



Nuts about trees? Tree quantity, species richness, and key species in smallholder agroforestry systems and their associations with groundnut (*Arachis hypogaea*) yields in Senegal

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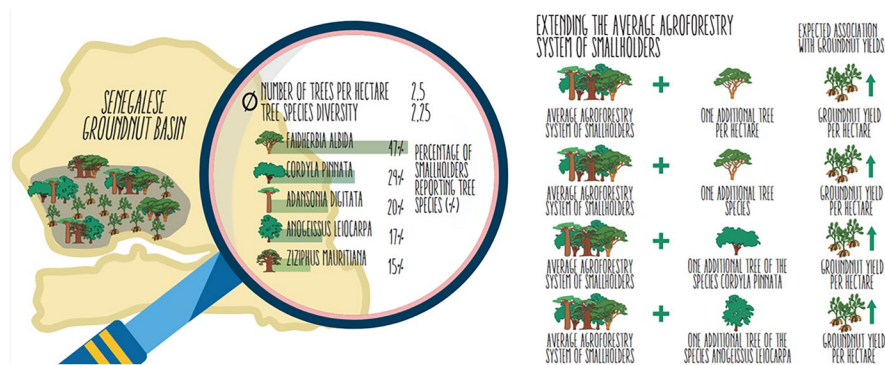
Abstract In the Sahel region, agroforestry potentially increases crop yields, alongside restoring and retaining soils. However, little is known about how diverse agroforestry systems perform across adopted-agricultural systems of smallholders in the region. We therefore investigate how varying smallholder agroforestry systems in the Senegalese Groundnut Basin associate with groundnut yields. We distinguish agroforestry systems by (a) tree quantity per hectare, (b) tree species richness and (c) quantities per hectare of the most frequently reported 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*, *Cordia pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa*, and *Ziziphus mauritiana* as the most frequently reported species. Our results indicate that groundnut yields initially increase with tree quantity and species

richness. However, higher tree densities are associated with lower groundnut yields, possibly reflecting increased competition between trees and crops for space, light, water, or soil nutrients. *Faidherbia albida* trees seem associated with higher groundnut yields only when present in greater numbers. For the species *Cordia pinnata* and *Anogeissus leiocarpa*, additional trees initially associate with increases in groundnut yields. The tree species *Ziziphus mauritiana* and *Adansonia digitata* show no clear association with groundnut yields, which may be partly due to their relatively low abundance in the sample. Our results suggest a remaining potential for increasing tree cover and tree species richness, as well as introducing or expanding certain tree species in established agroforestry systems to support groundnut production.

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Graphical abstract



Keywords Agroforestry · Smallholder production systems · Climate change mitigation and adaptation · Land restoration · Tree species · Groundnut production

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 (Mbow et al. 2020b; Yobom 2020). These trends threaten the livelihoods of 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. 2020a). 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 (Sambou et al. 2024a) and/or symbiotically interacting with soil bacteria that generate nitrogen (Fall et al. 2012; 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 (Bado et al. 2021; Shi et al. 2018). 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, Beillouin et al. (2021) and Kuyah et al. (2019) find that in past studies, agroforestry adoption in general is positively associated with crop yields compared to not practicing agroforestry. For instance, Amadu et al. (2020a), Amadu et al. (2020b) and Coulibaly et al. (2017), 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 richness 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 for instance by Sinare and Gordon (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.

Recent studies by Leroux et al. (2020, 2022a, b) 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, 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). A detailed overview of relevant studies examining the relationship between agroforestry practices or specific tree species and crop yields is provided in Table 4 in Appendix A. While these studies provide valuable insights into how the landscape structure of agroforestry parklands surrounding smallholders' fields in the study sites relates to crop productivity, there is limited knowledge about how tree quantity, tree species richness, and specific tree species within smallholders' agroforestry systems relate to groundnut yields, particularly when considering the distinct production systems.

To address this gap in the literature, we explore how agroforestry systems are associated with 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) tree species richness within the agroforestry system, and (c) the quantities per hectare of the most frequently reported tree species in our data are associated with smallholder's groundnut yield per hectare. This study thereby 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, our study contributes to a better understanding of how existing agroforestry systems could be modified to enhance synergies between land restoration and groundnut yields.

Materials and methods

Study area description

Our study is located in the Senegalese Groundnut Basin, which is the main agricultural region of Senegal, making up about 70% of the country's arable land (Faye and Du 2021). The Groundnut Basin lies within the Sudano-Sahelian climate zone of the Sahel region, characterized by annual precipitation rates of 500–900 mm (Mukai et al. 2023). This climate zone stretches along the Sahelian climate zone from West

