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Tree-Based Ecosystem Approaches (TBEAs) as Multi-Functional Land Management Strategies—Evidence from Rwanda

Miyuki Iiyama [1,2,*], Athanase Mukuralinda [2], Jean Damascene Ndayambaje [3], Bernard Musana [3], Alain Ndoli [4], Jeremias G. Mowo [2], Dennis Garrity [2], Stephen Ling [5] and Vicky Ruganzu [3]

1 Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba 305-8686, Japan
2 World Agroforestry Centre (ICRAF), Nairobi 30677-00100, Kenya; A.Mukuralinda@cgiar.org (A.M.); j.mowo@cgiar.org (J.G.M.); d.garrity@cgiar.org (D.G.)
3 Rwanda Agriculture and Animal Resources Development Board (RAB), PO Box 5016, Kigali, Rwanda; ndjeadamas@yahoo.fr (J.D.N.); bernard.musana@rab.gov.rw (B.M.); vicky.ruganzu@rab.gov.rw (V.R.)
4 International Union for Conservation of Nature (IUCN), Eastern and Southern Africa Region, PO Box 6935, Kigali, Rwanda; alain.ndoli@iucn.org
5 The World Bank, Washington, DC 20433, USA; sling@worldbank.org
* Correspondence: miiyama@affrc.go.jp or m.iiyama@cgiar.org; Tel.: +81-(0)29-838-6728 or +254-20-722-4215

Received: 19 March 2018; Accepted: 23 April 2018; Published: 27 April 2018

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Abstract: Densely populated rural areas in the East African Highlands have faced significant intensification challenges under extreme population pressure on their land and ecosystems. Sustainable agricultural intensification, in the context of increasing cropping intensities, is a prerequisite for deliberate land management strategies that deliver multiple ecosystem goods (food, energy, income sources, etc.) and services (especially improving soil conditions) on the same land, as well as system resilience, if adopted at scale. Tree based ecosystem approaches (TBEAs) are among such multi-functional land management strategies. Knowledge on the multi-functionality of TBEAs and on their scaling up, however, remains severely limited due to several methodological challenges. This study aims at offering an analytical perspective to view multi-functional TBEAs as an integral part of sustainable agricultural intensification. The study proposes a conceptual framework to guide the analysis of socio-economic data and applies it to cross-site analysis of TBEAs in extremely densely populated Rwanda. Heterogeneous TBEAs were identified across Rwanda's different agro-ecological zones to meet locally-specific smallholders' needs for a set of ecosystem goods and services on the same land. The sustained adoption of TBEAs would be guaranteed if farmers subjectively recognize their compatibility and synergy with sustainable intensification of existing farming systems, supported by favorable institutional conditions.

Keywords: East African Highlands; smallholder farmers; population pressure; sustainable intensification; tree-based ecosystem approaches (TBEAs); agroforestry; ecosystem services; multi-functionality; heterogeneity; landscape

1. Introduction

Globally compared, the population density of sub-Saharan Africa (SSA) as a region has remained relatively low at 43 persons/km^2 as of 2016 [1]. Yet, there has been a wide variation in the population distribution across the region with the population density of humid areas exceeding well over 250–500 persons/km^2. In East Africa—where the Great Rift Valley divides the land causing a significant heterogeneity in climates, soil, and slope conditions—well over 50% of the population is found in the Highlands which accounts for only 23% of the total area [2]. The region's land resources and diverse ecosystems have chronically faced rising population pressures. The population in the region has doubled over the last 30 years [3]; during 2000–2016 the region recorded population growth of 3% per year, exceeding that of the world (1.2%) and even of the SSA average (2.7%) [1]. The population in the region is further projected to grow at the fastest pace in the world by 2050 [1,4]. This rising population will drive ever more increasing demand for food, energy, and sources of income at the significant cost of the degradation of ecosystems.

The region's rising population has driven intensification of land use in smallholder farming systems consistent with Boserup's prediction [5]. Jayne et al. [6] confirmed, in densely populated African regions, some evidence of Boserupian intensification in response to rising population density, yet also highlighted some divergences. Intensification in Asia featured increased use of fertilizer per hectare, irrigation investments, increased mechanization, and cereal yield growth. On the other hand, the experience of densely populated Africa has been mainly associated with more continuous cultivation (higher "cropping intensities") of existing cropland and shifts to relatively high-value crops. Additionally, the relationship between population density and land intensification grows up to around 500 persons per km^2, beyond which the relation plateaus and then declines. Among several possible causes of this leveling-off beyond a threshold, Jayne et al. [6] pointed to soil degradation arising from a lack of soil nutrients due to continuous cultivation without recycling organic matter, whose lack of availability sets the low efficiency of inorganic fertilizer application. There is, therefore, an increasing consensus that sustainable agricultural intensification in densely populated African farming systems prerequisites raising soil organic matter, moisture retention, and other forms of soil rehabilitation, in addition to greater inorganic fertilizer use [7].

Rising population has also driven demand for energy with significant land use implications. The development of "modern" biofuel crops for the industrial and transport sectors, which often involves controversial global debates over indirect land use changes [8,9], has not yet fully materialized in East Africa to date. The hype over bioenergy crops, such as *Jatropha crucas* around 2008, led to some "land grabbing" by foreign investors, yet most operations have been forced to close down by now due to marginal returns on marginal land [10,11]. In places where the crop was introduced to smallholder conditions, there were multitudes of logistical challenges, including the lack of quality domesticated germplasms and management protocols to achieve optimal yields with less inputs [12]; constraints on achieving economies of scale for mobilizing farmers, feedstocks, processing; marketing under African farming system conditions; and the eventual lack of demand and markets for the final biofuel product [11,12].

In turn, over 90% of the SSA population still rely on wood fuel, i.e., firewood and charcoal, which together account for >80% of primary energy supply, relative to the ~10% global contribution of solid biomass [13]. Charcoal production has been cited as among the main causes of net greenhouse gas (GHG) emissions in SSA [14,15], as it generally relies on the selective cutting of live trees in forests and woodlands rather than on planted tree stands. These inefficient technologies lose 80–90% of biomass during carbonization [14,16]. Displacement for agriculture for food production is claimed to be the most important driver for permanent losses of carbon stocks, with charcoal often a byproduct of forest clearance. Production of charcoal, in turn, is known to have a significant landscape-level impact on forest degradation due to multitudes of tree cuttings at the production site level [16]. With projected population growth, meeting growing charcoal demand under the business-as-usual scenario will negatively impact land uses significantly in SSA [13,14]. In an extreme case, annual loss of carbon to meet charcoal demand is projected to reach up to 4.5 million ha of forest area in 2050, up from 1.5 million ha in 2010 [13]. While global policy debates emphasize the need for the poor to gain access to cleaner alternatives such as kerosene, liquefied petroleum gas (LPG), and electricity, modern energy sources are unlikely to provide primary household energy needs for most of the poor in SSA for some decades yet, due to the fiscally unsustainable magnitude of the subsidies and infrastructure required to do so. For the coming years, therefore charcoal will remain among the important energy sources to a wide range of urban socio-economic groups in SSA [13,14]. In view of this trend, an integrated strategy for sustainably supplying trees at the landscape scale and the promotion of efficient carbonization technologies is urgently needed to reduce wood harvest pressures, to sequestrate carbon, and to improve system resilience [13,17].

Classical debates over "land sharing" vs. "land sparing" have focused on which of them could better achieve the integration of biodiversity conservation and food production [18,19]. For the sustainable intensification, with increasing cropping intensities, of smallholder systems in the East African Highlands, deliberate land management strategies that ensure the delivery of multiple ecosystem goods (food, energy, income sources, etc.) and services (especially improving soil conditions) on the same land, as well as system resilience, need to be urgently identified, analyzed, and promoted.

Tree based ecosystem approaches (TBEAs) are part of land management options that can deliver multiple benefits [20–22]. Willemen et al. [20] define the key criterion for a tree-based system to be classified as a TBEA is a multi-objective management strategy at the landscape scale. TBEAs include agroforestry practices (woody perennials in agricultural systems) and forestry systems that are actively managed for multiple objectives, such as food, timber and non-timber forest production, and the supply of ecosystem services. Examples of ecosystem services include water flow regulation, climate change mitigation and adaptation, soil nutrient cycling, and rehabilitation [20].

Despite their importance, however, knowledge of the ecosystem service contribution of TBEAs to livelihoods in the tropics, especially within complex and dynamic land use mosaics, remains severely limited [22,23], beyond the classical debates over competitions between crops and trees [24]. Based on a systematic review of current evidence, Reed et al. [23] refer to several methodological challenges defining the current knowledge gaps. For example, the evaluation of the ecosystem service provision of trees is often based on anecdotal evidence and not well supported with robust evidence of the "true" functional value. If addressing functional values, the majority of analyses deal with the delivery of a single ecosystem service in isolation, despite the acknowledgement of interactions due to the direct provisioning of goods and the indirect non-provisioning ecosystem services on the same land. Furthermore, most studies are site-specific case studies, conducted at the farm scale, and thus leave us with little knowledge on the contribution of trees within the broader landscape or their heterogeneity.

The same methodological challenges indeed apply to the ecosystem service approach itself, for which existing tools and approaches for measuring, mapping, and putting values on ecosystem services still remain to be tested in practice [25]. Wu [25], in proposing "landscape sustainability science", has advocated a multi-dimensional perspective to assess key attributes of a landscape in terms of the composition (kinds and amounts), configuration (shape, connectivity, and spatial arrangement), and dynamics of the landscape mosaic. This multi-dimensional perspective to assess landscape sustainability can also be useful in facilitating the understanding of the multi-functionality of TBEAs by analyzing their composition, configuration, and dynamics within the landscape mosaic.

