneven, with urban residents enjoying a 90% rate of electricity access while rural areas estimate between 5% and 25% access, leaving approximately 90% of total energy needs met with biomass [1,8]. Household demands for biomass as fuel in rural Ethiopia results in less biomass available for other productive uses, such as fodder for animals or fertilizer to increase crop productivity [9]. Recent evidence from the Nile Basin of Ethiopia indicates that burning dung has measurable negative impacts on crop productivity, but this can be countered by increased availability of firewood from on-farm trees to replace dung as a household fuel that, instead, can be applied as fertilizer, thereby increasing yields [10].

Indicators of physical access to modern energy sources are associated with the concept of an energy ladder where households will switch to electricity or fossil fuels as the most modern fuel available for purchase within their means [11]. Other quantitative energy poverty measures traditionally emphasize the concept of a deficit where a household's economic access to a sufficient amount of fuel for basic needs is calculated in a similar way and correlated with conventional consumption-based measures of poverty, such as the poverty line [12]. Instead, recent policy-relevant empirical studies of household fuel choice emphasize contextual factors that reveal a large role for cultural preferences in cooking methods and diverse reasons for using or stacking different fuel sources [13]. For example, Ruiz-Mercado found that an open fire used for cooking also serves as a gathering spot for social interactions, healing, or spiritual practices and practical purposes, such as drying clothes [14]. Wood fires for cooking were found to be preferred by wealthier urban households in Ethiopia, as is the case in Italy or other countries that enjoy grilled foods, even for those with access to modern alternatives [15]. Focusing on the agency of the energy poor, local context and household preferences can be coherently considered in research on how energy relates to wellbeing [16]. This focus on the relation of energy to immediate environment, agency, and the circumstances of the household has been widely researched in cooler climates where poor quality energy-inefficient housing compounds issues of high cost and limited access to preferred sources of energy for vulnerable households. This concept of fuel poverty has underlined the importance of considering the environmental context of the household, including the quality of the dwelling space as key to drawing links between energy-focused policies and programs with resulting wellbeing outcomes [17].

Biomass on farms in rural settings has diverse and integral uses, such as fertilizing fields, fodder for animals, and constructing shelter. When households are forced to burn biomass for cooking or heating at the expense of their livelihood or shelter, at rates contrary to their longer-term wellbeing, household energy insecurity may contribute significantly to increasing vulnerability. Some direct wellbeing impacts of this energy related vulnerability are extensively studied including poor health outcomes due to indoor pollution, particularly associated with burning crop residue and dung, along with inefficient open fires for cooking [18]. Poor health, lower productivity, and missed education outcomes correlated with energy poverty are explored in many studies [19]. Time spent collecting biomass from depleted environmental sources reduces the time available for children to obtain an education or, particularly, for women who bear the major burden of collection to contribute in other meaningful ways to the household's livelihood and wellbeing [20].

The long-term cumulative effects of these negative outcomes coupled with the associated over-exploitation of the environment to meet energy requirements interact in a negative feedback cycle resulting persistent poverty in degraded areas [21]. By contrast, a positive feedback cycle is identified in a recent paper from the World Bank, concluding that the effects on poverty of environmental quality are greater than the effects of environmental quality on income alone so that poor households would actually disproportionately benefit from improvements in environmental quality [22]. Particularly relevant for Sub-Saharan Africa, what remains largely understudied are the potentially negative medium-term effects on household wellbeing and resilience of burning biomass that could have otherwise been employed to building livelihood assets, supporting household wellbeing, and improving the immediate environment [23,24].

On-farm trees are commonly planted worldwide to meet household fuel, fiber, and food requirements with a capacity to promote longer-term desirable outcomes of resilience and well-being, such as food security [25–27]. Notably, on-farm trees have been largely understudied compared with annual crops or intact forests [28–30]. An analysis of Earth satellite imaging demonstrated that more than 43% of global agricultural land in 2010 had more than 10% tree cover and failure to include these trees in global environmental monitoring efforts may lead to a significant undercounting of biomass and environmental services, such as carbon sequestration [31]. A systematic review of articles from 1950 to 2015 identified only 74 papers that have examined the relationships among trees, livelihoods, and food production, and only nine studies that have investigated longer-term datasets covering more than seven years [32]. Furthermore, the authors found weak empirical evidence for, and few studies on, the effects of trees on desirable livelihood and food security outcomes, beyond production and income [32]. As a result, the policy relevance for identifying alternative pathways that could promote the use of trees in sustainable development policies and programs has been limited.

Trees and other environmental assets have not been included in typical demographic, health, and poverty surveys, neglecting a very significant source of income, assets, and resilience for poor farmers [33–37]. Increasingly, there have been calls to address the lack of quantitative and panel evidence by a more systematic inclusion of resilience and environmental assets in agricultural adaptation monitoring systems measuring socio-economic and wellbeing outcomes [38]. Rather than proposing new indicators or embarking on new data collection programs, Rasmussen et al. [34] argue that more can be done to leverage existing datasets with innovative analytical approaches that link environmental, economic, and sociocultural factors when researching sustainable agriculture. Similarly, existing representative population datasets have been suggested as the best source for monitoring socioeconomic effects of large international environmental programs [33]. Cross-sectional data represents the primary means for monitoring socioeconomic and some health contributions of policy or programs, such as efforts related to sustainable development goals. However, this data often lack the time series dimension of panel data useful for multidimensional and econometric research on the capacity of alternative pathways to produce desirable outcomes and resilience, particularly over the medium and long-term [39,40]. An integrated use of panel econometric modeling and exploratory, multivariate analysis may effectively contribute to clarify latent relationships among actors' behavior/preferences and the local background context, evidencing more clearly the interplay between environmental sustainability and economically-resilient developmental paths. To date, this type of analysis has been limited by that lack of available longer term panels with an appropriate diversity of variables.

One of the few longer-term time series panel datasets with both on-farm trees and socioeconomic data is the Ethiopian Rural Household Survey (ERHS). Ethiopia, as a matter of national policy, is at the forefront of integrating trees into its sustainable development plans. The country is in the process of transitioning its development pathway from near total deforestation to the adoption of a new climate-resilient green economy on a strong sustainability policy, which suggests a direct link between trees and livelihood and food security outcomes, despite the limitations of the evidence base [41]. To date, generic best practices derived from case studies, randomized control trials on test plots, and imported technology that typically drive “top-down policy” have generally focused on community forests and not provided a fully adequate evidence base that includes on-farm or other trees [42].

More generally in the literature, traditional tree-oriented well-being studies have primarily focused on communal forests and the shared economic benefits [37,43–49]. However, to date, studies of private and communal wood lots in Ethiopia have had a limited scope and have typically aimed at understanding the productive constraints in increasing yields or the potential challenges to sustainable production [50,51]. Until recently, specific studies on household behaviors related to on-farm trees in Ethiopia have been limited to the rural demand for biomass or the links between agricultural investment and land tenure with permanent crops and trees [52,53]. Another paper focused on tree materials from forests and farms as a source of income-generating activities for small enterprises,

but did not consider how this income further contributed to livelihoods and well-being [54]. In new research from Southern Ethiopia proposing a contextually nuanced pathway from trees to desirable food security outcomes, Baudron and coauthors [55] found that complex biomass flows to the household rather than direct harvest from the forest contributed most to increased diet diversity. In other words, taking into account fuel requirements, exchange of different biomass products and the range of rural household capacities and assets is essential to accurate characterization of development capacity pathways. A recent mixed methods case study from Ethiopia documented the substitution of dung with firewood from on-farm trees for cooking fuel that, in turn, increased the availability and application of dung as fertilizer, resulting in subsequent crop productivity [56]. A key research challenge remains in further articulation of the pathways that planting on-farm trees' contribution of fuel, food, and income to a broader range of well-being and livelihood outcomes over the medium- and longer-term.