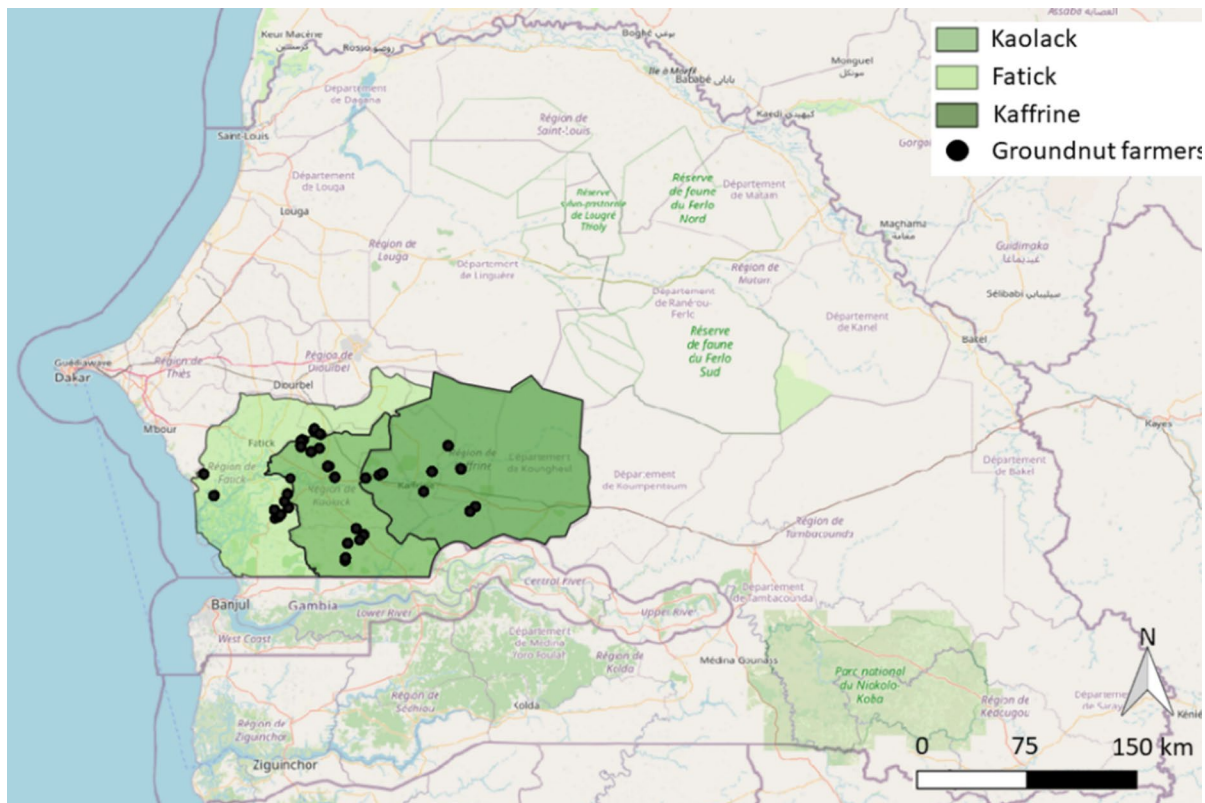


Fig. 1 Locations of groundnut-producing households from our sample in the study region within the Senegalese Groundnut Basin

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 (Bakoye et al. 2019; Georges et al. 2016; OEC 2021). Next to groundnut, 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). 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. 2020a). While managing trees on agricultural land is a traditional practice in this region (Cotillon et al. 2021; Parton et al. 2004), 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. 2024), 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). Figure 1 highlights the regions of Fatick, Kaolack, and Kaffrine in the Senegalese Groundnut Basin, which constitute the study area for our data collection.

Data collection and cleaning

From December 2022 to January 2023, we collected survey data from a total of 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 stratified 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. In each village, we then randomly selected 22 households to be interviewed. Interview dropout was very low and non-systematic. Therefore, our random sampling approach supports the representativeness of the sample of smallholder farmers in the study region.

The team of 11 enumerators conducted interviews with household heads in the Senegalese language, Wolof, at the respondents' homesteads, recording the responses in French. The enumerators received three days of training, and the survey was pre-tested by having each enumerator conduct four household interviews. Respondents provided information on tree species and quantities growing within their agroforestry systems on their cropland, sizes of the land on which they cultivated groundnut (in hectare), and output of groundnut (in kg) for the 2022 agricultural season. Our indicators for groundnut yield per hectare, total tree quantity per hectare, tree species richness and the quantities per hectare of the five most frequently reported tree species have been computed based on this information. The English translation of the survey questions relevant to our study are provided in Appendix B. The elicitation of tree species and crop yields through smallholders' report is based on previous studies assessing the relationship of agroforestry adoption and crop yield outcomes, such as the studies of Amadu et al. (2020a), Amadu et al. (2020b), Coulibaly et al. (2017), or Kassie (2016). To validate the reported tree species, we compared them with findings from other studies focusing on the Senegalese Groundnut Basin. This comparison shows that the frequency of reported species in our data aligns with the tree species commonly found in local agroforestry parklands, as identified through satellite data and cross-validated with field observations in studies by Leroux et al. (2020, 2022a, b), Ndao et al. (2022), and Rounsard et al. (2020). A synthesis of the tree species prevalence detected in these studies is presented in Table 5 in Appendix A. While recall data may be subject to bias, the strong overlap with findings from these studies suggests that our data is reasonably reliable.

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. Forty

groundnut farmers were uncertain about the quantity of groundnuts they produced during the season, and three reported zero production. These observations were excluded from the analysis. We also excluded respondents who were unsure of the land size on which they cultivated groundnuts, resulting in a final sample of 492 smallholders. As our data cleaning process did not systematically exclude any group of respondents, our subsample remains representative of smallholder groundnut producers in the study region. 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 Yuan (2011), we replaced "unknown" responses to our questions on input and tree quantities with the smallest observed value. To validate the groundnut yields per hectare in our dataset, we compared its distribution with that of the groundnut yields per hectare in the Living Standards Measurement Study conducted in Senegal in 2021–2022 (Agence Nationale de la Statistique et de la Démographie 2024) (See Appendix C, Fig. 3). This comparison shows a similar right-skewed distribution in both datasets, with the majority of yields concentrated below 1000 kg/ha, supporting the reliability of our data.

Most frequently reported tree species in our data

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 endogeneity of agroforestry adoption decisions in this study.

However, to reduce potential bias from recent adoption decisions, we exclude trees that have reportedly been planted or naturally regenerated within three years prior to our data collection. Moreover,

