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Nuts about trees? – Smallholders' diverse agroforestry systems and their relationship to groundnut yields in the Senegalese Groundnut Basin

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Abstract

In the Sahel region, agroforestry potentially increases crop yields, alongside restoring and retaining soils. Nonetheless, little is known about how diverse agroforestry systems perform across actual agricultural systems of smallholders in the region. We therefore investigate how smallholders' different agroforestry systems in the Senegalese Groundnut Basin relate to groundnut yields. We distinguish agroforestry systems by (a) tree quantity per hectare, (b) tree species diversity and (c) quantities per hectare of the most prevalent tree species in our data. Using data of 492 groundnut farmers, collected in the Groundnut Basin from December 2022 to January 2023, we estimate log-linearized Cobb-Douglas-production functions through ordinary least squares regression. 53 tree species were reported by 93.8% of smallholders. We identify *Faidherbia albida*, *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa*, and *Ziziphus mauritiana* as most prevalent species. Our results indicate that groundnut yields initially increase with tree quantity and species diversity. However, at too many trees per hectare the competition between trees and crops for space and nutrients seems to outweigh the benefits. *Faidherbia albida* trees are beneficial for groundnut yield outcomes only at a higher number of these trees. For the species *Cordyla pinnata* and *Anogeissus leiocarpa*, additional trees initially lead to increases in groundnut yields. The tree species *Ziziphus mauritiana* and *Adansonia digitata* appear to have no association with groundnut yields. We find a remaining potential of increasing tree cover or tree species diversity and introducing or expanding certain tree species in established agroforestry systems to enhance synergies between land restoration and groundnut productivity.

Keywords: Agroforestry, Tree quantity, Tree species diversity, Prevalent tree species, Groundnut yields, Smallholders, Senegalese Groundnut Basin

JEL codes: Q12, Q19, Q23

1. Introduction

In the African Sahel region, aggravating climate change effects such as increasing temperatures, decreasing precipitation rates and the increasing occurrence of extreme weather events lead to the degradation of arable soils (Yobom 2020; Mbow et al. 2021). These trends threaten the livelihoods of the mainly smallholding farmers of the region. In the Sudano-Sahelian climate of the region, the agricultural landscape is characterized by sedentary small-scale farmers producing groundnuts as a cash crop with millet, maize, and/or sorghum as food crops. In this context, agroforestry is widely promoted as a land restoration practice for farmers to mitigate and adapt to climate change effects.

In addition to its potential to restore and maintain arable soils (Muchane et al. 2020), the adoption and management of agroforestry systems also have the potential to increase crop yields (Mbow et al. 2020). Different tree species in agroforestry systems can, for instance, affect soil fertility and yield outcomes by increasing soil organic matter through leaf litter or sequestering carbon in soils (Rollan et al. 2018; Sambou et al. 2024a) and/or symbiotically interacting with soil bacteria that generate nitrogen (Fall et al. 2012). Tree species that form such a symbiotic relationship with bacteria in the soils are called nitrogen-fixing tree species (Rosenstock et al. 2014). With their root systems, trees can further prevent soil erosion through wind or water, and stabilize river banks. Their canopy provides shade for crops and reduces surface temperatures and evapotranspiration (Shi et al. 2018; Bado et al. 2021). Furthermore, agroforestry systems have been found to increase soil water-holding capacity (Chirwa et al. 2007). Agroforestry systems that incorporate diverse tree species are also known to mitigate pests and diseases (Soti et al. 2019; Sow et al. 2020) and exhibit greater resilience to weather shocks, as certain tree species may be more tolerant to heat stress or water scarcity than others (Orwa et al. 2009; Syampungani et al. 2010). However, if trees grow too densely on agricultural land, their competition with crops for light, water and soil nutrients might outweigh their benefits, leading to a reduction in yields (Neya et al. 2019).

In their structured literature reviews, Kuyah et al. (2019) and Beillouin et al. (2021) find that in past studies, agroforestry adoption in general is positively associated with crop yields compared to not practicing agroforestry. For instance, Coulibaly et al. (2017), Amadu et al. (2020a) and Amadu et al. (2020b), show that agroforestry adoption positively relates to maize yields in Malawi. Kassie (2016) equally shows a positive relationship between agroforestry adoption and maize yields in Ethiopia. While these studies focus on adoption and non-adoption of agroforestry and its relationships with crop yields, they are lacking more detailed information on how tree quantity, tree species diversity and the prevalence of specific tree species might relate to crop yields in agroforestry systems. Agroforestry systems can vary widely in their composition of tree species, crops, and management practices (World Agroforestry 2024). Thus, a binary distinction between practitioners and non-practitioners does not adequately capture these differences between agroforestry systems and the potential differences in their interrelations with cropping systems (Amare and Darr 2020).

Past experimental field studies in the context of the Sahel region, as structurally reviewed by e.g. Sinare et al. (2015), demonstrate in more detail, that specific tree species in agroforestry systems potentially increase the yields of groundnuts or millet, while others might have detrimental effects on crop yields. Adinya et al. (2010), for instance, find a positive association of agroforestry systems with trees of the species *Leuceana leucocephala* and groundnut yields in Nigeria. In the context of the Senegalese Groundnut Basin, Louppe et al. (1996) detect lower groundnut yields in vicinity of *Faidherbia albida* trees compared to control areas, while Roupsard et al. (2020) find increased millet yields in agroforestry systems with *Faidherbia albida* trees. Bright et al. (2021) find increased millet yields in a groundnut and millet agroforestry system with trees of the species *Guiera senegalensis.* Bright et al. (2017) also find a positive association between the presence of the shrub *Piliostigma reticulatum* on experimental fields in Senegal and yields of groundnuts and millet. In another experimental agroforestry system in Senegal however, Goudiaby et al. (2020) find a statistically significant decrease of groundnut yields if intercropped with trees of the species *Eucalyptus camaldulensis* compared to control fields. Fadl and Sheikh (2010) also find lower yields of groundnut, sesame and roselle in an agroforestry system with *Acacia senegal* trees as compared to the control fields in an experiment situated in Sudan. While such a research design provides in depth insights into the relationships between agroforestry practices and yields over time, they are limited to the specific experimental sites and agroforestry systems, and do not reflect real-life scenarios of smallholders' agricultural systems and their management. As agroforestry systems have been found to be particularly heterogeneous in the Sudano-Sahelian climate zone (Ndao et al. 2021), evidence derived from experimental fields to those systems is difficult to generalize.

Recent studies by Leroux et al. (2020, 2022a, 2022b) use remote sensing to map agroforestry parklands around smallholder farms in up to two study sites in the Senegalese Groundnut Basin. These studies relate tree density (Leroux et al. 2020; Leroux et al. 2022b) and tree species richness indicators (Leroux et al. 2022b) to millet yields and examine the role of *Faidherbia albida* parklands in providing ecosystem services in their vicinity (Leroux et al. 2022a). While these studies provide valuable insights into how the landscape structure of agroforestry parklands surrounding smallholders' fields in the study sites relates to millet productivity, there is limited knowledge about the relationship between tree quantity, tree species diversity, and specific tree species in smallholders' agroforestry systems and groundnut yields.