Two trees in Ethiopia, *Eucalyptus globulus* and *Ensete ventricosum* (enset), have a long history of being planted on farms. Searching for a solution to a fuel wood shortage that threatened the sustainability of the capital, Addis Ababa, the regime of Emperor Menelik II imported a variety of eucalyptus seedlings to be tested in a trial plantation in 1894–95 [57]. Eucalyptus matures in 5–10 years, can rapidly accumulate biomass, and has been estimated to vary in fuel wood production of between 10 and 30 m<sup>3</sup>/ha/year in Ethiopia [51]. According to Turnbull and Booth [58], “many people in Ethiopia are absolutely dependent on eucalyptus as a source of fuel and house building material”. In a wide-ranging review of the available literature, Davidson [59] concludes that eucalyptus is similar to other trees in characteristics, such as shade or soil erosion, but primarily distinct because of its low nutrient uptake and that negative criticism of the high total annual water requirements is an unwarranted artifact of limited analysis that does not take into account surprisingly high rates of biomass creation as a ratio of water use. Negative criticism of eucalyptus resulted in a policy banning eucalyptus in parts of Ethiopia in the late 1990s due to concerns about negative impacts on crop yields [60]. Although the water use can be a problem in dry contexts, it seems that the allelopathic properties of eucalyptus may have been overstated because most tests were undertaken in laboratory conditions on crop seeds or sprouts rather than in real-life farm conditions [59].

The first written scientific description of enset dates from 1867 [61], but cultural and linguistic evidence support the proposition that enset has been an important basis of the food system in the highlands of Ethiopia for thousands of years [62]. Enset is harvested 5–8 years after planting and is a drought resistant fodder source for animals and food source for humans with nutrient characteristics similar to potatoes [63]. Enset is a notable example of a productive asset for producing food while also a significant environmental asset protecting from soil erosion on the steep slopes where it is grown. Although once widely cultivated, the introduction of annual seed crops by Ethio-semites is speculated to have led to enset cultivation being replaced on flat land where it is easier to plow [62].

Progress in sustainability science requires that the contributions of understudied productive and environmental assets vital to rural contexts, such as on-farm eucalyptus and enset trees, be included in research on livelihood and well-being outcomes of resilient development pathways. Agricultural mosaics now cover much of the world; thus, measurement and modelling approaches that take trees, permanent crops, and a diversity of smallholder land uses into account are required to achieve local sustainable governance of these landscapes and resources [64–67]. Little space is available to extend agriculture without greater deforestation, and improving empirical information is critical to supporting alternative sustainable development pathways that meet the increasing demand for food, energy, and water—without further environmental damage [68,69]. On-farm trees are concurrently productive and environmental assets, found worldwide, with the capacity to promote longer-term desirable outcomes of resilience and well-being such as food security [24–26]. Notably, on-farm trees have been largely understudied compared with annual crops or intact forests [28–30]. Environmental assets, such as trees, are undercounted, their contributions underestimated, and unintentional costs over the long-term are largely unarticulated in the conventional evidence base for development and agricultural policy: this

undervaluation is the result of standard agro–socio–economic research and indicators that habitually concentrate on short-term production and consumption [70–72]. The research presented in this paper is intended to contribute novel insights to the growing literature on how to value on-farm trees to wellbeing and resilience from a unique 20-year panel dataset in a rural agricultural mosaic context.

In this paper, we investigate the potential contribution of on-farm trees to increase not only the amount of biomass available to rural Ethiopian households but also the capacity of on-farm trees to directly and indirectly transform this biomass to increase assets that practically improve livelihoods and wellbeing. From a broader perspective, we are also interested if there is evidence that planting more on-farm trees has the capacity to avert a vicious cycle of environmental degradation with associated poor wellbeing outcomes, and rather set rural households on a pathway for resilience and sustainability. The purpose of the work is to explore the relationships between local environment, assets, and wellbeing. Specifically the research will explore the relationship between on farm tree planting, home biomass management, and two socially important development outcomes. We provide a rather large amount of descriptive data about the study area to provide the necessary context for model development and interpretation of the econometric results.

## 2. Methodology

### 2.1. The Ethiopian Rural Household Survey Dataset

In Ethiopia during the latter part of the 20th century, access to a low level of assets was a common experience for rural households that suffered setbacks from natural disasters, such as the massive 1984 drought, alongside a politically-driven leveling of assets by policies, such as a program of land redistribution. The Ethiopian Rural Household Survey (ERHS), therefore, started with a pseudo-baseline, or at least a nearly equal starting point for most households, in 1989 to observe the emergence of different livelihood strategies and resilient development pathways in the subsequent 20-year period. Rural households had largely been depleted of assets [73]. Some families returned to their homesteads after forced migration due to the drought, conflict, or a villagization policy [74]. All households were allocated land through a new system based on an ability to farm and the size of the household [75]. As presented in the descriptive statistics below, this common starting point is clearly evident with remarkably little variation in types of assets or household plot size. This was a period during which many households initiated a process of rebuilding livelihoods, creating assets, and planting trees with the hope of better times ahead.

Since trees take years, or sometimes decades, to mature, medium- to-long-term data collection is required for research that begins with planting seedlings and seeks to measure the outcomes of those trees when mature. This relatively long maturation period slows research on trees and may explain in part why they are understudied in comparison to annual crops. This issue is even more acute when attempting to research the impact of planting trees in real-world contexts and communities [76].

The ERHS panel is, therefore, unique because it brings together observations of livelihood strategies, including planting trees, raising livestock, or establishing annual crops, with the measurement of assets and household characteristics in a 20-year panel dataset [77]. In 1989, the first round of sampling was completed in six (6) drought-affected communities. In 1994, and for the seven (7) subsequent rounds, an additional nine (9) villages were added to the panel. For this study, we focus on 1475 households representing the variety of agricultural systems across Ethiopia, who were consistently surveyed at five-year intervals in 1994, 1999, 2004, and 2009 [77].

More than 40 journal articles, ten book chapters, and numerous working papers and conference presentations have analyzed the ERHS panel data. Stefan Dercon, an author of at least half of these documents, has used econometric techniques in investigating the effect of shocks, seasonality, and infrastructure on consumption, livelihoods, and vulnerability, among other themes [78–81]. Other authors have written about the relationships among gender, education, assets, access to credit, and food aid to poverty-related variables that also primarily focus on consumption [82–85]. The dataset

and approaches to dealing with known issues are well documented. For example, the attrition rate for the sample is low at about 1% per year and Dercon suggests that inclusion of location or time-fixed effects have proven adequate to control any attribution bias [77]. A critical consideration during analysis of ERHS data is that all questions and modules are unfortunately not completely consistent for all rounds. Some of the ERHS variables are measured in each round and are, therefore, appropriate for modeling with econometric approaches. However, other important modules, such as household energy sources, decision making around planting trees, or certain types of risk exposure, can only be used as descriptive statistics to inform the model development or interpret results because they were only part of the household survey in a single round.