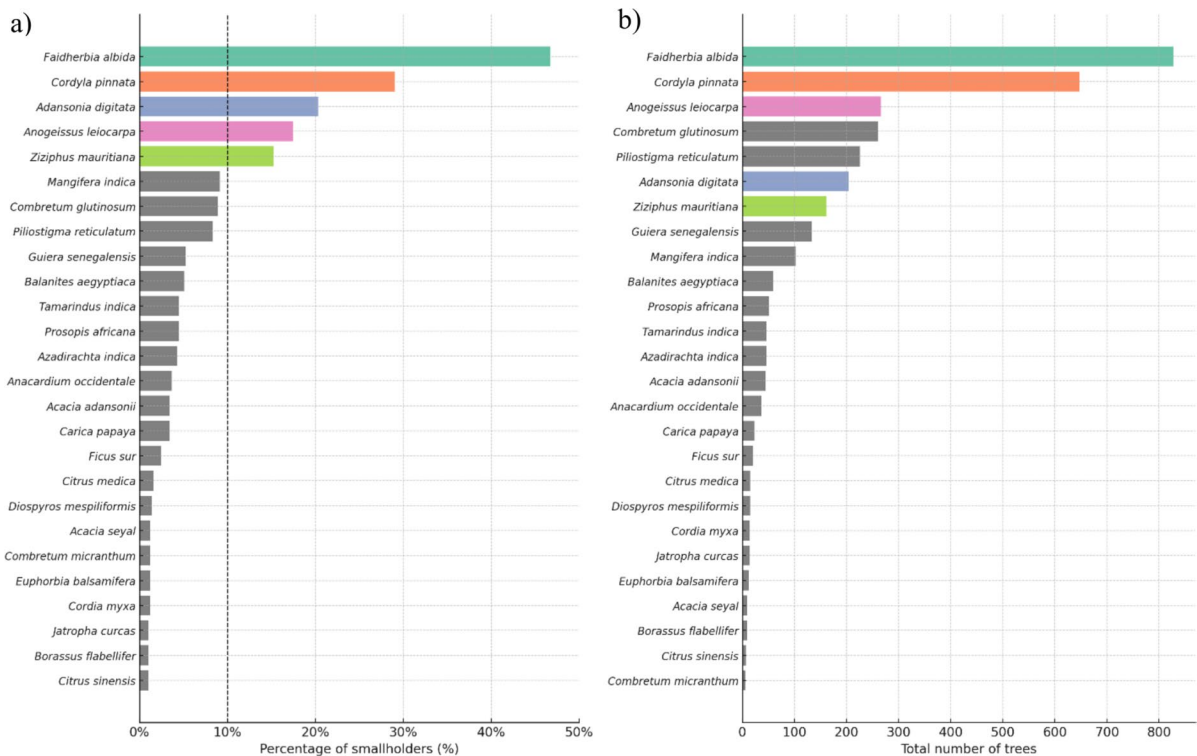


Fig. 2 Tree species reported by at least 1% of smallholder groundnut producers on their farmland, shown by **a** the frequency of reporting by individual smallholders and **b** the total abundance across the sample

trees in agroforestry systems typically realize their benefits only after three years of adoption (Coulibaly et al. 2017; Mercer 2004) and need special care and protection from livestock and fire for the first three years (Kalinganire 2022). Moreover, the root system of younger trees not yet accessing deeper soil layers (Bargués Tobella et al. 2017) might lead to a higher competition between younger trees and crops for water and nutrients. This could temporarily lead to lower yields and confound the assessment of longer-term tree–crop interactions. By excluding younger trees from our analysis, we therefore ensure that we derive a conservative estimate of real tree crop associations.

For our analysis, we focus on three agroforestry measures, (a) tree quantity per hectare, (b) tree species richness, and (c) the quantities per hectare of the most frequently reported tree species in our data. Tree quantity per hectare is a ratio of total number of trees to the hectares of land. Tree species richness reflects the total number of different tree species reported by respondents. The most frequently reported tree

species in our data are those reported by at least 10% of smallholders in our sample. Figure 2 displays the tree species reported by smallholders, highlighting *Faidherbia albida*, *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa* and *Ziziphus mauritiana* as the most frequently reported species in our sample. Those five tree species are also among the most abundant across our subsample and in smallholders' individual agroforestry systems, as shown in Fig. 2. 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.

Econometric analysis

To economically analyse the relationship between our agroforestry indicators—(a) tree quantity per hectare, (b) tree species richness, and (c) the quantities of the five most frequently reported tree species in

our data—and groundnut yields, 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 (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) assess 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). Accurate pruning of trees might enhance the productivity of crops. However, once trees are established, the main ways in which agroforestry systems affect crop yields are less dependent on smallholders' technical efficiency (Bado et al. 2021; Rosenstock et al. 2014; Sambou et al. 2024a) than other inputs such as fertilizers or labor (Coelli 2005). In this study, we are not investigating how agroforestry relates to the technical efficiency of smallholders. Therefore, we base our analysis on the studies of Amadu et al. (2020a), Branca et al. (2021), and Teuscher et al. (2015), and estimate log-linearized Cobb–Douglas production functions using OLS estimation. We chose an OLS regression model because the log-linearized Cobb–Douglas production function is linear in parameters, and our sample is randomly selected.

To answer our research questions, we apply the same regression model specification, varying only the agroforestry indicator used. This allows us to examine different dimensions of agroforestry through two distinct

model variations. First, we focus on the relationships of (a) total tree quantity per hectare and (b) tree species richness in the agroforestry system, as well as the interaction between these factors, with groundnut yield per hectare. Therefore, we specify the following equation:

$$\ln Y_i = \alpha_0 + \sum_{k=1}^K \alpha_k \ln X_{ik} + \gamma_1 Z_{il} + \gamma_2 AQ_i + \gamma_3 AQ_i^2 + \gamma_4 AD_i + \gamma_5 AD_i^2 + \gamma_6 AD_i AQ_i + \gamma_7 C + \varepsilon_i \quad (1)$$

In the second model variation, we apply the same specification as in Eq. (1), but replace the general agroforestry indicators with the quantities per hectare of the five most frequently reported tree species in our sample: *Faidherbia albida*, *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa*, and *Ziziphus mauritiana*. This allows us to assess species-specific effects on groundnut yields. This variation of the equation is specified as follows:

$$\ln Y_i = \alpha_0 + \sum_{k=1}^K \alpha_k \ln X_{ik} + \gamma_1 Z_{il} + \gamma_2 AS_i^\pi + \gamma_3 (AS_i^\pi)^2 + \gamma_4 C + \varepsilon_i \quad (2)$$

In both variations of the model, 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 l socio-demographic variables. ε_i denotes the stochastic error term in our models. To account for potential heteroscedasticity and ensure valid inference from the OLS regression, we apply robust standard errors. We selected the input and socio-demographic control variables to include in our model (see Table 1) based on the studies of Amadu et al. (2020a), Branca et al. (2021), Shah (2022), and Teuscher et al. (2015). As organic fertilizers are typically composed of manure, compost, and/or crop residues, it is often difficult for smallholders to recall exact application quantities in kilograms, as the study of Wollburg et al. (2021) suggests. Therefore, we use a binary variable to indicate whether organic fertilizer was applied, to ensure more reliable reporting. Additionally, previous studies in the context of the Senegalese Groundnut Basin, such as those conducted by Djiba et al. (2023) and Thuo et al. (2011), show that the application of chemical fertilizers on groundnuts is rather uncommon among smallholders. Moreover, since groundnuts