The main objective of this study is to offer a framework to view TBEAs as multi-functional land management strategies and simultaneously as an integral part of sustainable agricultural intensification in densely populated Africa. The framework is applied to the analysis of TBEAs which are among dominant features of agricultural landscapes in Rwanda. Rwanda is the most densely populated and thus, most land scarce region in the continent. A majority of farmers in Rwanda derive their livelihood from agriculture on small and fragmented land. Additionally, Rwanda's sloping topography gives rise to diverse agro-ecologies within compact geographical areas and provides environments where heterogeneous TBEAs can be applied. Through cross-site analysis of the contextual information of diverse agro-ecological zones in Rwanda, this study also aims to identify factors enhancing the adoption of heterogeneous TBEAs.

2. Materials and Methods

2.1. Agroforestry Systems in Rwanda

In Rwanda, the majority of farmers derive their livelihood from subsistence agriculture on small land less than 1 ha [26]. The area under agricultural production has been increasing over time at the expense of pastures, natural forests, and fallows. The environment is consequently being affected by various forms of land degradation, soil erosion, reduction of organic matter, loss of soil nutrients, soil acidification, and loss of biodiversity mainly due to agricultural expansion [27,28].

In the context of recent Rwanda, TBEAs mainly include agroforestry systems that are actively managed by smallholders to pursue multiple functions, i.e., to produce goods (e.g., wood fuel, stakes, timber, fruit, fodder) and services (e.g., soil erosion control, soil fertility enhancement, etc.) [29]. In Rwanda, agroforestry has been part of agricultural practices for hundreds of years. One important characteristic of traditional agroforestry is the retention and management of indigenous tree species—such as *Markhamia lutea*, Ficus spp., *Vernonia amygdalina*, *Iboza riparia,* and *Erythrina abyssinica*—on farms [30] for economic, social, ecological, and cultural purposes.

Since the 1970s, exotic agroforestry species have been introduced among smallholder farmers by government and externally funded projects, while indigenous tree species have been less valued and invested in [31]. For example, leguminous tree species such as *Sesbania sesban*, *Leuceana leucocephala*, and *Calliandra calothyrsus* were introduced, especially in the Plateau regions, with aims to improve soil fertility and fodder provision [32,33]. On the other hand, in the highland zones continuous cultivation on fragmented plots, coupled with heavy rainfall on fragile margins, has led to accelerated soil depletion. Hence, exotic tree species such as Eucalyptus spp. and Alnus spp., have been actively promoted as part of soil rehabilitation programs there [34,35].

At present, Rwandan agroforestry systems are dominated by a wide range of exotic and indigenous tree species that are suitable for different agro-ecological zones. Ndayambaje et al. [36] reported the most common observed agroforestry systems across the major altitude regions of Rwanda, which include:

- Farm woodlots, mostly with Eucalyptus spp., often involving multipurpose wood production and services (including fuel, timber, and stakes) to support high value crops (including beans, peas, and tomatoes) and to control soil erosion by retaining sedimentation from uphill;
- hedgerows, involving trees planted along contour lines for soil erosion control and on cropped bench terraces, leading to stabilization through increasing soil organic carbon, green manure, and generation of other benefits such as stakes for climbing crops, fodder, and wood fuel;
- trees on crop fields through intercropping, where crops are grown between trees coppiced regularly for reducing competition for light, or where trees are scattered on a farm without any arrangement at low density. This provides green manure for soil fertility improvement and other tree products such as wood fuel, fodder, and stakes;
- home gardens consisting of the mix of upper and under story trees—which include both indigenous and exotic fruit, timber, and fodder species—with crops and livestock to fill multiple functions, such as shelter, windbreaks, shade, and cultural functions in the proximity of homestead;
- boundary planting of trees for delimitation between two farms which act as live fencing, a buffer between roads and farms, while providing poles, fruits, wood fuel, and services like wind breaks.

Agroforestry systems in Rwanda thus well meet the criterion of TBEAs defined by Willem et al. [20] as they service multiple objectives on the same land as well as at the landscape scale. Biggelaar and Gold [37] indeed reported that tree species with multiple utilities and high locational flexibility were highly appreciated by Rwandese farmers, who were planting selected tree species in spatial and temporal combination with agricultural crops to fulfill productive functions of the tree species.

2.2. Conceptual Framework

The key aspect of TBEAs is a multi-objective system at the landscape level. Given the diverse TBEAs observed in Rwanda, a systematic understanding of TBEAs across landscapes is urgently needed; unpacking the complexity of factors driving and enabling their adoption. To enable such analyses, this study proposes a conceptual framework (Figure 1), developed by borrowing the concepts of the key attributions of a landscape from Wu [25] and the definition of TBEAs from Willemen et al. [20].

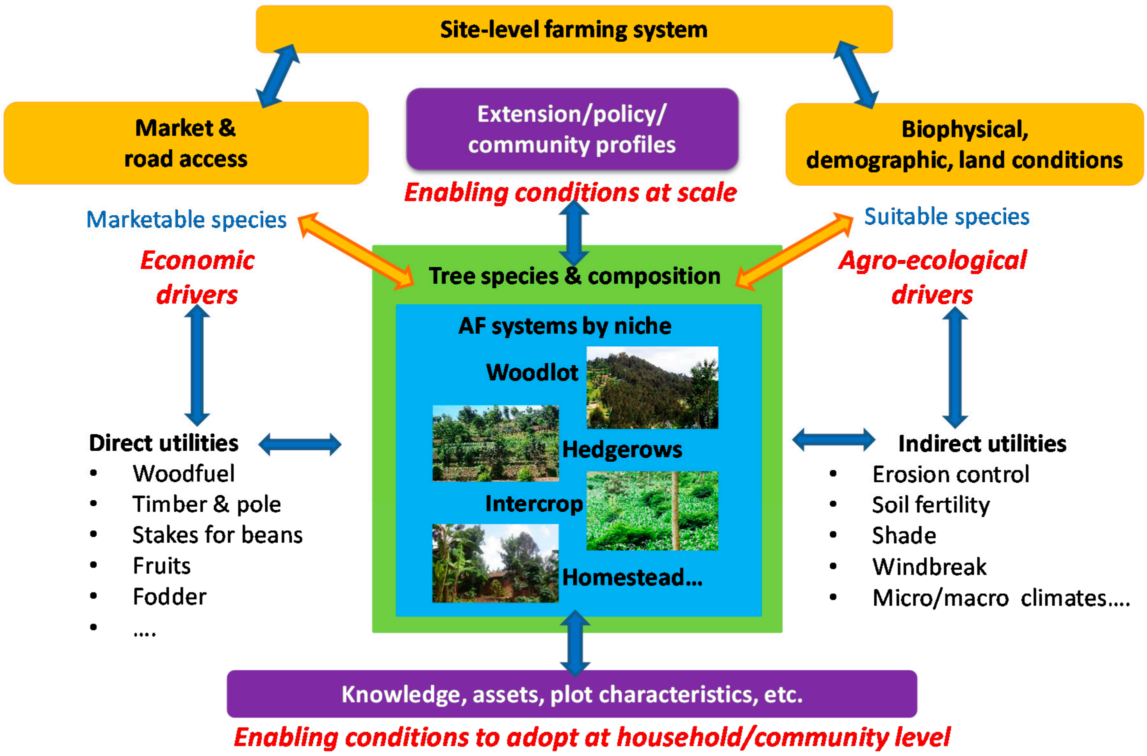


Figure 1. Conceptual framework to understand drivers and enabling factors of tree-based ecosystem approaches (TBEAs).

First, we define the key attributes of TBEAs or agroforestry adoption in the context of Rwanda from a multi-dimensional perspective, i.e., in terms of composition and configuration;

- Composition: species diversity.
- Configuration: spatial niches—ex. woodlots, hedgerows, intercrop, homestead, and boundary planting.

Second, we attempt to identify factors affecting the adoption of different TBEAs at scale. Many agroforestry adoption studies tend to treat the adoption of a single technology as a binary choice of planting a specific tree species or not within specific local conditions [38]. In contrast, TBEA research focuses on revealing contextual information affecting the adoption of different TBEAs. From a global TBEAs literature review, Willemen et al. [20] identified seven commonly reported drivers of TBEAs adoption at scale, including improving soil quality, income generation, food and fiber supply, household nutrition, nature conservation, and adaptation to climate change. They also identified diverse enabling conditions, which include well-established rights to trees and land; local agreements to control land us; access to credit or advisory services; policy reforms which can shift incentives in favor of TBEA implementation; prices of tree products and inputs relative to crops and purchased inputs; and the availability of local knowledge, capacity, and technical support. They, however, argued that there is still weak contextual information in the existing literature regarding the characterization of TBEAs at scale, and recommended the development of a shared conceptual framework and assessment strategy for TBEAs to inform cross-site comparative analysis.

Following Willemen et al. [20], we define drivers as site-level factors which drive the establishment of trees on a farm by farmers who derive a multitude of ecosystem services i.e., direct and indirect utilities from tree products and services in pursuing their livelihoods.

- Drivers: demand for ecosystem services—direct utilities from goods such as fuel, timber/pole, stakes, fruits, fodder, etc. and indirect utilities from services, such as soil erosion control, soil fertility, shade, windbreaks, etc.

We assume demand for particular trees is not only influenced by individual households' subjective preferences, depending on their resource endowments, but also strongly affected by agro-ecological and economic conditions at site-level. Agro-ecological drivers include biophysical and demographic conditions, as they pre-determine suitable, compatible, and less competitive tree species with local agro-ecologies and farming systems. Additionally, they drive farmers to demand specific environmental services from trees, ex. soil erosion control, fertility improvement, and climate regulations. Economic drivers on the other hand include market and infrastructural access as well as farming systems, as certain agricultural activities require particular tree products as inputs (examples, fodder for zero-grazing, stakes for climbing beans).

- Proxy variables for agro-ecological drivers: altitude, rainfall, relief (slope conditions), soil fertility conditions, population density, major farming/agro-ecological zones.
- Proxy variables for economic drivers: market/infrastructure access, degree of commercialization of farming activities, etc.

On the other hand, even given similar agro-ecological and economic drivers, socio-economic profiles of communities and institutional/policy factors make the modes of management and the intensity of adoption at scale more dynamic across sites. We define enabling conditions as institutional, policy, market factors, and community profiles which shift incentives in favor of TBEA adoption.