Although the ERHS data has been a source for a considerable number of studies with clear policy implications, new analysis can provide meaningful insights into understudied elements and test the relevance of alternative modeling or measurement methodologies. For instance, there is no example in the literature referencing the ERHS data that investigates dwelling value (DV) as an asset indicator. Rogg [86] compared different household and agricultural assets measured in the local currency birr and found in the 2004 ERHS dataset that the average Ethiopian household had 350 Birr in durable assets, 1722 Birr invested in livestock, and 736 Birr in food stocks. For that same period as we present in the descriptive statistics below, we calculate that the average DV is 2448 Birr. This simple example of new analysis shows, for the first time in the literature, that a rural African household's dwelling is, at least in this case, the household's most valuable asset.

Livelihood and environmental assets that develop over the medium-term have not been fully investigated using the ERHS data or, more generally, in the wellbeing and sustainable development literature. Thus, new analysis of existing datasets continues to be a valuable method of addressing this oversight in terms of timescale and overly narrow consideration of rural household and community assets. To date, only two (2) analyses, one (1) each qualitative and quantitative, have used the ERHS tree data. An ERHS study site was included in a qualitative analysis of eucalyptus planting and the visible landscape changes after the policy change, resulting in a greater sense of tenure security for the farmers [87]. In the quantitative analysis, the share of land allocated to trees and shrubs was a proxy for the willingness of households to invest in their farms and was correlated with perceived tenure insecurity [53]. No other papers have investigated the ERHS information about on-farm trees or examined trees as contributing to wellbeing or asset accumulation by rural households.

## *2.2. Descriptive Statistics and Exploratory Cross-Lagged Model to Confirm Reciprocal Relationship*

In this section, we present the descriptive statistics that informed the development of our econometric model. Here we provide a rather lengthy study site description in order to provide the necessary local context for the choices made in the econometric model development and interpretation of the econometric results. Household-level energy insecurity provides a useful context for establishing relationships between on-farm trees, biomass use and the development of assets. A summary graphic is available in the supplementary material to provide an overview of the key pathways from on-farm trees to household livelihood assets found in the ERHS dataset (Figure S1). We make extensive use of descriptive statistics in the text and supplementary materials because we believe that understanding the rural Ethiopian context is critical to the development of the model and interpretation of results. In turn, assets are presented alongside a wider set of wellbeing and resilience outcomes to illustrate correlations as the basis for a potential resilient development pathway related to planting trees and on-farm biomass management. Finally, the directionality of the reciprocal (i.e., causal) relationship between on-farm trees and asset creation are confirmed in an exploratory cross-lagged model.

From the beginning of the ERHS panel, survey respondents have identified the importance of assets for managing risks. The three most frequent responses when asked to describe 'the type of households that had suffered the least in times of famine' between 1984 and 1994 were those with household/farm tool assets, savings, and owned livestock. In fact by a ratio of ten-to-one, 238 respondents identified household/farm tool assets to be associated with suffering less during

famine as compared to only 24 respondents identifying food stocks as a key asset. Old age, illness and many dependents were the most frequently reported characteristics to describe households that suffered the most during times of famine. After these vulnerable group descriptions, the next most frequently reported characteristic of households that suffered the most during famine were those without enough livestock or fixed assets.

On-farm trees and assets generally increased over the study period (see Table 1). Eucalyptus and enset are by far the most common on-farm trees reported in the ERHS dataset (see Table S1 in supplementary materials). Households report owning these trees four-to-five times more often than the next most frequently reported avocado and gesho trees. No other species of trees are reported by more than 2% of respondents. Furthermore, only enset and eucalyptus trees are planted on-farms in large numbers while single tree plantings was most common for nearly all other trees types reported. Although the precise species name was not recorded in the ERHS dataset, it is known that most of the trees generally referred to as eucalyptus are *Eucalyptus globulus* and enset trees are *Ensete ventricosum*. The mean number of eucalyptus trees per household more than trebled over the study period while the mean number of enset trees per household dipped and then increased by 30% by 2009. The increasing number of households reporting both eucalyptus and enset trees decreased between 1999 and 2004 during a period with a serious drought. Regional governments restricted eucalyptus trees at this time because of concern that they would reduce land productivity and yields [88]. Although this regulation could have led to underreporting or fewer trees planted, it is likely that the drought was responsible for fewer trees being planted, seedlings dying, and trees being cut down to meet household energy and income requirements. ERHS respondents reported steady investment and increases in dwelling value between each survey round. Although the number of animals per household reflected in the tropical livestock unit indicators doubled over the study period, fewer households reported having animals in each round.

**Table 1.** Two most common on-farm trees and two most valuable household assets.

	<b>Eucalyptus Trees Households with Trees (Mean Number of Trees)</b>	<b>Enset Trees Households with Trees (Mean Number of Trees)</b>	<b>Dwelling Value Households reporting (Mean in Birr)</b>	<b>Tropical Livestock Unit Households with livestock (Mean in TLU)</b>
1994	519 (200)	422 (298)	1475 (1282)	1469 (2.44)
1999	869 (250)	493 (280)	1475 (1860)	1335 (2.82)
2004	595 (311)	395 (260)	1475 (2448)	1279 (2.9)
2009	859 (611)	431 (381)	1475 (3824)	1275 (5.02)

Households reported their personal reasons for growing trees in the 1999 round of the ERHS survey. Sale of on-farm trees as firewood or construction material was reported as the most common reason for planting eucalyptus. Enset was most commonly consumed as human food (see Table 2). See Table S1 in supplementary material for a list of all on-farm trees reported in 1999.

**Table 2.** Reason to plant eucalyptus and enset trees.

	<b>Eucalyptus # Households</b>	<b>Enset # Households</b>
Sell as firewood	495	24
Sell as construction material	440	19
For own firewood	193	3
For own construction material	264	13
Consumed as food	4	424
Animal fodder	0	11

Note: # Indicates the number of households (1475 total household observations) that reported at least one on-farm tree of this type.

A functioning seedling market is evident in all the ERHS communities except for one (1) poor and remote village called Dinki [84]. Most households for the period 1994–1999 report planting

seedlings from the market or their own nursery (see Table 3). There appears to be a small preference for female-headed households for acquiring seedlings from community nurseries and slightly fewer relying on their own nurseries. A relatively small number of households received their seedlings from the Ethiopian Government Ministry of Agriculture (MOA) or non-governmental organizations (NGOs). By contrast, 78% of enset seedlings came from the household's own nursery with only 12% of enset seedlings bought at the market and negligible access from other sources.