Table 1 Descriptive statistics of variables included in our analysis

Variable	Description	Mean	SD	Min	Max
<i>Outcome variable</i>					
Groundnut yield	Groundnut yield of the 2022 agricultural season in kg per hectare	835.20	1002.15	33.33	5000.00
<i>Agroforestry variables</i>					
Tree quantity	Number of trees per hectare (only trees older than three years)	2.50	4.56	0.00	50.00
Tree species richness	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 <i>Faidherbia albida</i> per hectare (only trees older than three years)	0.63	1.88	0.00	30.00
Cordyla pinnata	Number of trees of species <i>Adansonia digitata</i> per hectare (only trees older than three years)	0.47	1.48	0.00	14.00
Adansonia digitata	Number of trees of species <i>Anogeissus leiocarpa</i> per hectare (only trees older than three years)	0.11	0.34	0.00	3.00
Anogeissus leiocarpa	Number of trees of species <i>Anogeissus leiocarpa</i> per hectare (only trees older than three years)	0.22	0.91	0.00	12.00
Ziziphus mauritiana	Number of trees of species <i>Ziziphus mauritiana</i> per hectare (only trees older than three years)	0.10	0.31	0.00	2.50
<i>Production inputs</i>					
Family labor	Number of household members (living in the household) between the ages of 18 and 60	7.76	4.74	0.00	27.00
Hired labor	Dummy for having hired agricultural laborers (1 = yes)	0.30			
Improved seeds	Dummy for having used improved seeds (1 = yes)	0.05			
Livestock labor 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
<i>Household characteristics</i>					
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			
<i>Commune dummies</i>					
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			
Mbadakhouné	Dummy for household residing in the commune of Mbadakhouné (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			

Table 1 (continued)

Variable	Description	Mean	SD	Min	Max
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

are leguminous crops, they generally do not require nitrogen fertilizer, as other non-leguminous crops do (FAO 2025). We therefore do not include a variable on chemical fertilizer application. 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 richness, i.e. the number of different tree species growing on the land of household i . In the second model, AS_i^T represents (c) the quantity per hectare of the most frequently reported 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 richness 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). Commune-level fixed effects account for soil characteristics to some extent, as soils across the Senegalese Groundnut Basin are predominantly Arenosols with similar physical properties (Malou et al. 2021). Bakhom et al. (2024) additionally show that soils sampled from different areas in Senegal have similar bacterial profiles, suggesting ecological similarity. However, we acknowledge that we cannot control for within-commune variation in soil fertility beyond what is captured by these fixed effects. 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 richness 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:

$$\delta m = (exp.^{marginalproductm} - 1) \cdot 100\% \quad (3)$$

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.

Results and discussion

Descriptive statistics and variables

Within our sample, 93.8% of the respondents have trees of different species in their cropping systems. We recorded a total of 53 different tree species growing across the agroforestry systems of our respondents. Next to the five most frequently

reported tree species in our sample, *Faidherbia albida*, *Cordia 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. Smallholders reported up to 30 trees of *Faidherbia albida* and up to 14 *Cordia 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

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
<i>Agroforestry variables</i>				
Tree quantity	0.017	−0.034 to 0.067		
Tree quantity squared	−0.001	−0.002 to 0.000		
Tree species richness	0.262	0.027 to 0.497		
Tree species richness squared	−0.036	−0.077 to 0.005		
Tree quantity × tree species richness	0.001	−0.010 to 0.011		
<i>Faidherbia albida</i>			−0.026	−0.122 to 0.071
<i>Faidherbia albida</i> squared			0.001	−0.002 to 0.005
<i>Cordia pinnata</i>			0.130	−0.010 to 0.271
<i>Cordia pinnata</i> squared			−0.016	−0.028 to −0.004
<i>Adansonia digitata</i>			−0.149	−0.746 to 0.448
<i>Adansonia digitata</i> squared			0.016	−0.231 to 0.262
<i>Anogeissus leiocarpa</i>			0.103	−0.120 to 0.326
<i>Anogeissus leiocarpa</i> squared			−0.004	−0.027 to 0.019
<i>Ziziphus mauritiana</i>			0.238	−0.412 to 0.889
<i>Ziziphus mauritiana</i> squared			−0.107	−0.425 to 0.211
<i>Production inputs</i>				
Ln Family labor	0.063	−0.094 to 0.220	0.103	−0.054 to 0.260
Hired labor	0.076	−0.140 to 0.292	0.118	−0.099 to 0.336
Improved seeds	0.228	−0.231 to 0.687	0.244	−0.232 to 0.720
Livestock labor power	0.033	−0.360 to 0.426	0.019	−0.371 to 0.409
Organic fertilizer	0.282	−0.029 to 0.593	0.434	0.131 to 0.737
Ln Pesticides (liter/hectare)	−0.075	−0.119 to −0.030	−0.068	−0.112 to 0.023
<i>Household characteristics</i>				
Age of household head	−0.009	−0.017 to −0.002	−0.010	−0.018 to −0.003
Female household head	−0.205	−0.467 to 0.058	−0.225	−0.496 to 0.046
Primary school	0.171	−0.157 to 0.500	0.152	−0.185 to 0.489
Secondary school	0.236	−0.185 to 0.657	0.190	−0.229 to 0.610
R ² 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

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.