- Proxy variables for enabling conditions: access to advisory and credit services, community profiles such as migration/resettlement histories, tenure security, education level, off-farm income opportunities, transport means.

This conceptual framework guided our analysis of the socio-economic data to examine (i) inter-relationships among key attributes of TBEAs—composition (diversity), configuration (niches), and dynamics (factors driving the adoption, especially human needs for direct/indirect utilities derived from trees); and (ii) interactions among contextual factors to understand drivers, enabling conditions, and mechanisms of heterogeneous TBEAs adoption patterns.

2.3. Site Selection in the Six Agro-Ecological Zones

Rwanda is a hilly country with altitudes less than 1500 m in the eastern plateau but rising to between 1500 and 2000 m in the central plateau area and higher in the west and north. The variation in altitude affects rainfall patterns, while the presence of volcanoes in the highlands and of marshlands in the lowlands influence soil fertility and slopes, leading to heterogeneous agro-ecologies with diverse cropping potentials and local population densities. Six distinctive major agro-ecological zones of Rwanda were identified for this study: (A) Eastern Savanna; (B) Eastern Plateau; (C) Bubureka Highland; (D) Volcanic Highland; (E) Central Plateau; and (F) Congo-Nile Crest. Table 1 summarizes the biophysical and farming characteristics of the six agro-ecological zones of Rwanda, supplemented by the map in Figure 2 and the photos in Figure 3.

Table 1. Biophysical and farming characteristics of the six agro-ecological zones.

	Biophysical Characteristics				Farming Characteristics	
Agro-Ecological Zones	Elevation in Meter	Rainfall (mm Per Year)	Temperature (°C)	Soils (FAO Classification *)	Principal Crops	Animals
A Eastern Savanna	1200–1400	800–1000	>21	Ferrasols, Regosols Vertisols Acrisols, Histosols	Banana, cassava, maize, bush bean, rice	Ranch of cattle with free grazing
B Eastern Plateau	1200–1500	800–1000	20–21	Ferralsols	Banana, cassava, maize, bush beans	Cattle, goats
C Buberuka Highland	1900–2000	1200–1300	15–18	Allisols Ferrasols Luvisols Histisols, Regosols Cambisols	Wheat, maize, climbing beans, tea, Irish potato	Cattle zero grazing, sheep, goat
D Volcanic Highland	2200–2400	1300–1500	<15	Andosols	Irish potato, wheat, climbing beans, maize, pyrethrum	Ranch for cattle with free grazing, zero grazing; sheep, goat
E Central Plateau	1100–1700	1000–1500	18–20	Ferrasols Acrisols Lixisols Cambisols	Cassava, banana, coffee, bush beans, rice	Zero grazing of cattle and goat, pig
F Congo Nile Crest	1900–2500	1300–2000	<15–18	Luvisols Acrisols	Tea, coffee, Irish potato, wheat	Cattle free grazing and zero grazing sheep, and goat, pig

*: The Food and Agriculture Organization of the United Nations (FAO) developed a supra-national classification, also called World Soil Classification, which offers useful generalizations about soils pedogenesis in relation to the interactions with the main soil-forming factors.

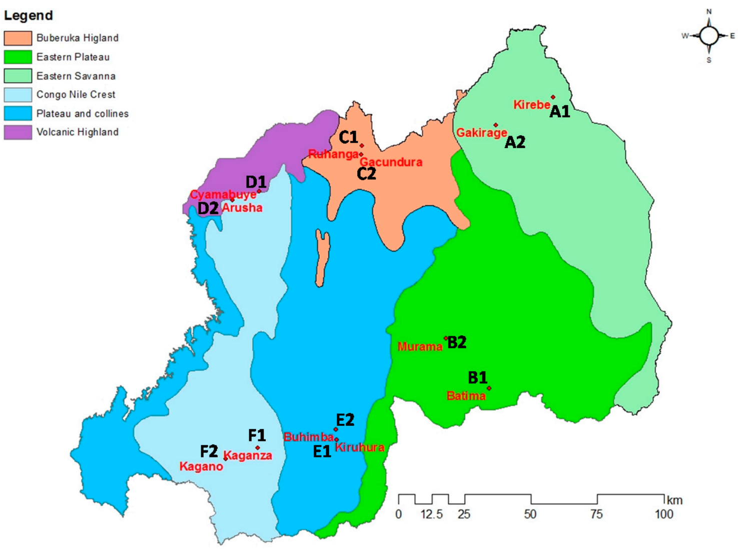
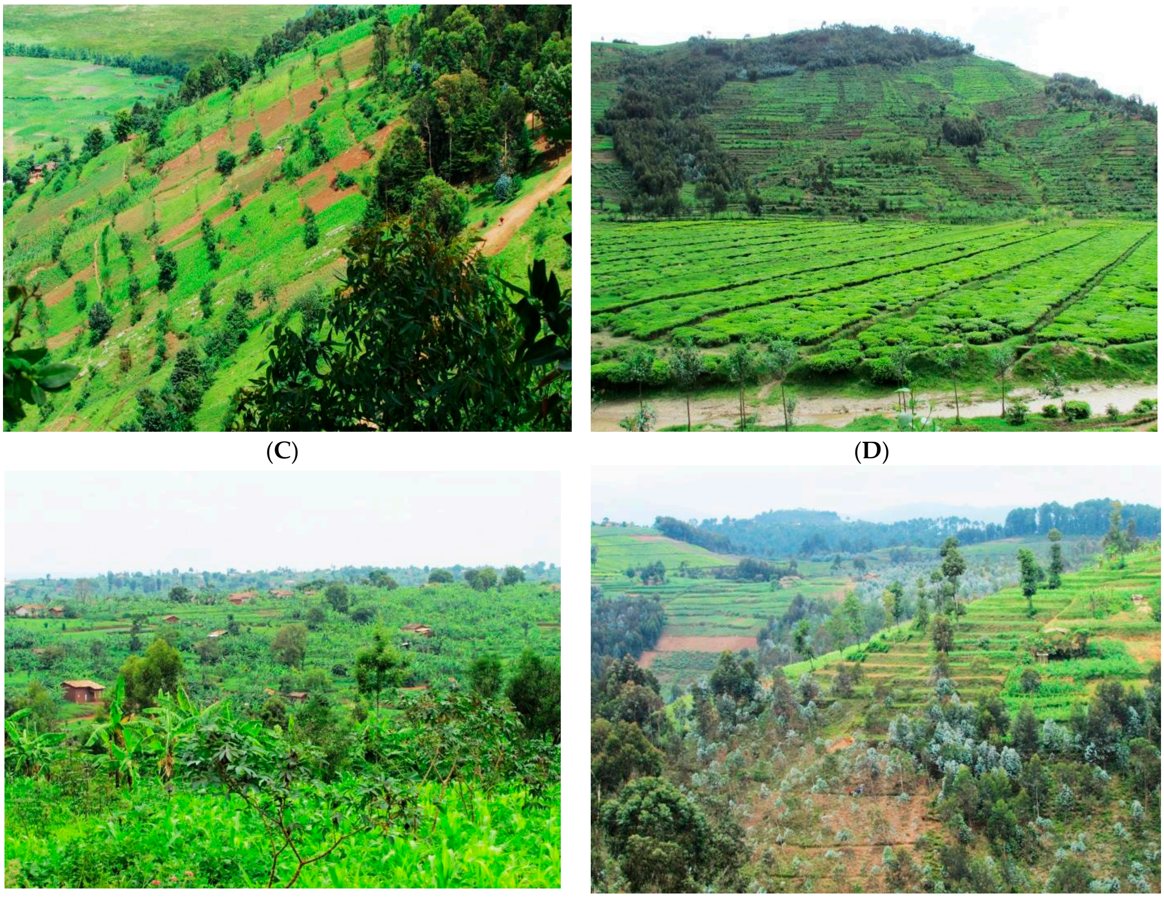


Figure 2. Map of the six agro-ecological zones with the location of the study sites [29].

(**A**) (**B**)

Figure 3. *Cont.*



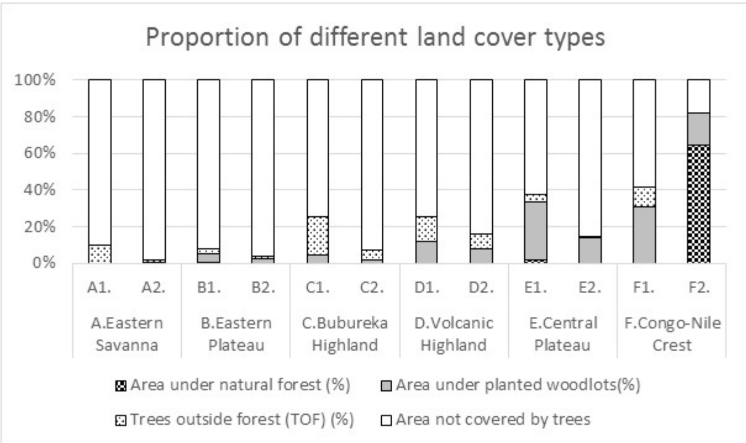
(**C**) (**D**) (**E**) (**F**)

Figure 3. Site illustrations of the six agro-ecological zones. (**A**) Eastern Savanna, characterized by indigenous acacia trees scattered on farms; (**B**) Eastern Plateau, characterized by some indigenous and exotic trees on farm; (**C**) Bubureka Highland, characterized by Alnus hedgerows and small Eucalyptus woodlots; (**D**) Volcanic Highland, characterized by Alnus hedgerows and small Eucalyptus woodlots; (**E**) Central Plateau, characterized by fruit and fodder trees on home gardens; (**F**) Congo-Nile Crest, characterized by eucalyptus woodlots.

