Agricultural Systems 181 (2020) 102815

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

The role of trees and livestock in ecosystem service provision and farm priorities on smallholder farms in the Rift Valley, Kenya

Ylva Nyberg[a,*], Johanna Wetterlind[b], Mattias Jonsson[c], Ingrid Öborn[a,d]

[a] *Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), P.O. Box 7043, SE-75007 Uppsala, Sweden*
[b] *Department of Soil and Environment, SLU, P.O. Box 234, SE-53223 Skara, Sweden*
[c] *Department of Ecology, SLU, P.O. Box 7044, SE-75007 Uppsala, Sweden*
[d] *World Agroforestry (ICRAF), P.O. Box 30677, 00100 Nairobi, Kenya*

ARTICLE INFO

Keywords:
Agroforestry
Farm size
Farming system
Farm trajectory
Labour
Trans Nzoia

ABSTRACT

Human beings are dependent on ecosystems and the services they provide. Some services are currently being overexploited, resulting in degradation and further pressure on already vulnerable people in e.g., sub-Saharan Africa. Long-term and stable delivery of ecosystem services (ES) is suggested to be enhanced by more diversified farming systems that e.g., mix crops with trees and livestock. Despite the amount of research on ES, few previous studies have identified and compared the roles of trees and livestock for ES considering farm priorities within smallholder systems. We studied the role of trees and livestock for ES provision as well as farm priorities for smallholders in Kenya. Twenty smallholder farms (0.2–0.8 ha) were studied for 1 year in a fully factorial design of high or low tree and livestock density systems. Data were collected on indicators for provisioning (crop, tree and livestock production), supporting/regulating (water infiltration, soil organic carbon and nutrients) and cultural (recreation and aesthetics) ESs. In addition, farm priorities were studied, considering nutrient management, on- and off-farm resources, food and consumption, and crop, tree and livestock species diversity. A mix of qualitative (e.g., semi-structured interviews, seasonal calendar) and quantitative (e.g., soil analyses, infiltration tests) methods were used to collect data. This study confirmed roles of trees and livestock for ES and farm priorities, although they in some cases appeared less important than family labour and farm size. Results showed that high tree density was related to higher workload, lower proportions of off-farm revenue as well as higher crop, fruit and tree diversity for the household. Tree or livestock density showed no clear relation to provisioning, supporting or regulating ES. However, cultural services were on average provided more by trees than livestock. Available family labour was positively related to both farm production (provisioning services) and crop, tree and livestock species diversity. The use of manure, compost and mineral fertilisers was overall low, and the application rate per unit area seemed higher on farms with less land which was reflected in higher soil P and Ca concentrations. The challenges of already small and reducing farm sizes need to be targeted seriously in research and development efforts. Also the issue of labour requirement and pathways for mechanization must be addressed to attract a new generation farmers to develop sustainable and profitable farm enterprises providing ES to the farm and the surrounding landscape.

1. Introduction

Humans are completely dependent on ecosystems and the services they provide. Some important services are being over-exploited, resulting in degradation of ecosystem services (ES). This is particularly problematic for people who are already vulnerable, e.g., smallholders in developing regions such as sub-Saharan Africa (Allen et al., 2018). In the Millennium Ecosystem Assessment (MA, 2005), ES are divided into provisioning (e.g., food and fuel), supporting (e.g., nutrient and water cycling), regulating (e.g., water and disease regulation), and cultural (e.g., aesthetics and recreation) services, which can be quantified using indicators (Hernández-Morcillo et al., 2013; Kearney et al., 2017; Kragt and Robertson, 2014). It has been suggested that long-term and stable delivery of ES can be enhanced by more diversified farming systems that e.g., mix crops with trees and livestock (Erisman et al., 2016; Kahane et al., 2013; Kuyah et al., 2016; Vandermeer et al., 1998).

---

* Corresponding author.

E-mail addresses: ylva.nyberg@slu.se (Y. Nyberg), johanna.wetterlind@slu.se (J. Wetterlind), mattias.jonsson@slu.se (M. Jonsson), ingrid.oborn@slu.se (I. Öborn).

https://doi.org/10.1016/j.agsy.2020.102815
Received 17 July 2019; Received in revised form 24 January 2020; Accepted 6 March 2020

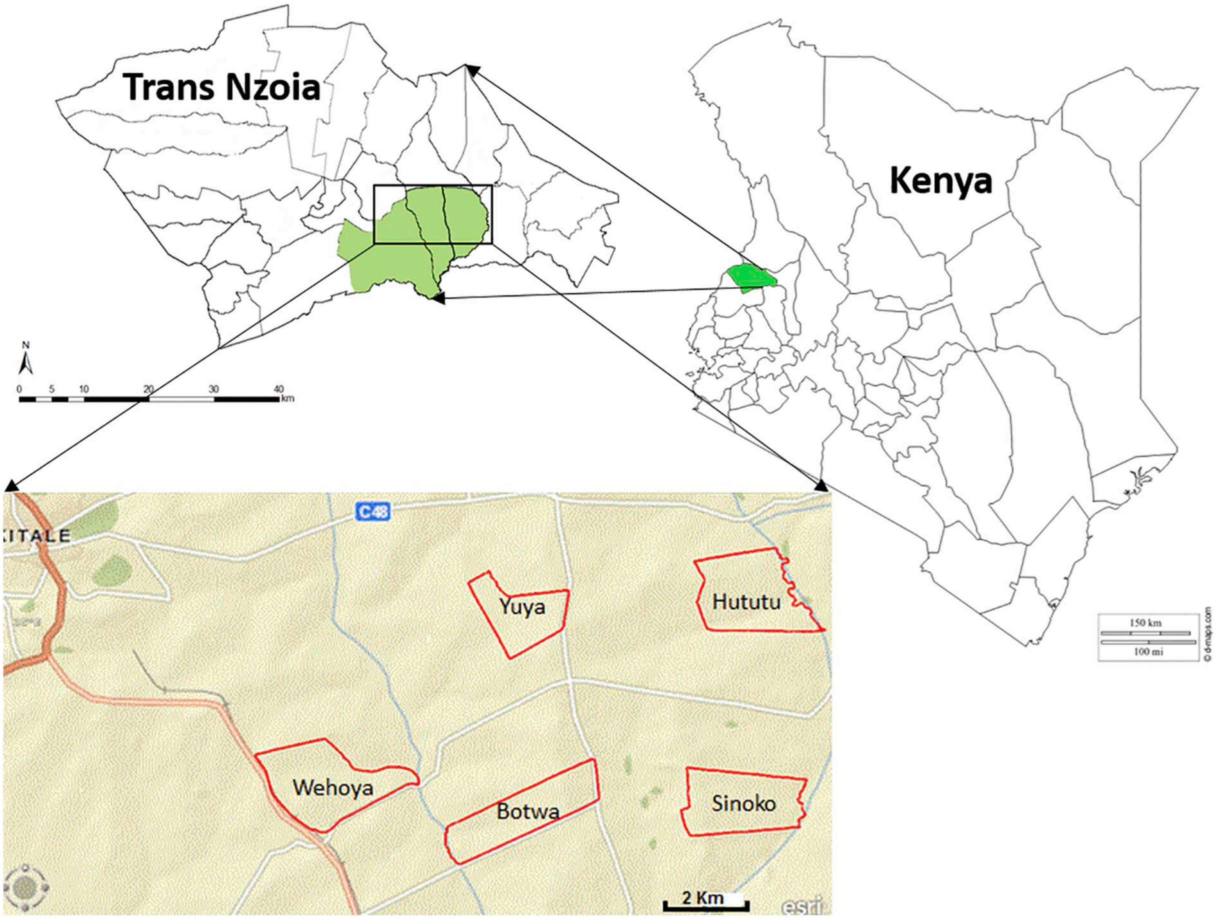

Fig. 1. Map showing the five settlements selected for this research study in Trans Nzoia County, Rift Valley, Kenya (modified with permission from Nyaga et al., 2015).

However, there are trade-offs between several farm management practices, often between short-term gains and long-term stability (Tittonell et al., 2011).

East Africa is the most densely populated part of sub-Saharan Africa and soils and agricultural landscapes in this region are becoming increasingly degraded (Blake et al., 2018). In these areas, research has indicated that in addition to maintaining diversified farming systems, improving the soil organic carbon (SOC) content on farms is key for restoring ES (Foley et al., 2005). Nutrient cycling plays an essential role in restoring soil fertility and here livestock can be important contributors to several ES services through recycling of nutrients and improving soil structure (Agegnehu and Amede, 2017; Henderson et al., 2016; Nowak et al., 2015; Pagliai et al., 2004). Recent studies also recommend that priority is given to having more trees on farms, which can also contribute to several ES (Kuyah et al., 2016; Lohbeck et al., 2018; Mutabazi et al., 2015). Mixing different species of crops, trees and livestock on farm can provide a variety of ES which potentially help to buffer the farming system against perturbations (Cabell and Oelofse, 2012; Erisman et al., 2016). Farmers have different priorities and often want to produce a variety of products and services on their farm. Crops are mainly grown for home consumption or sales, while trees and livestock have an additional role as providing insurance, i.e., when challenges arise, a tree or livestock can be sold to get fast cash (van der Ploeg et al., 2009). However, farmers often prefer livestock over trees as insurance and some claim that the benefits from livestock are necessary for farmers to invest in trees or agroforestry (Jerneck and Olsson, 2013). Trees and livestock are known to generate several ES including provisioning, supporting, regulating, and cultural (Henderson et al., 2016; Rönnbäck et al., 2007). However, both trees and livestock can potentially compete with crop resources (land, water, nutrients, labour) on farm. Therefore, their separate roles in delivering ES needs further research and quantification (Mutoko et al., 2015).

Soil organic matter affects several ES (Kearney et al., 2017). In addition, the use of organic fertilisers can both increase crop yields and decrease yield variability and thereby improve household resilience (Chen et al., 2018). Resilience is here defined as the disturbance a system can withstand without changing its functions (Folke, 2006). Both trees and livestock can potentially add organic material to the soil in the form of manure or litter, with positive effects on soil fertility and soil structure (Altieri and Nicholls, 2017). However, for smallholders the trade-offs in the use of crop residues and other types of organic material between e.g., mulch, fodder and fuel are challenging, just like trade-offs in other management aspects (Tittonell et al., 2015; Turmel et al., 2015). Drivers of change in farming systems and their management are both complex and vary between households, times and places. Therefore, it is important to consider variables which represent farm priorities and can indicate important linkages and trade-offs between ES and the relation to farm resources (Kebede et al., 2019). Available labour and farm size have been found to be two important resources that can drive changes in farm management (Dahlin and Rusinamhodzi, 2019; Muyanga and Jayne, 2014).

Building more sustainable farming systems requires a broad research approach which incorporates both social and ecological aspects (Cabell and Oelofse, 2012). Despite the amount of research on ES, and a general understanding that higher diversity within systems can lead to more sustainable development (Blicharska et al., 2019; Finney and Kaye, 2017; Isbell et al., 2017), few previous studies have identified and compared the roles of trees and livestock for ES considering farm priorities within smallholder systems (Benayas et al., 2009; Feld et al., 2009; Kuyah et al., 2016). Furthermore, there is a general lack of studies on cultural services within agroecosystems (Daniel et al., 2012; Kuyah et al., 2016), although tree attributes have been ranked highly as indicators for several cultural services (Hernández-Morcillo et al., 2013; Jim, 2006). The overall aim of this study was to identify potential effects of high and low tree and livestock density on ES and farm priorities. This was done on smallholder farms in Trans Nzoia County in the Rift Valley, Kenya. Our starting hypothesis was that farms with high tree and livestock density produce more ES and prioritize self-sufficiency higher than farms with low tree and livestock density.

Specific objectives were to determine whether high or low tree and livestock density have an impact on:

- provisioning ES, including farm production
- supporting and regulating ES, including nutrient cycling and water infiltration
- cultural ES, including recreation and aesthetics
- farm priorities in terms of nutrient management, on- and off-farm resources, food and consumption patterns and species diversity.

In the analysis, farm resources in terms of farm size and available family labour were accounted for.

