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The utility of farmer ranking of tree attributes for selecting companion trees in coffee production systems

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Abstract There is increasing interest in the potential of agroforestry to improve the productivity and sustainability of coffee production, but designing management options is knowledge intensive. Tree-crop interactions and the biophysical and socio-economic factors influencing farmers' decision-making about companion trees are complex and context-specific but fine scale data relating to them are rarely available. A novel method was used to analyse trees ranked by farmers for a range of attributes and evaluate the consistency of farmers' knowledge underpinning decisions about tree management in coffee production systems in Rwanda. Farmers' knowledge about tree planting was changing, in line with new shade management recommendations being promoted alongside a limited number of tree species, often freely distributed through eco-certification initiatives. Farmers had detailed knowledge about soil and water conservation processes associated with trees, but they traded these off against perceived competition for light, water and nutrients with coffee. The competitiveness of trees with coffee was influenced by combinations of attributes related to: crown architecture, foliage properties and growth patterns; as well as how trees responded to management, and, their utility. Farmers consistently ranked 20 tree species for 12 attributes (five related to ecology, four to management and three to utility). Given the paucity of data on tree attributes for many species, systematically acquired and consistent local knowledge complements global scientific information and can be useful in bridging knowledge gaps relating to the integration of tree diversity in coffee production systems, which is an increasingly important strategy for smallholder farmers adapting to climate change.

Keywords Rwanda · Local knowledge · Agroforestry · Ecosystem services · Shade

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Introduction

Over the last 40 years, the production of coffee, one of the most widely traded tropical commodities, has been driven by intensification strategies aiming to maximize short-term yields through the use of purchased inputs in full-sun production systems. The sustainability of intensive coffee monocultures, mostly grown on land recently converted from natural forests or located near conservation hotspots, has been increasingly questioned because of their environmental cost and the economic vulnerability of coffee farmers affected by fluctuating coffee prices (Philpott and Dietsch 2003). Over 25 million smallholder farmers are dependent on coffee for their livelihoods, of which more than 30% live in Sub-Saharan Africa, the world's most food insecure region. This, compounded with the increasing threat of climate change, creates an urgent imperative to develop sustainable coffee production systems that can improve smallholder livelihoods at same time as restoring ecosystem functions (Tscharntke et al. 2011).

Coffee naturally grows in shade, and coffee agroforestry practices around the world sit along a gradient of complexity from simple mixtures involving one or two companion tree species in regular arrangements to very species diverse multistrata systems (Somarriba et al. 2004). Companion trees can provide high-value marketable products that diversify income sources at the same time as agronomic benefits such as pest and disease control, soil nutrient enrichment and microclimate regulation (Jha et al. 2014). These benefits often offset or surpass yield losses associated with trees competing with coffee (Vaast et al. 2005). The relationship between shade and both coffee yield and quality varies with altitude, climate and soil conditions, as well as with the management of companion trees and coffee, creating the need for recommendations about shade to be site and context specific (Van Oijen et al. 2010). Along with their socio-economic value, the suitability of tree species for intercropping with coffee is largely determined by ecological attributes, which directly influence their competitiveness for light, nutrients and water. Other tree product attributes, such as wood burning properties, fodder value or fruit quality may also be important (Soto-Pinto et al. 2007). There is little scientific knowledge about ecological attributes of trees used in coffee agroforestry systems and developing a scientific understanding about them is complicated because expression of attributes varies with environmental and management factors, as well as the genetic makeup of the tree. Previous studies have shown local knowledge of farmers to be an important source of information to fill such knowledge gaps (Sinclair and Joshi 2001). Farmers often have a detailed understanding of tree attributes derived from direct experience (Cerdan et al. 2012) and their knowledge has been used to pool site specific information to derive customized recommendations on tree management (van der Wolf et al. 2016). Farmers in Nepal were found to have sophisticated knowledge about leaf digestibility and palatability attributes that they used to classify tree fodder types, and they were able to consistently rank fodders based on these criteria (Walker et al. 1999), in ways that corresponded with scientific assessment of nutritive quality (Thorne et al. 1999). While previous studies of local knowledge about companion trees in coffee (Cerdan et al. 2012) and cocoa (Anglaaere et al. 2011) have elucidated tree attributes that affect their suitability for intercropping, the consistency of farmer knowledge about these attributes has not been rigorously compared across farmers or sites. Farmer ranking of tree attributes conferring suitability for intercropping with coffee from along an altitudinal gradient in Kenya were presented (Lamond et al. 2016) and while consistency of ranking varied for both tree species and attributes, it was not quantified.

In this research, we aimed to acquire farmers' knowledge about incorporating trees in coffee fields across two districts in Rwanda and to apply an explicit probability model to estimate, quantitatively, how consistent and precise their knowledge was about tree attributes associated with suitability for intercropping trees with coffee.

Materials and methods

Study area

The study was conducted between 2009 and 2012 in three sites situated in the densely populated Western Province of Rwanda, the Nyamyumba sector (Rubavu district) and the Kivumu and Kigeyo sectors (Rutsiro district near the Gishwati National Park), between S 1.730 and S 1.837 and between E 29.310 and E29.265. The sites are within the catchment of Lake Kivu, with a mean altitude of 1500 m and bimodal annual rainfall of 1200 mm. Rubavu district has a population density of over 1000 km^{-2} who predominantly rely on agriculture (NISR 2012). The sampled farmers were from smallholdings ranging in size from < 0.1 to 6.0 ha with coffee plots generally between 0.1 and 1 ha. The main land use activities were based on food crop production (maize, cassava, beans, sorghum and vegetables) for household consumption and sale. The main cash crops in the area were coffee (*Coffea arabica*) and banana (*Musa* spp.).