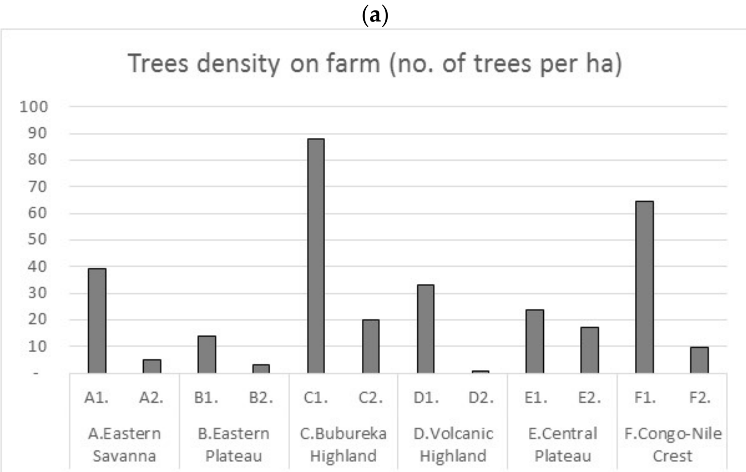
The administrative structure of Rwanda is organized into districts, sectors, and cells. In each agro-ecological zone, one representative district was selected, based on biophysical and socio-economic factors. In each district, two cells with contrasting outcomes with respect to the incorporation of TBEAs in the land management were selected for in-depth assessment of TBEA adoption at scale. Given the absence of objective, quantitative measures to assess the adoption of TBEAs at scale prior to this study, the cell selection exercise to determine where TBEAs have been implemented successfully at scale (Cell 1) and not (Cell 2), had to rely on subjective opinions of the local project partners, and were validated by the research team during the field trip in late November 2014. A summary of information on the selected cells in each of the six agro-ecological zones is listed in Table 2. The ex-post spatial analyses using available geo-processing tools from ArcGIS 10.1 Esri, Redlands, CA, U.S. generally confirmed that across the six agro-ecological zones, Cell 1 presented higher figures for trees outside forests (TOF; generally referred to as agroforestry trees), total tree cover excluding natural forests, and tree density in farmlands compared to Cell 2 (Figure 4).

Table 2. Selected sites and sampled households.

Agro-Ecological Zone	(A): Eastern Savanna	(B): Eastern Plateau	(C): Bubureka Highland	(D): Volcanic Highland	(E): Central Plateau	(F): Congo-Nile Crest
District	**Nyagatare**	**Bugesera**	**Burera**	**Nyabihu**	**Huye**	**Nyamagabe**
Cell 1	**(A1) Kirebe**	**(B1) Batima**	**(C1) Ruhanga**	**(D1) Cyamabuye**	**(E1) Kiruhura**	**(F1) Kaganza**
Total households	993	2003	1037	1057	1303	673
Sampled households	41	35	25	50	67	28
% sample	4.1	1.7	2.4	4.7	5.1	4.2
Cell 2	**(A2) Gakirage**	**(B2) Murama**	**(C2) Gacundura**	**(D2) Arusha**	**(E2) Buhumiba**	**(F2) Kagano**
Total households	1159	1290	1067	779	1019	1109
Sampled households	39	41	20	45	34	39
% sample	3.4	3.2	1.9	5.8	3.3	3.5



(**a**)



(**b**)

Figure 4. Tree covers and density in the study sites. (**a**) Proportions of different land cover types; (**b**) Tree density on farms of the study sites in the six agro-ecological zones.

2.4. Data Collection, Processing and Analysis

The conceptual framework proposed above guided the design of socio-economic data collection and analysis aimed at facilitating the functional and systemic characterization of diverse TBEAs observed in the study sites across Rwanda.

A household survey was conducted between November and December 2014. In each selected cell, about 30–50 random households were targeted through a stratified sampling procedure. In total, 464 households were interviewed in the 12 cells from the six agro-ecological zones. A structured questionnaire was administered to respondents' household heads or their representatives during the survey [39]. In designing the questionnaire, the thirty dominant indigenous and exotic tree species observed in Rwanda across different agro-ecological zones were pre-selected based on expert knowledge and literature review [31,36,37] as well as on-ground validation. Farmers were also allowed to answer up to ten additional species not included in the list. It turned out those additional species included many grass/flower species rather than trees and shrubs, thus we decided to focus on the analysis of the thirty perennial woody tree and shrub species (listed in Figure 5 below). Detailed questions were then asked for each of the thirty tree species based on farmers' recall. Topics included the number of trees, farmers' reasons for adoption in terms of utilities, and the niches on farm. The questionnaire was also designed to collect data on household profiles which could be aggregated for community profile variables as proxies for drivers and enabling conditions.

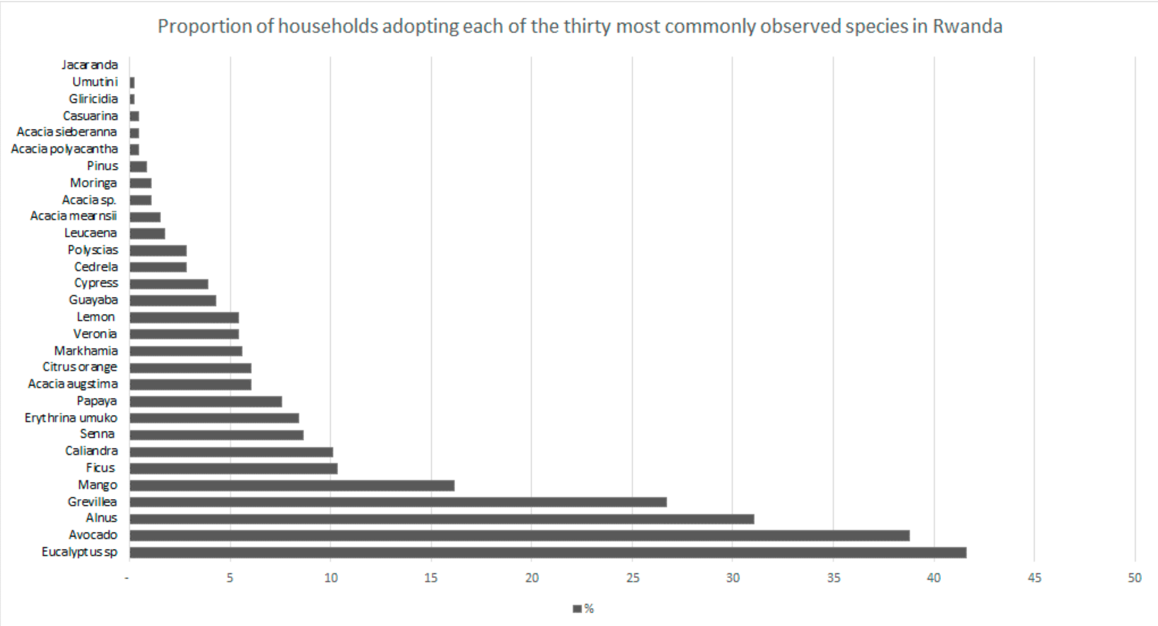


Figure 5. Adoption of the thirty species for all the study sites.

Understanding TBEAs in terms of multiple utilities is one of the most critical components of this analysis, as we assume that preferences for trees with multiple utilities are directly linked with drivers of adoption. In processing the data, utilities were categorized into: fruits; timber/pole; wood fuel (firewood, charcoal); fodder; bean stakes; fence/tools; medicine; cultural values; soil erosion control; other environmental services (shade, windbreak, soil fertility, micro/macro climates); and others (not categorized above or no answers provided). During the survey, interviewed farmers often referred to more than two utilities for one specific tree species with the most important ranked as the primary utility and others as secondary. In order to capture the multi-functional role of TBEAs in the farmers' perspective, we created a weighted index to reflect multi-dimensional utilities of specific tree species, following the formula of Iiyama et al. [40]. We calculated utility scores for each household, giving a higher weight to the primary utility than to other secondary utilities. For example, if a farmer answered that firewood was the only utility derived from his/her Alnus spp. on the farm, this species was given a score of 1.0 for fuel. If a farmer answered that Alnus was primarily for fuel, but also for soil erosion control as a secondary benefit, then the species got 0.7 as the fuel score and 0.3 as the soil erosion control score. If more than two secondary utilities were mentioned—say soil control and bean stakes, aside from fuel as the primary utility—then the species got the scores for fuel 0.7, for soil erosion control 0.15, and for stakes 0.15. In this way, the score for one particular species would not exceed 1.0, but with higher numbers of secondary utilities, the scores would be subdivided into multiple utilities. Once utility scores were calculated for each species, they were aggregated by utility types for each household, and they were also used as weights to disaggregate all the tree stands managed by a household by distinctive utilities.

Given the absence of commonly used quantitative measures to assess scaling up of TBEAs (e.g., percentage of land area or population engaged in TBEA implementation), the adoption at scale is defined loosely if a TBEA is considered a common practice in an area by many land managers or communities [20]. For this study, we simply used the proportion of the surveyed households adopting particular TBEAs against the total surveyed households in each study site as proxy variables of the adoption at scale. Descriptive statistics were used to quantify the proportion of households adopting TBEAs per site by different TBEAs definitions in terms of tree species, abundance, niches, and utilities respectively.

Simple correlation analysis was then used to identify which quantified proxy variables represented site-level agro-ecological drivers, economic drivers, and enabling conditions that were significantly associated with TBEAs adoption indicators. For agro-ecological drivers, relevant GIS derived figures or official statistics per study site were used as proxy variables (ex. median for altitude, annual rainfall, mode for relief, proportion of very fertile soil types, total cell areas, forest/woodlot areas, number of households, populations etc.). For economic drivers and enabling conditions, descriptive statistics of the socio-economic survey were mainly used as proxy indicators (ex. accesses to market, infrastructure, service, and plot characteristics, etc.). The wide variation in the number of sampled households across the 12 surveyed sites, from 20 to 67, required caution in dealing with mean values at the site-level. Correlation analysis was first performed for weighted cases according to the number of households sampled per site (464 cases in total corresponding to all surveyed households), and derived statistical values were adjusted for the actual 12 sites. The Pearson correlation for each pair of variables derived by SPSS Statistics 24.0 IBM, Armonk NY, U.S. was used to calculate *t*-value, and subsequently *p*-value. The *t*-value statistic has a degree of freedom of 10 (12 site cases minus 2) and hence specific correlations were tested to be statistically significant at 1–5% level.