To address this gap in the literature, we explore how diverse agroforestry systems relate to groundnut yields in actual agricultural systems of smallholder groundnut farmers in the Senegalese Groundnut Basin. Specifically, we examine how (a) the total quantity of trees per hectare, (b) the total tree species diversity within the agroforestry system, and (c) the quantities per hectare of the most prevalent tree species in our data relate to smallholder's groundnut yield per hectare. We expect that a certain quantity of trees per hectare in an agroforestry system is necessary to achieve beneficial outcomes for crop yields but a certain quantity should not be exceeded to ensure that the competition between trees and crops does not outweigh those beneficial outcomes. We further expect to observe higher groundnut yields in an agroforestry system with higher tree species diversity. Third, we expect that different tree species relate differently to soil fertility and yield outcomes due to their individual species-specific characteristics.

Learning how tree quantity, tree species diversity and quantities of specific tree species relate to groundnut yields in actual farming systems of smallholders in the Sudano-Sahelian climate, provides detailed information for governmental bodies, non-governmental organizations, and farmer associations as well as smallholder farmers to design and manage agroforestry systems to achieve increased yields. In addition to supporting the promotion of agroforestry adoption among non-practitioners, we want to understand how existing agroforestry systems could be modified to enhance synergies between land restoration and groundnut yields.

2. Materials

2.1 Study area

Our study is located in the Senegalese Groundnut Basin, which lies within the Sudano-Sahelian climate zone of the Sahel region. The Sudano-Sahelian climate is characterized by annual precipitation rates of 500 mm to 900 mm (FAO 2002) and stretches along the Sahelian climate zone from West to East Africa, bordering the Sahara Desert to the south (Yobom and Le Gallo 2021). The regions' economy relies on agricultural production of the mainly smallholding farmers (Baoua et al. 2021; FAO 2024), with groundnuts being the main export good (Georges et al. 2016; Bakoye et al. 2019; OEC 2021). Next to groundnuts, smallholders in the Sudano-Sahelian climate zone mainly produce millet and maize (Georges et al. 2016; Yobom and Le Gallo 2021). Agricultural production is mainly rainfed, and the agricultural season thus aligns with the rainy season from July to October (Cotillon et al. 2021). The Groundnut Basin is the main agricultural region of Senegal, making up about 70% of the country's arable land (Faye and Du 2021). In recent decades, the effects of climate change pose a severe threat to the agricultural production systems of smallholders in the Sahel region (Mbow et al. 2020). While managing trees on agricultural land is a traditional practice in this region (Parton et al. 2004; Cotillon et al. 2021), agroforestry has been promoted in recent decades as one of the most promising natural regeneration practices in this context (Diallo et al. 2020). Groundnut, millet, and maize cropping systems are suitable for the integration of agroforestry (Diallo et al. 2020). Predominant agroforestry tree species in the Senegalese Groundnut Basin are *Faidherbia albida* and *Cordyla pinnata* (Sambou et al. 2024b), with *Faidherbia albida* primarily found in the northern regions and *Cordyla pinnata* mainly located in the southern parts of the Groundnut Basin (Leroux et al. 2022b).

2.2. Data collection and cleaning

From December 2022 to January 2023, we collected data from 606 smallholder farmer households in the Senegalese Groundnut Basin. Our data collection focused on three of the five regions within the Groundnut Basin—Fatick, Kaolack, and Kaffrine—since these regions lie within the Sudano-Sahelian climate zone. For the selection of households, we followed a multi-stage random sampling approach. For each of the three study regions, we randomly selected five communes and within each commune, we chose two villages at random.

The team of 11 enumerators conducted interviews in the Senegalese language, Wolof, at the respondents' homesteads, recording the responses in French. Each enumerator conducted two interviews per village. Depending on the availability of enumerators, we thus selected up to 22 households from each village to participate in the household survey. Respondents provided information on tree species and quantities within their agroforestry systems, crop land sizes (in hectare), and groundnut yields (in kg) for the 2022 agricultural season. Our indicators for groundnut yield per hectare, total tree quantity per hectare, tree species diversity and the quantities per hectare of the five most prevalent tree species have been computed based on this information. The English translation of the survey questions relevant to our study are provided in Appendix A. For our research, we focus on a subsample of smallholders who grow groundnuts and indicated their output of groundnuts, in kilograms (kgs), produced during the 2022 agricultural season. Smallholders who were uncertain of the quantities of groundnuts they produced within that season, were excluded from our analysis. Therefore, our sample size reduced to 492 smallholders. We further replaced values above the 99th percentile in continuous variables with the 99th percentile value, to account for extreme values driving our analysis. This imputation approach is commonly applied to handle outliers (Frey 2018; Sullivan et al. 2021) and ensures that we are more likely to underestimate the economic and statistical relationships in our estimations rather than overestimating them. For the same reason and based on e.g. Yuan (2011), we replaced "unknown" responses to our questions on input and tree quantities with the smallest observed value.

2.3. Most prevalent tree species in our data

Within our sample, 93.8% of the respondents have trees of different species in their cropping systems. Managing trees on agricultural land is a traditional practice, dating back centuries (Parton et al. 2004), and only a small margin of our respondents do not report any trees. Following Branca et al. (2021), we thus assume that yield outcomes of agroforestry practices do not depend on agroforestry adoption decisions being influenced by socio-economic and structural characteristics of households, or skills of smallholders to optimize resources. We therefore do not specifically control for the endogeneity of agroforestry adoption decisions in this study. However, to mitigate potential endogeneity through recent adoption and tree species selection decisions, we exclude trees that have reportedly been planted within three years prior to our data collection. This decision is further motivated by the fact that trees in agroforestry systems typically realize their benefits only after three years of adoption (Mercer 2004; Coulibaly et al. 2017) and need special care and protection from livestock and fire for the first three years (Kalinganire 2022).

For our analysis, we focus on three agroforestry measures, (a) tree quantity per hectare, (b) tree species diversity, and (c) the quantities per hectare of the most prevalent tree species in our data. Tree quantity per hectare is a ratio of total number of trees to the hectares of land. Tree species diversity reflects the total number of different tree species reported by respondents. The most prevalent tree species in our data are those reported by at least 10% of smallholders in our sample. Figure 1 displays the tree species reported by smallholders, highlighting the most prevalent species in our sample. The frequent reporting of *Faidherbia albida*, *Adansonia digitata,* *Anogeissus leiocarpa* and *Ziziphus mauritiana* aligns with the studies by Leroux et al. (2020) and Ndao et al. (2022), who identified these species as dominant in agroforestry parklands in the northern Groundnut Basin.