Local knowledge acquisition

Initial local knowledge acquisition was conducted in 2009 using a knowledge based systems (KBS) approach (Sinclair and Walker 1998). The Agro-ecological Knowledge Toolkit (AKT5) methodology was followed and associated software used to create an electronic knowledge base and carry out analyses using automated reasoning procedures (Walker and Sinclair 1998). A small purposive sample of 26 farmers affiliated with the coffee cooperatives in the Rubavu and Rutsiro district were interviewed during farm visits using semi-structured guidelines. In terms of gender, women farmers affiliated with coffee cooperatives represented less than a third of farmers, we included eight women and 18 men to ensure coverage of common knowledge of both genders. The topics explored were knowledge of shade tree interactions with coffee and tree management for the provision of ecosystem services. The selection of farmers was informed by extension agent's knowledge of farmers' engaged with shade coffee programs in the different communities and on their willingness/availability to participate in the interview. Three focus group discussions (total of 9 farmers) were held about tree attributes important to coffee intercropping and a feedback sessions was organized with farmers interviewed and extension officers (total 16 people). The causal diagrams presented in the results were generated from the knowledge represented in the AKT5 software as connected formal statements conforming to the diagram syntax (Cerdan et al. 2012; Lamond et al. 2016).

Tree attribute ranking

Ranking has been used in agroforestry research to assess the importance of tree use-categories, preferences or needs (Gausset 2004). Here we adapted the methodology to elicit information about tree attributes. In this survey, we investigated whether coffee farmers agreed on ranking commonly managed trees and shrubs in terms of the expression of a range of ecological, management and utility attributes influencing intercropping with coffee. One hundred farmers (67 men and 33 women) randomly selected from local coffee cooperative lists were interviewed, stratified according to three villages (Nyamyumba in Rubavu district, Kivumu and Kigeyo sectors in the Rutsiro district) because of their diversity in market access and proximity to forest resources. In each of the three villages, we purposefully selected all women affiliated to local cooperatives. However the sample size was too small to disaggregate the analysis based on gender. The interviews were facilitated with an interpreter and a local field guide organized appointments, in advance, based on farmers' availability. They lasted between 50 min to one and half hours based on the farmers' willingness to engage and discuss ranking results. Qualitative information was recorded when this was useful to explain ranking decisions. The twelve attributes used in the survey (Table 1) were derived from the initial local knowledge acquisition and were identified by farmers as properties influencing the suitability of trees for intercropping with coffee. Ecological attributes were observable properties of trees that farmers said influenced how competitive they were in capturing light, nutrients, water and space. Management attributes were composites (involving more than one trait), that described how trees responded to management interventions. Utility attributes (firewood burning length and timber strength and durability), were observable properties of trees affecting their usefulness to farmers. Twenty tree and shrub species were selected for ranking (encompassing all woody perennials and including *Carica papaya* and *Draceana afromontana* identified as trees by farmers) selected because they occurred on more than three farms in both: (1) a tree inventory of 60 farms (CAFNET project, unpublished), and (2) the initial local knowledge acquisition, ensuring that they were reasonably common species that farmers would be likely to have experience of.

Clear pictures of each of these twenty species were put on cards and shown to sample farmers who identified those they had direct experience of, ten of which were then randomly selected for pairwise ranking for each attribute ("Appendix"). The final ranking order given by farmers and explanations for this were recorded. Ranking data were analyzed using

Table 1 Tree attributes used in the coffee farmers ranking survey in Rubavu/Rutsiro districts, Western Rwanda

Type	Tree attribute	% Of tree pairs ranked in the same order by at least 80% of farmers	Description of ranking scale	Impact
Ecological	Crown spread	72	Widest to narrowest	Competition for light and space, microclimate, erosion control
	Crown density	71	Least to most dense	
	Root spread	62	Widest to narrowest	Competition for nutrients, water and space, erosion control
	Root depth	64	Deepest to shallowest	
	Growth rate	73	Fastest to slowest	Return on investment, management, competition
Management	Growth after pruning	60	Fastest to slowest	Shade management
	Easiness to prune	60	Easiest to hardest	Shade management
	Leaf litter decomposition rate	69	Fastest to slowest	Nutrient release, erosion control
	Leaf litter benefits to the soil	66	Most to least beneficial	Soil fertility improvement
Utility	Firewood burning length	67	Longest to shortest	Suitability for firewood (quality)
	Timber strength	67	Strongest to weakest	Suitability for different timber uses
	Timber durability	60	Most to least durable	

the 'Rank analyses' package in R (Lamond et al. 2016) that fits the Bradley–Terry model (BTm, Bradley and Terry 1952) to the data. The BTm model estimates the likelihood that farmers perceive one tree to be above another tree with respect to the attribute in question and allows statistical evaluation of the consistency with which different farmers have ranked trees. The 'rank analysis' package also performs a Wald test that provides information about whether the difference between each pair of trees is significant and, therefore, allows the grouping of the trees into functional groups, with respect to the attribute in question (Dataverse repository, Lamond et al. 2014). The more functional groups shown by the analysis, the higher the precision of the farmers attribute ranking methodology.

Results

Characterization of common tree species on coffee farms

Thirty-five tree species occurring within coffee plots or along coffee plot boundaries were identified and discussed with farmers during the initial local knowledge acquisition phase. We summarized the detailed information elicited from the local knowledge phase about the 20 species selected for ranking and indicated the percentage of farms on which each of those species occurred during the subsequent attribute ranking survey (Table 2).

Farmers involved in the ranking survey had a mean of 12.7 of these 20 selected species. Some of the trees were found in specific niches on farms in accordance with their perceived ecological attributes and end use; *Mangifeira indica* was viewed as highly competitive because of its large and dense crown and *Vernonia amygdalina* was commonly used as a live-fence, both were limited to boundaries. Several species of *Leucaena*, introduced to the area through soil erosion control programs, were used for stabilizing bench terraces and for fodder. Almost all trees in coffee plots were managed for multiple purposes. Fourteen species were managed for both shade and mulch. Five exotic fruit trees were amongst the most frequently occurring, with a mean of 4.6 fruit species per farm. There were ten native species and farmers had a mean of 4.8 per farm. *Markhamia lutea* was the most frequent tree

Table 2 List of the 20 trees and shrubs commonly found on coffee plots in Rubavu/Rutsiro districts, Western Rwanda, and used in the ranking survey with information about their frequency, propagation and utility