**Table 3.** Source of eucalyptus seedlings 1994–2009.

	Male-Headed Household	Female-Headed Households
Bought from market	36% (188/523)	35% (57/163)
Own nursery	34% (179/523)	29% (47/163)
Community nursery	14% (74/523)	21% (34/163)
MOA nursery	10% (54/523)	12% (19/163)
NGO nursery	2% (12/523)	1% (1/163)
Other	3% (17/523)	3% (5/163)

Household-level energy security involves tradeoffs of on-farm biomass use. On the whole, ERHS households reported collecting most of their fuel from on-farm energy sources such as dung, firewood and crop residue (see Table 4). All households, except for a single household using dung for fuel, reported using more than one source of energy indicating a propensity to mix or trade-off between different energy sources. Dung and crop residue are important on-farm sources of energy along with twigs and leaves. There is a cultural component to the cooking of the staple bread injera where a mix of fuels is used, including dung, which extends the duration of fire at a low heat [89]. Roughly equal numbers of households collect firewood from their own land, unmanaged open access areas, and managed forests. Approximately two-thirds, 1053 households, purchase some kerosene at the market. Additionally, two (2) households report using biogas produced by an FAO project in ERHS village of Adele Keke.

**Table 4.** Source of energy by number of households in 1995 (# of households reporting use).

	Own Land	Open Access	Community Forest	State Forest	Market	Other
Firewood	334	348	238	39	31	24
Dung	338	99	18	0	0	3
Charcoal	8	7	12	2	37	0
Twigs	201	160	101	14	3	8
Leaves	113	42	38	2	5	0
Crop residue	228	40	0	0	13	5

Note: # Indicates the number of households (1475 total household observations) that reported collecting these energy sources (row) from these areas (column).

Competing productive uses for dung and crop residue were more frequently reported than their use as fuel (see Table 5). Despite being the most commonly reported cooking fuel, dung is more commonly collected for use as fertilizer or a construction material. Crop residue is most commonly used for livestock fodder. As noted above in Table 2, wood can be used as a construction material, source of income or as the preferred household fuel source. These trade-offs at household level to ensure energy security have clear implications for the availability of biomass to support other household efforts to increase the productivity of the land, health of the livestock, or improve their dwelling.

Collection of biomass for household energy needs is clearly gendered activity for the ERHS survey participants. Although adult males collect firewood at similar rates as adult females, adult females and other members of the households are more likely to collect other types of biomass (see Table 6). Adult women primarily collect dung and crop residue while children and other members of the household collect twigs and leaves. Overall, it is clear that women and children bear the large part of the effort in biomass collection.



**Table 5.** Use of crop residue and dung (# of households reporting use).

Collect Dung or Crop Residue	Dung for Fertilizer	Crop Residue as Fodder	Dung for Construction	Crop Residue for Construction
1036	841	669	427	293

Note: # Indicates the number of households (1475 total household observations) that reported collection and different uses for crop residue or dung.

**Table 6.** Fuel collection actors disaggregated by gender (percentages in total sampled population).

	Adult Male	Adult Female	Children or Other Family Members
Fire wood	28.36	30.27	41.36
Dung	12.57	56.98	30.45
Crop residue	17.42	49.24	33.33
Twigs	15.53	37.88	46.59
Leaves	14.53	29.05	56.42

One of the most striking statistics about biomass collection reported by ERHS households is that collecting firewood on-farm requires less than half the time for collecting firewood from other sources. The average time for collecting firewood from their “own land” was 26.12 min while collecting firewood from “open access”, “community forest”, or “state forest” required an average of 61.48, 70.38, and 60.64 min respectively.

Tradeoffs in biomass use in order to ensure sufficient fuel for basic household energy security has implications for the household efforts to improve wellbeing, resilience, and create assets. Biomass collection on farm can clearly save time that can be made available for other activities. Several authors have indicated time saving along with increased fuel availability and land productivity are all pathways to improved food security and diet diversity [56,90]. Here we present correlations of the ERHS households most valuable assets in 1994 and 2009 with common measures of wellbeing including a diet diversity score (Table 7). Based on sample heterogeneity and small deviations from normality in the sampled variables, we used a non-parametric correlation technique (Spearman rank analysis) instead of a more classical technique adopting Pearson moment product correlation coefficients [91]. Non-parametric Spearman analysis is suitable to identify both linear and non-linear pair-wise correlations between variables [92], giving more value to an exploratory analysis of (apparent and latent) relationships between dwelling value (or tropical livestock units) and selected contextual variables [93].

**Table 7.** Dwelling value and tropical livestock unit (Spearman’s Rho correlation coefficients with wellbeing and asset measures).

	Dwelling Value, Spearman’s Rho ( <i>p</i> -Value)		Tropical Livestock Unit, Spearman’s Rho ( <i>p</i> -Value)	
	1994	2009	1994	2009
Household size	0.29 *	0.27 *	0.36 *	0.33 *
Household dietary diversity score	0.27 *	0.30 *	0.36 *	0.36 *
Head of household years of education	−0.00	0.15 *	0.15 *	0.20 *
Average years of education all HH members	0.15 *	0.15 *	0.23 *	0.23 *
Per capita expenditure	0.06 *	0.31 *	0.21 *	0.30 *
Land owned	−0.07 *	0.06 *	0.58 *	0.48 *
Land planted	−0.03	0.11 *	0.59 *	0.62 *
Household asset index	0.05	−0.17 *	0.36 *	−0.17 *
Agricultural asset index	0.04	−0.02	0.46 *	−0.03

Note: \* Indicates significant at  $p < 0.05$ ; sample size is 1475 observations.

From the beginning to the end of the ERHS panel, there is a strong significant correlation between the asset measures and wellbeing indicators such as diet diversity, average education and per capita expenditures. The Tropical livestock unit (TLU) variable is strongly correlated with measures of land

owned and planted. In 1994, the TLU was more significantly correlated with an indexed measure of household and agricultural assets, but not as strongly in 2009. Dwelling value is not correlated with land access or the asset indexes in any consistent significant way. There may be issues with that asset index due to insufficiently appropriate assets being included in the questionnaires or types of common assets changing over time.

Assets often help households better manage shocks by providing a store of value or opportunity to adapt strategies in order to minimize loss of wellbeing [57,74]. Dwelling value and TLU are correlated with fewer crop-related and fewer total shocks reported by the households (see Table 8). As is often the case, having more of an asset such as livestock will make a household more exposed to shocks affecting that asset category as we see in the ERHS 1994 data with livestock-related shocks. Nonetheless, dwelling value and TLU are both correlated with desirable outcomes from drought where households report eating more meals. They also were less likely to report being forced to miss meals or eat less preferred foods as a coping strategy. TLU is also significantly correlated with lower likelihood of selling a productive asset. Assets appear to be generally associate with desirable wellbeing and resilience outcomes in the ERHS dataset. Now we turn to developing a model to measure how much on-farm trees can shift the tradeoffs for household level energy security and support building these key assets.

**Table 8.** Correlation of assets and reported shock exposure and drought-related effects in 1994. (Spearman's Rho correlation coefficients).