2. Materials and methods

In Trans Nzoia (Fig. 1), smallholder farms with high or low tree and livestock density, and combinations of them were carefully selected using criteria listed below (see Section 2.2 and Table 1). In total 20 farms were selected for this study. Indicators for ES and variables representing farm priorities (Supplementary Tables 1 and 2) were selected and measured on the farms during a 12 months period in 2012–2013 using both qualitative and quantitative methods.

2.1. Study site and settlement selection

The recent history of the settlements in Trans Nzoia was large-scale farming by British colonialists settling between World War I and II, and leaving around independence in 1962 (Soini, 2007). Each of the five settlements selected for this study was a large-scale farm before independence, but later subdivided and sold to smallholders. Since the land is suitable for farming (Otieno et al., 2015), people from different tribes moved in after the colonial period. The study areas were chosen to have (1) mainly Ferralsols (Government, 1985), relatively high annual rainfall (mean 1000–1200 mm) and cool annual temperature (mean minimum and maximum temperature 10 and 27 °C, respectively) (Jaetzold et al., 1983) to avoid results confounded by different biophysical settings, (2) a similar land use history of large-scale maize production during colonial time, (3) enough small-scale households willing to collaborate in order to find farms fitting the farm selection criteria, and (4) not frequently affected by flooding (to minimize the risk of non-representative production conditions). The selected settlements were Botwa, Hututu, Sinoko, Wehoya, and Yuya, which were treated as blocks. The five settlements lie within the agro-ecological zone 'upper midland' (FAO, 1996), in an undulating landscape and have a population density of around 330 persons km^{-2} (KNBS, 2017). Thanks to Mt. Elgon, the Cherangani hills, and the high altitude (1800–1900 m above sea level) (USGS, 2018), Trans Nzoia has high potential for growing maize (one crop per year) and for dairy production. Common crops and livestock are maize, beans, sweet potatoes and chicken, cattle, sheep and goats. Due to lack of natural forests and high demand for fuelwood, building materials, and fruit, many farms also include trees in their farming system (i.e., agroforestry) (Nyaga et al., 2015).

2.2. Farm selection

Farms were selected to achieve a fully factorial design with high and low density of trees and livestock (Table 1 and Fig. 2), denoted crop (C), crop and tree (CT), crop and livestock (CL), and crop, tree and livestock (CTL) farms. Twenty farms were selected (one each of the four farm types in every settlement) according to the following specific criteria:

1. Each farm should have maize production in order to have at least one crop to compare production between the farms, and a size less than one hectare to have limited variation in farm size.
2. Farms should have either low tree density of no more than six trees on the homestead and no more than 15 trees ha^{-1} on farmland, or high tree density of more than six trees on the homestead and 75 or more trees ha^{-1} spread on farmland (dispersed or in hedgerows and some in woodlots). Include trees representing at least two functional groups of timber and leguminous species. Trees are defined here as woody perennials of at least 1.3 m height.
3. Farms classified as having high livestock density had cattle that were fed mostly within the farm. Farms with low livestock density did not have any cattle but could have chicken and small ruminants.

All studied farms were located on one piece of land consisting of areas for crops, trees, livestock and homestead. Actual tree and livestock density were measured on the farms at the beginning of the year (Table 1). Tree density was calculated for homestead and farmland separately for the selection criteria. Whole farm tree density was also calculated (Table 1) to see that it was representative for the area, which was confirmed (Reppin et al., 2019). Livestock density was quantified using the tropical livestock unit (TLU) concept by Jahnke and Delgado

Table 1
Farm characterization of the study farms selected to have high or low tree and livestock density ($n = 20$).

Farm characterization parameters	CTL[a]	CL	CT	C
No. of farms	5	5	5	5
Tree density[b] as number of trees ha^{-1}, mean (range)	High 871 (155–2605)	Low 27 (18–46)	High 521 (202–822)	Low 34 (10–88)
Livestock density as tropical livestock unit (TLU[c]) ha^{-1}, mean (range)	Cattle 2.6 (1.4–4.1)	Cattle 3.9 (1.5–7.3)	No cattle 0.4 (0.03–1.5)	No cattle 0.2 (0–0.4)
Farm size (ha), mean (range)	0.52 (0.20–0.61)	0.51 (0.20–0.81)	0.43 (0.20–0.81)	0.48 (0.28–0.81)
Age of contact person (person carrying out majority of farm work), mean (range)	37 (20–51)	43 (25–74)	42 (31–79)	37 (29–42)
Number of adult household members (≥18 years), mean (range)	2.8 (2–3)	2.4 (2–3)	3.0 (1–7)	2.0 (2–2)
Number of household members < 18 years, mean (range)	6.2 (3 − 11)	3.2 (0–7)	2.4 (0–4)	4.2 (2–6)
Clay content (%) in maize/bean field, mean (range)	35 (31–40)	40 (20–52)	41 (33–56)	43 (27–50)

[a] CTL = Crop-tree-livestock farms with high tree and livestock density; CL = Crop-livestock farms with low tree density and high livestock density; CT = Crop-tree farms with high tree density and low livestock density; C = Crop farms with low tree and livestock density.

[b] Short-term shrubs such as *Sesbania sesban* are often harvested within 1 year and was therefore not included in the tree count.

[c] TLU where 250 kg = 1 = water buffalo, adult cattle = 0.7, calf = 0.4, sheep/goat = 0.1, hen/dove = 0.01, dogs and cats excluded (Jahnke and Delgado, 1982).

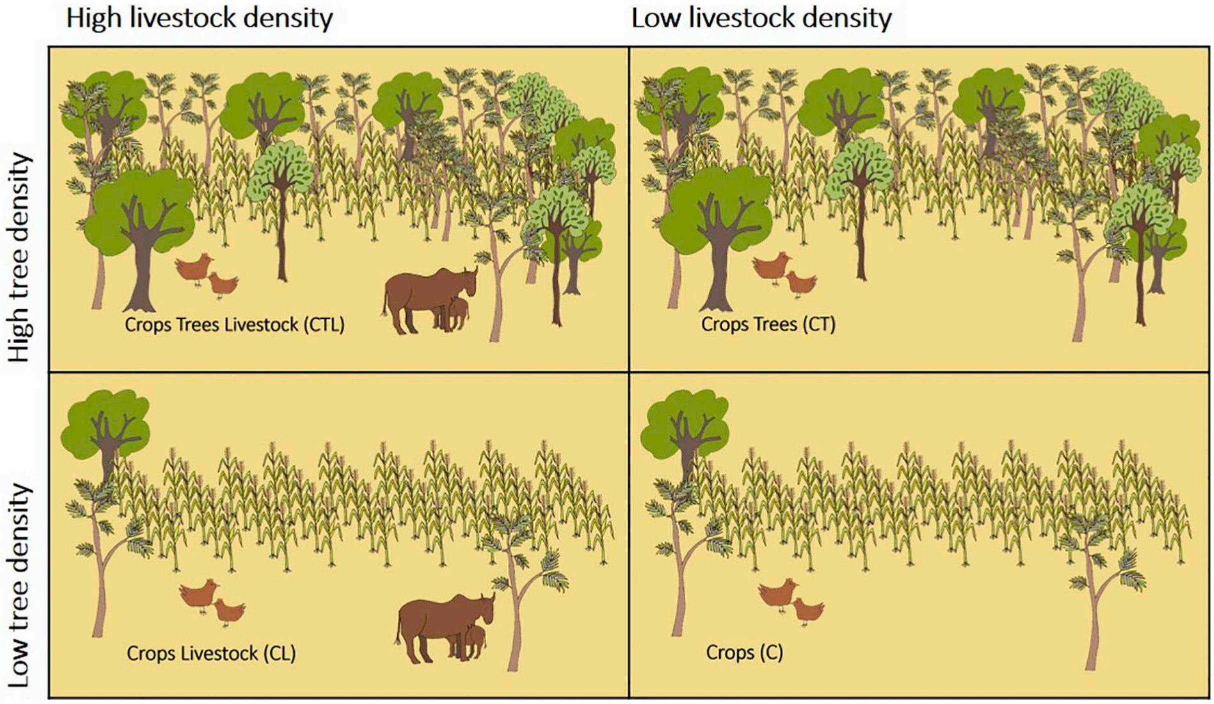

Fig. 2. Illustration of study farms selected to have either high or low tree and livestock density, in combinations with crops: Crop-tree-livestock farms (CTL) have high tree density and high livestock density including cattle; crop-tree farms (CT) have high tree density and low livestock density excluding cattle; crop-livestock farms (CL) have low tree density and high livestock density including cattle; and crop farms (C) have low tree density and low livestock density excluding cattle (illustration by Ylva Nyberg).

(1982) where 250 kg = 1 = water buffalo, adult cattle = 0.7, calf = 0.4, sheep/goat = 0.1, hen/dove = 0.01, dogs and cats excluded.

2.3. Choice of indicators for ecosystem services

Since ES is a wide concept and difficult to evaluate and compare between different studies (Egoh et al., 2012), several indicators for the same services were analyzed in this study (Supplementary Table 1). Crop yields of maize and beans, and farm production of firewood, fruit, eggs, and milk, were chosen to represent provisioning services. Crop yield is a commonly used indicator of provisioning services (Egoh et al., 2012). Farm products of crops, livestock and trees in monetary value per hectare (ha) land was also used as a provisioning service indicator (exchange rate of 1 KES = 0.01 USD). For each of crop, livestock and tree production, the annual return on investment (ROI, Eq. (1)) was calculated as:

$$\mathrm{ROI} = \mathrm{Profit}/\mathrm{Investments} \quad (1)$$

where profit = revenues – investments (Friedlob and Plewa Jr, 1996).

Indicators for supporting services, included percentage of total soil carbon (here assumed to be equal to SOC), total soil carbon/nitrogen (C/N) ratio, available phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K) levels, and soil pH (Supplementary Table 1). The indicators used for soil structure maintenance, a regulating service, were topsoil bulk density and water infiltration capacity, which can be associated directly with water retention, one of the most frequently assessed services in the literature (Feld et al., 2009).

Cultural services provided by having crops, trees, and livestock were analyzed, as was the presence of ornamental plants (Supplementary Table 1). Indicators of the proportions of tree and livestock species on a farm used for cultural (e.g., recreational or aesthetic), services were calculated. Proportions were used to overcome the fact that number of trees was a selection criterion for the farms, although actual numbers of trees were also included as an indicator.

2.4. Choice of key variables representing different farm priorities

To understand the prioritizations made by farmers in general and especially in relation to livestock and trees, categories such as nutrient management, on- and off-farm resources, food and consumption and species diversity were considered (Supplementary Table 2). Key variables for nutrient management included annual application of organic and inorganic amendments and the proportion of maize residues returned to the fields (either left in situ or composted and returned) or fed to livestock. The category of on- and off-farm resources included several key variables that have been identified and used in earlier research related to the balance of on- and off-farm revenue (Ifejika Speranza et al., 2014; Kebede et al., 2019). The key variables were land per capita, average person-hours spent on farm work per day, total and proportion of total revenue earned off-farm (Supplementary Table 2).

Food and consumption was considered as another relevant category since more than 20% of the sub-Saharan African population have a diet with enough calories but lacking essential vitamins, minerals, and protein (Kahane et al., 2013). Milk and fruits are important sources of vitamins and protein, however, not always affordable for poor people (Kahane et al., 2013). Milk and fruit intake were therefore chosen as key variables together with the proportion of total food consumed which is purchased and proportion of revenue used to buy food.

Species diversity for crops, trees and livestock can be related to resilience. When there is a drought, some crops may die and others survive and therefore a large number of crop species can be used as an indicator of resilience in agriculture (Mutabazi et al., 2015). Numbers of crop, livestock, and tree species were included as key variables together with the Shannon diversity index for trees, which combines species richness and evenness (Shannon and Weaver, 1949). The Shannon diversity index (H, Eq. (2)) is calculated as:

$$H = (-1) * ((p_1 * \ln(p_1)) + (p_2 * \ln(p_2)) + \ldots + (p_n * \ln(p_n))) \quad (2)$$

where p is the proportion of each specie and n is the number of species (Shannon and Weaver, 1949).