Tree species	Frequency (% of farms it occurred on)	Propagation method	Provisioning services	Regulating and supporting services	Spatial arrangement	
					Intercropped	Boundary
Psidium guajava (e)	98	Farm (seed)	Fruit, income, firewood	Shade, erosion control	*	*
Ficus thonningii (n)	97	Cuttings	Firewood, timber (planks, poles), medicine	Shade, mulch, erosion control	*	*
Markhamia lutea (n)	95	n. reg, transplanting, nursery	Timber (planks, poles), firewood, charcoal	Shade, mulch	*	*
Persea americana (e)	95	Farm (seed)	Fruit, income, firewood, timber (poles)	Shade, mulch, weed suppression, erosion control		*
Carica papaya (e)	93	Farm (seed)	Fruit		*	
Grevillea robusta[a] (e)	87	Nursery	Timber (planks, poles), charcoal, firewood, income	Shade, mulch, weed suppression, erosion control	*	*
Erythrina abyssinica (n)	85	Cuttings	Firewood, medicine, timber (mortar)	Nitrogen fixing, shade, erosion control	*	*
Ricinus communis (n)	81	n. reg, transplanting	Firewood, medicine, timber (stakes)	Mulch	*	*
Citrus limon (e)	73	Farm (seed)	Fruit, medicine, income		*	*
Mangifera indica (e)	70	Farm (seed)	Fruit, income, firewood, timber (poles, stakes)	Shade		*
Vernonia amygdalina (n)	70	Farm (cuttings), n. reg	Firewood, medicine, timber (poles, stakes)	Mulch, erosion control		*
Polyscias fulva (n)	61	Nursery	Planks	Shade, mulch	*	
Cedrela serrata (e)	60	Nursery	Timber (planks), income	Shade, mulch	*	*
Leucaena diversifolia[b] (e)	43	Nursery	Fodder, firewood, timber (stakes)	Nitrogen fixing, shade, mulch, erosion control	*	
Inga oerstedania (e)	35	Nursery	Firewood, timber (poles)	Shade, mulch, weed suppression	*	
Maesa lanceolata (n)	31	n. reg	Firewood, charcoal	Erosion control	*	
Millettia dura (n)	29	n. reg	Firewood, charcoal, timber (stakes, poles)		*	*
Dracaena afromontana (n)	26	n. reg	Fiber		*	*
Bridelia micrantha (n)	24	n. reg	Firewood, timber (poles, stakes), medicine	Mulch, shade, erosion control	*	

Table 2 continued

Tree species	Frequency (% of farms it occurred on)	Propagation method	Provisioning services	Regulating and supporting services	Spatial arrangement	
					Intercropped	Boundary
Alnus acuminata (e)	20	Nursery	Firewood, timber (planks, poles, stakes)	Nitrogen fixing, shade, mulch, erosion control	*	*

e exotic; *n* native; *n.reg* natural regeneration

[a]Occasionally planted as clumps (woodlots)

[b]Occasionally planted on terraces

that farmers nurtured from natural regeneration, present in 95% of coffee fields, while *Ficus thonningii, Erythrina abyssinica* and *Vernonia amygdalyna* were commonly propagated through cuttings when used as a live-fence on field boundaries. Native forest species such as *Maesa lanceolata*, *Milletia dura* and *Bridelia micrantha* were less common but still occurred on at least a quarter of farms and were retained for firewood, they occurred mainly in the village of Kigeyo, located near to Gishwati forest. *Grevillea robusta* was the most commonly planted exotic timber species, valued for its fast growth, timber and firewood as well as mulch production. A few shade and mulch trees had been introduced through project nurseries (from 2007 to 2010) for shading and mulching, including *Cedrela serrata, Polyscias fulva, Inga oerstediana* and *Alnus acuminata.*

Ecosystem services and competitiveness

During the local knowledge acquisition study, farmers expressed detailed knowledge of ecosystem services provided by trees in coffee fields and their impact on coffee yields and overall income. The analysis of statements in the knowledge base represents farmers' understanding of the complex causality influencing how companion trees affect soil conservation and other agronomic services on the one hand and adverse competitive effect on the other.

Soil nutrient cycling and erosion control

Farmers described how nutrient cycling of leaf litter to improve soil fertility and coffee yield was a benefit from companion trees (Fig. 1). While chemical fertilizers could be purchased through farmer cooperatives, costs were prohibitive. Instead, most farmers relied on recycling and transferring organic matter grown on various parts of the farm to meet soil fertility requirements. Several strategies were used including transfer of: grasses, crop residues, banana leaves, coffee pulp and husks, and pruned tree branches. There was a growing interest amongst farmers in intercropping trees with coffee to produce *in-situ* mulch because of: decreasing land availability, increasing demand for livestock fodder (driven by the One-Cow-Per-Poor-Family national programme), increasing incidence of banana wilt disease, and new knowledge disseminated by extension agents about the