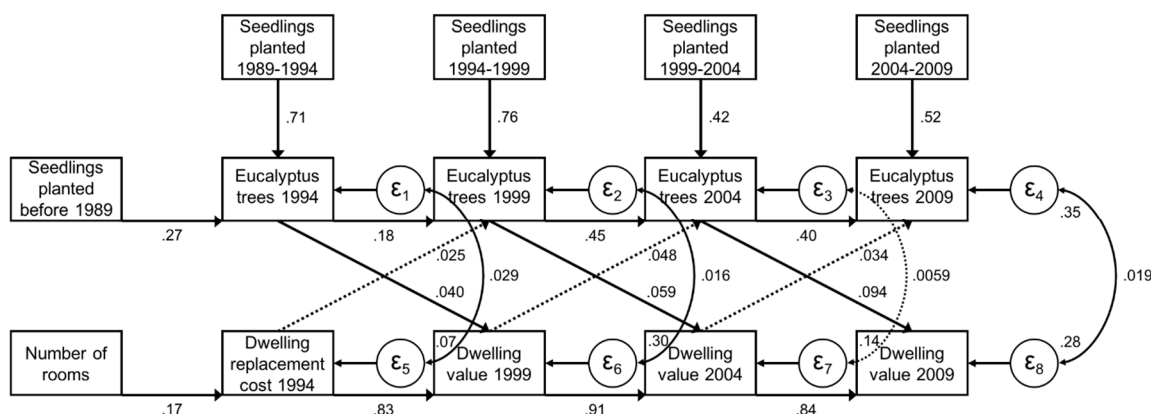
	Dwelling Value Spearman's Rho ( $p$ -Value)	Tropical Livestock Unit Spearman's Rho ( $p$ -Value)
Number of reported shocks	−0.22 *	−0.01
Crop-related shocks	−0.19 *	−0.20 *
Livestock-related shocks	−0.22 *	0.16 *
Drought-number of meals	0.13 *	0.36 *
Drought-reduced number of meals	−0.12 *	−0.25 *
Drought-ate less preferred wild foods	−0.17 *	−0.28 *
Drought-sold productive assets	−0.01	−0.15 *

Note: \* Indicates significant at  $p < 0.05$ ; sample size is 1475.

### 2.3. Recursive Dependency Implied with an Exploratory Cross-Lagged Variable Model

Our econometric modelling is built around a core recursive relationship between the number of eucalyptus trees grown on farm and the value of the dwelling represented by replacement cost along with improvements and repairs of the walls and roof. A simple cross-lagged model demonstrates clearly the unidirectional relationship of maturing eucalyptus to dwelling value with no significant feedback relationship (see Figure 1). In other words, there is a significant relationship of households growing more trees having more valuable houses but no significant relationship of more valuable households through their presumed wealth necessarily growing more trees.

In Figure 1, solid lines represent significant relationships at a  $p$ -value  $< 0.001$ . There is strong serial correlation of the key variables and also significant correlation of the cross-lagged variables in only one direction from the trees towards dwelling value. The cross-lags in the direction from dwelling value to trees are all not significant ( $p$ -values = 0.20, 0.68, 0.83). Errors are all significantly correlated except for the survey round in 2004. The coefficients between variables are included in the figure and were calculated with a maximum likelihood estimator. As these coefficients can be interpreted as amount of variance explained, trees explain a relatively large and significant amount of the non-serial-related variance in dwelling value.



**Figure 1.** Cross-lagged model relating standardized log measures of eucalyptus trees and seedlings to dwelling value.

### 2.4. Random Effects Econometric Models

Illustrating the dichotomy between building assets with biomass or burning it for fuel, trees directly contribute lumber for dwelling construction and, at the same time, provide firewood as the most preferred energy source for ERHS survey participants. The first econometric model we develop seeks to estimate the contribution of trees to dwelling value over time for the participating ERHS households. Both crop residue and dung are commonly used for both fuel and construction, but the preferred use for crop residue is as fodder for livestock. We develop a second model linking biomass with asset creation focused on the directional correlation reported between harvesting crop residue as fodder to maintain livestock. On-farm trees are also included in the model as an indirect support to livestock as a substitute fuel source, thereby, increasing the availability of crop residue.

#### 2.4.1. (Model 1) Dwelling Value: Contribution of On-Farm Tree to the Households’ Most Valuable Asset

To estimate the contribution of on-farm trees to household assets in the ERHS panel dataset, we follow the generalized two-stage least squares approach with random effects. We begin with a model that includes endogenous and exogenous variables with unit specific and time varying error components [94,95]:

$$\psi_{i,t} = \mathcal{Y}_{i,t} \gamma + \mathcal{X}_{i,t} \beta' + \mathcal{Z}_i + \mu_i + v_{i,t} \tag{1}$$

where:

$\psi_{i,t}$  is the dependent variable representing assets; dwelling value in model 1 and tropical livestock unit in model 2;

$\mathcal{Y}_{i,t}$  is vector of endogenous time varying variables correlated with  $v_i$ ;

$\mathcal{X}_{i,t}$  is a vector of exogenous time varying variables;

$\mathcal{Z}_i$  is a vector of time constant exogenous variables;

$\gamma$  is a vector of coefficients accounting for the partial effect of instruments;

$\beta'$  is a regression coefficient estimated following the matrix method described by Balestra and Varadharajan-Krishnakumar [94];

$\mu_i$  is a random effects estimator for the time constant error identically distributed over the panel; and

$v_{i,t}$  is the idiosyncratic error with a zero mean and uncorrelated with  $\mathcal{X}_{i,t}$ .

In Model 1, the standardized log of dwelling value is the dependent variable. We select the two (2) most commonly planted on-farm trees, eucalyptus and enset, as the initial independent variables. We then identify additional time constant and time varying explanatory variables to increase the explained variance and act as controls in the model. A reverse step-wise procedure was adopted with

the aim to remove multicollinear variables from analysis and reduce the overall redundancy with the goal of a parsimonious final model illustrating the key relationships of interest. Many variables in livelihoods and wellbeing research are highly multicollinear, zero-inflated, and generally associated with overall consumption-based measures of poverty and, therefore, were not included in the models presented here (see Table 9 for a summary of the variables selected for use in the model and Table S2 supplementary material for a list of test variables). Some variables that would have been potentially interesting lacked sufficient data, such as income from selling timber, because they were not included in all rounds of the ERHS.

**Table 9.** Variables included in the model.

Variable (Standardized Natural Log)	Between Standard Deviation	Within Standard Deviation	Variable
Dwelling value (dependent)	0.92	0.39	$\psi_{i,t}$
Number of eucalyptus trees (endogenous time varying)	0.82	0.57	$\mathcal{Y}_{1,i,t}$
Number of enset trees (endogenous time varying)			$\mathcal{Y}_{2,i,t}$
Number of eucalyptus seedlings planted in the previous 5–10 years (instrumental time varying)	0.75	0.66	$\gamma_1$
Number of enset seedlings planted in the previous 5 years (instrumental time varying)			$\gamma_2$
Crop residue harvested (independent time varying)	0.74	0.67	$\mathcal{X}_{1,i,t}$
Household size (independent time varying)	0.81	0.59	$\mathcal{X}_{2,i,t}$
Mean replacement cost (independent context explanatory)	0.62	0.0	$\mathcal{Z}_{1,i}$
Female-headed households (independent context explanatory)	0.42	0.0	$\mathcal{Z}_{2,i}$
Constant (independent context explanatory)	1.00	0.0	$\mathcal{Z}_{3,i}$

Time-constant characteristics are less common in a dataset that spans 20 years for rural households where growing families change composition, infrastructure is developed or innovation may have been introduced. At the same time, characteristics such as education level of the head of the household are zero-inflated in the ERHS dataset with very few educational opportunities available because of the social challenges described in the previous section. Using a reverse step-wise procedure, we nonetheless find that the inclusion of the following time-constant characteristics at the household and community level serve as valuable independent variables in the model to control for unit level and context level variability.