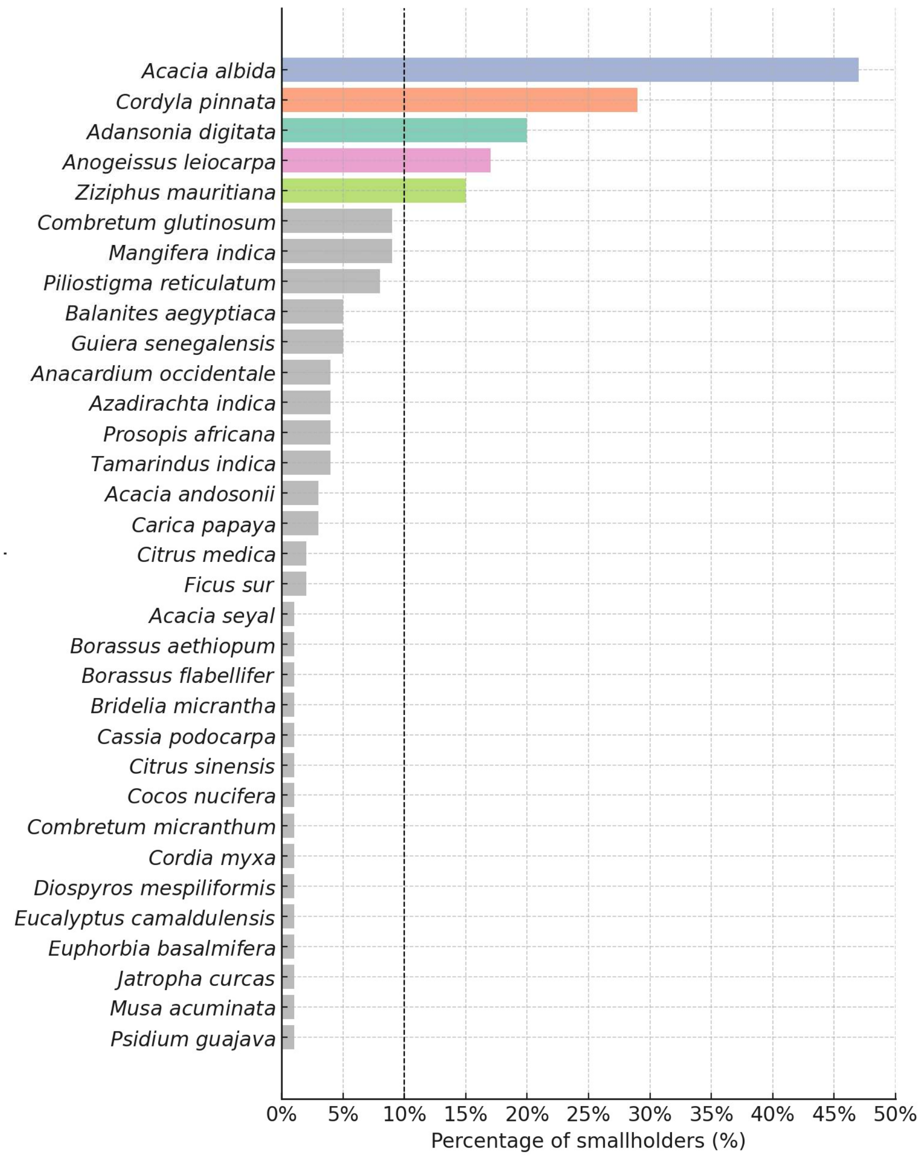

Figure 1. Prevalence of tree species on groundnut farms reported by at least 1% of smallholders.

Almost half of our sampled households reported having trees of the species *Faidherbia albida*. Due to its reverse phenology, *Faidherbia albida* trees increase soil fertility by adding biomass to the soil during the rainy season in the Sudano-Sahelian climate zone (Mokgolodi et al. 2011). Furthermore, soils under the canopies of *Faidherbia albida* trees have shown higher levels of organic carbon and total nitrogen compared to soils outside the canopies (Stephen et al. 2020). While *Faidherbia albida* trees fix nitrogen in soils, the nitrogen-fixing capacity of this species is comparatively low. In a field experiment, Ndoye et al. (1995) for instance compared the nitrogen-fixing capacity of different Acacia species and found relatively low levels of nitrogen-fixation for *Faidherbia albida* trees compared to other species such as *Acacia seyal* and *Acacia senegal*. However, *Faidherbia albida* trees can adapt to different climatic conditions and soil types (Sambou et al. 2024b). While multiple studies, such as Roupsard et al. (2020), or Leroux et al. (2022a, 2022b) find a beneficial relationship between *Faidherbia albida* parklands and millet productivity, scarce evidence, such as the study of Louppe et al. (1996), suggests a detrimental relationship between this tree species and groundnut yields. Next to *Faidherbia albida, Codyla pinnata* is one of the main agroforestry tree species in Senegal (Sambou et al. 2024b). This tree species is mainly known for its nitrogen-fixing capacities (Sambou et al. 2024b). Being a deciduous tree species, *Cordyla pinnata* trees shed their leaves and contribute to soil fertility through increased biomass. Unlike *Faidherbia albida* trees however, *Cordyla pinnata* trees do not shed their leaves at the beginning of the agricultural season but during the dry season (Samba 2001). *Adansonia digitata*, commonly known as Baobab, is one of the most important agroforestry tree species across the Sahel region, primarily providing food, fodder, and medicine (Kalinganire 2022). *Adansonia digitata* also holds substantial cultural importance and plays an essential role in various cultural ceremonies (Meinhold and Darr 2021). However, *Adansonia digitata* does not have any specific soil fertility-enhancing characteristics (Kyndt et al. 2009; Meinhold and Darr 2021). Also *Anogeissus leiocarpa* is a deciduous tree species that sheds its leaves during the dry season, thereby contributing to soil organic matter and increasing soil fertility (Seghieri et al. 2012). While *Anogeissus leiocarpa* is not a nitrogen-fixing species, Mesele and Huising (2024) find increased nitrogen and carbon content in the soils under its stand in the Opara forest reserve in Nigeria. *Ziziphus mauritiana* is an evergreen species (Orwa et al. 2009; Seghieri et al. 2012). The species is non-native to Senegal (Orwa et al. 2009) but rather common in our respondents agroforestry systems. As this tree species is very heat and drought resistant, it is grown to protect soils and crops from heat and erosion (Orwa et al. 2009). In their experimental study in Niger, Bado et al. (2021) show a positive association of *Ziziphus mauritiana* in millet and cowpea agroforestry systems with organic carbon and nitrogen levels in the soil, even though *Ziziphus mauritiana* is not a nitrogen-fixing tree species (Palejkar et al. 2012).

3. Econometric analysis

To economically analyse the relationship between our agroforestry indicators—(a) tree quantity per hectare, (b) tree species diversity, and (c) the quantities of the five most prevalent tree species in our data—and crop outputs, production analysis provides statistical means to account for agricultural inputs influencing outputs, while focusing on our indicators. In past studies, the relationship between adoption of climate smart agricultural practices, particularly agroforestry, and crop yields has been analyzed using stochastic frontier frameworks and employing Translog or Cobb-Douglas production functions. Shah et al. (2022), for instance, apply a stochastic frontier model for the Cobb-Douglas production function to analyze land productivity and technical efficiency of small-scale farms in Pakistan by comparing agroforestry adopters and non-adopters. Branca et al. (2021) asses the effects of climate-smart agricultural practices on maize yields in Malawi employing a log-linear Cobb-Douglas production function. They then estimate the parameters employing an ordinary least squares (OLS) regression model. For the same research aim, Amadu et al (2020a) use a Translog production function as a conceptual framework and employ an endogenous switching regression model.