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 richness, 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 additionally ran our regression model using a binary agroforestry adoption indicator as robustness check. The results are reported in Appendix E and are consistent with past studies, such as those of Amadu et al. (2020a), Amadu et al. (2020b), Coulibaly et al. (2017), or Shah (2022), showing a positive association of agroforestry adoption and crop yields. Additionally, the variance inflation factors (VIFs) are below 5, indicating no critical multicollinearity among the independent variables, according to Sarma (2021). The Shapiro–Wilk test (Shapiro and Wilk 1965) confirms that the residuals are normally distributed. Together, these diagnostic results (Appendix D) support the use of OLS regression for our analysis. To ensure the robustness of our tree species richness indicator, we additionally estimate our regression model using the Shannon and Simpson diversity indices, which account for both the number of tree species and their relative evenness (Appendix E). The consistency of results across these alternative specifications supports the reliability of our findings. As an additional robustness check, we also re-estimated the model without excluding recently planted or naturally regenerated trees, and the results remain consistent (Appendix E).

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 shows a negative association with groundnut yields. One possible explanation is that pesticide use tends to coincide with pest infestations, which themselves reduce yields, a

pattern documented by Asare-Nuamah (2022). The number of household members aged between 18 and 60 years residing in the household serves as a proxy for household labor. While some of these members may not be fully involved in the household's farming activities, this proxy still shows a positive association with groundnut yields. Hiring labor and animal labor power also show a positive association with groundnut yields. Additionally, the utilization of improved seeds relates to slightly higher groundnut yields. We also observe that the household head being female and a higher age of the household head are negatively associated with 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 Amadu et al. (2020a), Branca et al. (2021), or Teuscher et al. (2015). Further, the commune-level fixed effects account for variation across communes in factors such as soil type and fertility, rainfall, and temperature, which can affect yield outcomes. Controlling for these factors at the communal level helps ensure that they do not confound our estimates. While reported yields are significantly higher in some communes compared to others, the fixed effects serve purely as controls and are not central to our analysis. For this reason, we do not report the commune-level fixed effects in Table 2.

Tree quantity and tree species richness

In our sample, tree quantity shows a rather positive association with groundnut yields. Our results indicate that groundnut yields are initially positively associated with the number of trees per hectare of agricultural land, irrespective of 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. Based on our estimates, increasing the sample mean of 3 trees per hectare by one additional tree, while holding other factors constant, corresponds to 1.11% higher groundnut yields (Table 3). This suggests that higher tree cover in existing agroforestry systems may be associated with improved synergies between land restoration and groundnut yields. Our results for the economic association between tree

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 richness	$0.262 + 2 * (-0.036) * AD_i + 0.001 * AQ_i$	$AD_i = 3; AQ_i = 3$	0.049	5.02
<i>Faidherbia albida</i>	$-0.026 + 2 * 0.001 * AS_i^\pi$	$AS_i^\pi = 2$	-0.022	-2.18
<i>Cordyla pinnata</i>	$0.130 + 2 * (-0.016) * AS_i^\pi$	$AS_i^\pi = 1$	0.098	10.30
<i>Adansonia digitata</i>	$-0.149 + 2 * 0.016 * AS_i^\pi$	$AS_i^\pi = 1$	-0.117	-11.04
<i>Anogeissus leiocarpa</i>	$0.103 + 2 * (-0.004) * AS_i^\pi$	$AS_i^\pi = 1$	0.095	9.97
<i>Ziziphus mauritiana</i>	$0.238 + 2 * (-0.107) * AS_i^\pi$	$AS_i^\pi = 1$	0.024	2.43

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 richness 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 $(\exp^{\text{marginal product}} - 1) \cdot 100\%$. These associations are not to be interpreted as causal effects. AQ_i represents tree quantity per hectare; AD_i represents tree species richness, and AS_i^π represents the quantity per hectare of the most frequently reported tree species π .

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) find a potential to increase tree cover in Senegalese agroforestry parklands on a landscape level to enhance crop yields. 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. The potential competition between trees and crops would explain our negative estimate for the association between the squared term of tree quantity per hectare and groundnut yields. The range of the confidence intervals of our tree quantity estimates further suggest that tree quantity as an agroforestry indicator alone does not statistically significantly associate to yield outcomes. According to previous studies, tree species selection is also associated with increased crop yields (Diallo et al. 2019; Kuyah et al. 2019; Neyá et al. 2019).

Our tree species richness indicator provides more detailed information on the compositions of

agroforestry systems. The tree species richness variable shows a much stronger and statistically significant association with groundnut yields. Greater tree species richness on the agricultural land is associated with higher groundnut yields per hectare. Based on our results, an increase in the number of tree species in the agroforestry system from the rounded sample mean of 2 to 3, while holding other factors constant, is associated with a 5.02% higher groundnut yield. The confidence interval indicates high statistical certainty for our estimated coefficient. The literature on the relationship between tree species richness in agroforestry systems and crop yield outcomes is scarce. However, the structured literature review by Kuyah et al. (2019) and the results of the studies by Leroux et al. (2022b) and Nesper et al. (2017) corroborate our findings. 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. (2022b) suggest a positive relationship between millet yields and tree species richness in the landscape surrounding smallholder fields in Senegal. Nesper et al. (2017) found increased coffee bean production in agroforestry systems with higher shade tree species richness in India. 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. However, our coefficient for the squared term of tree species richness suggests that beyond a certain point, higher

species richness is associated with lower groundnut yields. Based on the studies of Kuyah et al. (2019) and Neya et al. (2019), we interpret this as potentially reflecting situations where a high number of tree species coincides with high overall tree density, leading to increased competition with crops for nutrients and light. The interaction term between tree quantity per hectare and tree species richness suggests that agroforestry systems with both higher tree numbers and greater species richness tend to show a stronger positive association with groundnut yields. This aligns with the findings of Kuyah et al. (2019), Leroux et al. (2022b), and Nesper et al. (2017). This pattern may point to the potential relevance of extending agroforestry systems by introducing additional tree species, rather than increasing the number of trees of the same species, as being more positively associated with groundnut productivity.

Quantities of the most frequently reported tree species

The analysis of the tree quantities for the five most frequently reported tree species in our sample shows that each of the five most frequently reported tree species in our sample individually associate differently with groundnut yields. For the quantity of trees per hectare of the species *Faidherbia albida*, we find an initial negative association with groundnut yields. This association between *Faidherbia albida* and groundnut yields turns positive after a certain threshold of *Faidherbia albida* trees per hectare. An increase in *Faidherbia albida* trees per hectare from the rounded sample mean of 1 to 2 is associated with a 2.18% lower groundnut yield. In our sample, higher yields are only observed at greater quantities of *Faidherbia albida* trees per hectare.