- Female-headed household;
- Number of rooms in the house;
- Mean replacement value of dwelling in 1994.

Again, following the reverse step-wise procedure, we identify the standardized log of crop residue produced by the household and the household size as additional time varying explanatory variables. It is important to note that dummy variables representing time fixed effects were tested in the model and were all found to be insignificant. Although these time fixed effects have been found to be significant for other econometric analyses of outcomes related to consumption where inflation or the small survey drop-out rate may have been more important [53], these time effects seem to exert less effect on our medium-term variables of interest dwelling value and trees planted.

A Durbin  $X^2$  test indicates that the standardized log of the number of eucalyptus trees and enset trees, when regressed against dwelling value, are endogenous with a Durbin  $X^2$  statistic of 10.719 at a significant  $p$ -value of 0.005. Therefore, selecting among the potential instruments that were not significantly correlated with the error residuals, we identified a lagged variable for the number of eucalyptus seedlings planted in the previous five-to-ten year period and recent enset seedlings planted in the previous zero-to-five years to the model as instruments. These instruments were particularly attractive because there is a clear causal relation between planting seedlings and the eventual number of mature on-farm trees. Yet, seedlings appear to have been sufficiently available equally to wealthier households with higher value dwellings as well as those less-well-off and, therefore, consistent with the tests indicating the number of seedlings planted as an exogenous variable. A significant Wu-Hausman test indicates that eucalyptus and enset seedlings may in fact be used as instruments to reduce endogeneity with an F-statistic value of  $F(2, 5892) = 5.36$  and a significant  $p$ -value of 0.005. The variables in the used to parameterize the equation are summarized along with their between and within standard deviations in Table 10. See Tables S3 and S4 in supplementary materials for full details on first stage regression tests and statistics where the Wald  $X^2$  test for eucalyptus and enset as instruments were both significant at probability  $X^2$  less than 0.0001.

With the variables identified for the model, we tested the appropriateness of using the random effects approach. A Breusch-Pagan LM Lagrangian multiplier test is highly significant, indicating preference for a model with specific individual effects instead of a pooled OLS estimator with a  $\bar{\chi}$  of 4397.35 with a probability  $> \bar{\chi}$  of 0.000. Random effects are specifically indicated while fixed effects are rejected by a Hausman test that is not significant rejecting the hypothesis of systematic differences with a  $X^2$  of 5.83 with a probability  $> X^2 = 0.212$ .

**Table 10.** Correlation of variables used in Model 2 with residual error as an indication of endogeneity.

Standardized Log Variable	Variable Type	Correlation with Residual Error
Crop residue	$\mathcal{Y}_{1,i,t}$ (Endogenous time varying)	0.030 *
# of enset tree	$\mathcal{Y}_{1,i,t}$ (Endogenous time varying)	−0.036 *
# of eucalyptus trees	$\mathcal{X}_{i,t}$ (Exogenous time varying)	0.005
Household size	$\mathcal{X}_{i,t}$ (Exogenous time varying)	0.017
Self-reported primary use of crop residue for fodder	$\mathcal{Z}_i$ Time constant	−0.008
Longitude of ERHS community	$\mathcal{Z}_i$ Time constant	−0.007
Female-headed household	$\mathcal{Z}_i$ Time constant	−0.048 *

Note: # Indicates the number of households (1475 total household observations) that reported tree type; \* Indicates significant at  $p < 0.05$ .

#### 2.4.2. (Model 2) Tropical Livestock Units: Direct Contribution of Crop Residue and Indirect Contribution of On-Farm Trees Contribution to the Households' Second Most Valuable Asset

We use the same modeling approach as described in Equation (1). The standardized log of Tropical Livestock Unit is the dependent variable. Crop residue is an independent variable of primary interest along with the other variables from Model 1 household size, eucalyptus, and enset trees. Three time constant variables are also identified:

- Female-headed households;
- Self-reported primary use of crop residue for fodder dummy variable;
- Longitude of ERHS community.

The number of eucalyptus trees, household size and longitude are employed as instruments for the three endogenous variables in the generalized two-stage least squares calculations. The Wald test  $X^2$  for the three first stage regressions for crop residue, enset trees and female-headed households were 1891, 2408, and 498, respectively. All had a probability less than  $X^2$  with  $p$ -values less than 0.0001 (see Table S4 in supplementary materials).

### 3. Results

On-farm eucalyptus trees over time significantly contribute to an increase in dwelling value. The generalized two-step least squares (GTSLS) random effects model resulted in a strong effect of on-farm eucalyptus trees that accounts for the largest variation in dwelling value once the time constant median value of dwellings in the village is controlled (see Table 11). The overall  $R^2$  for the model is 0.342 with a Wald  $X^2$  value of 1730.66 and probability  $> X^2$  equal to 0.000. The causal direction of the correlation of eucalyptus tree planting and dwelling value indicated in the cross-lagged model above is confirmed with the significant results of a first stage of the G2SLS regression for all variables at a  $p$ -value of 0.04 or less except for the number of rooms (see supplemental materials). This resulting second stage partial estimation of the number of eucalyptus trees can be described in a qualitative sense as mature eucalyptus trees that have survived at least five years. The resulting coefficient of 0.25 of the standardized log value for the contribution of these mature trees therefore explain essentially 25% of the variability in dwelling value accounted for in the model. In other words, planting eucalyptus trees accounts for about 9% of the dwelling values reported in the ERHS dataset.

The other time constant variables included in the model explain variation in dwelling value in line with expectations. A higher number of rooms indicates a higher dwelling value with a significant coefficient of 0.12. By contrast, female-headed households reported a significantly lower dwelling value, with a negative coefficient of  $-0.94$ . Larger household size and higher levels of crop residue also positively contributed to dwelling value, with coefficients of 0.09 and 0.034, respectively.

After inclusion of the instrumental variables in the first stage, the number of enset trees no longer significantly contributed to dwelling value with a  $p$ -value of 0.28. This is consistent with the descriptive statistics above that would indicate that wealthier households may have more enset trees and higher reported dwelling values, but enset is primarily planted to meet food requirements while eucalyptus is planted to meet energy and construction needs. Using seedlings as an instrument effectively controlling for the endogeneity is consistent with the descriptive statistics that indicate richer households at any one moment have a higher probability of more on-farm trees, but households did not need to be wealthy in the first place to plant trees. Later in the discussion, we will pick up this theme of access to seedlings and contribution of on-farm trees to increased dwelling value.

**Table 11.** Results of Model 1 of on-farm tree contribution to dwelling value.

Standardized Log Values	Coefficient	Standard Error
Households with trees of eucalyptus trees	0.25 *	0.05
Household size	0.09 *	0.018
Crop residue	0.03 *	0.009
Mean initial dwelling value in local area	0.71 *	0.035
Number of rooms	0.12 *	0.015
Female-headed household	$-0.09$ *	0.037
Number of observations	5900	
Overall R-square	0.34	

\* Indicates significant at  $p < 0.05$ .