2.5. Semi-structured interviews with farm households and crop, livestock, and tree inventory

Crop yields, farm production and farm management data (e.g., on use of soil amendments) were collected using semi-structured interviews in combination with the Participatory Rural Appraisal (PRA) seasonal calendar tool (Cavestro, 2003). During farm visits at the beginning of the project, an inventory was also carried out for each household, in order to assess the crop, tree, and livestock densities and species diversities.

In order to track flows of revenues and expenditures per household, farmers were encouraged to participate in record keeping, especially of economic flows within, to, and from the farm. Farmers were given forms to fill in that were checked and updated during monthly farm visits throughout the year. Some farmers were not able to fill in the forms themselves and were instead interviewed when visited and sometimes phoned for updates, questions, and/or to clarify irregularities. The same field assistant and interpreter were involved during the whole annual cycle of field work.

2.6. Soil sampling for bulk density, carbon and soil nitrogen, phosphorus, and potassium

Three topsoil bulk density cores were collected in the maize/bean field, dried, and weighed for bulk density calculations, and a farm average was determined. Topsoil (0–15 cm depth) was sampled in the largest maize/bean field, the homestead, and in two to four more fields. The topsoil was systematically collected as a composite sample with 20–40 subsamples from at least two crop rows, depending on the field size. The soil samples were analyzed for soil pH ($CaCl_2$), SOC, total nitrogen (N) and extractable plant nutrients. Total SOC and N were analyzed (CNS 2000 dry combustion analyzer), and the C/N ratio was calculated. Extractable P, K, Mg, and Ca were determined by Mehlich 3 extraction (Mehlich, 1984), followed by element analysis using atomic emission spectrometry (ICP). Farm averages were calculated for all elements.

2.7. Double-ring water infiltration tests

To determine the water infiltration rate, double-ring tests were used (Brady and Weil, 2002). For this, two metal rings (20 and 30 cm diameter) were pressed around 5 cm into the soil. Water was poured into the inner ring and between the rings, to measure the infiltration rate in the inner ring while preventing water moving horizontally in the soil. Measurements continued until the rate was stable. Six double-ring tests were carried out in the maize/bean field on every farm and farm mean infiltration rate was used in further data analysis.

2.8. Data preparation and statistical analysis

All indicators and key variables (Supplementary Tables 1 and 2) were response variables in statistical analyses using the lm function in R 3.4.2 (R Core Team, 2019). The linear model was based on the fully factorial design with high and low tree and livestock density and their interactions. Farm size (ha) and family labour (available number of persons) were added as co-variates. Adults (18 years and above) were counted as one person and children (below 18 years) were counted as half a person since children also contribute in terms of labour. These factors were added both in order to see any effects of farm size and family labour as well as to make sure that the potential effects of tree or livestock density were based on average farm size and family labour availability. A factor for settlements (blocks) was added after the co-variates and before the other factors. In the significant interaction between tree density and livestock density, a comparison of all combinations/farm types (crop-tree-livestock; crop-livestock; crop-tree; crop) was carried out using the compact letter display function in the multcompview package. These pairwise *t*-tests were adjusted for multiple comparisons using Tukey's method to determine any significant differences. Throughout the analyses, gaussian distributions were expected, though in some cases log-transformations were necessary. However, ES indicators or farm priority key variables that were based on proportions were logit transformed before analyses to fulfill assumptions of the parametric test. The logit transformation (Eq. (3)) was calculated as:

$$z = \ln(p/(1-p)) \tag{3}$$

where z = logit value and p = proportion (Welham et al., 2014). The significance level was set to $P < .05$. Standardized Z-scores were used to compare all indicators and variables for the different farm types in radar diagrams. Z-scores (Eq. (4)) were calculated as:

$$Z = (x - \mu)/\sigma \tag{4}$$

where Z is the Z-score, x is the data point, μ is the overall mean and σ is the standard deviation (Geher and Hall, 2014). If a Z-score is zero, it indicates that the data point's score is identical to the mean score. A correlation matrix was also prepared, to examine potential correlations among soil properties.

3. Results

3.1. Ecosystem service indicators and farm priorities

When considering an overview of the indicators (Fig. 3), the provisioning ES seemed to vary in relation to the selection criteria with trends of more tree products for high tree density farms and more milk production for high livestock density farms. Crop farms showed patterns of higher egg production and farms with low livestock density seemed to have higher bean yields. Supporting and regulating ES indicators varied least but low livestock density farms showed patterns of higher C/N ratio and higher P and K for CL farms. Patterns for farm priority key variables showed that crop farms seemed to rely more on off-farm revenue than other farms (Fig. 3). CTL farms tended to spend more person-hours on farm work. Some of the variation in ES between farms could be explained by the co-variates (Table 2, Fig. 3). The first analyses showed a closer connection between ES and the co-variates (family labour and farm size) than to tree and livestock density. Further, the actual livestock density (in TLU ha^{-1}) and tree density were found not to correlate with any of farm size or family labour.

3.2. Provisioning services

The farm average production among the high or low tree and livestock density farms ranged between 1687 and 2208 kg ha^{-1} for maize and 77–183 kg ha^{-1} for beans (Table 2). Firewood farm average production over 12 months was 14,000 KES with high tree density and 700 KES with low tree density. Similarly the farm average milk production varied greatly from 3000 KES to 21,000 KES for those with low and high livestock density respectively. Fruit and egg production per household varied less and ranged between 3000–7000 KES for fruits and 160–315 eggs on average. The total value of all crop, livestock and tree production was similar between high tree and high livestock density with a farm average of 268,000 KES compared to 180,000 KES for farms with low tree or low livestock density. Tree or livestock density was however not significantly associated with the studied provisioning services including crop production (maize, common beans), firewood, fruits, eggs, milk or total farm production. Family labour was instead found to have positive associations with fruit ($P = .01$), milk ($P = .04$) and total farm production ($P = .04$) (Fig. 4a–c, Table 2), whereas farm size was not related to crop, tree or livestock provisioning services. Comparing the three farm components (crops, livestock, trees) more closely revealed that the annual ROI (Eq. (1)) varied widely between components and between farm types (Fig. 4d). Livestock had a ROI

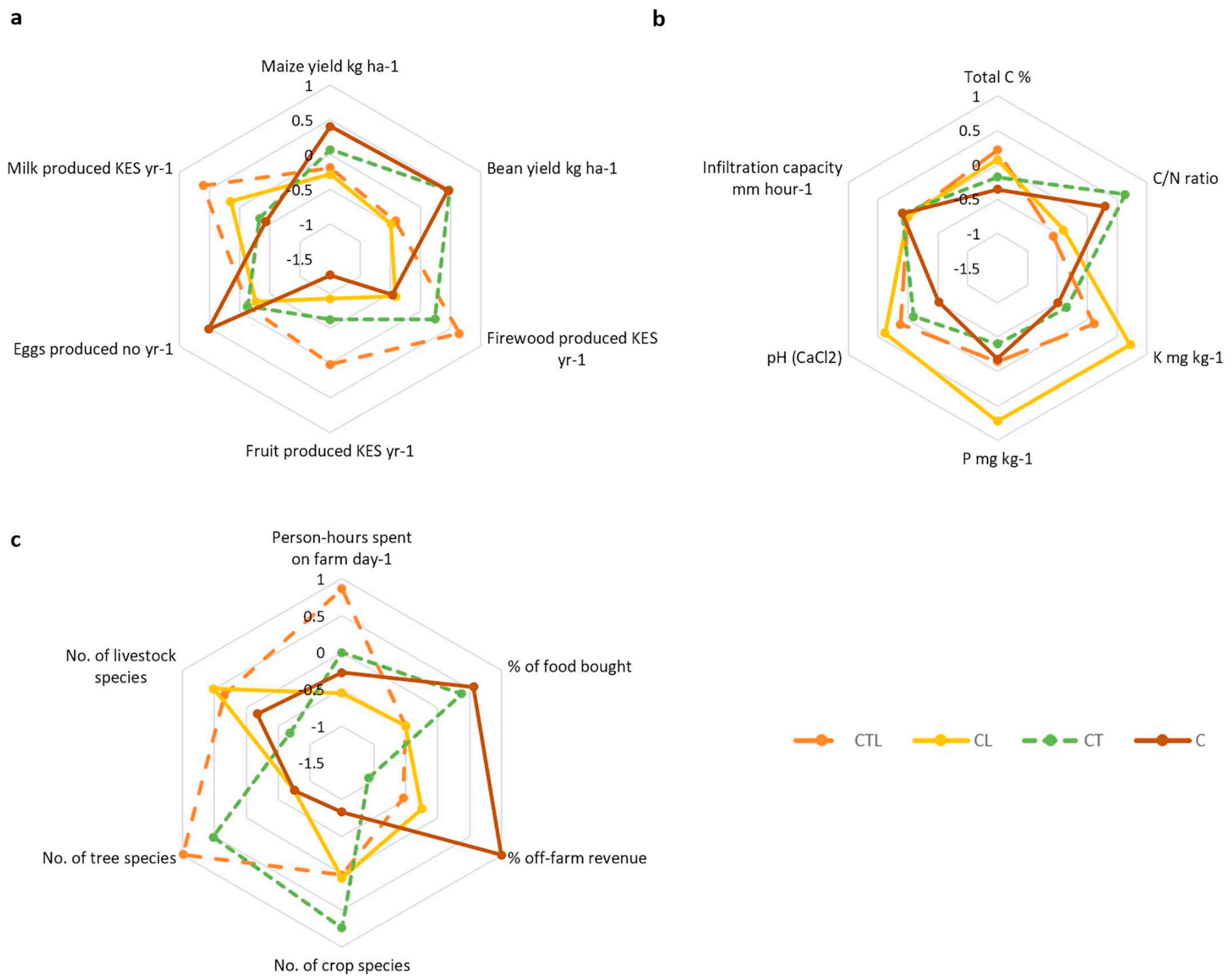

Fig. 3. Indicators of ecosystem services (ES) and key variables of farm priorities, represented as standardized *Z*-scores (Eq. (4)) for the high or low tree and livestock density farms (Fig. 2) in radar diagrams including selected a) provisioning ES – farm products, b) supporting and regulating ES – represented by water infiltration capacity of the soil and soil characteristics important for soil fertility; total soil organic carbon (SOC), total carbon – nitrogen (N) ratio (C/N ratio), soil acidity (pH), available plant nutrients – phosphorus (P) and potassium (K) and c) farm priorities in terms of on and off-farm resources, food variables and species diversity – represented by daily person-hours spent on farm-work and proportions of purchased food and off-farm revenues, as well as numbers of crop, tree and livestock species. Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

ranging between 0.6 and 6, crops had ROI between 3.4 and 8.3 and varied the least between the farm types. Trees had the highest variation with ROI between 1.3 and 48. Due to the longer rotation time for livestock and especially trees, compared to crops, the annual ROI can vary considerably between the years depending on the stage of production within the rotation cycle.

3.3. *Supporting and regulating services*

No significant associations were found between the two experimental factors, livestock and tree density, and the selected soil parameters used as indicators for supporting and regulating ES (Table 2). However, some of the soil quality ES indicators had a significant relation with farm size where higher concentrations of available soil P ($P = .008$) and Ca ($P = .04$) and a higher soil pH ($P = .02$) was found on smaller farms (Fig. 5a,b). Labour was not associated with any of the supporting and regulating ES indicators. Settlements, used as blocks in the statistical analysis, differed significantly in SOC content and water infiltration capacity ($P = .02$ respectively $P = .002$) with Yuya having the highest levels (Table 2).

3.4. *Cultural services*

On average 3–6 tree species per farm had roles in terms of beauty or recreation with both low and high tree density. A larger proportion ($P = .001$) of tree species (average 54%) therefore provided cultural services on low tree density farms compared with on average 7% on high tree density farms (Table 2). The most common reasons for planting trees were to produce fruit, firewood, timber, shade, and medicine. However, on low tree density farms, the cultural services (especially shade for recreation) had a high priority since more than half of the trees were used for cultural services on these farms. Some farmers also talked about planting trees to bring rain (assumed as a regulating service) or to get good sticks for herding cows or poles to hold bananas, or because of high demand for the seeds (provisioning services). Some traditional meanings of certain tree species were

Table 2
Selected ecosystem services' indicators (mean and 95% confidence intervals (CI)) for the study farms with high or low tree and livestock density ($n = 20$).