While our results contradict the evidence gathered on the relationship between *Faidherbia albida* trees and millet or maize yields (Amadu et al. 2020b; Leroux et al. 2022a), 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 and Gordon (2015) equally find a negative association between groundnut yields and trees of this species. Considering the pathways through which this tree

species may affect soil fertility, our positive estimate for the squared term of *Faidherbia albida* tree quantity per hectare might be explained. One main fertilizing capacity of this tree species is due to its reverse phenology. Its 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). Diallo et al. (2019) and Stephen et al. (2020) for instance found that *Faidherbia albida* trees mostly increased soil nutrients directly under the trees' canopies compared to outside the canopies. Also, Louppe et al. (1996) found that groundnut yields sampled under the canopy of *Faidherbia albida* trees were higher than those sampled outside the canopy. Against this background, our results suggest that higher groundnut yields tend to be associated with agroforestry systems that contain a greater number of *Faidherbia albida* trees, compared to systems with fewer trees of this species.

For the quantity of *Cordyla pinnata* trees per hectare, we observe an initially positive association with groundnut yields. The estimated coefficients of 0.13 and -0.016 for the linear and squared terms of *Cordyla pinnata* tree quantity per hectare suggest that adding one tree to the sample mean is associated with a 10.30% higher groundnut yield. However, after a certain threshold, additional *Cordyla pinnata* trees per hectare seem associated with lower 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 (Samba 2001; Sambou et al. 2024b). In line with Kuyah et al. (2019), the coefficient of the squared term for *Cordyla pinnata* trees per hectare may reflect potential competition for space and nutrients between these trees and groundnuts when tree density is high.

Adansonia digitata trees per hectare seem initially associated to a decrease in groundnut yields according to our regression results. 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 associated with an 11.04% lower groundnut yield. The wide confidence intervals for our estimates indicate that the statistical relationship between *Adansonia digitata* and groundnut yields in our data is rather uncertain. The low statistical certainty of our estimates for the quantity per hectare of *Adansonia digitata* trees may partly be explained by the relatively low abundance of this species in individual agroforestry systems within our sample. This uncertainty also aligns with the literature, suggesting no specific soil fertility enhancing capacities of this tree species (Kyndt et al. 2009; 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 Bayala et al. (2014) and Sinare and Gordon (2015), 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. Rather than enhancing crop yields, this species is primarily known for providing food, fodder, and medicine, and is therefore considered one of the most important agroforestry tree species in the Sahel region (Kalinganire 2022).

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. Based on our estimates, an additional tree of this species compared to the rounded sample mean is associated with a 9.97% higher groundnut yield. 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 squared term is relatively narrow around the estimate of -0.004 , suggesting a negative association between higher densities of *Anogeissus leiocarpa* trees and groundnut yields. Literature on crop yields in agroforestry systems with *Anogeissus leiocarpa* trees is scarce. However, our results are in line with Mesele and Huising (2024) findings of increased soil fertility associated with *Anogeissus leiocarpa* trees in the context of forest landscapes in Nigeria. 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). Similar to our results for general tree quantity and for *Cordyla pinnata*, the negative association captured by the squared term for *Anogeissus leiocarpa* trees per hectare may reflect situations

where potential competition between trees and crops becomes more pronounced at higher tree densities, potentially offsetting soil fertility-related benefits.

Our regression results further suggest a positive association between the number of *Ziziphus mauritiana* trees per hectare and groundnut yields. 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 . Similar to *Adansonia digitata*, the wide confidence interval of our estimates for the quantity of *Ziziphus mauritiana* trees may be related to the relatively low abundance of this species in individual smallholder agroforestry systems, with a maximum of only 2.5 trees per hectare reported in our sample. Based on our estimates, an increase of one *Ziziphus mauritiana* tree per hectare compared to the sample mean is associated with a 2.43% higher groundnut yield. The negative coefficient for the squared term of *Ziziphus mauritiana* tree quantity suggests that, beyond a certain point, higher numbers of trees may be associated with lower groundnut yields. However, the wide confidence intervals around our estimates suggest that, within our sample, the number of *Ziziphus mauritiana* trees may not be statistically associated with groundnut yield outcomes. These statistically uncertain results diverge from Bado et al. (2021), who reported increased soil fertility in agroforestry systems with higher quantities of *Ziziphus mauritiana* trees than those observed in our sample. Additionally, this tree species is very heat and drought resistant and can be grown to protect soils and crops from heat and erosion (Orwa et al. 2009). However, *Ziziphus mauritiana* trees do not shed their leaves and lack nitrogen-fixing capabilities (Palejkar et al. 2012; Seghieri et al. 2012), which may limit their contribution to soil fertility. Further research is needed to better understand the association between *Ziziphus mauritiana* trees and groundnut yields.

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. However, as discussed in Sect. "Data collection and cleaning", the recorded tree species align well with findings

from previous studies, supporting the general 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 (Diallo et al. 2019; Louppe et al. 1996; Stephen et al. 2020). Consequently, given the low tree densities observed in agroforestry systems within our sample, our study likely underestimates both the statistical and economic strength of the associations between agroforestry indicators and groundnut yields. Given the generally low tree density, and the resulting limited crown cover and shading, tree management practices such as thinning or pruning, which are typically used to reduce shade or tree density (Esche et al. 2023; Kerr and Haufe 2011), are likely to play only a minor role in shaping the association between trees and groundnut yields in our context. However, not accounting for such practices may additionally contribute to our estimates understating the full potential of tree–crop associations. Excluding younger trees, whose root systems may compete directly with those of crops (Bargués Tobella et al. 2017), could likewise contribute to our study understating the strength of the observed associations between trees and crops. Nevertheless, given the direction of potential bias, our results provide clear evidence of the existence and direction of associations 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.