3. Results

3.1. Diversity

Among the thirty tree species examined, the seven most commonly adopted, by over 10% of all the surveyed households, across the six agro-ecological zones were Eucalyptus spp., *Persea americana* (avocado), *Alnus acuminata*, *Grevillea robusta*, Ficus spp., *Calliandra calothyrsys,* and *Mangifera indica* (mango) (Figure 5).

Species had varying adoption rates across the study sites. Figure 6 presents the varying adoption rates of the twelve species dominant in at least one of the study sites. Figure 7 presents mean tree species numbers per household (species diversity) across the study sites. Bubureka Highland (C) and Eastern Plateau (B) sites had a relatively high mean species diversity, whereas a low mean diversity of species was reported in the contrasted agro-ecological zones; in Eastern Savanna (A) which presents the driest climate, and Volcanic Highland (D) which presents the coolest climate among the six agro-ecological zones.

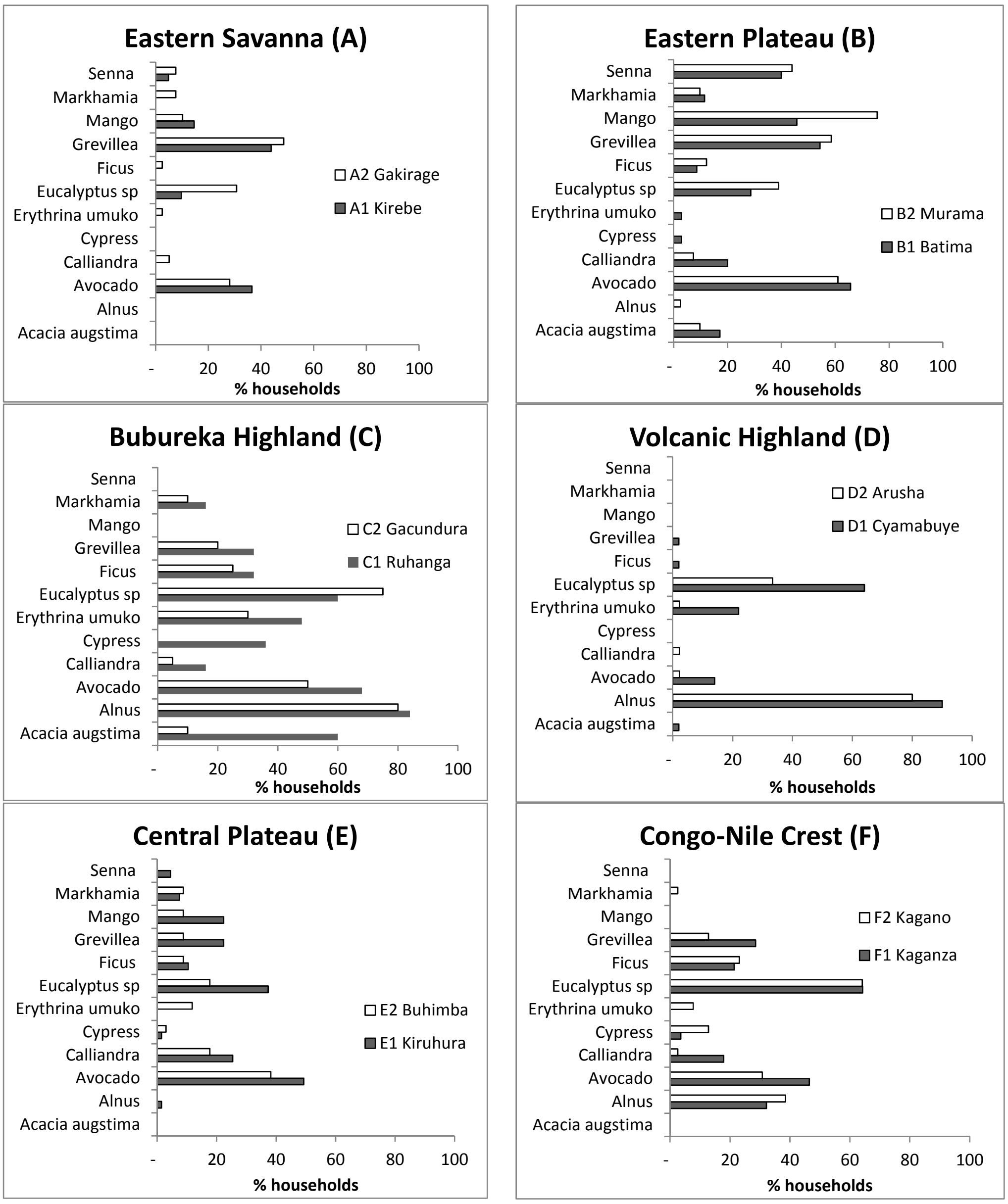


Figure 6. Adoption of the top twelve common tree species.

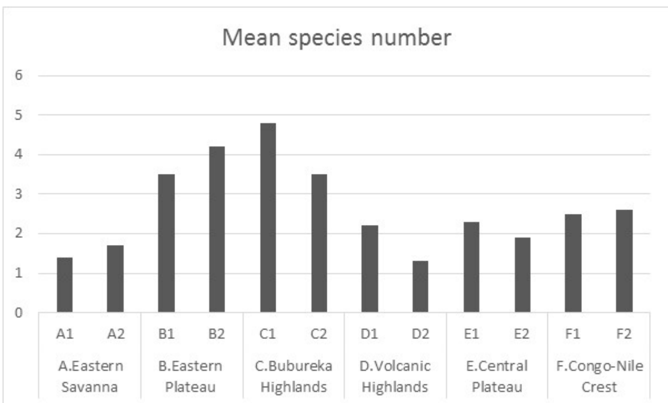
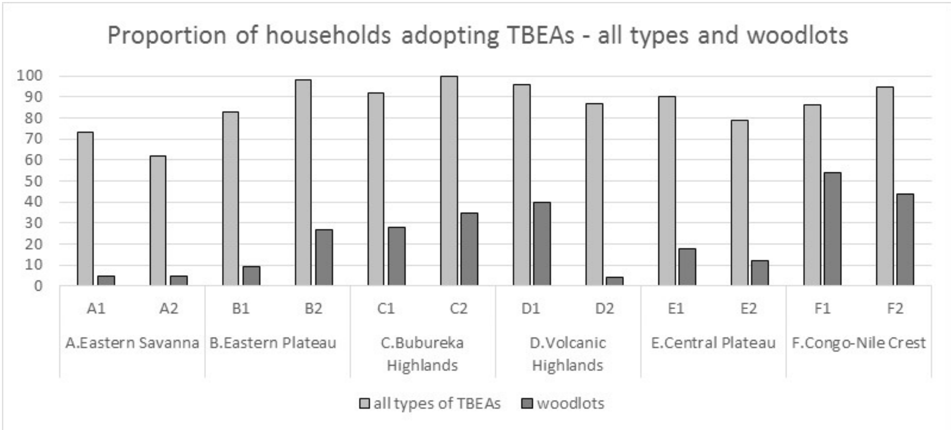


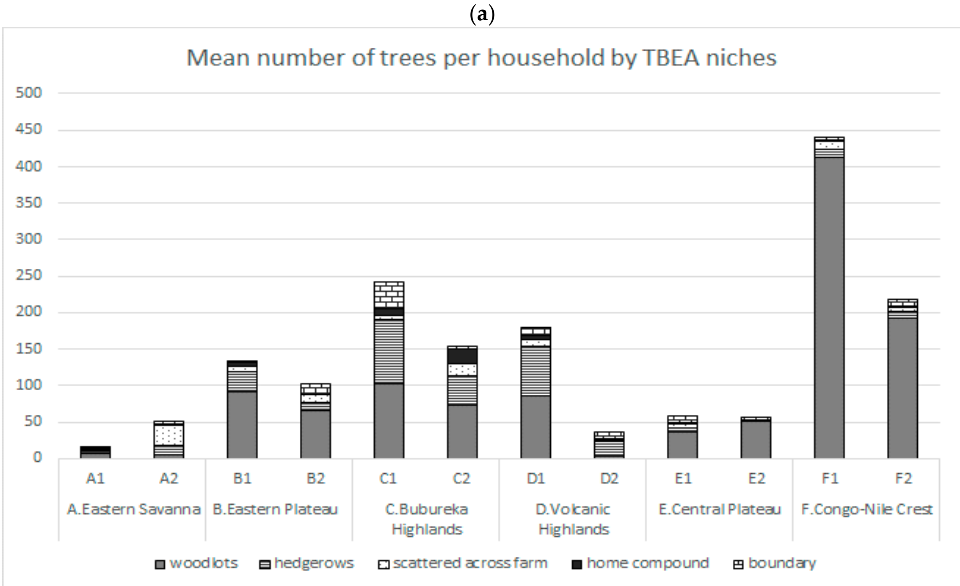
Figure 7. Mean species diversity.

3.2. Niches

Figure 8a presents the proportion of the surveyed households for each study site adopting any form of TBEAs and those specifically adopting TBEAs of the woodlot niche. Additionally, Figure 8b shows the mean number of trees by niche category.



(**a**)



(**b**)

Figure 8. Adoption of TBEAs and mean number of trees by niche. (**a**) Proportion of the surveyed households adopting any form of TBEAs versus woodlot; (**b**) Mean number of trees by niche.

Across the six agro-ecological zones, the adoption of any kind of on-farm trees was generally high. In some sites, the general adoption rate was even close to 90–100%, while it was relatively low in Eastern Savanna (A). In contrast, the mean number of trees per household varied greatly across the six agro-ecological zones, and even between the cells within the same agro-ecological zone. In the Highland Systems, where woodlot adoption was relatively high, and especially in the Congo-Nile Crest (F), the mean number of trees was very high. There the farmers planted trees such as eucalyptus more exclusively in woodlots but planted fewer trees in other niches. In contrast, at Bubureka Highland sites (C1, C2) and site D1 of the Volcanic Highland, at least 50% of trees on farms were found outside woodlots, and especially in hedgerows. In site D2, where woodlot adoption was low at 4%, the overall number of trees was smaller compared to that in the other highland sites.