No	Indicators and units (farm average unless stated)	Low tree density	High tree density	Low livestock density	High livestock density	Significant results
		Mean (95% CI)[a]	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)	
	Provisioning ecosystem services					
1	Maize yield (kg ha^{-1})	2013 (1386–2640)	1882 (1255–2509)	2208 (1570–2845)	1687 (1050–2324)	
2	Bean yield (kg ha^{-1})	98 (46–209)	143 (67–305)	183 (86–395)	77 (36–164)	
3	Firewood produced, 1000 KES yr^{-1}	0.7 (0 – 11)	14 (3–24)	6 (0–16)	9 (0–19)	
4	Fruits produced, 1000 KES yr^{-1}	3 (0–8)	7 (2 – 12)	4 (0–9)	6 (1 – 11)	B $P = .01$ +
5	Eggs produced, no yr^{-1}	289 (0–619)	187 (0–518)	315 (0–652)	160 (0–496)	
6	Milk produced, 1000 KES yr^{-1}	9 (0 – 22)	16 (2–29)	3 (0–17)	21 (8–34)	B $P = .04$ +
7	Total value of produce (crop, livestock, tree) ha^{-1} yr^{-1} (1000 KES)	180 (121–268)	268 (180–400)	180 (121–268)	268 (180–400)	B $P = .04$ +
	Supporting/Regulating ecosystem services					
8	% total soil organic carbon (SOC)	1.78 (1.64–1.95)	1.83 (1.70–1.98)	1.76 (1.61–1.91)	1.87 (1.71–2.02)	S $P = .02$
9	C/N ratio (soil carbon:nitrogen ratio)	13.9 (13.6–14.3)	14.0 (13.6–14.3)	14.2 (13.8–14.6)	13.7 (13.3–14.0)	
10	Available P (mg kg^{-1})	32 (22–43)	20 (10 – 31)	20 (9–31)	33 (22–44)	F $P = .008$ –
11	Available K (mg kg^{-1})	405 (296–513)	365 (257–473)	313 (203–423)	457 (347–567)	
12	Available Mg (mg kg^{-1})	183 (146–220)	182 (145–219)	159 (122–197)	206 (168–244)	
13	Available Ca (mg kg^{-1})	853 (715–990)	921 (783–1058)	822 (682–961)	952 (812–1092)	F $P = .04$ –
14	pH ($CaCl_2$)	5.14 (4.95–5.33)	5.17 (4.98–5.37)	5.06 (4.87–5.26)	5.25 (5.05–5.45)	F $P = .02$ –
15	Bulk density (g cm^{-3}) in maize/bean field	1.16 (1.08–1.25)	1.19 (1.11–1.28)	1.17 (1.09–1.26)	1.19 (1.10–1.27)	
16	Infiltration capacity in maize/bean field (mm hour^{-1})	277 (248–306)	276 (247–305)	279 (250–308)	274 (245–304)	S $P = .002$
	Cultural ecosystem services					
17	% of livestock species used for some cultural services	2.2 (0.7–6.8)	1.8 (0.6–5.6)	3.9 (1.2–11.8)	1.0 (0.3–3.3)	
18	% of tree species used for some cultural service	54 (32–75)	7 (3–16)	28 (13–50)	19 (8–37)	T $P = .001$ –
19	No of tree species used for some cultural service	3 (3–4)	6 (6–7)	5 (4–5)	5 (4–5)	
20	No of farms with ornamental plants	8	10	10	8	

Indicators measured in percentages were logit transformed (Eq. (3)). Significant results in the last column are based on associations (positive with + and negative with −) the factors of settlement (S), tree density (T) and livestock density (L) as well as the co-variates of farm size (F) and family labour (B) in a linear model.

[a] In case confidence intervals included negative values, they were adjusted to 0.

mentioned by four farmers as reasons to plant them. *Markhamia lutea* was believed to prevent people from quarrelling and was credited with saving the Luhya tribe. It was also said to be used when building a ceremonial house for male circumcision. *Spathodea campanulata* (also called 'nandi flame' or 'African tulip tree') was believed to repel mosquitoes by smell and to prevent lightning striking to the house when it flowered. One farmer also said that *Cypressus* was used as a Christmas tree. No farmer planted crops for cultural services. However, 18 out of 20 farmers had plants for decoration purposes only (two crop-livestock farms had no ornamentals).

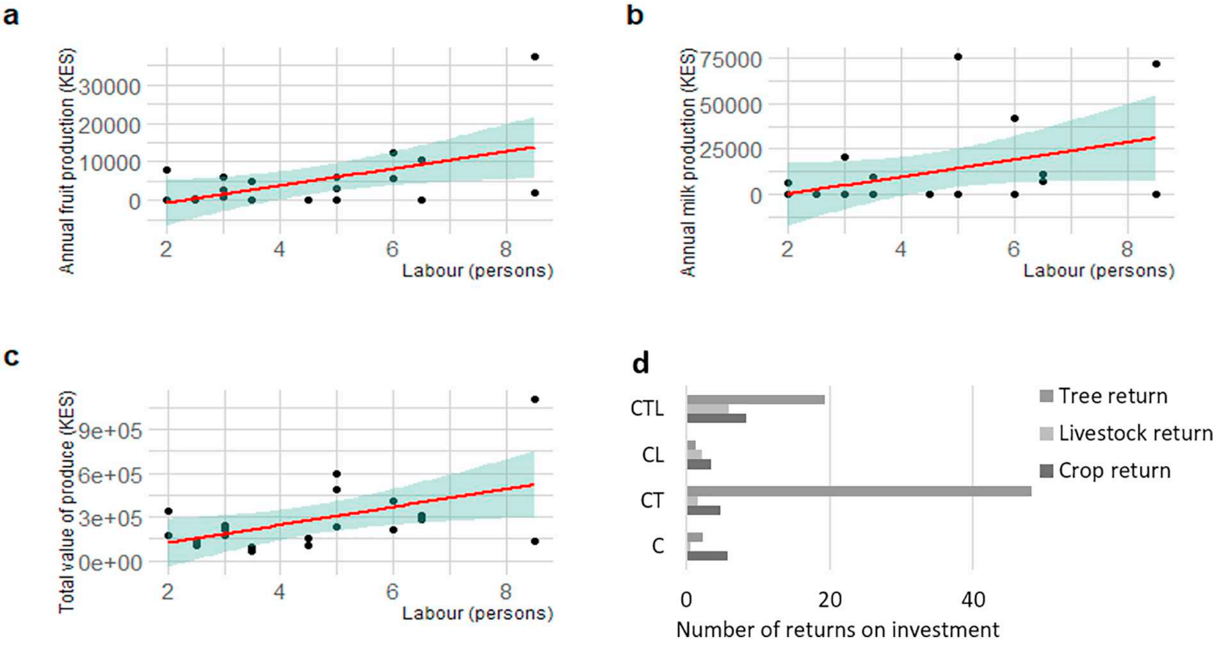

Fig. 4. Significant positive relations between family labour and annual a) value of fruit ($P = .01$) and b) milk ($P = .04$) production (Kenya Shillings - KES) per farm, and c) total annual value of produce (crop, animal, tree) expressed per farm area (ha) ($P = .04$). The line indicates the linear trend from the linear model and the shaded area shows the confidence interval. In d), the annual return on investment (ROI = (Revenue-Investments)/Investments) for the three farm components trees, livestock and crops is illustrated for the high or low tree and livestock density farms (no statistics done). Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

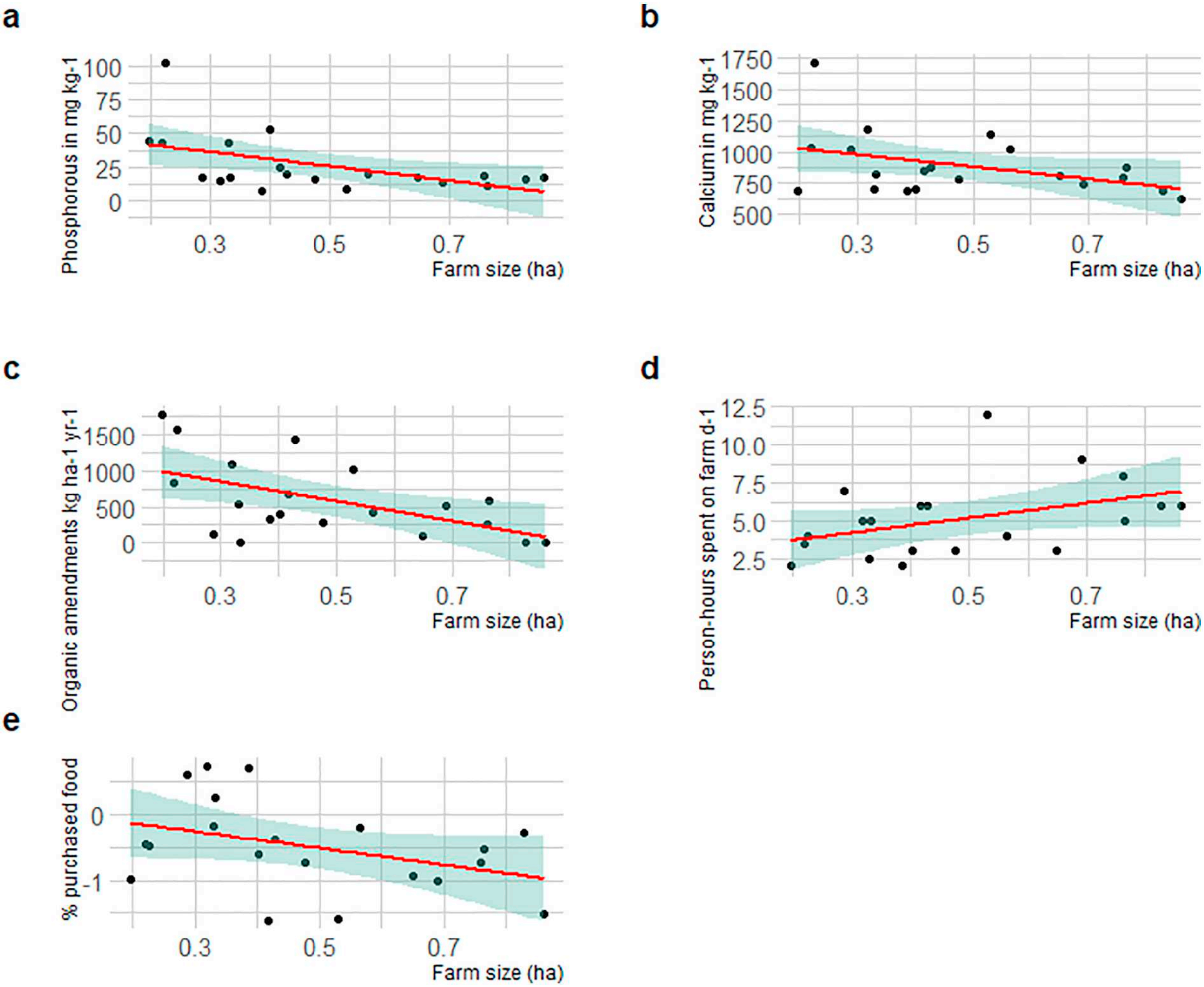

Fig. 5. Significant negative relations with farm size were found for a) soil phosphorous (mg P kg^{-1} soil; Mehlich) ($P = .008$), b) soil calcium (mg Ca kg^{-1} soil; Mehlich) ($P = .04$), c) application of organic soil amendments, i.e., manure and compost (kg ha^{-1} yr^{-1}) ($P = .02$) and e) percentage of purchased food of total food consumed (in monetary terms) ($P = .04$). There was a positive relation between d) person-hours spent on the farm per day and the farm size ($P = .008$). The line indicates the linear trend from the linear model and the shaded area shows the confidence interval.