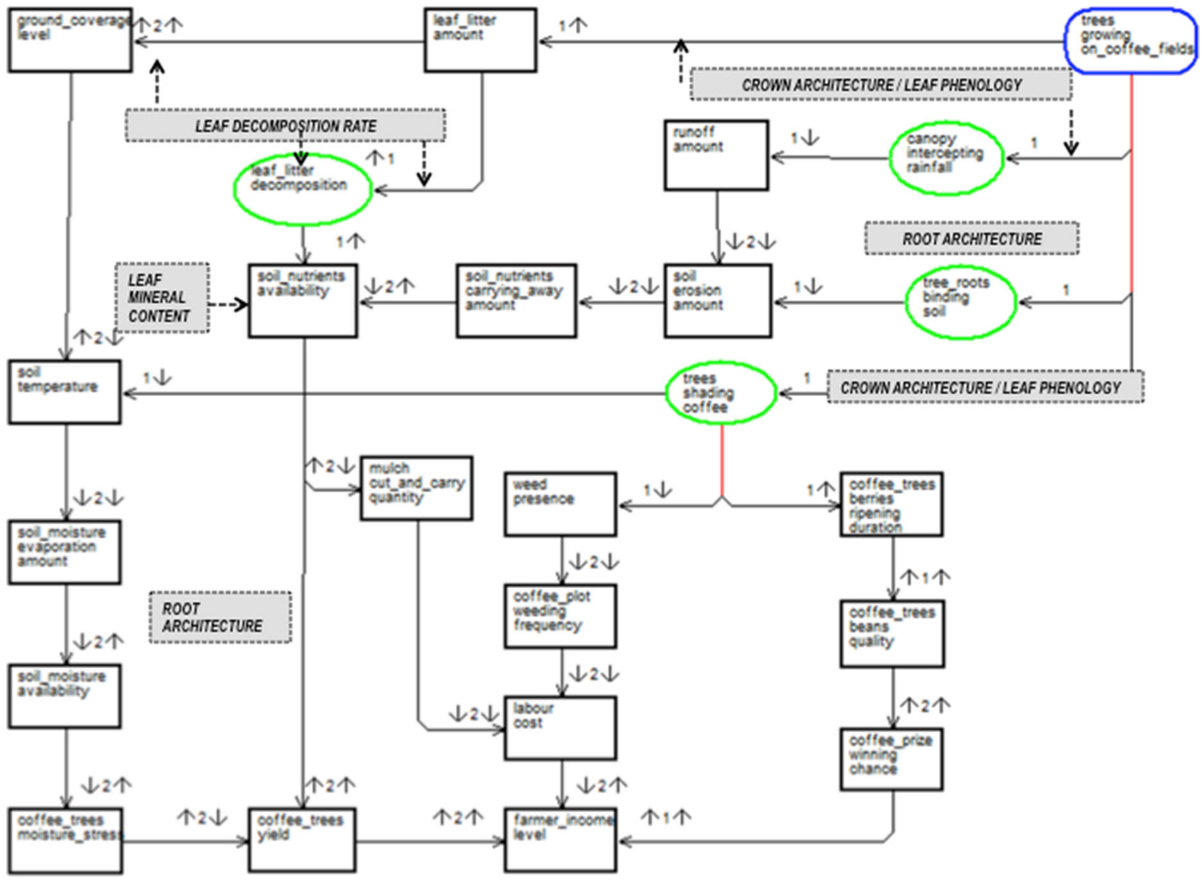

Fig. 1 Diagram showing farmers' causal knowledge about how trees in coffee fields affect coffee yield and overall income from the coffee plot. Nodes represent human actions (boxes with rounded corners), processed (ovals), or attributes of objects, processes or actions (boxes with straight edges). Arrows connecting nodes denote the direction of causal influence. The first small arrow on a link indicated either an increase (↑) or decrease (↓) in the causal node, and the second arrow on a link to the same for the effect node. Numbers between small arrows indicate whether the relationship is two-way (2), in which case ↑A causing ↓B also implies ↓A causing ↑B, or one-way (1), which indicates that this reversibility does not apply. Important tree attributes are represented in grey shaded boxes with dotted arrows showing the processes they influences

benefits of coffee agroforestry. By producing mulch from tree litter directly in coffee plots, farmers were able to reduce the land allocated solely to mulch production and the labour involved in transferring it. The main tree attributes known to influence soil nutrient cycling were related to the crown branch structure and foliage properties (density, size of the leaf, leaf phenology and leaf decomposition rate). Farmers were attempting to reduce soil erosion using trenches, progressive terraces, mulching, grass strips and tree belts. They mentioned that trees helped stabilize soil through their root systems, contributed to better infiltration of water, which was especially important on steep slopes and close to the lake. Farmers also said that trees intercepted rainfall, thereby reducing surface run-off across soil; with the magnitude of interception associated with crown architecture and leaf phenology.

Other agronomic services

By increasing ground cover and providing shade, farmers said that trees help reduce soil temperature and evaporation, thereby reducing water stress on coffee plants in the dry season, resulting in positive effects on yield. Weed suppression from shading and mulch was another important service provided by trees in coffee fields compared to full-sun, leading to a reduction in associated labor costs. There was new knowledge that farmers had recently learned from extension workers, relating to shade coffee quality. This was that shade prolonged the duration of coffee berry ripening in turn leading to larger bean weight (an immediate quality measure), as well as enhancing bean quality, giving farmers a higher chance of winning national prizes such as the 'Cup of Excellence'.

Competitiveness

Although farmers mentioned many benefits they also reported some disadvantages of planting trees with coffee, mainly linked to competition for light and water (Fig. 2).

Farmers knew that high shading intensity caused an increase in coffee vegetative growth to the detriment of flowering and fruiting which, in turn, decreased coffee yields. Shading intensity was determined by a combination of ecological attributes of both crown and foliage. Rainfall interception by the tree crown was also seen as negative in the wet season as rainfall would not reach the ground, thus leading to moisture stress and soil compaction which would in turn decrease coffee yields. Whilst farmers knew that shade management through pruning reduces the negative impact of shade, they did not always act on it and had knowledge gaps about tree species selection, optimal tree density and spatial arrangements that affected both shading and rainfall interception. Crown attributes and ease of pruning were identified as important for management. There was sparse and inconsistent knowledge about the interaction of trees with pests and diseases.

Attribute ranking

During the survey, we found that individual farmers were able to rank trees for the range of attributes they were presented with by comparing individual tree pairs (Figs. 3, 4). Less common species such as native