Our research aims to analyze how actual and diverse agroforestry practices of smallholders affect agricultural productivity of groundnut farmers in the Senegalese Groundnut Basin. In production economics, productivity describes the output generated per unit of input, while technical efficiency investigates how well producers use their inputs to produce the highest level of output given the technology (Coelli 2005). In this study, we are not investigating how agroforestry relates to the technical efficiency of smallholders, as the main pathways by which agroforestry systems influence crop yields do not strongly depend on smallholders' technical efficiency once the trees are planted (Rosenstock et al. 2014; Bado et al. 2021; Sambou et al. 2024a). Therefore, we base our analysis on the studies of Teuscher et al. (2015), Amadu et al. (2020a), and Branca et al. (2021) and estimate log-linearized Cobb-Douglas-production functions using OLS estimation.

To answer our research questions, we split our analysis into the following two distinct regression models. First, we focus on the relationships of (a) total tree quantity per hectare and (b) tree species diversity in the agroforestry system, as well as the interaction between these factors, with groundnut yield per hectare. Therefore, we specify the following equation:

$$lnY_i = ß_0 + \sum_{k=1}^{K} ß_k lnX_{ik} + \gamma_1 Z_i + \gamma_2 AQ_i + \gamma_3 {AQ_i}^2 + \gamma_4 AD_i + \gamma_5 {AD_i}^2 + \gamma_6 AD_i AQ_i + \gamma_7 C + \varepsilon_i \qquad (1)$$

Second, we use equation (2) to estimate the relationship between groundnut yields per hectare and (c) the quantities per hectare of the five most prevalent tree species observed in our sample, that are *Faidherbia albida*, *Cordyla pinnata, Adansonia digitata, Anogeissus leiocarpa,* and *Ziziphus mauritiana:*

$$lnY_i = ß_0 + \sum_{k=1}^{K} ß_k lnX_{ik} + \gamma_1 Z_i + \gamma_2 AS_i^{\pi} + \gamma_3 (AS_i^{\pi})^2 + \gamma_4 C + \varepsilon_i \qquad (2)$$

In both models, Y_i represents groundnut yield, in kg per hectare, for household i. X_i is a vector of k inputs and Z_i is a vector of socio-demographic variables. ε_i denotes the stochastic error term in our models. We selected the input and socio-demographic control variables to include in our model (see Table 1) based on the studies of Teuscher et al. (2015), Amadu et al. (2020a), Branca et al. (2021) and Shah et al. (2022). In the first model, AQ_i is an indicator for (a) the quantity of agroforestry trees per hectare, and AD_i represents (b) tree species diversity, i.e. the number of different tree species growing on the land of household i. In the second model, AS_i^{π} represents (c) the quantity per hectare of the most prevalent tree species, denoted by π, in our data: *Faidherbia albida*, *Cordyla pinnata, Adansonia digitata, Anogeissus leiocarpa,* and *Ziziphus mauritiana.* The squared terms of our agroforestry indicators serve to derive information on a potential saturation in the relationship between total tree quantity per hectare, tree species diversity and tree quantities per hectare of the tree species and groundnut yields. C represents the commune level fixed effects, which are included in the model to account for spatial differences in climate, environmental and institutional factors that might affect crop yield and growth of specific tree species simultaneously (Kuyah et al. 2019; Sambou et al. 2024b). The outcome variable and the continuous input variables were log-transformed employing the natural logarithm. Following Battese (1997), we added a small constant, in our case 0.01, to all zero input values before we log-transformed the variables. The other variables were included in the model without transformation.

To interpret our regression results, we estimate the marginal effect for each of our indicators at a one-unit increase from their rounded sample mean. When estimating the marginal effect of our total tree quantity and tree species diversity variables, we hold respective interaction variable constant at their rounded sample mean. Since our regression models estimate the log-normalized groundnut yield outcomes and include squared terms of our agroforestry indicators, the marginal effects are not constant across the regressions. Therefore, we estimate the percentage changes δ in groundnut yields associated with a one-unit increase in each indicator m from their rounded sample mean using the following equation:

$$\delta_m = \left(exp.^{marginal\ product_m} - 1\right) \cdot 100\% \tag{3}$$

Based on this, we derive information on the marginal percentage increase or decrease associated with an additional (a) tree per hectare in general, (b) tree species, or (c) tree per hectare of the species *Faidherbia albida*, *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa* or *Ziziphus mauritiana* relative to their respective sample mean.

4. Results and discussion

4.1. Descriptive statistics and variables

We recorded a total of 53 different tree species growing across the agroforestry systems of our respondents. Next to the five most common tree species in our sample, *Faidherbia albida*, *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa* and *Ziziphus mauritiana*, about 9% of the smallholders in our sample reported trees of the species *Mangifera indica* and *Combretum micranthum*, respectively. About 8% of the respondents reported trees of the species *Piliostigma reticulatum* and about 5% respectively reported trees of the species *Guiera senegalensis* or *Balanites aegyptiaca* growing on their agricultural land.

Table 1 shows the descriptive statistics of our groundnut yield outcome variable, our agroforestry indicators, control variables for input use and household characteristics, as well as the commune dummies used as fixed effects in our regressions. We recorded a wide variety of agroforestry systems on groundnut farms in the Senegalese Groundnut Basin. These systems included up to 50 trees per hectare of up to 7 different tree species. Specifically, smallholders reported up to 30 trees of *Faidherbia albida* and up to 14 *Cordyla pinnata* trees per hectare. The maximum number of *Adansonia digitata* trees in these agroforestry systems is 3 trees per hectare. Smallholders further reported up to 12 trees per hectare of the species *Anogeissus leiocarpa.* For *Ziziphus mauritiana*, the highest reported number was 2.5 trees per hectare. In these diverse systems, smallholders produced an average of 835.2 kg groundnuts per hectare during the 2022 agricultural season.

Table 1. Descriptive statistics of variables included in our analysis.