There was no difference in the share of livestock species used for cultural services (like pets or for status) between high and low tree and livestock density farms. For livestock the share ranged between 1–3.9% compared to 7–54% for tree species. Livestock were generally kept for productive reasons (to get milk, eggs, meat, manure, or offspring) or in order to provide a certain service (plough, security, vermin control). Indirectly, both livestock and trees were also assets that could be sold if needed and thereby acted as savings. Doves, cats and dogs were kept as pets by a few farmers and one farmer said another benefit of having a dog was to feel proud. However, the doves were also eaten and kept in order to warn about the presence of snakes. Dogs were mainly kept for security, while cats were kept in order to keep rats and snakes away. Family labour or farm size had no associations with the cultural ES indicators.

3.5. *Farm priorities*

3.5.1. *Nutrient management*

The amount of organic (manure or compost) and inorganic fertilizer applied to crops varied between high and low tree and livestock density, with average rates of 505–689 kg ha^{-1} for organic materials and 91–147 kg ha^{-1} for inorganic (Table 3). However, there were no significant associations with either tree or livestock density, or family labour. A negative association was instead found between farm size and added organic amendments per ha ($P = .02$, Fig. 5c). Livestock density had, as expected, a positive association ($P = .001$) with the proportion of maize residues that were used for fodder. High livestock density farms utilized on average 38% of maize residues for fodder compared to just 3% on low livestock density farms. However, there were no significant relationships between tree or livestock density and the proportion of maize residues returned to fields, which was on average below 15% for all except C farms (average 40%) (Table 3).

3.5.2. *On and off-farm resources*

The proportions of on and off-farm revenue and the time spent on farm work differed among the farm types and both of them were related to tree density (Fig. 3). Farmers with high tree density spent more ($P = .05$, Table 3) person-hours per day (6.2 h) working on their farms compared with farmers with low tree densities (4.0 h). The highest workload was on CTL farms with 7.3 h per day of work on average (Supplementary Fig. 1a). Proportions of off-farm revenue were on average 12 and 41% for high and low tree density farms respectively (Table 3). The same number for C farms was on average 57%. The proportion of off-farm revenue of total revenues and value of produce showed a negative association ($P = .02$, Supplementary Fig. 1b) to tree density, but not to any other factor. Total off-farm revenue ranged, on

Table 3

Results of selected farm priority key variables (mean and 95% confidence intervals (CI)) for the study farms with high or low tree and livestock density ($n = 20$).

No	Key variables and units (farm average unless stated)	Low tree density	High tree density	Low livestock density	High livestock density	Significant results
		Mean (95% CI)[a]	Mean (95% CI)	Mean (95% CI)	Mean (95% CI)	
	Nutrient management					
1	Annual organic amendments manure/compost (kg ha^{-1})	505 (180–829)	689 (365–1013)	547 (218–877)	646 (317–976)	F $P = .02$ −
2	Annual inorganic amendments in maize/bean fields (kg ha^{-1})	101 (36–167)	136 (71–201)	147 (80–213)	91 (24–157)	
3	% maize residues returned to field (left or composted)	21 (10–39)	12 (5–23)	23 (11–42)	10 (5–22)	
4	% maize residues used as fodder	12 (4–30)	12 (4–28)	3 (1–9)	38 (16–65)	L $P = .001$ +
	On and off-farm resources					
5	Land per capita (ha person^{-1})	0.10 (0.06–0.13)	0.11 (0.07–0.15)	0.10 (0.06–0.14)	0.10 (0.07–0.14)	F $P = .0003$ + B $P = .001$ −
6	Average person-hours spent on farm work day^{-1}	4.0 (2.7–5.4)	6.2 (4.8–7.5)	4.7 (3.3–6.1)	5.5 (4.1–6.9)	F $P = .04$ + T $P = .05$ +
7	Annual total off-farm revenue farm^{-1} (1000 KES)	86 (50–122)	49 (13–85)	85 (48–122)	50 (13–87)	
8	% off-farm revenues of all revenue and value of produce[b]	41 (21–65)	12 (5–26)	24 (11–45)	23 (10–44)	T $P = .02$ −
	Food and consumption					
9	% purchased food of total food consumed	39 (30–47)	37 (29–46)	46 (37–55)	31 (23–39)	F $P = .04$ − L $P = .02$ −
10	% of revenues used to buy food	21 (15–29)	20 (14–27)	23 (17–31)	18 (13–25)	
11	Milk consumption farm^{-1} year^{-1} (1000 KES)	6 (3 − 12)	10 (5–21)	7 (3–16)	8 (4–16)	
12	Fruit consumption farm^{-1} year^{-1} (1000 KES)	4 (0–8)	6 (1 − 10)	4 (0–9)	6 (1–10)	B $P = .02$ +
	Species diversity					
13	No. of crop species farm^{-1} year^{-1}	9.8 (8.8–10.9)	11.5 (10.4–12.5)	10.6 (9.5–11.6)	10.7 (9.7–11.8)	B $P = .02$ + T $P = .03$ + T:L $P = .03$
14	No. of livestock species	3.1 (2.6–3.7)	2.7 (2.1–3.3)	2.4 (1.9–3.0)	3.4 (2.8–3.9)	B $P = .01$ + L $P = .04$ +
15	No. of tree species	9 (4–15)	28 (22 − 33)	17 (12 − 22)	20 (15–25)	B $P = .02$ + T $P = .0004$ +
16	No. of fruit species	1.1 (0–2.2)	2.6 (1.5–3.8)	2.1 (1.0–3.3)	1.6 (0.4–2.7)	T $P = .05$ +
17	Tree diversity Shannon index	1.47 (1.17–1.76)	1.97 (1.67–2.27)	1.79 (1.49–2.10)	1.64 (1.34–1.95)	T $P = .02$ +

Key variables measured in percentages were logit transformed (Eq. (3)). Significant results in the last column are based on associations (positive with + and negative with −) the factors of settlement (S), tree density (T), livestock density (L) and the interaction between tree and livestock density (T:L) as well as the co-variates of farm size (F) and family labour (B) in a linear model.

[a] In case confidence intervals included negative values, they were adjusted to 0.

[b] Gifts to the household was neither included in off-farm income nor in total income. However, gifts were included and shown in Fig. 6.

average, between 49,000 and 86,000 KES among low and high tree and livestock density farms, but no significant associations were found. Livestock density was not associated with any key variable for on and off-farm resources and tree density showed no relation to land per capita. Instead, as could be expected, a larger farm was connected to more land per capita ($P = .0003$) just like more family labour meant less land per capita ($P = .001$). A larger farm size also meant more time spent on farm work ($P = .04$). Family labour was not associated to any other variable than land per capita.

All farmers had different livelihood strategies (Fig. 6). Crop farms relied heavily on off-farm revenues (with more than 50% of revenues coming from off-farm), whereas CL farms had problems making ends meet without selling land and bricks (i.e., soil) to manage their expenditures (Fig. 6). The CT farms sold much of their crop harvest in order to buy the foods they preferred and these farms also received substantial money from relatives. The CTL farms mainly relied on revenues from trees, livestock, and when working as casual labour, and had the highest turnover rate in real numbers (smallest turnover rate per person) due to their large families (Table 1).

3.5.3. *Food and consumption*

Purchased food as a proportion of total food consumed (economic value) decreased both with larger farm size (Fig. 4e) and higher livestock density (Fig. 5f) ($P = .04$ respectively $P = .02$, Table 3), but was not affected by tree density or family labour. Close to half (45–48%) of all food was bought on CT and C farms, while the proportion was 31% on CL and CTL farms. The proportion of revenues used to buy food ranged between 18 and 23% and was not affected by any of the analyzed factors. The milk consumption ranged between a value of 6000 and 10,000 KES and fruits were 4000 to 6000 KES on average per year and farm. There were no significant associations with tree or livestock density, or farm size on average milk or fruit consumption per year and family. However, family labour had a positive relation to fruit consumption ($P = .02$, Fig. 7a).

3.5.4. *Species diversity*

The annual crop diversity was on average 9–12 crops per farm and year (Supplementary Fig. 1d). An interaction between tree and livestock density indicated that farms with high livestock density had similar crop diversity irrespectively of tree density, while for farms with low livestock density the tree density played a significant positive role for crop diversity ($P = .03$, Table 3). CT farms had a significantly higher average number of crop species compared to C farms (Supplementary Fig. 1d). More family labour was related to higher species diversity of crops ($P = .02$, Fig. 7b), livestock ($P = .01$, Fig. 7c) and trees ($P = .02$, Fig. 7d), but was not related to Shannons index (Eq. (2), Table 3). Tree density had a positive relationship with the number of tree species ($P = .02$), number of fruit types ($P = .04$) and Shannon's diversity index for trees ($P = .02$, Supplementary Fig. 1c, Table 3). The diversity of trees ranged between on average 9 species on low tree density farms to 28 species on high tree density farms. Tree density was not related to livestock diversity. Livestock density was similarly positively related to number of livestock species ($P = .04$), which was between 2 and 3 species on average per farm but was not linked to tree diversity. Farm size had no association with species diversity for crops, trees or livestock.

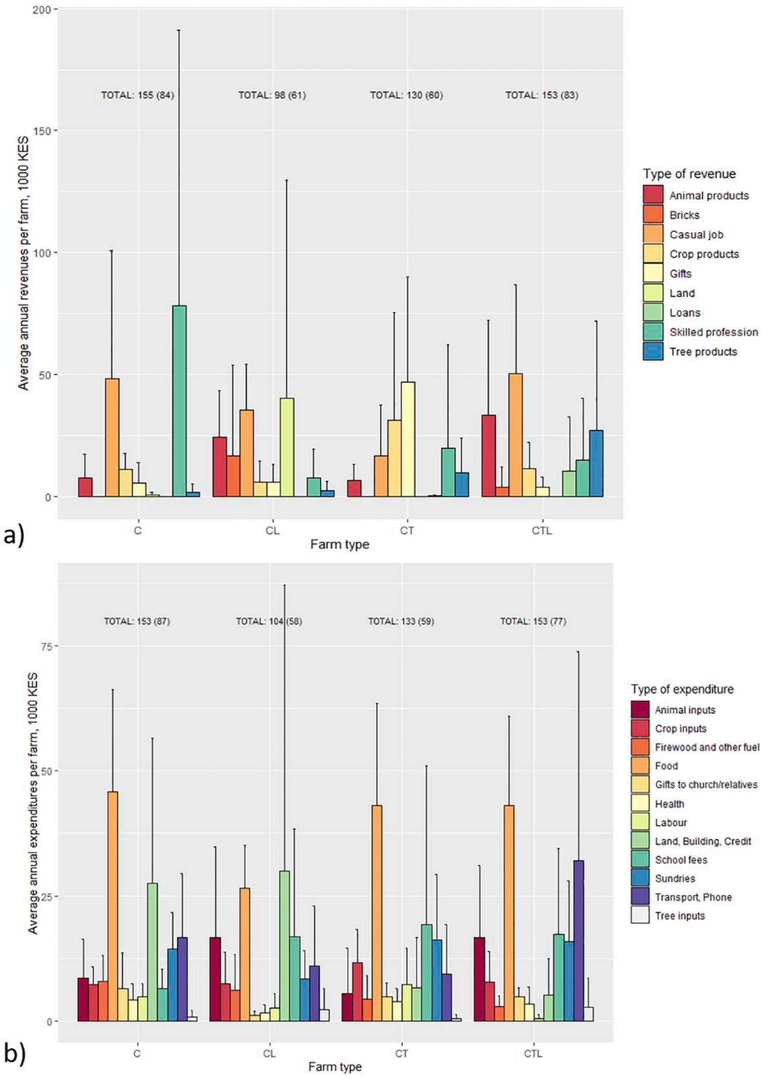

Fig. 6. Average mean values and standard deviation of annual a) sources of revenues and b) expenditures per farm in thousand Kenya Shillings (KES) for the high or low tree and livestock density farms and their combinations (Fig. 2; $n = 20$). Total annual revenue and expenditure per farm are given in numbers above the histogram with standard deviation in brackets. Crop-tree-livestock farms (CTL) were selected to have high tree and livestock density; crop-tree farms (CT) to have high tree and low livestock density; crop-livestock farms (CL) to have low tree and high livestock density; and crop farms (C) to have low tree and livestock density.