Figure 9 captures a few symbolic tree species that were characteristic of the major agroforestry systems defined by niches in each of the land use systems. In the Eastern Savanna (A), major agroforestry systems were boundary planted trees of grevillea and eucalyptus, and scattered trees of Senna at both sites. In the Eastern Plateau (B) and Central Plateau (E), avocado and Calliandra were among symbolic tree species, while their strategic niches on farms varied widely. Aside from homestead in both sites, avocado trees were more likely found scattered on farms in (B) and boundary in (E). The niches of Calliandra varied across sites. In the Highland agro-ecologies of Bubureka (C), Volcanic (D) and Congo-Nile Crest (F), Alnus and Eucalyptus were widely adopted tree species (Figure 7). Eucalyptus trees were more often found in woodlots especially in Congo-Nile Crest (F), while their niches varied between sites. In Volcanic Highland (D), these trees were found either in woodlot or homestead niches at (D1), while more households adopted the trees in homestead and boundary and less in woodlot at (D2). Alnus trees were more likely to be planted in contour hedges especially on highly sloped land, and at site (C1), whose counterpart site (C2) showed rather less importance of Alnus for hedges, and found they were more scattered on farms or homesteads.

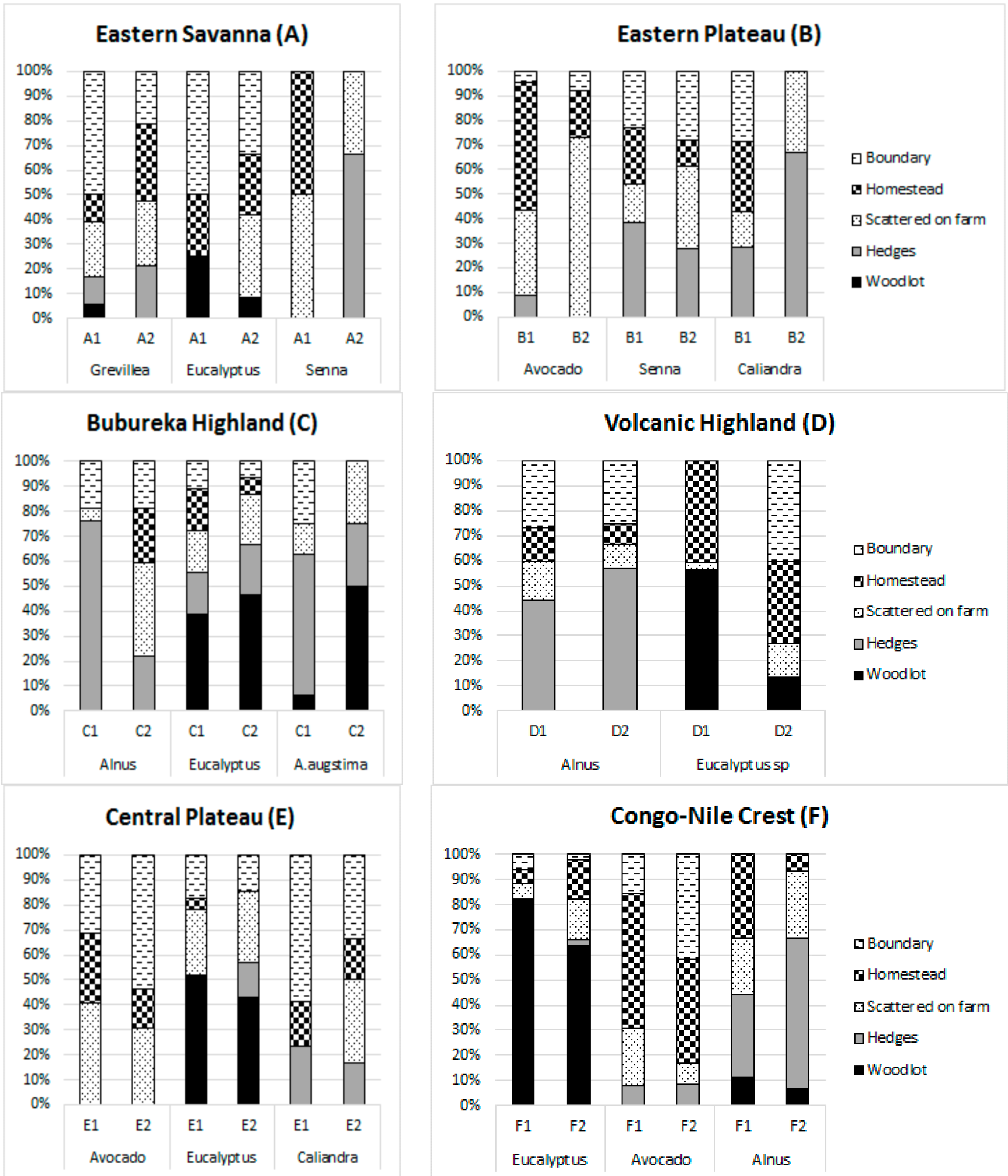


Figure 9. Key tree species adopted in different niches observed in each study site.

3.3. Utilities

Figure 10 shows that the major tree species dominant for the respective study sites were perceived by farmers to serve for multiple objectives. There were variations in preferred utilities from specific tree species across the agro-ecological zones and also between sites in a specific system. For example, Alnus, which was adopted by over 80% of the households in Bubureka Highland (C) and Volcanic Highland (D) (Figure 6), was associated with utilities such as fuel, stakes, and environmental service. Provision of stakes was given a higher weight in Bubureka Highland (C) sites than in Volcanic Highland (D) sites which gave a relatively higher weight to environmental services, i.e., soil erosion control. Furthermore, within Volcanic Highland (D), D1 households gave a higher weight to stakes while D2 households gave a higher weight to fuel. Calliandra, primarily introduced for the provision of fodder and soil fertilization, was perceived also to provide fuel and stakes in Eastern (B) and Central (E) Plateau sites which gave varying weights to different utilities.

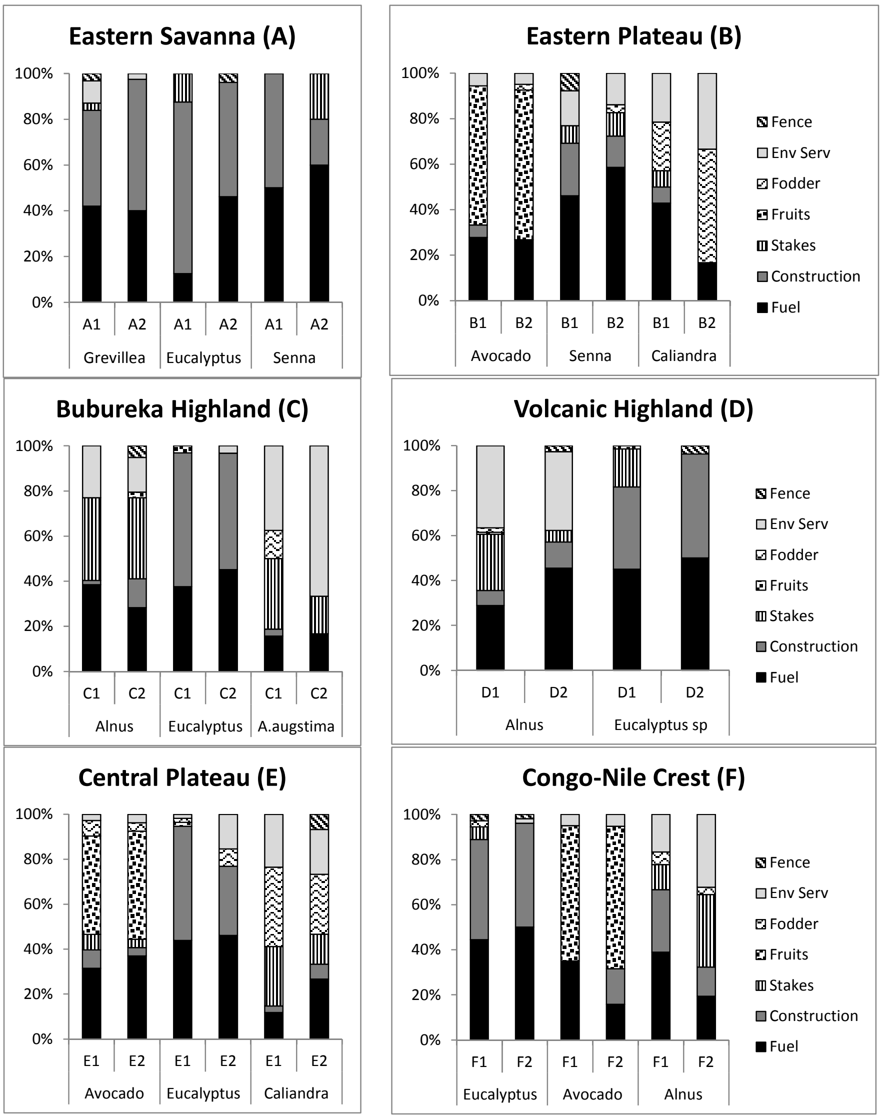
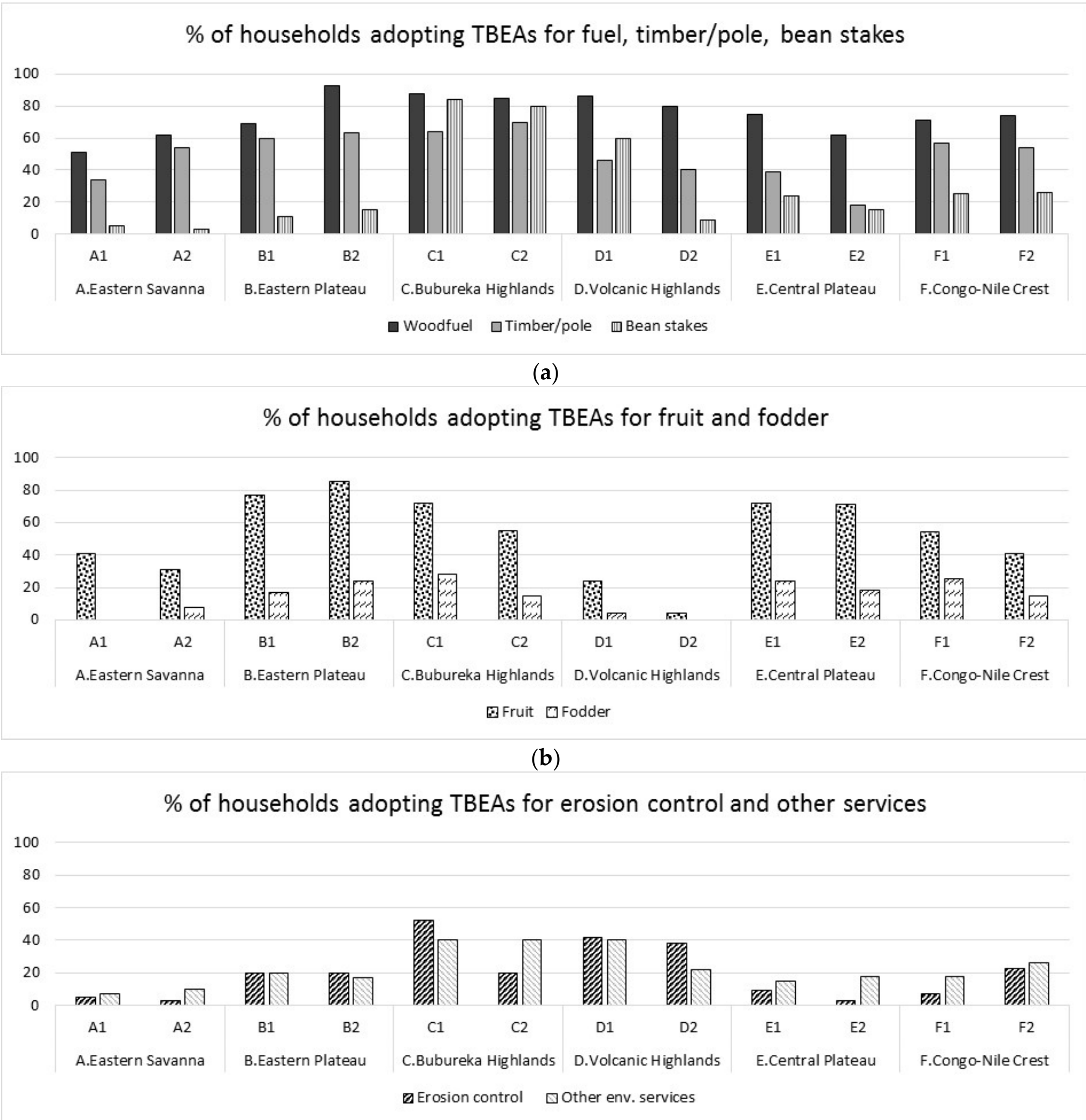