Variable	Description	Mean	SD	Min	Max
Outcome variable					
Groundnut yield	Groundnut yield of the 2022 agricultural season in kg per hectare	835.20	1002.15	33.33	5000.00
Agroforestry variables					
Tree quantity	Number of trees per hectare (only trees older than three years)	2.50	4.56	0.00	50.00
Tree species diversity	Number of different tree species on agricultural land (only trees older than three years)	2.25	1.33	0.00	7.00
Faidherbia albida	Number of trees of species *Faidherbia albida* per hectare (only trees older than three years)	0.63	1.88	0.00	30.00
Cordyla pinnata	Number of trees of species *Adansonia digitata* per hectare (only trees older than three years)	0.47	1.48	0.00	14.00
Adansonia digitata	Number of trees of species *Anogeissus leiocarpa* per hectare (only trees older than three years)	0.11	0.34	0.00	3.00
Anogeissus leiocarpa	Number of trees of species *Anogeissus leiocarpa* per hectare (only trees older than three years)	0.22	0.91	0.00	12.00
Ziziphus mauritiana	Number of trees of species *Ziziphus mauritiana* per hectare (only trees older than three years)	0.10	0.31	0.00	2.50
Production inputs					
Family labour	Number of household members between the ages of 18 and 60	7.76	4.74	0.00	27.00
Hired labour	Dummy for having hired agricultural labourers (1=yes)	0.30			
Improved seeds	Dummy for having used improved seeds (1=yes)	0.05			
Livestock labour power	Dummy of having livestock to work on agricultural fields (1=yes)	0.97			
Organic fertilizer	Dummy of using organic fertilizer (1=yes)	0.86			
Pesticides	Amount of pesticides applied in litres per hectare	3.80	16.20	0.00	200.00
Household characteristics					
Age of household head	Age of household head in years	51.35	14.09	18.00	94.00
Female household head	Female headed household (1=yes)	0.17			
Primary school	Dummy for household head having finished primary school education (1=yes)	0.12			
Secondary school	Dummy for household head having finished secondary school education (1=yes)	0.05			
Commune Dummies					
Diagane Barka	Dummy for household residing in the commune of Diagane Barka (1=yes)	0.08			
Dianké Souf	Dummy for household residing in the commune of Dianké Souf (1=yes)	0.08			
Diokoul	Dummy for household residing in the commune of Diokoul (1=yes)	0.05			
Diossong	Dummy for household residing in the commune of Diossong (1=yes)	0.07			
Fimla	Dummy for household residing in the commune of Fimla (1=yes)	0.06			
Kahi	Dummy for household residing in the commune of Kahi (1=yes)	0.06			
Keur Maba	Dummy for household residing in the commune of Keur Maba (1=yes)	0.08			
Keur Mboucki	Dummy for household residing in the commune of Keur Mboucki (1=yes)	0.06			
Mbadakhoune	Dummy for household residing in the commune of Mbadakhoune (1=yes)	0.05			
Ndiébel	Dummy for household residing in the commune of Ndiébel (1=yes)	0.07			
Nguelou	Dummy for household residing in the commune of Nguelou (1=yes)	0.08			
Ouadiour	Dummy for household residing in the commune of Ouadiour (1=yes)	0.07			

Paos Koto	Dummy for household residing in the commune of Paos Koto (1=yes)	0.07
Passi	Dummy for household residing in the commune of Passi (1=yes)	0.06
Taiba Niassene	Dummy for household residing in the commune of Taiba Niassene (1=yes)	0.08
Observations		492

4.2. Econometric results

Table 2 shows the results of the OLS regression analyses, first, including the variables for (a) tree quantity per hectare and (b) tree species diversity, and second, (c) the tree quantities per hectare of the tree species *Faidherbia albida*, *Cordyla pinnata*, *Adansonia digitata, Anogeissus leiocarpa* and *Ziziphus mauritiana*. To ground our study in existing literature that examines binary agroforestry adoption and its impact on crop yield outcomes, we also ran our regression model using a binary agroforestry adoption indicator. The results are reported in Appendix B and are consistent with past studies, such as those of Coulibaly et al. (2017), Amadu et al. (2020a), Amadu (2020b), or Shah (2022), showing a positive association of agroforestry adoption and crop yields.

Table 2. OLS estimates for Cobb-Douglas production function parameters on groundnut yield per hectare (ln).

VARIABLES	Coefficient	95 % Confidence interval	Coefficient	95 % Confidence interval
Agroforestry variables				
Tree quantity	0.017	-0.034 0.067		
Tree quantity squared	-0.001	-0.002 0.000		
Tree species diversity	0.262	0.027 0.497		
Tree species diversity squared	-0.036	-0.077 0.005		
Tree quantity x tree diversity	0.001	-0.010 0.011		
Faidherbia albida			-0.026	-0.122 0.071
Faidherbia albida squared			0.001	-0.002 0.005
Cordyla pinnata			0.130	-0.010 0.271
Cordyla pinnata squared			-0.016	-0.028 -0.004
Adansonia digitata			-0.149	-0.746 0.448
Adansonia digitata squared			0.016	-0.231 0.262
Anogeissus leiocarpa			0.103	-0.120 0.326
Anogeissus leiocarpa squared			-0.004	-0.027 0.019
Ziziphus mauritiana			0.238	-0.412 0.889
Ziziphus mauritiana squared			-0.107	-0.425 0.211
Production inputs				
Ln Family labour	0.063	-0.094 0.220	0.103	-0.054 0.260
Hired labour	0.076	-0.140 0.292	0.118	-0.099 0.336
Improved seeds	0.228	-0.231 0.687	0.244	-0.232 0.720
Livestock labour power	0.033	-0.360 0.426	0.019	-0.371 0.409
Organic fertilizer	0.282	-0.029 0.593	0.434	0.131 0.737
Ln Pesticides (liter/hectare)	-0.075	-0.119 -0.030	-0.068	-0.112 -0.023
Household characteristics				
Age of household head	-0.009	-0.017 -0.002	-0.010	-0.018 -0.003
Female household head	-0.205	-0.467 0.058	-0.225	-0.496 0.046
Primary school	0.171	-0.157 0.500	0.152	-0.185 0.489
Secondary school	0.236	-0.185 0.657	0.190	-0.229 0.610
R2 adjusted	0.242		0.225	
Observations	492		492	
Robust standard errors; Intercept and commune-level fixed effects are included in the models but not reported for brevity				

For our control variables, the regression results show that smallholders utilizing organic fertilizers such as manure, compost, or crop residues on their groundnut fields obtained higher groundnut yields in the 2022 agricultural season. On the contrary, a higher application of pesticides on fields relates negatively to groundnut yields. This might be related to pesticide use being correlated with smallholders experiencing pest infestations that adversely affect yields, which is a relationship shown by e.g. Asare-Nuamah (2022). Family labour power, hiring labour and animal labour power in form of having at least one cow, horse or donkey for agricultural work, relate positively to groundnut yields. Additionally, the utilization of improved seeds relates to slightly higher groundnut yield outcomes. We also observe that the household head being female and a higher age of the household head are negatively related to groundnut yields, whereas having obtained primary and secondary school education is positively associated with groundnut yields. The generally positive relationships of agricultural input variables and household characteristics with groundnut yields align with previous crop productivity analyses, such as those by Teuscher et al. (2015), Amadu et al. (2020a), or Branca et al. (2021).