4. Discussion

4.1. Provisioning services

Crop production and total farm production were not affected by tree or livestock density. The fact that high tree density did not result in lower crop production (although trees and crops can compete for light, water, and nutrients) could be because crops can benefit from ecosystem services provided by trees, such as improved water infiltration or nutrient cycling (Kuyah et al., 2016; Rao et al., 1997). Otherwise it could be due to that only few trees were located within the maize and bean fields. The recorded maize yield was lower than reported by Nyaga et al. (2017) for larger farms in the same area. However, it was similar to those observed by Kiboi et al. (2017) in Kenya's Central Highlands in the same year and also within the mean of Kenyan average maize production 2009–2013 (1.5–2.0 t ha^{-1}) reported by Ministry of Agriculture, Livestock, and Fisheries in Kenya (in Sheahan et al. (2016)).

Production of tree and livestock products such as fruit, firewood, milk and eggs showed no statistically significant associations with tree or livestock density. This is probably due to a large variation within the farm types. However, higher tree density demanded more person-hours of work. At the same time, available family labour was the only factor that positively affected several provisioning ES indicators. Based on this, it would have been interesting to include more farms and of a larger range in size in the study. An alternative way to design the study could also have been to have tree and livestock density as continuous variables, which would have required different selection criteria for the farm selection, in order to see if effects for trees or livestock could come out more clearly.

Family labour had positive associations to fruit, milk and total farm production. With a future global challenge of increasing food production without expanding agricultural areas (Foley et al., 2011), this shows potential for improvements in intensification of production through more and effective use of labour (Dorward, 2013). Sustainable ways of mechanization should be addressed to attract a young generation of fulltime smallholder farmers to develop sustainable and profitable farm enterprises (Baudron et al., 2015). In addition, there was no relation between farm size and crop, tree or livestock provisioning services. Since tree and livestock products were measured per farm and not ha^{-1}, this suggests that tree and livestock productions do not necessarily need large land areas.

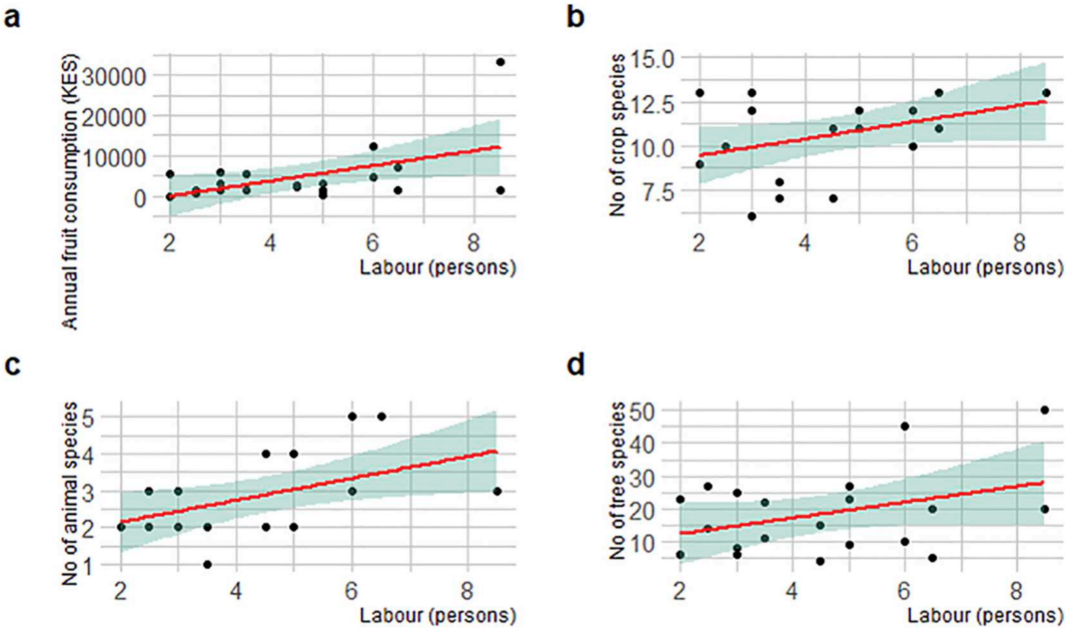

Fig. 7. Significant positive relations between family labour and a) annual fruit consumption ($P = .02$), b) number of crop ($P = .02$), c) livestock ($P = .01$) and d) tree ($P = .02$) species on the farm. The line indicates the linear trend from the linear model and the shaded area shows the confidence interval.

Return on investment was lowest for livestock products, probably due to extensive milk production and that farmers value livestock high as a security (Jerneck and Olsson, 2013). The high ROI for trees is related to the long rotation period of trees in some cases. The investments are high when planting trees but little investment is required in later years and high revenue could be returned from harvesting small numbers of trees. The importance of a planned balance between planting and cutting is clear and was practiced on the majority of farms. Farms with a combination of high tree and livestock density gave on average the highest ROI for both crops and livestock, while CL farms gave the lowest crop and tree ROIs. Potentially this may indicate that trees have positive associations to other production, even if not significant in a small sample of farms like this.

The household economy presented here included only revenues, expenditures, and values of products that were used, sold or bought during one particular year (Fig. 6). The value of possession of land, livestock, trees, other assets, or savings during the study period were not considered. However, these assets can provide important insurance (Kearney et al., 2017). Overall, the average annual revenue of the study farms ranged between 98,000 and 155,000 KES a year or 268–425 KES a day, which equals to 2.6–4.2 USD a day, and can be compared with the extreme poverty line of 1.90 USD a day (Worldbank, 2019). The livestock component was associated with relatively high expenditure compared with crops or trees, but a milking cow is highly attractive, resulting in potential daily revenues and reduced food expenditure (as found in this study). The same reasoning could potentially apply to the lower expenses for building materials, land, and credits for high tree density farms, as wood can be assumed to come from within the farm. Crop-livestock farms had the lowest total revenue and lowest revenue from crops (Fig. 6), indicating that they had more difficulty making ends meet. The ROI for livestock products however seemed to increase with tree density (Fig. 4). Crop-livestock-tree farms were more self-sufficient than others with on average higher production and revenue from the farm.

Decreasing farm size leads to households becoming gradually more dependent on off-farm revenue sources (Mutoko et al., 2014). The role of farm size has been highlighted earlier (Fan and Chan-Kang, 2005), but the threshold farm size to sustain a household has yet to be determined. However, the farm size in this study (0.2–0.8 ha) seems to be near the threshold, since C farmers seemed to use their farm more as an additional source of food and had a relatively high proportion (57%) of off-farm revenue (Table 3).

4.2. *Supporting and regulating services*

Poor management of both cattle and the manure itself is common in these areas and leads to low amounts of nutrients returned to the soil (Castellanos-Navarrete et al., 2015). But even when storage and application losses are considered, manure has been found to be the largest contributor of major crop nutrients to Kenyan soils, and crop residues were found to be the cheapest (Castellanos-Navarrete et al., 2015). Long-term application of manure, compost, and/or crop residues can be expected to improve infiltration capacity (Ouattara et al., 2007) and increase carbon sequestration (indicated by the SOC content) (Hemmat et al., 2010). However, no significant associations between tree or livestock density and water infiltration or SOC were found. Instead a larger farm size meant lower concentrations of available soil P and Ca per unit area and lower application rate of organic amendments. Partly this could be explained by that TLU was not correlated to farm size, i.e., the manure was spread over a larger area. In further research, it would be interesting to include farms with even higher livestock density to get more input to the supporting and regulating ES discussion. That would likely mean that larger farms would have to be included, which also could have made it easier to find and understand the contributions of tree and livestock density for ES and farm priorities better.

4.3. *Cultural services*

Recreation and aesthetic enjoyment are the most commonly measured cultural services (Egoh et al., 2012), and in this study they were represented by on-farm indicators. It was found that crops were only planted for provisioning purposes even if all except two CL farms (90%) had additional ornamental plants. This is a clear sign that beauty is highly valued by smallholders as has been shown earlier (Franzel and Scherr, 2002). Unlike in other parts of the world (Roy, 1955), few livestock (partly doves, dogs and cats) had any cultural values. But instead, trees carried several important cultural services (e.g., shade for recreation in the homestead and beauty for aesthetic values) that were prioritized even on farms with low tree density. Shade is very important in agricultural landscapes where temperatures are high (Chambers and Longhurst, 1986) and can also promote social interaction in smallholder communities (Quandt et al., 2018). Shade was also found to be the third most common use of trees in Western Kenya by Reppin et al. (2019). Trees are however often planted for multiple purposes (Mekoya et al., 2008) and several examples of traditional beliefs were found here, just like in an earlier study (Diawuo and Issifu, 2015). These results are particularly interesting since primary data on cultural services commonly are retrieved from natural parks set aside for recreation and tourism (Egoh et al., 2012), while cultural services present within the agricultural landscape are rarely accounted for (Kuyah et al., 2016).

4.4. Farm priorities

4.4.1. Nutrient management

Livestock had a positive association with the proportion of maize residues fed to livestock, but no association with other organic (manure and compost) or inorganic amendments (fertilisers). Another Kenyan study found that around 50% of crop residues were returned to fields, while the other 50% were used as fodder or fuel for cooking (Berazneva et al., 2018). In this study an even smaller proportion of residues (< 15% on all except C farms) was returned. Crop residues are the cheapest nutrients to return to the soil, but smallholders often feed them to livestock or burn them (Castellanos-Navarrete et al., 2015; Tittonell et al., 2015). A portion of the nutrients contained in the residues fed to livestock will be returned to the soil if the manure is used. With higher livestock density one could expect the applications of manure to be larger compared with low livestock density. However, in this study no associations between livestock and nutrient dynamics were found, using the amount of manure or soil nutrient concentrations as indicators. The results may reflect the small farm sizes. Farms smaller than one hectare have difficulties in maintaining soil fertility and productivity, since their ability to accumulate cash for productive investments is minimal (Stephens et al., 2012).

4.4.2. On and off-farm resources

Farms with high tree density had higher proportion of on-farm revenue and lower proportions of off-farm revenue. The results could indicate a higher market orientation and/or a higher self-sufficiency orientation. The higher market orientation is reflected in higher revenues from tree, crop and livestock products (Fig. 6), and higher self-sufficiency through less fuel expenditures and lower proportions of off-farm revenues. High tree density indicated more hours of work on-farm, perhaps an indication of a more long-term commitment to the farm. The extra work hours needed on high tree density farms may potentially give them less time to work off-farm. In other studies, trees (especially in woodlots) are normally associated with reduced labour demand (Dewees, 1991). Most trees need only seasonal or annual attention compared to daily or weekly attention for livestock and crops, and trees save labour through e.g., easy access to fuelwood. However, in cases of agroforestry with e.g., high numbers of trees in hedgerows, the labour requirement is higher (Hoekstra, 1987). Earlier research has indicated that production can be increased with more intensive farm management, but it may not pay off unless the labour is from within the family (Mutoko et al., 2014). Family labour and production were found to be positively associated also in this study. Using more family labour to produce mainly for the market rather than for consumption has been found to improve the production efficiency on smallholder farms (Mutoko et al., 2014), while hiring labour is not economically efficient according to Dewees (1991). However, there is a need for more research on the relationships between labour demand and crop production for certain management practices, since they have been found to be closely related (Dahlin and Rusinamhodzi, 2019). The lack of associations to livestock density could indicate that a larger variation in livestock density is needed to detect clear differences among these variables.

Available land per capita was positively associated to farm size and negatively associated to family labour which is quite logical but also means that smaller farms with larger potential family labour force has to be more intensive or rely more on off-farm revenue. All 20 study farms had relatively large parts of their revenues from off-farm (on average 12–41%, Table 3) compared to a study of smallholders in Ethiopia where the average was 9% (Kebede et al., 2019). Crop farms had the largest proportions of off-farm revenues (Fig. 3), possibly indicating a direction of exiting farming for those households (Appel and Balmann, 2019).