Figure 10. Multiple utilities derived from key species observed in each study site.

Figure 11 presents the proportions of households adopting different TBEAs by utility. Over 50% of the surveyed households across the six agro-ecological zones referred to fuel as the major utility derived from tree species planted on farms. In particular, higher proportions of farmers referring to fuel were found in the highland systems (C, D, F). Some other utilities also seemed to follow geographical patterns. Proportionally more households in the highland systems—especially in sites C1, C2, and D1—reported bean stakes as an important utility, compared to those in lowland systems. The adoption of trees for the utility of fruit varied considerably across the systems, relatively high in the temperate climate zones of Eastern (B) and Central (E) Plateaus, and very low in Volcanic Highland (D) whose high altitude could restrict horticultural development without available germplasm of suitable temperate fruit species. Fodder adoption was generally moderate, at not more than 25%, yet relatively more adopted in Eastern Plateau (B), Bubureka Highland (C), Central Plateau (E), and Congo-Nile Crest (F) regions where zero grazing was commonly adopted. In contrast, the adoption was minimum in Eastern Savanna (A) and Volcanic Highland (D) where free grazing was still common. In general, farmers seemed to give more weight to utilities from goods such as fuel, timber, and fruits. Still, some farmers regarded ecosystem services as important secondary or subsidiary utilities derived from trees. Especially, significant proportions of farmers in Bubureka (C) and Volcanic (D) Highlands considered utilities from soil erosion control important.



(c)

Figure 11. Adoption of TBEAs defined by utilities. (**a**) Wood fuel, timber/pole, bean stakes; (**b**) Fruit, fodder; (**c**) Erosion control, other environmental services.

3.4. Contextual Information

Table 3 summarizes the key results of the correlation analysis by listing the signs and magnitudes of the significance of site-level indicators, representing context proxies (Supplementary Materials Tables S1 and S2) which were found significantly associated with TBEA adoption proxy variables. Among the proxy variables for agro-ecological drivers, high altitude—which was in general highly correlated with sharply sloped landscape and higher annual rainfall—was positively correlated with hedgerows in terms of niche, soil erosion control and environmental services in terms of utility, and species such as eucalyptus and Alnus. In contrast high altitude was negatively correlated with fruits in terms of utility and species such as avocado and mango. The higher proportion of very fertile soils was negatively correlated with overall tree number under agroforestry systems, and the numbers of trees in woodlots, and eucalyptus. Higher population density was significantly correlated with more trees in agroforestry systems, woodlots, fuel, and eucalyptus.

Table 3. Site-level factors significantly correlated with TBEA adoption indicators.

	Agro-Ecological and Economic Drivers					Enabling Conditions							
	High Altitude, Steep Slope, High Rainfall	**% of Very Fertile Soil**	**Pop. Density Excl. Natural Forests and Woodlots**	**Market Access**	**Maize Wheat Irish Potato Climbing Bean System**	**Agronom Office Accessible**	**Fragmentation Index**	**% Plots Owned**	**% Plots on Sloped Land**	**Migration Experience**	**Head Education**	**Transport Asset Values**	**Off-Farm Remittance Income**
AF adoption summary													
Overall agroforestry		-	+		++		+	++		- -			+
AF excluding woodlots						+		++		-			
Multi-purpose Alnus hedgerows													
Alnus	++					++		+	++				
Hedges	+					++		+					
Erosion control	++					++		+					
Other environmental services	+					++		++	+	-			
Bean stakes					+	+	+	+	+	-			
Multi-purpose Eucalyptus woodlots													
Eucalyptus	+	- -	+		++		+	++	++	- -		+	++
Woodlots		- -	+		++		+	+	+	- -		+	++
Timber/pole		-			+		++					+	
Wood fuel		-	++		+	+		++		-			+
Fruit agroforestry													
Avocado	-			+			+					+	
Mango	-								-		+	+	
Fruit	-			+			+					++	++
Fodder agroforestry													
Calliandra	-						+				+		
Fodder	-			+			++			-	+		

Note: ++ (- -) Correlation is significant at the 0.01 level. + (-) Correlation is significant at the 0.05 level.

For economic drivers, market access (negative of distance to market) was found to positively correlate with TBEA adoption in terms of utilities such as fruits and fodder, and avocado as a species.

Some farming system proxies which were more commercially grown in the Highland systems, positively correlated with some of the TBEA adoption indicators. The Highland systems were more favorable for growing crops such as maize, wheat, Irish potatoes, and climbing beans compared to the Plateau and Savannah systems Additionally, controlling for the agro-ecological zones, some sites (Cell 1) had higher commercialization scores than others (Cell 2) (Supplementary Material Table S1). Thus, the aggregated indicator of crop commercialization for highland crops was found strongly correlated with some of the TBEA adoption variables, especially with the overall tree number, eucalyptus, woodlots, timber/pole, bean stakes, and somewhat with fuel and other environmental services.

Among enabling conditions, agricultural extension office ('agronom') accessibility and the proportion of plots owned, were positively associated with some TBEA adoption indicators, such as tree number excluding woodlots, and especially with the adoption of Alnus hedgerows for soil erosion control and other environmental services. Plot fragmentation index was correlated with woodlots as niche, fruit, bean stakes, and especially timber/pole and fodder as utilities, and eucalyptus and avocado for species. The proportion of plots located on sloped land was positively correlated with Alnus/Eucalyptus as species, woodlots as niche, and other environmental services as utilities, while negatively associated with mango.

Among community profile variables, migration experience was negatively correlated with TBEA adoption in general, especially woodlots and eucalyptus. Household head education level was positively correlated with more trees of mango, Calliandra, and fodder utility. Transport asset value was positively correlated with more trees in woodlot as niches, Eucalyptus, fruit utility, and avocado. Off-farm remittance income was associated with more trees overall, woodlot niches, fruits, wood fuel, and Eucalyptus.

4. Discussion

The classic trees versus crops discussion that has been discussed especially in the African context for decades has focused around the question of whether farmers could better cultivate crops (and obtain fuels etc. from outside the agricultural system) or whether they should allow for some yield loss from the trees in their fields to generate additional added-value in non-crop output. Some studies attempt to quantify the competition between crops and trees based on nutrition and light conditions for different "intercrop" (mixing trees and crops at certain spacing) conditions [41]. A recent study from Rwanda in fact verified that trees negatively affected staple crop yield due to trees reducing the amount of available light (shading), however farmers tended to have trees on farm despite deriving little income from them [24]. This indicates that farmers may decide to adopt trees on farms not only for income but also non-income benefits [24]. In Rwanda or elsewhere, famers may plant and manage selected tree species in spatial and temporal combination with agricultural crops to fulfill multiple productive functions of tree species depending on their locational flexibility [37]. Our proposed analytical perspective attempted to understand TBEAs from a multi-dimensional perspective, especially in terms of species, spatial niches, utilities, and landscape configurations to understand farmers' strategies.

The evidence from Rwanda presented that TBEAs turned out to be multi-functional in meeting farmers' needs by delivering multiple ecosystem goods and services in various strategic niches to the farm/landscape. The study also revealed geographically heterogeneous patterns in TBEAs. Two symbolic TBEAs were identified in extremely densely populated Highland zones. They were; multi-purpose Alnus contour hedgerow (species and niche) for fuel; stakes for commercial crops as well as for soil erosion control (utilities); and eucalyptus woodlot systems (species and niche) for fuel, stakes, and timber (utilities). We further analyzed contextual factors associated with the adoption, at scale, of these systems.