On-farm trees may substitute as a preferred source of energy and allow for more crop residue to be used as fodder for livestock (see Table 12). Overtime, increased availability of dung as fertilizer may increase crop productivity. The pathway between on-farm trees and increased TLU may involve more related variables but it still provides significant results from the GTSLS Model 2.

The first-stage results indicate strongly significant instruments for the endogenous variable crop residue at a  $p$ -value  $< 0.001$ , for inclusion of eucalyptus trees, household size, longitude, and self-reported collection of crop residue and dung (see Table 13). Only household size and longitude were significant in the first stage for predicting female-headed households (see Table S4 in supplementary material).

**Table 12.** Results of Model 2 of on-farm tree contribution to tropical livestock unit.

Standardized Log Values	Coefficient	Standard Error
Crop residue	1.03 *	0.05
Households with trees enset trees	0.161 *	0.08
Female headed households	−0.695	0.39
Collect crop residue and dung	0.12 *	0.03
Number of observations	5900	
Overall R-square	0.31	

\* Indicates significant at  $p < 0.05$ .

**Table 13.** Results of the first stage regression of instruments on crop residue in Model 2.

Standardized Log Values	Coefficient	Standard Error
Households with Trees eucalyptus trees	0.144 *	0.01
Household size	0.344 *	0.01
Collect crop residue and dung	0.194 *	0.02
Longitude of location	0.237 *	0.01
Number of observations	5900	

\* Indicates significant at  $p < 0.05$ .

#### 4. Discussion

Trees on farms contribute to household-level energy security that, over time, allows biomass that is not burnt for cooking and heating to be transformed through more productive uses into valuable assets that support sustainable livelihoods and wellbeing. This development pathway logic is consistent with research demonstrating how poor households access forest resources to improve shelter or obtain assets [96,97]. In a similar way to how household assets may be used to cope with risks, the forest itself is used as an environmental asset that provides a safety net of alternative resources during times of shocks such as droughts that affect rural agricultural livelihoods [98,99].

We demonstrate with two econometric models how on-farm trees significantly increased the value of rural Ethiopian households' two most valuable private assets, their dwelling and livestock. The model results indicate strong significant correlations for tree variables, R-squared values above 0.3, and highly significant Wald chi-squared tests that support the validity for the proposed models. Reverse step-wise regression eliminated many variables that were likely multicollinear and added little additional information to the bottom-line relationship of trees to household level energy security and assets. A direct pathway to increased dwelling value where on-farm timber from eucalyptus is used to repair and improve the home is consistent with self-reported descriptive statistics and modeled results. The number of eucalyptus trees on a farm is the largest predictor of dwelling value after the initial time constant control variable. Inclusion of female headed households resulted a negative coefficient with dwelling value improvement in the model results perhaps reflecting the overall challenges for female headed households to build assets.

A second indirect pathway demonstrated in a first stage of the regression a significant contribution of eucalyptus trees to increased availability of crop residue that in turn is the largest determinant of increased livestock values represented by the Tropical Livestock Unit variable. This is consistent with the self-reported importance of crop residue for animal fodder for these rural households. Recent work by Baudaron et al. [55] follows a similar pathway logic from biomass to assets to wellbeing. They investigated the impact on food security related to distance to forests and found that the biomass flows as fodder and fertilizer the likely mechanism behind the positive relationship identified relating forest access to increased dietary diversity. Although the logic is similar, it is important to note that their conclusions were drawn from identified association of food security-related outcomes with spatial

proximity to a natural forest, and our results focus on the results of econometric modeling of outcomes for on-farm trees.

Female-headed ERHS households had a strongly negative relationship with increased livestock ownership in the model results perhaps reflecting cultural norms regarding large animal ownership. The gender disparities identified in both increased dwelling value and increased livestock ownership for female-headed households should be subjects of further research.

In addition to these clearly evident pathways, there may be multiple other indirect pathways, such as using crop residue to thatch roofs or selling firewood to finance construction and repair costs to be explored in other datasets with these variables consistently measured. The enabling effect of on-farm trees to promote feedback between the widespread use of animal dung for fertilizer and the higher availability of crop residue the following year that is not quantitatively captured in either existing ERHS data but probably has an unmeasured effect on the crop residue variable in our models. In fact, increased dung available for fertilizer has been a primary justification for rural afforestation programs and policy in Ethiopia over many years [52]. The bottom-line finding is that having biomass above and beyond the minimum requirement for cooking and heating creates opportunity for asset creation on small farms, and on-farm trees were shown to be a popular and effective way to increase on-farm biomass availability in Ethiopia between 1989 and 2009.

ERHS households reported a preference for using dung and crop residue for productive uses as fertilizer and fodder rather than as fuel. At the same time, many households reported the use of dung and crop residue for cooking fuel, and most of this biomass was collected on their own farms. This represents a clear sign of energy insecurity when a household burns a fuel that they prefer to use for another purpose and could potentially be a robust indicator to enhance measurement of household energy insecurity to complement fuel/energy poverty measures. Recent case study research from the highlands of Ethiopia using mixed methods confirmed the continued existence of this chronic household energy insecurity as a negative feedback of biomass removal from the environment leading to less biomass being regenerated and available to the community [56]. Firewood remained overall the most frequently used energy source for the ERHS households but was often collected in open access areas or in communal forests, as well as from on-farm sources. Households collecting in open access areas tended to collect less firewood than those with an on-farm or communal forest source. Also, this fuel collection takes more time. This was particularly evident for women collecting fuel in open access areas and likely indicates on-going environmental degradation [100]. Households that had access to communal forests seemed to report using similar amounts of preferred fuels as those households with on-farm trees.

Communal forests have been a focus for research and policy related to meeting biomass requirements for fuel and construction by the Ethiopian government and international organizations since the 1970's but these projects faced challenges with reported tree survival rate of less than 20% [9]. Following this tradition, most literature relating trees to wellbeing outcomes, with specific interest in food security, has focused on communally-managed woodlots and forested areas rather than on-farm trees. Access to communal forests has been associated with greater dietary diversity [101]. By contrast, deforestation has also been associated with poor dietary outcomes of households and children [102,103]. Research from Southern Ethiopia suggests in much the same way that it is the biomass flows to the household, rather than the direct harvest of food products from the forest, that contribute to the dietary diversity [55]. These dietary correlations are also found in the ERHS data, but with private control of on-farm trees; private tree ownership implies a similar, but distinct, capacity pathway for contributing to a wide range of livelihood outcomes. From the 20-year panel, there is a high survival rate implied by the cross-lagged data between seedlings and trees, as well as trees between rounds. Although communal forest and on-farm trees may address household energy insecurity as a pathway to improve wellbeing, on-farm trees may suffer less of the access and maintenance challenges in communal forest management.



As authors have emphasized the role of communal and national forests as environmental assets that promote desirable wellbeing and resilience outcomes, we propose that on-farm trees function promote many of those same outcomes but through the transformation of environmental assets into livelihood assets even more directly related to the outcomes of interest. As put forth in the fuel poverty literature, the quality of housing has a significant impact on both the amount of fuel required, but also the enjoyment of wellbeing benefits from obtaining sufficient fuel [104,105]. We find strong correlations of improved consumption, education, and diet diversity with more valuable Ethiopian homes that are in better repair. We found significant correlations of dwelling value with less risk exposure. Dwelling value and in particular livestock assets were strongly significantly correlated with improved coping to drought. In fact the promotion of common environmental assets and on-farm trees may be complimentary, rather than substitutive, goals. Recent research from a watershed management area in Ethiopia confirmed that household level trees were major contributors to achieving project goals by meeting community fuel and fodder needs while relieving pressure on existing forests and at the same time increasing productivity by increasing dung available for fertilizer [56].