Conclusion

Agroforestry systems in our sample vary considerably and show different associations with groundnut yield outcomes. Our analysis of how total tree quantity and tree species richness are associated with groundnut yields suggests that yields tend to increase initially with a higher number of trees and greater tree species richness in the agroforestry system, irrespective of tree species. However, at higher tree densities, the competition between trees and crops for space and nutrients appears

to outweigh the benefits. An additional tree or tree species per hectare relative to the sample mean is associated with a 1.1% and 5.0% increase in groundnut yield, respectively, suggesting that greater tree cover and species richness may be associated with higher groundnut productivity on smallholder farms.

Our results also suggest that *Faidherbia albida* trees are only associated with higher groundnut yields when the agroforestry system includes a greater number of these trees per hectare. Lower numbers of these trees per hectare are not associated with higher groundnut yields in our sample. A higher quantity per hectare and proximity of *Faidherbia albida* trees to crops may be important factors in shaping the association between trees of this species and groundnut yields. For the tree species *Cordia pinnata* and *Anogeissus leiocarpa*, higher numbers of trees per hectare are initially associated with higher groundnut yields. However, beyond a certain threshold, additional trees are associated with lower yields. In our sample, *Adansonia digitata* and *Ziziphus mauritiana* trees are present in over 10% of smallholders' agroforestry systems, but only at low quantities per hectare. As a result, we only observe statistically uncertain associations of these two species with groundnut yields. Further research could provide additional and more generalizable insights about the relationships of these tree species and crop yields.

We demonstrate that agroforestry practices are versatile, and tree quantity, tree species richness and tree species selection seem relevant factors 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 fostering synergies between land restoration and groundnut production. Increasing tree density or tree species richness and introducing or expanding specific species within existing agroforestry systems may foster such synergies.

Further research gathering detailed information, for instance on 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 and crop 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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Author contributions Luisa Müting: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization; Petros Suzgo Kay-ovo Mkandawire: Methodology, Software, Validation, Formal analysis, Writing—Review & Editing; Oliver Mußhoff:

Writing—Review & Editing, Supervision, Project administration, Funding acquisition.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Appendix A: Synthesis table of previous literature

Table 4 Overview of studies examining the relationship between agroforestry systems and crop yields in similar study contexts

Source	Agroforestry indicator/ tree species	Crop species	Detected relationship with yields	Geographical context	Method
Sinare et al. (2015)	Different agroforestry studies with individual agroforestry indicators and specific tree species	Different crop species	The study points out individual relationships between tree and crop species	Sudano-Sahelian West Africa	Structured literature review
Kuyah et al. (2019)	Different agroforestry studies with individual agroforestry indicators	Synthesis across different crop species	Generally positive	Sub-Saharan Africa	Structured literature review
Beillouin et al. (2021)	Different agroforestry studies with individual agroforestry indicators	Synthesis across different crop species	Generally positive	Worldwide	Structured literature review
Kassie (2016)	Adoption of Eucalyptus agroforestry (binary)	Maize	+	Ethiopia	Survey; Cobb–Douglas production function estimated through OLS regression
Coulitbaly et al. (2017)	Binary agroforestry indicator, where smallholders are classified as adopters if they maintained fertilizer trees continuously over a five-year period	Maize	+	Malawi	Survey; Endogenous switching regression
Amadu et al. (2020a)	Binary agroforestry indicator, where smallholders are classified as adopters if they have at least one fertilizer tree species (<i>Faidherbia albida</i> , <i>Gliricidia sepium</i> , <i>Tephrosia vogelii</i> , <i>Sesbania sesban</i> , <i>Cajanus cajan</i>) on their farmland	Maize	+	Malawi	Survey; Translog production function estimated through endogenous switching regression
Amadu et al. (2020b)	Binary agroforestry indicator, where smallholders are classified as adopters if they have at least one fertilizer tree species (<i>Faidherbia albida</i> , <i>Gliricidia sepium</i> , <i>Tephrosia vogelii</i> , <i>Sesbania sesban</i> , <i>Cajanus cajan</i>) on their farmland	Maize	+	Malawi	Survey; Double hurdle regression model

Table 4 (continued)

Source	Agroforestry indicator/ tree species	Crop species	Detected relationship with yields	Geographical context	Method
Louppe et al. (1996)	Presence of <i>Faidherbia albida</i> (trees (about 10 trees/ha) and proximity to trunks	Groundnut	Yields in <i>Faidherbia albida</i> plots were lower than in control plots overall; however, yields were higher closer to the tree trunks compared to areas further away	Senegal	Field experiment
Gaafar et al. (2006)	Density of <i>Acacia Senegal</i> trees (trees/ha)	Sorghum roselle	– –	Sudan	Field experiment
Adinya et al. (2010)	Binary indicator of smallholders having <i>Leuceana leucocephala</i> trees on their farmland	Groundnut	+	Nigeria	Field experiment installed on farmer fields; Cobb–Douglas production function; Multiple regression analysis
Fadl and Sheikh (2010)	Presence of <i>Acacia senegal</i> (375 trees/ha)	Groundnut Sesame Roselle	– – –	Sudan	Field experiment
Samba et al. (2012)	Soil was extracted at different distances to <i>Cordyla pinnata</i> trees and used to cultivate crop seeds	Groundnut	+	Senegal	Field experiment
Sanou et al. (2012)	Comparison of yields under and outside the canopy of <i>Adansonia digitata</i>	Millet	+	Burkina Faso	Field experiment
Bright et al. (2017)	Presence of <i>Piliostigma reticulatum</i> (1000 shrubs/ha)	Millet Groundnut	+	Senegal	Field experiment
Neya et al. (2019)	Tree canopy cover (in %)	Millet Red sorghum White sorghum	– – –	Burkina Faso	Field experiment
Goudiaby et al. (2020)	Presence of 8-year-old <i>Eucalyptus camaldulensis</i> trees (1500 trees/ha)	Groundnut	–	Senegal	Field experiment
Bright et al. (2021)	Presence of <i>Guiera senegalensis</i> trees (1500 shrubs/ha)	Millet Groundnut	+	Senegal	Field experiment
Bado et al. (2021)	Presence of <i>Ziziphus mauritiana</i> trees (80 trees/ha)	Millet Cowpea	+	Niger	Field experiment

Table 4 (continued)