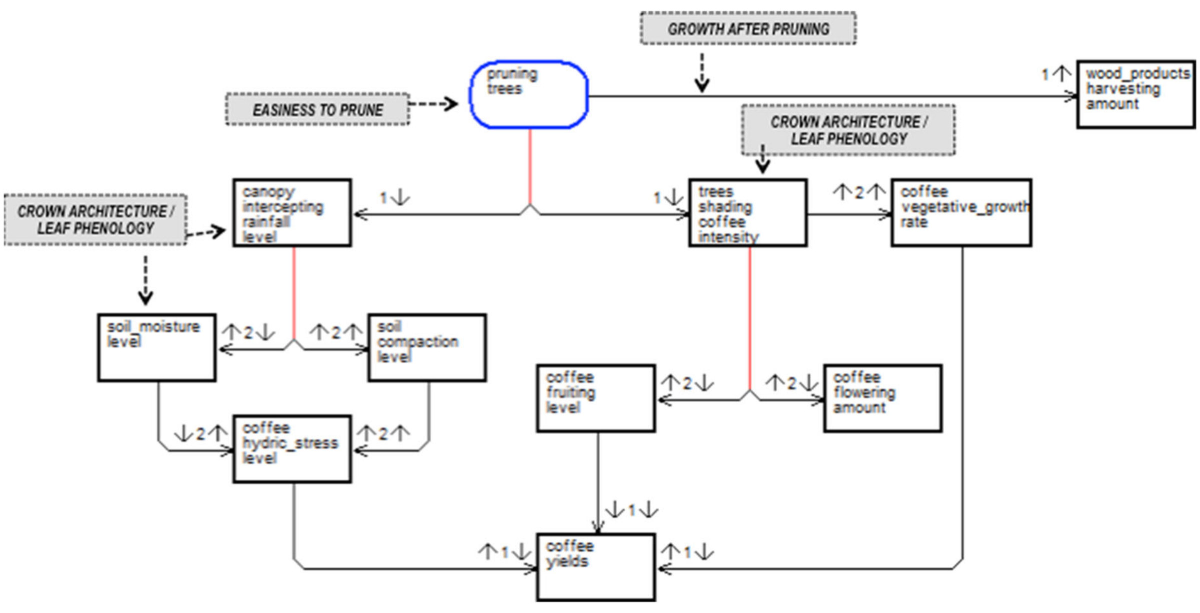

Fig. 2 Diagram showing farmers' causal knowledge about how tree pruning can reduce the negative influence of shade on coffee yields whilst providing wood porducts. See Fig. 1 for explanation of symbols

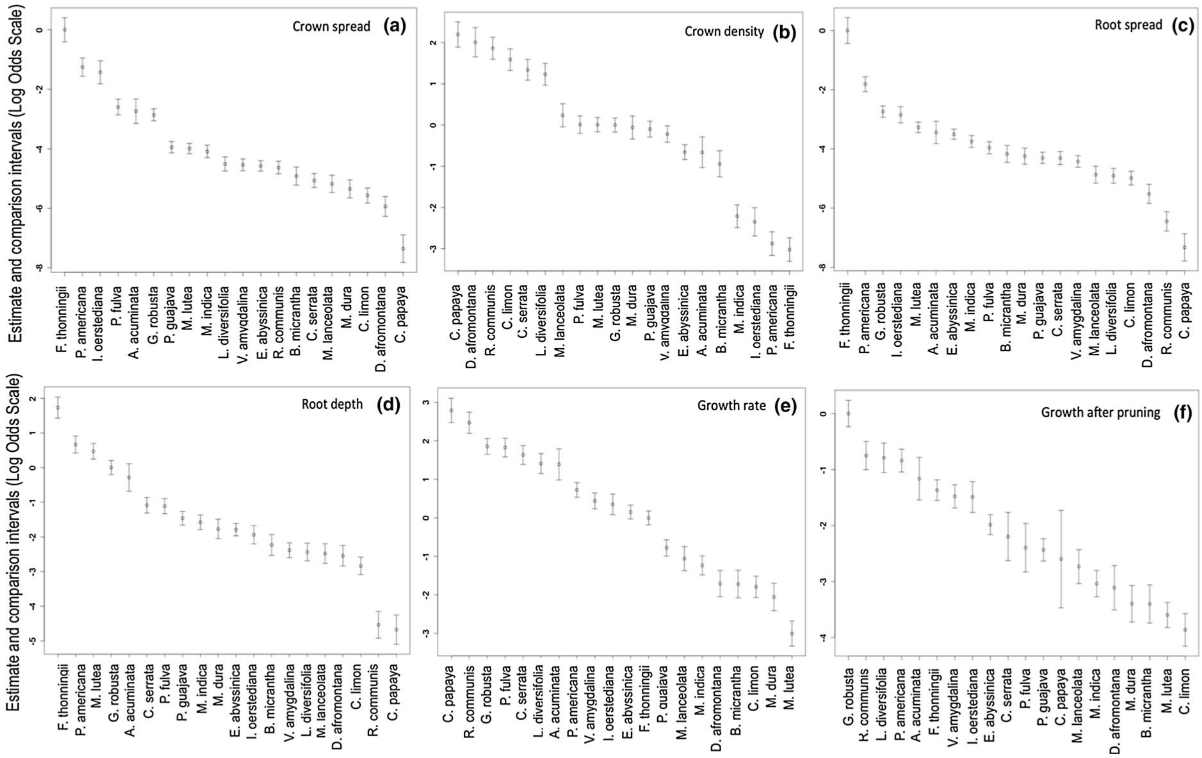

Fig. 3 Trees ranked by farmers according to different attributes: crown spread (*large to narrow*) (**a**); crown density (*least dense to most dense*) (**b**); root spread (*widest to narrowest*) (**c**), root depth (*deepest to shallowest*) (**d**); growth rate (*fastest to slowest*) (**e**); growth after pruning (*fastest to slowest*) (**f**)

forest species (*B. micrantha, M. dura, M. lanceolata*) or newly introduced trees (*I. oerstediana* and *A. acuminata)* were ranked least frequently. The precision of farmers' ranking of trees varied both by attribute as well as tree species. Overall, farmers agreed on which group of trees or which specific tree performed with respect to the expression of a specific attribute, but their ability to further distinguish between certain trees varied from attribute to attribute and this was linked to how the tree was used and how observable the attribute was to farmers. We define a tree pair to be consistently ranked for a particular attribute if 80% or more of the farmers that compared this pair of trees for the attribute agreed on the order (Table 2). The majority of tree pairs were consistently ranked for all attributes (the proportion of tree pairs consistently ranked ranged from 60 to 73%, depending on the attribute). The highest consistency was found for ecological attributes that were easily observable, such as growth rate (73%), and crown spread (72%) and density (71%), whereas management and utility attributes, that are more subjectively judged by farmers, such as easiness to prune, growth after pruning, and timber resistance (60% in all three cases), were less consistently ranked.

There were fewer distinctions amongst trees ranked for crown spread than for crown density where clusters of trees represent clear low, medium and high crown density categories (Fig. 3a, b). In terms of root spread and depth, trees at either end of the spectrum were easily identified, but the majority of species were not distinguishable from one another (Fig. 3c, d). Farmers consistently ranked trees for growth rate, with species clearly distinguished from one another along the spectrum (Fig. 3e). Most slow growing species were native whilst fast growing species were mainly recent introductions. Differences for re-growth rate after pruning (Fig. 3f) could derive from differences in the timing and method of pruning, leading to different re-sprouting responses. Only two farmers ranked *Carica papaya* for pruning.