The multi-purpose Alnus contour hedgerow system was common in the Highland zones (C and D), where 80+% of surveyed households adopted the trees. Proportionally more households in the Highland systems reported bean stakes, timber/pole, soil erosion control, and other environmental services as important utilities derived from trees on farms, and Alnus could match such needs. Demand for these utilities from tree products and services corresponded to economic and agro-ecological drivers defined by particular farming system contexts—i.e., demand for stakes for climbing bean which is among the highly profitable commercial food crops in the region, and demand for soil erosion control and soil fertility as the regions are susceptible to soil degradation due to continuous cultivation on extremely sloped landscapes and high population pressures [35].

In Highland systems, eucalyptus woodlots were perceived to contribute to the provision of goods such as timber/pole, wood fuel, and income from selling them. Being among the most commonly adopted agroforestry form/type in Rwanda with an estimated 36–40% adoption rate at the national level [26,42], eucalyptus woodlot on agricultural land is reported to have a positive gross margin with secure land tenure and rising wood fuel prices [43]. Indeed, eucalyptus, which had been introduced to East Africa between the late 19th and early 20th centuries, has been among the most dominant species across the region, with the largest plantations found in Ethiopia and Rwanda [44]. Opposed to its dominance across the landscapes in the region, environmentalists often raise concerns that eucalyptus can have negative impacts on soil water balance, while researchers advocate for unbiased assessments at the temporal and spatial scales, and relative to the socio-economic and livelihood benefits to farmers [44]. For example, an experiment in Southern Rwanda found while soil moisture, nutrients, and light were significantly reduced in the crop fields next to the eucalyptus woodlots, combining cropping with eucalyptus woodlots was more profitable than solely cultivating crop, and revenue from extra wood gains exceeded the corresponding revenue losses in crop yield. These results depended on crop field size and orientation against the niche of the woodlot [45]. The current study's findings confirmed that eucalyptus woodlots were more likely to be adopted in sites dominated by less fertile soils, and more fragmented plots with tenure security. This can support the view that they are mostly adopted in strategic farm niches which are essentially unsuitable (degraded, very steep slopes) for farming among fragmented plots on varied topography [46].

While it is beyond the scope of this study, the yield of eucalyptus and its environmental impact can be greatly influenced by the types of management [44]. Eucalyptus management is divided between seed stand and coppice stand. One possible reason why eucalyptus has been popular among Rwandese farmers is the ability to coppice with evidence of substantially higher yields, resulting in an increase of 20–50% for 3–4 years with a smaller fraction of labor costs than establishing the initial seedling crop [44]. At the same time, it is argued that many eucalyptus plantations in Rwanda are not growing to their full potential, with neglected management of multi-stemmed coppices of various age and poor-quality trees resulting in poor stocking and low yield [47]. There is a huge economic argument for investing in upgrading old plantations to raise profitability through the provision of quality seeds/clones together with manuals and extensions on best practices on species choice and intensive weeding [47].

This study further confirmed that TBEAs were compatible with cropping/farming systems to better optimize resource use. Within Highland systems, inter-site differences of TBEA adoption outcomes, especially for Alnus hedgerows and eucalyptus woodlots, were found to be significantly driven by degrees of commercialization of key cash crops—such as climbing beans, Irish potatoes, and wheat—thus making TBEAs an integral part of agricultural intensification in Rwanda, when supported by an enabling environment.

In contrast, agro-ecological conditions in Savanna and Plateau systems, with relatively flat landscapes and extensive farming systems under relatively low population pressures, do not seem to provide sufficient incentives for intensively managed TBEAs. Rather fruit and/or fodder agroforestry systems were found in varied niches depending on site-specific contexts. It is worth noting that farmers perceived fruit and fodder species as multi-functional by providing fuel, stakes, and environmental services simultaneously. Independent of agro-ecological patterns, better market access and ownership of transport means provided economic drivers and enabling conditions for the adoption of commercially valuable tree products such as timber/pole, fruit, and fodder. Market accessibility may be particularly critical for perishable products such as fruit and dairy products. Household head education level was correlated significantly with higher tree numbers of fruit and fodder species, indicating fruit/fodder-based TBEAs were knowledge-intensive, and thus an investment in education is critical for scaling up.

The results of the study also indicated the potentials of TBEAs, when adopted at scale if supported by enabling secure tenure conditions, to contribute to sequestrating carbon and improving system resilience to climate change. It is argued that woody biomass stock from eucalyptus woodlots in Rwanda are potentially sufficient to reduce the wood fuel supply-demand gap in the country, thus contributing to reducing pressures on deforestation and degradation [31,36]. Indeed, it is claimed that practically all charcoal in Rwanda is derived from trees planted on private woodlots, with virtually no illegal charcoal production activities affecting natural forests [42,48]. This is in stark contrast with the situations in other African countries where charcoal production is a major driver of degradation of natural woodlands [13,49,50]. Smallholder farmers in dryland conditions are no exception to derive multiple benefits from tree species, not only to procure materials for charcoal production, but also to derive ecosystem services, such as shade and climate regulations [40]. Yet, wood for charcoal is mostly harvested from trees scattered on landscapes which are available for "free" to households. There planting trees is an inherently risky venture and the survival rates are low, due not only to harsh climatic conditions, but also to damages caused by multiple users under not-completely-exclusive tenure systems [50]. Guaranteed exclusive access under secure tenure to multi-functional benefits of trees may be an essential condition for active investment in tree planting by smallholders.

We also extend our perspective to understand challenges for "modern" biofuel development discourses in African or other smallholder systems in the world. For example, around 2008, jatropha was considered as a "silver bullet" to solve energy insecurity in low-income countries and to support economic development. In Africa, the crop was promoted among smallholder farmers, whereas its introduction through large scale plantations by investors incited "land grabbing" and food vs. fuel debates [10]. Before the hype, naturalized jatropha stands were found on farms with utility as a fence in parts of rural Africa. Yet, the hype drove farmers' high expectations on jatropha as a highly valuable commercial crop, not an energy crop, and farmers kept relying on firewood for own domestic fuel and on charcoal for income [11]. Some farmers decided to allocate prime agricultural plots to exclusively planting jatropha or intercropping, with a singular objective to maximize income which solely depended on yields of seeds [12]. Once no realization of expected high returns became evident due to agronomy constraints along with the eventual absence of markets [12], farmers uprooted the stands which did give little scope for provision of other multiple benefits while occupying prime niches [11].

These days, landscape design approaches to coordinate diverse land management objectives from a wide array of stakeholders are gaining popularity to incorporate bioenergy development [51]. For African conditions, where numerous farmers have fragmented plots and must pursue diversified livelihoods, the adaptation of TBEAs at scale still crucially depends on whether trees provide individual farmers with multiple utilities in strategic niches.

5. Conclusions

In response to rapidly rising population pressures and subsequent competitions over land and ecosystems in delivering multiple needs of farmers, smallholder systems in densely populated East African Highlands have been driven to intensify agriculture by increasing cropping intensities and introducing high-value crops. Evidence from Rwanda suggests possibilities to achieve sustainable agricultural intensification by incorporating TBEAs, especially in the extremely densely populated Highland systems. The findings also indicate that farmers deliberately adopt trees on farm systems not just concerning crops vs. tree competition on a single plot, but considering adopting them in strategic niches across their fragmented land, over varied topographies, to maximize benefits from their multi-functionality. For example, Alnus hedgerows on sloped land deliver goods (such as fuel, stakes, and wood products) and services (such as improving soil conditions on the same land). Furthermore, some TBEAs, such as eucalyptus woodlot, which may not primarily deliver direct environmental benefits itself, can have potential to contribute to reducing pressures of deforestation and degradation under extremely high population pressures when adopted at scale, by occupying strategic niches of less fertile soils for crop production. Their widespread adoption in Rwanda today further confirms that the sustained adoption of TBEAs at scale is driven and guaranteed if farmers subjectively recognize tangible benefits from trees and their compatibility and synergy with sustainable intensification of existing farming system, supported by favorable institutional conditions.

In the medium-to-long term, the further rapid population growth projected in Rwanda and East African Highlands can swallow up the benefits of TBEAs to sustain and improve livelihoods. Tends in education, urbanization, demographic transitions, and new technologies around agriculture and agricultural processing industries may drive people into non-agricultural pursuits. Land and agricultural policies that explicitly acknowledge land constraints in densely populated areas are urgently required to reduce rural poverty and promote broad-based rural income growth [6]. For TBEAs to contribute to have a broad based structural transformation, even more sustainable management of trees better integrated with crops across landscapes, for profitable business and employment opportunities, are required. For example, promotion of planting mixed stands of eucalyptus and N-fixing trees can contribute to enhancing soil quality for crops as well as woodlot productivity [45], and can encourage recycling of organic matter into soil [47]. Future research should address improvements in tree management through the provision of quality seeds/clones together with manuals and extensions on best practices for species choice and intensive weeding [47].

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/5/1360/s1. Table S1: Proxies for agro-ecological and economic drivers, Table S2: Proxies for enabling conditions.

Author Contributions: M.I., A.M., J.D.N., B.M. and A.N. conceived and designed the study, implemented the data collection, and analyzed the data; J.G.M., D.G., S.L. and V.R. contributed to refining concepts, methods, and analysis; M.I. wrote the paper.

Acknowledgments: This study is based on a longer study in 2015 entitled "Taking to scale tree-based systems that enhance food security, improve resilience to climate change, and sequester carbon in Rwanda," conducted by the World Agroforestry Centre (ICRAF) and supported by PROFOR, BNPP and TerrAfrica. The team greatly appreciates the stakeholders for having participated in the consultation and validation process of the study. We sincerely appreciate valuable comments by the reviewers to improve the quality of the analysis and arguments.

Conflicts of Interest: The authors declare no conflict of interest.

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