4.2.1. Tree quantity and tree species diversity

In our sample, tree quantity relates rather positively to groundnut yields. Our results suggest an initial percentage increase in groundnut yields for additional trees per hectare of agricultural land, irrespective of the tree species. The coefficient of the squared term of tree quantities suggests a tipping point at which the initially positive association of tree quantity per hectare and groundnut yields reverses. When increasing the rounded sample mean of 3 trees per hectare by an additional tree while holding other factors constant, we would expect a 1.11% increase in groundnut yields (Table 3). This shows the remaining potential to increase tree cover in existing agroforestry systems of smallholder farmers in the region to enhance synergies in land restoration and groundnut yields. Our results for the economic relationship between tree quantity per hectare and groundnut yields are in line with the literature. In a structured literature review on ecosystem services of agroforestry systems, Kuyah et al. (2019) show that agroforestry systems generally relate to increased crop yields. On an experimental field in Niger, Diallo et al. (2019) further found increased soil fertility under the canopy of trees and in soils neighbouring the tree canopy as compared to a treeless cropland. Leroux et al. (2020, 2022b) demonstrate the potential to increase tree cover in Senegalese agroforestry parklands to about 35% on a landscape scale to enhance millet productivity. However, past studies observed reduced yields in agroforestry systems in which trees competed with the crops for water, light and nutrients (Kuyah et al. 2019). In Sudan, Gaafar et al. (2006) for instance, found reduced yields of sorghum and roselle in *Acacia Senegal* agroforestry systems with high tree density compared to low tree density agroforestry systems. Leroux et al. (2020) also detect a decrease in millet yields associated with overly dense tree covers in surrounding agroforestry parklands. The potential competition between trees, if they are too densely growing, and crops would explain the negative relationship we find between the squared term of tree quantity per hectare and groundnut yields. The range of the confidence interval of our tree quantity estimates further suggests that tree quantity as an agroforestry indicator alone does not determine the yield outcomes. Tree species selection additionally plays a role to achieve increased crop yields (Diallo et al. 2019; Kuyah et al. 2019; Neya et al. 2019).

Table 3. Marginal effects and percentage change in groundnut yield related to our agroforestry indicators.

Agroforestry indicator	First derivative formula	Given value	Marginal effect at given value	Percentage change in yield at given value
Tree quantity	$0.017 + 2 * (-0.001) * AQ_i + 0.001 * AD_i$	$AQ_i = 4$; $AD_i = 2$	0.011	1.11%
Tree species diversity	$0.262 + 2 * (-0.036) * AD_i + 0.001 * AQ_i$	$AD_i = 3$; $AQ_i = 3$	0.049	5.02%
Faidherbia albida	$-0.026 + 2 * 0.001 * AS_i^{\pi}$	$AS_i^{\pi} = 2$	−0.022	-2.18%
Cordyla pinnata	$0.130 + 2 * (-0.016) * AS_i^{\pi}$	$AS_i^{\pi} = 1$	0.098	10.30%
Adansonia digitata	$-0.149 + 2 * 0.016 * AS_i^{\pi}$	$AS_i^{\pi} = 1$	−0.117	-11.04%
Anogeissus leiocarpa	$0.103 + 2 * (-0.004) * AS_i^{\pi}$	$AS_i^{\pi} = 1$	0.095	9.97%
Ziziphus mauritiana	$0.238 + 2 * (-0.107) * AS_i^{\pi}$	$AS_i^{\pi} = 1$	0.024	2.43%

Notes: Marginal effects are calculated for each agroforestry indicator when adding one unit to their rounded mean. Interaction variables in the calculation of the marginal effect of tree quantity and tree species diversity are held constant at their rounded mean values. We estimate the percentage change in yield associated with a one unit increase from the rounded sample mean of our indicators through the formula $\left(exp.^{marginal\ product} - 1\right) \cdot 100\%$.

Our tree species diversity indicator provides more detailed information on the compositions of agroforestry systems. The tree species diversity variable shows a much stronger and statistically significant relationship to groundnut yields. Additional tree species on the agricultural land relate to relatively large initial percentage increases in groundnut yields per hectare. When increasing the number of tree species in the agroforestry system from the rounded sample mean of 2 to 3 tree species and holding other factors constant, we would expect a 5.02% increase in groundnut yields, based on our results. The confidence interval indicates high statistical certainty for our estimated coefficient. However, the coefficient for the squared term of tree species diversity suggests that after reaching a saturation point, each additional tree species is associated with a percentage reduction in groundnut yields. The literature on the relationship between tree species diversity in agroforestry systems and crop yield outcomes is scarce. However, the results of the study by Nesper et al. (2017), the structured literature review by Kuyah et al. (2019) and the study by Leroux et al. (2022b) corroborate our findings. Nesper et al. (2017) found increased coffee bean production in agroforestry systems with higher shade tree species diversity in India. Similarly, Kuyah et al. (2019) reported that past studies observed positive crop yield effects in mixed agroforestry systems featuring both nitrogen-fixing and non-nitrogen-fixing tree species. The results of Leroux et al. (2022) suggest a positive relationship between millet yields and tree species diversity in the landscape surrounding smallholder fields in Senegal. Additionally, Soti et al. (2019) and Sow et al. (2020) demonstrate that landscape diversity can positively influence pest control, providing a pathway to enhance crop yields. Studies focusing on soil fertility in forest areas have further identified higher soil organic carbon and greater soil fauna diversity, suggesting higher soil fertility, in forests with greater tree species diversity (Korboulewsky et al. 2016; Li et al. 2019). These findings might be transferred to the agroforestry context to explain our results. The interaction term between tree quantity per hectare and tree species diversity indicates that having more trees and a greater variety of tree species in the agroforestry system enhances the positive relationship of the two indicators with groundnut yields.

4.2.2. Quantities of the most prevalent tree species

The analysis of the tree quantities for the five most prevalent tree species in our sample shows that each of the five most prevalent tree species in our sample - *Faidherbia albida, Cordyla pinnata, Adansonia digitata, Anogeissus leiocarpa,* and *Ziziphus mauritiana* - individually relate differently to groundnut yields.

For the quantity of trees per hectare of the species *Faidherbia albida*, we find an initial negative relationship with groundnut yields. The relationship between *Faidherbia albida* and groundnut yields turns positive after a certain threshold of *Faidherbia albida* trees per hectare. When increasing the quantity of *Faidherbia albida* trees per hectare from the rounded sample mean of 1 to 2, we would however expect a decrease in groundnut yields by 2.18%. Yield increases seem to only realize at a higher quantity per hectare of *Faidherbia albida* trees. While our results contradict the evidence gathered on the relationship between *Faidherbia albida* trees and millet or maize yields (Leroux et al. 2022a; Amadu et al. 2020), they align with the scarce evidence on the relationship between *Faidherbia albida* trees and groundnut yields in our study context. Louppe et al. (1996), for instance, find lower groundnut yields in the vicinity of *Faidherbia albida* trees compared to control areas. In their structured literature review, Sinare et al. (2015) equally find a negative association between groundnut yields and trees of this species. Considering the pathways of soil fertility effects of this tree species, our positive estimate for the squared term of *Faidherbia albida* tree quantity per hectare might be explained. The main fertilizing capacity of this tree species is due to its reverse phenology rather than through nitrogen fixation as other fertilizer tree species (Ndoye et al. 1995). The leaf litter adds biomass to the soils under and surrounding its canopy at the beginning of the agricultural season (Mokgolodi et al. 2011; Stephen et al. 2020). In their study on experimental fields in Niger, Diallo et al. (2019) for instance found that *Faidherbia albida* trees mostly increased soil nutrients directly under the trees' canopies. While they also detected higher soil fertility in the surrounding areas, the greatest effects of *Faidherbia albida* trees on soil fertility were observed directly beneath the canopies. Stephen et al. (2020) equally found higher soil nutrient levels under the canopy of *Faidherbia albida* stands compared to outside the canopies. Also, Louppe et al. (1996) found that groundnut yields sampled under the canopy of those trees were higher than those sampled outside the canopy. Against this background, our results suggest that increased groundnut yields are more likely to be observed if the agroforestry system contains a higher number of *Faidherbia albida* trees, rather than agroforestry systems with lower quantities of this species.