As competition and policy trade-offs for management of food–energy–water resources are predicted to increase dramatically in the coming decades, broadening the evidence base through research on the links between well-being, environmental assets, and socio-ecological processes is fundamental to improving the understanding of resilience dynamics and create better-informed policies [67,106,107]. However, intuitive, empirical evidence, similar to that presented in this study, is rare in large part because of a paucity of coherent and appropriate panel data for studying the important role of trees and environmental assets in the outcomes socio-ecological systems from existing observational datasets [33–35,49]. For example, most households in the ERHS dataset procured their seedlings at a market. The community without a market that sold seedlings did not have many on-farm trees, with only two households reported eucalyptus trees grown from seedlings provided by the Ministry of Agriculture. Novel empirical results and identification of an alternative resilient development pathway require datasets with a diversity of variables, such as informal seedling markets, as well as a diversity of seeds and other non-industrial inputs, that more broadly represent the essential elements of rural agricultural livelihoods, markets and the foundational socio-ecological system on which they rely.

Arnold and Perssin, in their sweeping survey of research on woodfuel, concluded renewed attention to woodfuel and timber as a co-products of agriculture and agro-forestry activities is overdue [108]. Further research on biomass as the foundation of household energy security pathways promises new insights into the role not only of seeds and seedlings, but also other environmental assets that contribute to rural livelihoods. Research that bridges productive and environmental assets should be encouraged and include a measurement of medium- and longer-term outcomes. A particularly exciting area for further investigation is the dual nature of trees and permanent crops as productive and environmental assets providing a wide range of socioeconomic benefits and environmental services [109].

Taken as a whole, a broad range of positive effects on well-being, livelihoods, and resilience can be observed over the medium term, from access to seedlings to cultivation of on-farm trees. Meaningful improvement in well-being, livelihoods, and assets takes time. Female-headed households may face increased challenges regarding energy security, or asset creation in general, which requires further investigation. Additional research is required on the role of tree-oriented investment by rural households in the accumulation of assets and the observed improvements in well-being and resilience outcomes over the medium and longer term.

Our research is limited in similar ways to more general ongoing challenges of sustainability science as a whole. In our investigation, we were limited for econometric modeling to the panel data that was collected in the ERHS whose primary purpose was to characterize the productive agricultural aspects and their relation to largely consumption based food security measures. Although modules on gender, decision-making, shocks or energy use appeared in some rounds, other important sustainability

information was missing almost entirely, such as data on environmental assets, environmental services, or governance of common spaces. Our use of household panel data also limited analysis of environmental and contextual issues at landscape or regional level that typically strengthen sustainability focused research. Our use of statistical tests for inclusion of variables in the econometric model is necessarily reductionist and insights potentially could be made by further investigation of some of the borderline significant variables in different approach, such as factor analysis or beginning with other environmental assets than on-farm trees. We chose to limit our focus on the core relationship of the most common trees to the most valuable assets for clarity in presentation of the main findings but certainly see the value of future investigations into a broader set of variables with more sophisticated statistical techniques, such as three-stage least squares models.

We believe this work contributes to a number of promising opportunities for future research. There is great potential for researching the comparative benefits of different trees, including native species, on farms and their benefits, but that will require a sampling frame that is able to capture a representative sample in this context where most trees are rare with most species only reported by one or two households out of 1475. Use, income, and distribution of benefits from on-farm tree products in different farming systems could potentially contribute to better understating of the cost benefit and appropriateness of policies promoting on-farm or common area tree planting in different contexts. This could also include more investigation of gender and wealth dynamics at the intra-household level. Much of the interest in biomass management research is related to agricultural and food security outcomes. The inclusion of nutritional analysis potentially could integrate these related lines of inquiry around cooking, nutrition-sensitive agriculture and nutritional wellbeing outcomes. The potential of natural assets as instruments including soil, seedlings, and seeds, requires further investigation to see the value of potential wide-spread application of these instruments in different contexts. Finally and most importantly, we believe environmental outcome-related lines of inquiry about on-farm trees such as reduced soil erosion due to larger availability of biomass or the valuation of improved environmental services at different spatial scales. Unfortunately, the data available over longer time periods, such as the 20-year ERHS panel, is limited in these respects and may require novel approaches to explore. We support calls for socio-economic datasets to include a wider variety of environmental indicators and information about trees, fiber, and permanent crops.

## 5. Conclusions

Asset creation related to adequate on-farm biomass and on-farm trees provides a compelling pathway for linking environmental and productive asset creation in the rural context to desirable wellbeing and resilience outcomes. We used panel econometric modelling approaches to measure the effect of planting the two most common on-farm trees on dynamics of the two most valuable rural Ethiopian household assets. Contextually appropriate instruments, including seedlings, successfully reduced endogeneity of asset-related variables in a generalized two-stage least squares modeling approach. Planting eucalyptus results in significant positive increases in dwelling value where timber from the trees themselves potential represent a large part of the investment over time. A small, but significant, coefficient for crop residue confirms the positive relationship between on-farm trees, annual crops and increases in dwelling value. On the other hand, available crop residue is highly correlated with increasing values for livestock. Both eucalyptus and enset tree planting increased crop residue in the ERHS dataset presumably through expanding overall biomass on the farm through provision of the more preferred wood fuel, twigs and leaves. Despite indications that on-farm trees saved time for fuel collection for both men and women, a dummy variable for female headed households presented a negative correlation indicating that beneficial outcomes of on-farm trees were not as pronounced for these households. This requires further research into the specific challenges of asset creation for female-headed households.

Combining observations of fuel preference, fuel source, and fuel use may provide new indicators of household level energy security. Increases in the burning of biomass that the household sees as

more productive for another use would be a clear sign of stress. At the community or population level this may be an indication of eroding socio-ecological resilience and the sign of a negative energy environment feedback loop. Further research with datasets that include these three dimensions of household energy insecurity should be undertaken to better understand if this relationship holds true in different contexts.

Our measurements indicate that on-farm trees may increase households' most important asset dwelling value by 9% and significantly contribute to additional Tropical Livestock Units. Extrapolated nationally, the contribution of on-farm trees to rural households' assets would represent billions of USD in value. Mixed method research from large integrated watershed programs supports the observation of on-farm tree contributions to meet household energy requirements, relieve pressure on common areas and, perhaps, protect forests or other environmental assets. As large programs of work on sustainable development will necessarily be taking place in rural areas that are now dominated by agricultural mosaic landscapes that feature many on-farm trees, better accounting for their contributions, and exploration of approaches to multiply their benefits may make considerable progress to reaching sustainable development goals.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2071-1050/10/12/4716/s1>, Table S1: Different tree types and household frequencies from ERHS 1994; Table S2: Tropical Livestock Unit G2SLS Results; Table S3: Dwelling Value G2SLS Results; Table S4: Tropical Livestock Unit G2SLS Results; Figure S1: Key pathways from on-farm trees to household assets and wellbeing.

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