4.4.3. Food and consumption

The proportion of revenues used for purchasing food was similar between farms in this study (18–23%) and as compared to smallholders with similar land per capita in Ethiopia (24%) (Kebede et al., 2019). However, increased livestock density and farm size both lead to smaller proportions of purchased food of total food consumed. For example, milk is a relatively expensive food item that is commonly used for tea every day (Hansen et al., 2011) and may therefore partly explain the results. The larger farm size gave larger land per capita, which should naturally lead to a lesser need for purchased food, especially since labour was not associated with the proportion of purchased food. Lower proportions of purchased food could be a sign of higher self-sufficiency.

Several studies have found a positive relationship between tree cover and dietary diversity (Ickowitz et al., 2014; Sibhatu et al., 2015), while having livestock correlates with higher milk consumption (Nicholson et al., 2004). However, Sibhatu et al. (2015) found that off-farm revenue also had positive associations with dietary diversity, but that differences were less clear in e.g., Kenya, where smallholders had relatively high overall diversity. The relatively high diversity in the study area could explain the lack of significant differences between high and low tree density in terms of milk and fruit consumption. The higher fruit consumption found when available family labour was high, can either simply be due to more people eating fruit or that it takes more labour to make the most of the fruit products at a certain time.

4.4.4. Crop, tree and livestock species diversity

Tree density and family labour were positively associated with several variables related to on farm diversity of crops, trees and livestock, even if crop diversity generally was high on the majority of farms (9–12 crops per farm). Diversifying farming systems is recommended in order to secure sustainable and robust future global food production (Kahane et al., 2013). Our results showed that farms with higher tree and livestock density also had larger crop species diversity. This was probably related to that farmers with high tree density spent more time on farm-work and therefore could attend to a larger number of crop species. In other words, high tree density was perhaps an indication of farms that had chosen a diversification trajectory, investing both in market orientation and self-sufficiency. Crop diversification on smallholder farms has further been found to increase farm revenues (Nguyen, 2017), that can be connected to the higher proportion of on-farm revenue for high tree density farms in this study.

The Shannon index for tree diversity ranged between 1.47 and 1.97 among high and low tree density the farms included this study (Table 3), which is slightly lower than results reported by Nyaga et al. (2015) on farms of a larger size range in the same settlements (1.83–2.31) but similar to the farm average found by Reppin et al. (2019) in Western Kenya (1.65).

4.5. Farm trajectories

Based on the results of this study, there seem to be two directions or trajectories for smallholders with 0.2–0.8 ha of land: towards a higher diversity of crops, trees and livestock, or towards a simpler farming system with just a few crops. The former is more labour demanding, but also potentially more productive and resilient (Cabell and Oelofse, 2012) and has been identified by Kebede et al. (2019) as a diversification trajectory, which is common with shrinking farm sizes. The simpler farming system is relatively sensitive to disturbances, but makes it easier for the owner to seek a higher proportion of off-farm revenue and thereby relying less on the farm performance, which is a way of getting a resilient revenue but not a resilient farm. In one sense this is a specialization trajectory, where farmers focus on a limited number of crops, but it is also a kind of exiting direction since off-farm revenue will slowly overtake the on-farm revenue or value, which was already the case on some of the studied farms. The more diverse farms seemed to be both more market-oriented as well as more self-sufficient in their production than the less diverse farms.

5. Conclusions

This study confirmed roles of trees and livestock for ES and farm priorities, although they in some cases appeared less important than family labour and farm size. Tree or livestock density alone showed no clear associations with provisioning, supporting or regulating ES. Cultural services like recreation and aesthetics were provided mainly by trees and were of high priority on the study farms.

High tree density was associated with higher crop, fruit and tree species diversity. It also resulted in a higher workload and meant higher proportions of on-farm revenue. Trees are more long-term products and investing in trees could be related to longer-term commitment to the farming system. High livestock density showed a reduced proportion of purchased food, probably meaning that milk for consumption was the main benefit from high livestock density.

The overall finding was that both tree and livestock density, among these 20 farms, seemed to have inferior associations to ES and farm priorities compared to family labour and farm size. The available family labour positively influenced both farm outcome (provisioning services) and risk spreading (crop, tree and livestock species diversity). The use of organic amendments (manure, compost) and mineral fertilisers was overall low, and the application rate per unit area seemed higher on farms with less land which was reflected in higher soil P and Ca concentrations. The nutrient supply and soil fertility need to be boosted on smallholder farms, e.g. through better integration of crop and livestock production, re-use of crop residues and inclusion of nitrogen fixing plants, e.g. grain legumes and leguminous fodder shrubs. Nutrient cycling and the use of plant nutrients and organic matter needs to be improved and more efficient to sustainably enhance productivity in smallholder agriculture.

Crop farms relied significantly more on off-farm revenue compared to the other farm types, and seemed to be in a trajectory of exiting farming. Farms of high tree density had signs of both a higher level of market orientation and self-sufficiency, but they also had higher labour requirements. The challenge of (too) small farm sizes and reducing farm sizes need to be targeted seriously in research and development efforts aiming at sustainable intensification and diversification of smallholder farming and market opportunities. Also the issue of labour requirement and pathways for mechanization must be addressed to attract a new generation farmers to develop sustainable and profitable farm enterprises providing ES to the farm and the surrounding landscape.

Declaration of competing interest

No potential conflict of interest is reported by the authors. All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments, or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Acknowledgements

This study was carried out with funding from the Swedish Ministry for Foreign Affairs as part of its special allocation on global food security and the Swedish University of Agricultural Sciences (SLU). The 20 farmer families in Botwa, Hututu, Sinoko, Wehoya, and Yuya in Trans Nzoia County are gratefully acknowledged for giving their time and sharing their experiences, which formed the basis for this paper. Essential assistance from the field assistant and interpreter, Sara Wanjiru, personnel from the NGO (Vi Agroforestry) who made this research possible, Johannes Forkman for statistical advice and Christine Watson for review and editing is gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2020.102815.

References

Agegnehu, G., Amede, T., 2017. Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: a review. Pedosphere 27, 662–680.

Allen, M.R., Dube, O.P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S., Kainuma, M., Kala, J., Mahowald, N., Mulugetta, Y., Perez, R., Wairiu, M., Zickfeld, K., 2018. Framing and context. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, In Press ed.

Altieri, M.A., Nicholls, C.I., 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. Clim. Chang. 140, 33–45.

Appel, F., Balmann, A., 2019. Human behaviour versus optimising agents and the resilience of farms – insights from agent-based participatory experiments with FarmAgriPoliS. Ecol. Complex. 40.

Baudron, F., Sims, B., Justice, S., Kahan, D.G., Rose, R., Mkomwa, S., Kaumbutho, P., Sariah, J., Nazare, R., Moges, G., Gérard, B., 2015. Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement. Food Secur. 7, 889–904.

Benayas, J.M.R., Newton, A.C., Diaz, A., Bullock, J.M., 2009. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325, 1121–1124.

Berazneva, J., Lee, D.R., Place, F., Jakubson, G., 2018. Allocation and valuation of smallholder maize residues in Western Kenya. Ecol. Econ. 152, 172–182.

Blake, W.H., Rabinovich, A., Wynants, M., Kelly, C., Nasseri, M., Ngondya, I., Patrick, A., Mtei, K., Munishi, L., Boeckx, P., Navas, A., Smith, H.G., Gilvear, D., Wilson, G., Roberts, N., Ndakidemi, P., 2018. Soil erosion in East Africa: an interdisciplinary approach to realising pastoral land management change. Environ. Res. Lett. 13, 124014.

Blicharska, M., Smithers, R.J., Mikusiński, G., Rönnbäck, P., Harrison, P.A., Nilsson, M., Sutherland, W.J., 2019. Biodiversity's contributions to sustainable development. Nat. Sustain. 2, 1083–1093.

Brady, N.C., Weil, R.R., 2002. The nature and properties of soils 13thEdition. Agrofor. Syst. 54, 249.

Cabell, J.F., Oelofse, M., 2012. An indicator framework for assessing agroecosystem resilience. Ecol. Soc. 17.

Castellanos-Navarrete, A., Tittonell, P., Rufino, M.C., Giller, K.E., 2015. Feeding, crop residue and manure management for integrated soil fertility management – a case study from Kenya. Agric. Syst. 134, 24–35.

Cavestro, L., 2003. PRA-Participatory Rural Appraisal Concepts Methodologies and Techniques. Padova University, Padova PD, Italia.

Chambers, R., Longhurst, R., 1986. Trees, seasons and the poor. IDS Bull. 17, 44–50.

Chen, Y., Camps-Arbestain, M., Shen, Q., Singh, B., Cayuela, M.L., 2018. The long-term role of organic amendments in building soil nutrient fertility: a meta-analysis and review. Nutr. Cycl. Agroecosyst. 111, 103–125.

Dahlin, A.S., Rusinamhodzi, L., 2019. Yield and labor relations of sustainable intensification options for smallholder farmers in sub-Saharan Africa. A meta-analysis. Agron. Sustain. Dev. 39, 32.

Daniel, T.C., Muhar, A., Arnberger, A., Aznar, O., Boyd, J.W., Chan, K.M.A., Costanza, R., Elmqvist, T., Flint, C.G., Gobster, P.H., Grêt-Regamey, A., Lave, R., Muhar, S., Penker, M., Ribe, R.G., Schauppenlehner, T., Sikor, T., Soloviy, I., Spierenburg, M., Taczanowska, K., Tam, J., von der Dunk, A., 2012. Contributions of cultural services to the ecosystem services agenda. Proc. Natl. Acad. Sci. 109, 8812–8819.

Dewees, P.A., 1991. The Impact of Capital and Labour Availability on Smallholder Tree Growing in Kenya. University of Oxford. https://ora.ox.ac.uk/objects/uuid:52a3c258-afb6-40b2-9cae-11bbf9fbefd1.

Diawuo, F., Issifu, A.K., 2015. Exploring the African traditional belief systems in natural resource conservation and management in Ghana. J. Pan Afr. Stud. 8, 115–131.

Dorward, A., 2013. Agricultural labour productivity, food prices and sustainable development impacts and indicators. Food Policy 39, 40–50.

Egoh, B., Drakou, E.G., Dunbar, M.B., Maes, J., Willemen, L., 2012. Indicators for Mapping Ecosystem Services: A Review. European Commission, Joint Research Centre (JRC).

Erisman, J.W., van Eekeren, N., de Wit, J., Koopmans, C., Cuijpers, W., Oerlemans, N., Koks, B.J., 2016. Agriculture and biodiversity: a better balance benefits both. AIMS Agric. Food 1, 157–174.

Fan, S., Chan-Kang, C., 2005. Is small beautiful? Farm size, productivity, and poverty in Asian agriculture. Agric. Econ. 32, 135–146.

FAO, 1996. Agro-Ecological Zoning Guidelines. Food and Agricultural Organisation, Rome.

Feld, C.K., Martins da Silva, P., Paulo Sousa, J., De Bello, F., Bugter, R., Grandin, U., Hering, D., Lavorel, S., Mountford, O., Pardo, I., Pärtel, M., Römbke, J., Sandin, L., Bruce Jones, K., Harrison, P., 2009. Indicators of biodiversity and ecosystem services: a synthesis across ecosystems and spatial scales. Oikos 118, 1862–1871.

Finney, Denise M., Kaye, Jason P., 2017. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. Journal of Applied Ecology 54, 509–517. https://doi.org/10.1111/1365-2664.12765.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Folke, C., 2006. Resilience: the emergence of a perspective for social–ecological systems analyses. Glob. Environ. Chang. 16, 253–267.

Franzel, S.C., Scherr, S.J., 2002. Trees on the Farm: Assessing the Adoption Potential of Agroforestry Practices in Africa. CABI.

Friedlob, G.T., Plewa Jr., F.J., 1996. Understanding Return on Investment. John Wiley & Sons.

Geher, G., Hall, S., 2014. Straightforward Statistics: Understanding the Tools of Research. Oxford University Press.

Government, K., 1985. Kenya Soil Map, Gateway to Land and Water Information. Kenya Government. http://www.flowman.nl/kiogorokenyasoilsmap.htm.