For the relationship between the quantity of *Cordyla pinnata* trees per hectare and groundnut yields, we observe an initially positive association of groundnut yields. The estimated coefficients of 0.13 for *Cordyla pinnata* trees per hectare and -0.016 for the squared term of this variable, suggests that an additional *Cordyla pinnata* tree per hectare compared to the sample mean is associated with an increase in groundnut yields of 10.30%. After reaching a tipping point of *Cordyla pinnata* trees per hectare, additional trees of this species are however associated with a decrease in yields. Our results align with past experimental field studies in the Senegalese context. For instance, Samba et al. (2012) reported increased soil fertility and groundnut yields in experimental agroforestry systems featuring *Cordyla pinnata* trees, and Diatta et al. (2017) documented increased soil fertility in *Cordyla pinnata* agroforestry parklands. The nitrogen-fixing capacity of this tree species and its leaf litter contribute to increased soil fertility (Sambou et al. 2024b; Samba 2001). In line with Kuyah et al. (2019), the coefficient of the squared term for *Cordyla pinnata* trees per hectare suggests competition for space and nutrients between these trees and groundnuts if the trees grow too densely.

Adansonia digitata trees per hectare relate to an initial decrease in groundnut yields according to our regression results. The confidence interval for the estimated coefficient of tree quantity per hectare of *Adansonia digitata* trees ranges widely from -0.746 to 0.448, indicating low statistical certainty for the estimate. The squared term of this indicator suggests that after a certain quantity of *Adansonia digitata* trees per hectare, additional trees may be associated with an increase in groundnut yields. However, based on our estimates, an additional *Adansonia digitata* tree per hectare compared to the rounded sample mean is expected to relate to an 11.04% decrease in groundnut yields. The wide confidence intervals further indicate that the statistical relationship between *Adansonia digitata* and groundnut yields in our data is uncertain. The low statistical certainty of our estimates for the quantity per hectare of *Adansonia digitata* trees aligns with the literature, suggesting no specific soil fertility enhancing capacities of this tree species (Meinhold and Darr 2021). The limited previous studies on the relationship between *Adansonia digitata* trees and crop yields corroborate this statistically uncertain relationship. Some studies, such as those presented in the structured reviews by Sinare et al. (2015) and Bayala et al. (2014), identify potential trade-offs between *Adansonia digitata* trees and cereal yields, whereas Sanou et al. (2012) find higher millet yields under *Adansonia digitata* trees compared to a control plot.

Our results further suggest that the quantity of *Anogeissus leiocarpa* trees per hectare is associated with an initial increase in groundnut yields with additional trees. When adding an additional tree of this species compared to its rounded sample mean, we would expect a 9.97% increase in groundnut yields. However, the confidence interval for the estimated coefficient of tree quantity per hectare of this species ranges from a -0.12 to 0.326. The confidence interval for the parameter of the squared term is narrower around the estimate of -0.004, indicating a likely percentage decrease in yields if too many *Anogeissus leiocarpa* trees are grown per hectare. Literature on yield effects of agroforestry systems with *Anogeissus leiocarpa* trees is scarce. However, our results are in line with Mesele and Huising's (2024) findings of increased soil fertility associated with *Anogeissus leiocarpa* trees in the context of forest landscapes in Nigeria. Similar to our results for general tree quantity and tree quantity of *Cordyla pinnata* trees, the negative relationship of the squared term for *Anogeissus leiocarpa* trees per hectare suggests that the competition between trees outweighs their benefits for soil fertility, if trees grow too densely.

Our regression results further indicate an increase in groundnut yields for additional *Ziziphus mauritiana* trees per hectare. The confidence interval for the statistical certainty of this estimate is however wider compared to tree quantities of the other tree species, ranging between -0.412 and 0.889. Based on our estimates, we would expect an increase of 2.43% for one additional *Ziziphus mauritiana* tree per hectare compared to its sample mean. The negative estimator for the squared term of tree quantities for *Ziziphus mauritiana* suggests a likely decrease in groundnut yields associated with additional trees of this species after a certain quantity of these trees is reached. The confidence interval for this estimate is also rather wide and ranges from -425 to 0.211. The wide confidence intervals for our estimated coefficients indicate that the number of *Ziziphus mauritiana* trees might not be statistically related to groundnut yield outcomes in our sample, with potential yield changes varying widely. These statistically uncertain results diverge from Bado et al. (2021), who reported increased soil fertility in agroforestry systems with *Ziziphus mauritiana* trees. However, our findings might be due to *Ziziphus mauritiana* trees not shedding their leaves and lacking nitrogen-fixing capabilities (Palejkar et al. 2012; Seghieri et al. 2012).

4.3. Limitations

While our study provides information on the relationship between crop yields and diverse agroforestry systems of smallholders, there are some limitations to this study that should be noted. First, we used smallholders' recall data on groundnut yields, input uses, land sizes, as well as tree species and quantities, which might induce measurement bias, as for instance Wossen et al. (2019) point out. The prevalence of the recorded tree species in our study, however, aligns with findings from Leroux et al. (2020), supporting the reliability of smallholders' reports. Second, we do not focus on the spatial locations of trees on the fields to understand how proximity of trees to crops might relate to yield outcomes. From past studies, we know that trees relate to higher soil fertilities and crop yields in their vicinity and especially under their canopy (Louppe et al. 1996; Diallo et al. 2019; Stephen et al. 2020). Consequently, our study likely statistically and economically underestimates the relationships detected between agroforestry indicators and groundnut yields. Nevertheless, given the direction of potential bias, our results provide clear evidence of the existence and direction of relationships between our indicators and groundnut yields. Third, our study specifically examines the relationship between agroforestry systems and groundnut yields. Consequently, we do not evaluate the full economic, cultural, medical, or nutritional values that different tree species provide to agroforestry practitioners. However, policymakers and practitioners should also consider these values of tree species when designing policies, interventions, or agroforestry systems.

5. Conclusion

In the context of climate change exacerbating the degradation of arable lands in the African Sahel region, agroforestry is gaining importance as a natural regeneration practice with potential livelihood benefits for smallholders (Mbow et al. 2021). The adoption of agroforestry practices has been found to potentially increase soil fertility and crop yields in this context (Kuyah et al. 2019). Yet, empirical research on how actual and diverse agroforestry systems of smallholder farmers relate to crop yields is limited. With our study, we add to the literature by focusing on detailed indicators for actual and diverse agroforestry systems among smallholder groundnut farmers in the Senegalese Groundnut Basin.