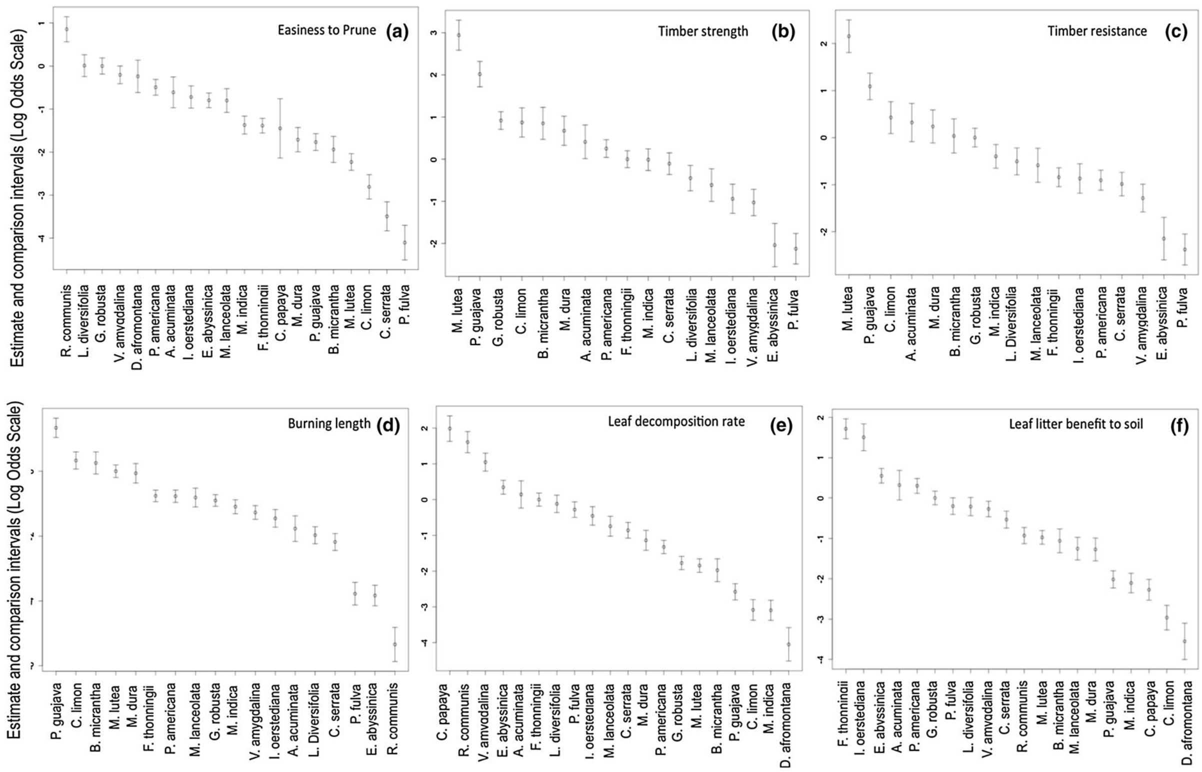

Fig. 4 Trees ranked by farmers according to different physical attributes: **a** easiness to prune (*easiest to hardest*); **b** timber strength (*strongest to weakest*); **c** timber durability (*most to least durable*); **d** burning length (*longest to shortest*); **e** leaf decomposition rate (*fastest to slowest*) and **f**, leaf litter benefit to the soil (*most to least*)

For the management attribute ‘easiness to prune’, trees were less consistently ranked than for other attributes perhaps because different pruning tools and strategies were used and ease of pruning may vary with tree age (Fig. 4a). For timber attributes, 17 trees were ranked since three were not used for that purpose. The tree ranked highest for timber strength was *M. lutea*, a native species used for wood plank production (Fig. 4b). Other species with strong timber were trees used for stakes or poles only and not for the sale of planks (*P. guajava* and *C. limon*). There was less consistency in the ranking for timber durability that could be because of gender differences in experience and the variety of uses as planks, poles or stakes (Fig. 4c). Eighteen trees were ranked for firewood burning length (Fig. 4d). *C. papaya* and *D. afromontana* were never used for firewood by farmers. *P. guajava* had the longest burning length followed by *C. limon*, though the latter was planted for fruit production and rarely pruned for firewood. Trees less commonly used for firewood included *P. fulva, E. abyssinica* and *R. communis* which had slower burning qualities. Trees were clearly distinguished in terms of leaf decomposition rate with explanation about how texture affected decomposition processes (Fig. 4e). The amount of mulch generated by trees was linked to foliage density and to deciduousness. *Ficus thonningii, P. americana* and *E. abyssinica* were deciduous trees that provided high leaf biomass and were contributing significantly to soil fertility (Fig. 4f). *Inga oesterdiana* and *M. lutea* showed progressive shedding of a nutrient-rich leaf litter that was particularly valued by farmers.