Hansen, A.W., Christensen, D.L., Larsson, M.W., Eis, J., Christensen, T., Friis, H., Mwaniki, D.L., Kilonzo, B., Boit, M.K., Borch-Johnsen, K., Tetens, I., 2011. Dietary patterns, food and macronutrient intakes among adults in three ethnic groups in rural Kenya. Public Health Nutr. 14, 1671–1679.

Hemmat, A., Aghilinategh, N., Rezainejad, Y., Sadeghi, M., 2010. Long-term impacts of municipal solid waste compost, sewage sludge and farmyard manure application on organic carbon, bulk density and consistency limits of a calcareous soil in central Iran. Soil Tillage Res. 108, 43–50.

Henderson, B., Godde, C., Medina-Hidalgo, D., van Wijk, M., Silvestri, S., Douxchamps, S., Stephenson, E., Power, B., Rigolot, C., Cacho, O., Herrero, M., 2016. Closing system-wide yield gaps to increase food production and mitigate GHGs among mixed crop–livestock smallholders in Sub-Saharan Africa. Agric. Syst. 143, 106–113.

Hernández-Morcillo, M., Plieninger, T., Bieling, C., 2013. An empirical review of cultural ecosystem service indicators. Ecol. Indic. 29, 434–444.

Hoekstra, D.A., 1987. Economics of agroforestry. Agrofor. Syst. 5, 293–300.

Ickowitz, A., Powell, B., Salim, M.A., Sunderland, T.C.H., 2014. Dietary quality and tree cover in Africa. Glob. Environ. Chang. 24, 287–294.

Ifejika Speranza, C., Wiesmann, U., Rist, S., 2014. An indicator framework for assessing livelihood resilience in the context of social–ecological dynamics. Glob. Environ. Chang. 28, 109–119.

Isbell, Forest, Adler, Paul R., Eisenhauer, Nico, Fornara, Dario, Kimmel, Kaitlin, Kremen, Claire, Letourneau, Deborah K., Liebman, Matt, Polley, H. Wayne, Quijas, Sandra, Scherer-Lorenzen, Michael, 2017. Benefits of increasing plant diversity in sustainable agroecosystems. Journal of Ecology 105, 871–879. https://doi.org/10.1038/nature10282.

Jaetzold, R., Schmidt, H., Hornetz, B., Shisanya, C., 1983. Farm Management Handbook of Kenya. Vol. II. Natural conditions and farm management information. Ministry of Agriculture, Kenya. Cooperation with German Agricultural Team of German Agency for Technical Cooperation.

Jahnke, H.E., Delgado, C.L., 1982. Livestock production systems and livestock development in tropical Africa. Am. J. Agric. Econ. 65, 462–463.

Jerneck, A., Olsson, L., 2013. More than trees! Understanding the agroforestry adoption gap in subsistence agriculture: insights from narrative walks in Kenya. J. Rural. Stud. 32, 114–125.

Jim, C.Y., 2006. Formulaic expert method to integrate evaluation and valuation of heritage trees in compact city. Environ. Monit. Assess. 116, 53–80.

Kahane, R., Hodgkin, T., Jaenicke, H., Hoogendoorn, C., Hermann, M., Keatinge, J.D.H., d'Arros Hughes, J., Padulosi, S., Looney, N., 2013. Agrobiodiversity for food security, health and income. Agron. Sustain. Dev. 33, 671–693.

Kearney, S.P., Fonte, S.J., García, E., Siles, P., Chan, K.M.A., Smukler, S.M., 2017. Evaluating ecosystem service trade-offs and synergies from slash-and-mulch agroforestry systems in El Salvador. Ecol. Indic. 105, 264–278.

Kebede, Y., Baudron, F., Bianchi, F.J.J.A., Tittonell, P., 2019. Drivers, farmers' responses and landscape consequences of smallholder farming systems changes in southern Ethiopia. Int. J. Agric. Sustain. 1–18.

Kiboi, M.N., Ngetich, K.F., Diels, J., Mucheru-Muna, M., Mugwe, J., Mugendi, D.N., 2017. Minimum tillage, tied ridging and mulching for better maize yield and yield stability in the Central Highlands of Kenya. Soil Tillage Res. 170, 157–166.

KNBS, 2017. Population distribution by sex, number of households, area and density by county and district. Statistics, K.N.B.o. (Ed.) In: 2009 Population and Housing Census, . https://www.knbs.or.ke/download/population-distribution-by-sex-number-of-households-area-and-density-by-county-and-district/ p. 5.

Kragt, M.E., Robertson, M.J., 2014. Quantifying ecosystem services trade-offs from agricultural practices. Ecol. Econ. 102, 147–157.

Kuyah, S., Öborn, I., Jonsson, M., Dahlin, A.S., Barrios, E., Muthuri, C., Malmer, A., Nyaga, J., Magaju, C., Namirembe, S., Nyberg, Y., Sinclair, F.L., 2016. Trees in agricultural landscapes enhance provision of ecosystem services in sub-Saharan Africa. Int. J. Biodivers. Sci., Ecosyst. Serv. Manag. 12, 255–273.

Lohbeck, M., Winowiecki, L., Aynekulu, E., Okia, C., Vågen, T.G., 2018. Trait-based approaches for guiding the restoration of degraded agricultural landscapes in East Africa. J. Appl. Ecol. 55, 59–68.

MA, 2005. Millenium ecosystem assessment- synthesis report. In: Sarukhan, J., Whyte, A. (Eds.), Ecosystems and Human Well-being.

Mehlich, A., 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15, 1409–1416.

Mekoya, A., Oosting, S.J., Fernandez-Rivera, S., Van der Zijpp, A.J., 2008. Farmers' perceptions about exotic multipurpose fodder trees and constraints to their adoption. Agrofor. Syst. 73, 141–153.

Mutabazi, K.D., Amjath-Babu, T.S., Sieber, S., 2015. Influence of livelihood resources on adaptive strategies to enhance climatic resilience of farm households in Morogoro, Tanzania: an indicator-based analysis. Reg. Environ. Chang. 15, 1259–1268.

Mutoko, M.C., Hein, L., Shisanya, C.A., 2014. Farm diversity, resource use efficiency and sustainable land management in the western highlands of Kenya. J. Rural. Stud. 36, 108–120.

Mutoko, M.C., Hein, L., Shisanya, C.A., 2015. Tropical forest conservation versus conversion trade-offs: insights from analysis of ecosystem services provided by Kakamega rainforest in Kenya. Ecosystem Serv. 14, 1–11.

Muyanga, M., Jayne, T.S., 2014. Effects of rising rural population density on smallholder agriculture in Kenya. Food Policy 48, 98–113.

Nguyen, H.Q., 2017. Analyzing the economies of crop diversification in rural Vietnam using an input distance function. Agric. Syst. 153, 148–156.

Nicholson, C.F., Thornton, P.K., Muinga, R.W., 2004. Household-level impacts of dairy cow ownership in coastal Kenya. J. Agric. Econ. 55, 175–195.

Nowak, B., Nesme, T., David, C., Pellerin, S., 2015. Nutrient recycling in organic farming is related to diversity in farm types at the local level. Agric. Ecosyst. Environ. 204, 17–26.

Nyaga, J., Barrios, E., Muthuri, C.W., Öborn, I., Matiru, V., Sinclair, F.L., 2015. Evaluating factors influencing heterogeneity in agroforestry adoption and practices within smallholder farms in Rift Valley, Kenya. Agric. Ecosyst. Environ. 212, 106–118.

Nyaga, J., Muthuri, C., Barrios, E., Öborn, I., Sinclair, F., 2017. Enhancing maize productivity in agroforestry systems through managing competition: lessons from smallholders' farms, Rift valley, Kenya. Agrofor. Syst. 1–16.

Otieno, S., Jayne, T., Muyanga, M., 2015. Effect of soil pH on accumulation of native selenium by Maize (Zea mays var. L) grains grown in Uasin Gishu, Trans-Nzoia Kakamega and Kisii counties in Kenya, Global Advances in Selenium Research from Theory to Application. In: Proceedings of the 4th International Conference on Selenium in the Environment and Human Health 2015. CRC Press, pp. 117.

Ouattara, K., Ouattara, B., Nyberg, G., Sédogo, M.P., Malmer, A., 2007. Ploughing frequency and compost application effects on soil infiltrability in a cotton–maize (Gossypium hirsutum–Zea mays L.) rotation system on a Ferric Luvisol and a Ferric Lixisol in Burkina Faso. Soil Tillage Res. 95, 288–297.

Pagliai, M., Vignozzi, N., Pellegrini, S., 2004. Soil structure and the effect of management practices. Soil Tillage Res. 79, 131–143.

Quandt, A., Neufeldt, H., McCabe, J.T., 2018. Building livelihood resilience: what role does agroforestry play? Clim. Dev. 1–16.

R Core Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.r-project.org/index.html.

Rao, M.R., Nair, P.K.R., Ong, C.K., 1997. Biophysical interactions in tropical agroforestry systems. Agrofor. Syst. 38, 3–50.

Reppin, S., Kuyah, S., de Neergaard, A., Oelofse, M., Rosenstock, T.S., 2019. Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. Agrofor. Syst. 94, 203–220.

Rönnbäck, P., Crona, B., Ingwall, L., 2007. The return of ecosystem goods and services in replanted mangrove forests: perspectives from local communities in Kenya. Environ. Conserv. 34, 313–324.

Roy, P., 1955. The sacred cow in India. Rural. Sociol. 20, 8.

Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. The University of Illinois Press, Urbana, pp. 117.

Sheahan, M., Ariga, J., Jayne, T.S., 2016. Modeling the effects of input market reforms on fertiliser demand and maize production: a case study from Kenya. J. Agric. Econ. 67, 420–447.

Sibhatu, K.T., Krishna, V.V., Qaim, M., 2015. Production diversity and dietary diversity in smallholder farm households. Proc. Natl. Acad. Sci. 112, 10657–10662.

Soini, E., 2007. Land Tenure and Land Management in the Districts around Mount Elgon: An Assessment Presented to Mount Elgon Regional Ecosystem Conservation Programme (MERECP). (ICRAF Working Paper).

Stephens, E.C., Nicholson, C.F., Brown, D.R., Parsons, D., Barrett, C.B., Lehmann, J., Mbugua, D., Ngoze, S., Pell, A.N., Riha, S.J., 2012. Modeling the impact of natural resource-based poverty traps on food security in Kenya: the Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model. Food Secur. 4, 423–439.

Tittonell, P., Vanlauwe, B., Misiko, M., Giller, K.E., 2011. Targeting Resources within Diverse, Heterogeneous and Dynamic Farming Systems: Towards a 'Uniquely African Green Revolution'. Springer Netherlands, Dordrecht, pp. 747–758.

Tittonell, P., Gérard, B., Erenstein, O., 2015. Tradeoffs around crop residue biomass in smallholder crop-livestock systems – what's next? Agric. Syst. 134, 119–128.

Turmel, M.-S., Speratti, A., Baudron, F., Verhulst, N., Govaerts, B., 2015. Crop residue management and soil health: a systems analysis. Agric. Syst. 134, 6–16.

USGS, 2018. Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, US Geological Survey. US Geological Survey. https://lta.cr.usgs.gov/SRTM1Arc p. Elevation data.

van der Ploeg, J.D., Laurent, C., Blondeau, F., Bonnafous, P., 2009. Farm diversity, classification schemes and multifunctionality. J. Environ. Manag. 90, S124–S131.

Vandermeer, J., van Noordwijk, M., Anderson, J., Ong, C., Perfecto, I., 1998. Global change and multi-species agroecosystems: concepts and issues. Agric. Ecosyst. Environ. 67, 1–22.

Welham, S.J., Gezan, S.A., Clark, S.J., Mead, A., 2014. Statistical Methods in Biology: Design and Analysis of Experiments and Regression. Chapman and Hall/CRC.

Worldbank, 2019. How is the Global Poverty Line Derived? How is It Different from National Poverty Lines? https://datahelpdesk.worldbank.org/knowledgebase/articles/193310-how-is-the-global-poverty-line-derived-how-is-it.