For this study, we focused on a sample of 492 small scale groundnut farmers in the Senegalese Groundnut Basin. We analysed how (a) the total quantity of agroforestry trees per hectare, (b) the tree species diversity and (c) the quantities of the five most prevalent tree species in our data - *Faidherbia albida*, *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa* and *Ziziphus mauritiana* - relate to groundnut yields. Based on the framework of Cobb-Douglas production functions, we estimated the relationship between our agroforestry indicators and groundnut yields employing OLS regressions.

Across our sample, agroforestry systems varied greatly and related differently to groundnut yield outcomes. Our analysis of the relationship of total tree quantity and tree species diversity with groundnut yield shows that groundnut yields initially increase with additional trees and additional tree species in the agroforestry system, regardless of its species, until a quantity of trees per hectare is reached at which the competition between trees and crops for space and nutrients outweighs the benefits. However, if an additional tree per hectare or an additional tree species were introduced to the mean agroforestry system of our sample, we would expect groundnut yield increases of about 1,11% or 5,02%, respectively. This shows that there is still potential to increase the tree cover and tree species diversity on smallholders' farms in order to promote synergies between soil restoration and groundnut yields.

We also find that *Faidherbia albida* trees only have beneficial effects for groundnut yields when the agroforestry system includes a higher number of these trees per hectare. Lower numbers of these trees per hectare do not appear to have a positive effect on groundnut yields. Our study suggests that the quantity per hectare and location of these trees may be critical to realize synergies between groundnut yields and land restoration. For the tree species *Cordyla pinnata* and *Anogeissus leiocarpa*, additional trees first relate to increases in groundnut yields until a certain number of trees is surpassed, and additional trees relate to decreases in yields. *Ziziphus maritiana* and *Adansonia digitata* trees seem to be not associated with groundnut yields in our sample.

We demonstrate that agroforestry practices are versatile, and tree quantity, tree species diversity and tree species selection play a crucial role in alleviating climate change effects on smallholders' livelihoods and achieving increased crop yields. Beyond informing policy strategies to promote agroforestry adoption among non-practitioners, we emphasize the substantial potential of engaging current practitioners to modify existing agroforestry systems with the aim of simultaneously enhancing land restoration and groundnut production. Increasing tree density or tree species diversity and introducing or expanding specific species within existing agroforestry systems could, for instance, foster such synergies.

Further research gathering detailed information on e.g. the location of trees on smallholders' fields, ages of trees, as well as soil properties, could enhance a detailed understanding of the relationships between specific tree species and crops. Future research that examines interactions between different tree species in an agroforestry cropping system and its effects on crop yields could additionally contribute to understanding the complex relationships between multiple different species in agroforestry systems.

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CRediT authorship contribution statement

Luisa Müting: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization; Petros Suzgo Kayovo Mkandawire: Methodology, Software, Validation, Formal analysis, Writing - Review & Editing; Oliver Mußhoff: Writing - Review & Editing, Supervision, Project administration, Funding acquisition

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Declaration of Competing Interest

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

Data availability

Data will be made available at request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors utilized ChatGPT 3.5 to enhance the article's readability and assist in creating Figure 1. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix A Survey questions

Table A. Survey questions

What is the size of the agricultural land on which you cultivated groundnuts this farming season, in hectares?	
…	
How many kilograms of groundnut did you produce this farming season? (referring to 2022)	
…	
In the following, I would like to ask you a few more questions about agroforestry. This time, I am interested in your agricultural system and practices.	
Do you practice agroforestry?	Yes No
How many trees grow on the land you use for agriculture?	Number
How many different tree species grow on this land?	Number
Repeat for each tree species:	
Now, I will ask you questions about the different tree species one by one.	
Please name the tree species (n) that grows on the land you use for agriculture.	Text
How many trees of the species (insert tree species names) grow on this land?	Number
Have you planted trees on the land you use for agriculture in the past three years?	
How many different tree species have you planted on this land?	Number
Repeat for each tree species:	
Now, I will ask you questions about the different tree species one by one.	
Please name the tree species (n) that you have planted on the land you use for agriculture.	Text
How many trees of species (n) have you planted on this land?	Number

Appendix B Robustness checks

Table B.1. OLS estimates for Cobb-Douglas production function parameters on groundnut yield per hectare (ln) with agroforestry adoption dummy.

VARIABLES	Coefficient	95 % Confidence interval
Agroforestry dummy		
Agroforestry adoption	0.306	-0.043 0.655
Production inputs		
Ln Family labour	0.083	-0.071 0.237
Hired labour	0.093	-0.122 0.308
Improved seeds	0.251	-0.218 0.720
Livestock labour power	-0.006	-0.390 0.378
Organic fertilizer	0.344	0.027 0.661
Ln Pesticides (liter/hectare)	-0.071	-0.115 -0.027
Household characteristics		
Age of household head	-0.010	-0.017 -0.003
Female household head	-0.225	-0.486 0.036
Primary school	0.144	-0.180 0.468
Secondary school	0.201	-0.211 0.614
R-squared adjusted	0.233	
Observations		492

Robust standard errors; Intercept and commune-level fixed effects are included in the models but not reported for brevity

Table B.2. OLS estimates for Cobb-Douglas production function parameters on groundnut yield per hectare (ln) in a single regression model.

VARIABLES	Coefficient	95 % Confidence interval	
Agroforestry variables			
Tree quantity	0.018	-0.088	0.125
Tree quantity squared	-0.001	-0.002	0.000
Tree species diversity	0.283	0.037	0.528
Tree species diversity squared	-0.034	-0.075	0.007
Tree quantity x tree diversity	-0.006	-0.019	0.007
Faidherbia albida	-0.069	-0.197	0.059
Faidherbia albida squared	0.003	0.000	0.006
Cordyla pinnata	0.071	-0.105	0.247
Cordyla pinnata squared	-0.005	-0.019	0.009
Adansonia digitata	-0.362	-0.977	0.254
Adansonia digitata squared	0.112	-0.146	0.370
Anogeissus leiocarpa	0.043	-0.187	0.273
Anogeissus leiocarpa squared	0.012	-0.007	0.030
Ziziphus mauritiana	-0.006	-0.662	0.650
Ziziphus mauritiana squared	-0.001	-0.326	0.324
Production inputs			
Ln Family labour	0.075	-0.081	0.231
Hired labour	0.084	-0.138	0.306
Improved seeds	0.214	-0.257	0.684
Livestock labour power	0.054	-0.345	0.453
Organic fertilizer	0.343	0.026	0.660
Ln Pesticides (liter/hectare)	-0.076	-0.121	-0.030
Household characteristics			
Age of household head	-0.009	-0.017	-0.002
Female household head	-0.199	-0.471	0.072
Primary school	0.157	-0.183	0.497
Secondary school	0.262	-0.174	0.698
R2 adjusted	0.239		
Observations			492
Robust standard errors; Intercept and commune-level fixed effects are included in the models but not reported for brevity			

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