Discussion

Drivers of tree diversity on coffee plots

Despite a history of the Government promoting full-sun coffee in Rwanda (Donovan et al. 2002), most coffee fields (82%) had 10 or more tree species, including a range of native trees. There were four interacting drivers of increasing tree cover on coffee farms: decreasing land availability, resettlement, decreasing availability of forest resources as deforestation progresses, and the promotion of agroforestry by extension services. Farmers explained that increased pressure on land, and the need to optimize space for the simultaneous production of essential goods (fruits, timber, firewood, mulch), made it necessary to integrate trees with coffee. These findings are consistent with trends reported for smallholder coffee farms in Latin America (Méndez et al. 2010). Along with decreasing farm size, farmers' decisions about tree management and positioning on farms was related to the 'Imidugudu' human resettlement policy implemented in Rwanda after 1997. This is a policy that regrouped previously scattered rural homesteads and settlement patterns in new village sites initially set up to assist war-displaced people but also to foster access to services and diversify rural economic opportunities (Isaksson 2013). In the research site this had caused the abandonment of home gardens and fruit trees could now only be grown in or around coffee fields despite trade-offs from heavy shade. Deforestation in the region had decreased access to firewood, the major source of cooking energy, as well as stakes, widely used for growing climbing beans, a food staple. Similar to other parts of Rwanda, where access to open forest resources has dwindled, farmers were compelled to meet their needs from on-farm trees, triggering an increase in uptake of agroforestry practices (Ndayambaje and Mohren 2011). Farmers had extensive knowledge of vegetative propagation for some native trees and forest species were present on least a quarter of farms, though mainly in the village closest to the Gishwati forest area. This demonstrates the importance of farmers' knowledge for the *in situ* conservation of tree species and genetic diversity (Dawson et al. 2013). External tree planting initiatives, whether for erosion control or more recently for coffee shade management, focused on a few largely exotic species, as a result of limited seed availability and nationally formulated recommendations. This situation is fairly typical of tree planting programs in East Africa where tree seed supply tends to dictate the species that are promoted, often through free seedling distribution, rather than trees being selected based on their agroecological suitability and assessment of community needs, coupled with due consideration of the value of maintaining threshold levels of tree diversity across landscapes (Smith Dumont et al. 2017).

Trade-offs between coffee production and other ecosystem services

Coffee fields were important farm niches for integrating a diversity of trees. In terms of environmental services, farmers were particularly knowledgeable about soil nutrient improvement and erosion control and how these processes affected coffee yields. Soil nutrient deficiencies and erosion problems are common in coffee farms across Rwanda (Nzeyimana et al. 2013) and particularly in the study area (Pinard et al. 2014). As many farmers could not afford fertilizers, soil fertility management was mainly done through mulching and practices had recently shifted towards integrating trees in coffee fields for the production of leaf litter, which reduced labor costs. Our findings show that farmers have sophisticated knowledge about mulching processes, which is consistent with other studies (Soto-Pinto et al. 2007), but provides novel information in the context of Rwanda where previous work on trees and mulch have focused mainly around on-station experiments with a few exotic species (Dusengemungu and Zaongo 2006). Other agronomic benefits of trees in coffee fields frequently mentioned by farmers related to weed suppression and the reduction of water stress during the dry season, which is consistent with the scientific literature (Staver et al. 2001). There were knowledge gaps in terms of the impact of shade on pest and disease interactions and on coffee quality because farmers lacked long-term experience of managing trees in their coffee farms. Despite recognizing the numerous utilities of trees in coffee, farmers were aware that too much shade or too dense a tree canopy was detrimental to coffee yields. As new knowledge is built through the recent experience of managing trees in coffee farms in Rwanda, it will be important to ensure that it can be efficiently and effectively shared amongst farmers (Valencia et al. 2015).

Consistency in ranking tree attributes

Coffee farmers could readily and consistently rank trees against a range of ecological, management and utility attributes. This indicates that farmers' knowledge could be useful in informing the development of agroforestry recommendations. The consistency of ranking varied with the knowledge and experience farmers had, showing greater consistency in their ranking of trees commonly managed on farms but lower consistency for newly introduced species. Ranking was most consistent for ecological attributes that were easily observable, such as those related to leaf litter, crown properties and growth rate which is comparable to tree attribute ranking by farmers in Kenya (Lamond et al. 2016) although the present results indicate higher precision than those achieved in Kenya. This may reflect the use of tighter protocols for conducting the ranking, with explanations elicited from farmers about the reasons for their ranking. Farmers ranked trees less consistently for root attributes such as spread and depth than they did crown attributes. This is likely to be because they are more difficult to observe and root growth is influenced both by pedoclimatic conditions and tree and soil management, with large intra-species variation (Schroth 1995).

Ranking was particularly useful for composite attributes like 'leaf litter benefits to the soil' which combined leaf biomass, deciduousness and speed of decomposition, known to vary widely according to the species' nutrient uptake and litter recycling ability (Montagnini et al. 1993). Farmers ranked trees for 'leaf litter benefits to soil' consistently, corroborating local scientific results showing higher coffee berry production under *P. americana* and *F. thonningii*, as a result of positive effects on soil nutrient content (Pinard et al. 2014). These two species were amongst the most frequent on farms and used for mulch. Leguminous species were ranked highly in terms of soil benefits, including *E. abyssinica* (a locally propagated native species) and *I. oesterdania* (promoted by advisory services) which come from genera that are commonly used for mulch in Central America (Somarriba et al. 2004). Although literature was only available at the genus level, scientifically measured leaf decomposition rates corroborate the farmers' ranking, with *Erythrina* sp. decomposing faster than *Inga* sp. and *P. americana* (Duarte et al. 2013).

While the ranking method enabled us to assess the consistency of knowledge amongst farmers about the magnitude of interactive effects of different species in relation to specific attributes, it does not provide information about trees in absolute terms. Various approaches have been successfully applied to obtain scores rather than ranks from farmers (Franzel et al. 1995), but these have more often related to information about preferences rather than knowledge (Abeyasekera 2001). We used ranking because it is rapid and repeatable. We found that it was clear to both the farmer and researcher what one species being ranked above or below another meant with respect to the attribute in question, and that this is more easily understood by farmers, and is less open to variable interpretation, than scoring methods. The ranking enables qualitative evaluation and discussion of interactions amongst coffee farm system components that determine the magnitude of interactive effects. We have shown that farmers consistently ranked trees in terms of attributes that control interactions, so that different (groups of) tree species can be distinguished in terms of the size of their interactive effects.

We searched available literature (Web of Science) and tree databases (Plant Resources of Tropical Africa; TRY-Global database of plant traits; Biodiversity Heritage Library) to compare farmers' ranking with scientific data but found very few data on the attributes and species that farmers ranked except that on decomposition rates referred to above. Comparisons are complicated by the fact that management and utility attributes often cannot be assessed with single plant trait measurements. Where data are available, comparison amongst species is limited, not only by the lack of standardization in measurement units and protocols but also because of localized variation in tree genetic, environmental and management factors affecting expression of attributes. This makes consistent ranking of attributes by farmers complementary to information that is available scientifically, largely because there are no comparable scientific datasets of relevant attributes for the species that farmers are integrating with coffee. Companion trees directly and indirectly affect coffee production (and other ecosystem services) through a variety of agro-ecological processes and have productive functions in themselves. Farmers' ranking of tree species against attributes enables prediction of the magnitude of interactive effects amongst farming components useful in developing recommendations related to agronomic performance and the reduction of competition with coffee whilst providing livelihood benefits. For example trees with slowly decomposing leaves may be preferred for planting on contours for controlling erosion but those with fast decomposing leaves would be preferred for nutrient cycling in coffee plots. A tree might have a wide and dense crown but the farmer may be able to manipulate the shade if the tree is easy to prune. This information can be integrated in multiple criteria decision-support tools to better inform tree selection and management of companion trees for different farmer circumstances (van der Wolf et al 2016). This can contribute to the promotion of a wider diversity of trees. including native species of conservation interest (Smith Dumont et al. 2017).

Conclusion

In many parts of the world, coffee growing has shifted from complex to more simplified agroforestry practices or to unshaded, full-sun systems. In contrast, in the Western Region of Rwanda, farmers are moving away from historically encouraged full-sun coffee, where intercropping was prohibited, to the incorporation of increasing amounts and diversity of tree cover in coffee fields. As farm sizes and access to natural forest resources decrease, farmers coffee fields are increasingly important farm niches for integrating a diverse mix of tree species, including retention of some native forest species, to obtain products that diversify income and improve soil and water conservation. New knowledge about shade benefits was being disseminated and nurseries set up by government advisory services and cooperative networks, but these focused on a narrow range of mainly exotic species. Farmers had consistent and detailed knowledge of a range of tree attributes and how they influenced tree-coffee interactions determining their suitability for use in specific on-farm niches, but their knowledge was strongly linked to their experience and influenced by their access to rural advisory services. Given the paucity of global scientific data about tree attributes, acquiring farmers' ranking of trees for key ecological, management and utility attributes is a cost-effective way of obtaining information that can be used to build decision-support tools to guide the selection and management of a diversity of companion trees in coffee.

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Appendix

See Fig. 5.

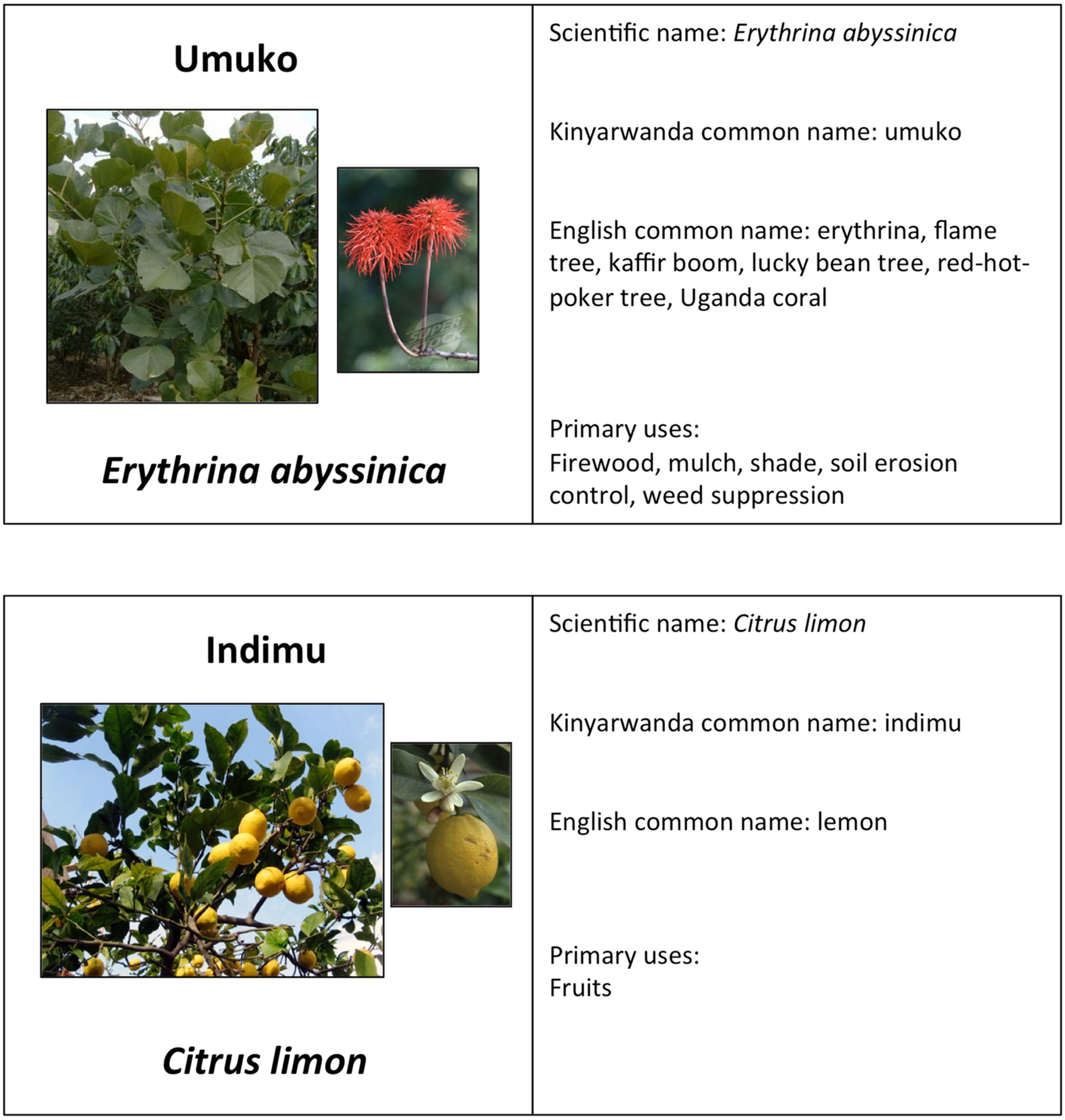

Fig. 5 Example of tree cards used in the tree attribute survey with coffee farmers in Rubavu/Rutsiro districts, Wester Rwanda

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