Source	Agroforestry indicator/ tree species	Crop species	Detected relationship with yields	Geographical context	Method
Leroux et al. (2020)	Number of trees; tree density (trees/ha) and tree cover (in %) in agroforestry parklands	Millet	Relationships follow an inverted U-shape; The ideal tree cover seems to be at 30–40%	Senegal	Remote sensing
Roupsard et al. (2020)	Proximity to trunks of <i>Faidherbia albida</i> trees	Millet	+	Senegal	Remote sensing and field experiment
Leroux et al. (2022a)	Tree canopy cover of <i>Faidherbia albida</i> parklands; Proximity to <i>Faidherbia albida</i> trees	Millet	Greater proximity of crops to trees relates positively to yields, while the relationship with tree canopy cover follows an inverted U-shape	Senegal	Remote sensing
Leroux et al. (2022b)	Tree density (trees/ha) and tree species richness in surrounding agroforestry parklands	Millet	The relationship of tree density and yields follows an inverted U-shape, while tree species richness relates positively to yields	Senegal	Remote sensing

The described relationships do not imply causality

Table 5 Overview of studies supporting the validity of smallholders' recall of tree species occurrence in our study region

Author and year	Study area	Type of tree species data	Tree species prevalence in the study
Leroux et al. (2020)	Senegalese Groundnut Basin	Remote sensing + field inventory	<i>Faidherbia albida</i> identified as dominant species
Leroux et al. (2022b)	Senegalese Groundnut Basin	Household surveys + GPS tracking	<i>Faidherbia albida</i> , <i>Cordyla pinnata</i> , and <i>Adansonia digitata</i> identified as dominant species
Ndao et al. (2022)	Senegalese Groundnut Basin	Species distribution models (SDM) using 9258 georeferenced tree points	Among the 16 dominant specie are <i>Faidherbia albida</i> , <i>Azadirachta indica</i> , <i>Adansonia digitata</i> , and <i>Cordyla pinnata</i>
Leroux et al. (2022a)	Senegalese Groundnut Basin	Field data + Remote sensing	<i>Faidherbia albida</i> identified as dominant species
Roupsard et al. (2020)	Senegalese Groundnut Basin	Field transects + UAV imagery	<i>Faidherbia albida</i> identified as dominant species

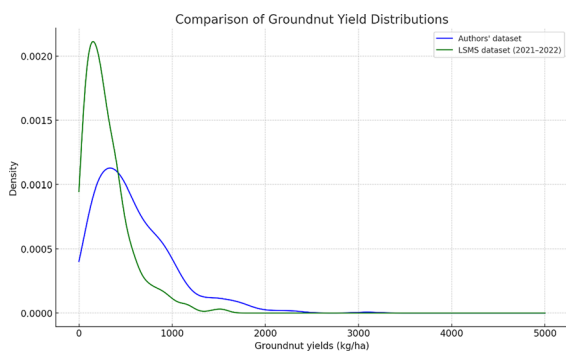


Fig. 3 Kernel density plots of groundnut yield distributions in the authors' dataset and the Living Standards Measurement Study dataset of Senegal, conducted in 2021–2022 by the Agence Nationale de la Statistique et de la Démographie (2024). For comparability, both distributions are limited to the range of 0 to 5000 kg/ha

Appendix B: Survey questions

Table 6 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 C: Comparison of groundnut yield distribution

Appendix D: OLS regression diagnostics

Table 7 Variance inflation factors (VIF) for explanatory variables in the regression model

Variable	VIF
Diagane Barka	2.38
Keur Maba	2.36
Taiba Niassene	2.28
Nguelou	2.24
Dianké Souf	2.24
Diossong	2.19
Ouadiour	2.17
Ndiébel	2.16
Paos Koto	2.14
Kahi	2.12
Passi	2.09
Keur Mboucki	2.02
Diokoul	1.94
Mbadakhouné	1.85
Age of household head	1.33
Family labor	1.28
Organic fertilizer	1.23
Secondary school	1.20
Female household head	1.19
Primary school	1.19
Pesticides	1.16
Hired labor	1.14
Improved seeds	1.10
Livestock labor power	1.05
Mean VIF	2.93

Table 8 Results of the Shapiro–Wilk test indicating normal distribution of regression residuals

Shapiro Wilk test				
Variable	W	V	z	Prob > z
residuals	0.99726	0.907	−0.234	0.59231

Appendix E: Robustness checks

Table 9 OLS estimates for Cobb–Douglas production function parameters on groundnut yield per hectare (ln) with agroforestry adoption dummy

Variables	Coefficient	95% Confidence interval
<i>Agroforestry dummy</i>		
Agroforestry adoption	0.306	−0.043 to 0.655
<i>Production inputs</i>		
Ln Family labor	0.083	−0.071 to 0.237
Hired labor	0.093	−0.122 to 0.308
Improved seeds	0.251	−0.218 to 0.720
Livestock labor power	−0.006	−0.390 to 0.378
Organic fertilizer	0.344	0.027 to 0.661
Ln Pesticides (liter/ hectare)	−0.071	−0.115 to −0.027
<i>Household characteristics</i>		
Age of household head	−0.010	−0.017 to −0.003
Female household head	−0.225	−0.486 to 0.036
Primary school	0.144	−0.180 to 0.468
Secondary school	0.201	−0.211 to 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 10 OLS estimates for Cobb–Douglas production function parameters on groundnut yield per hectare (ln) in a single regression model

Variables	Coefficient	95% Confidence interval
<i>Agroforestry variables</i>		
Tree quantity	0.018	−0.088 to 0.125
Tree quantity squared	−0.001	−0.002 to 0.000
Tree species richness	0.283	0.037 to 0.528
Tree species richness squared	−0.034	−0.075 to 0.007
Tree quantity x tree species richness	−0.006	−0.019 to 0.007
Faidherbia albida	−0.069	−0.197 to 0.059
Faidherbia albida squared	0.003	0.000 to 0.006
Cordyla pinnata	0.071	−0.105 to 0.247
Cordyla pinnata squared	−0.005	−0.019 to 0.009
Adansonia digitata	−0.362	−0.977 to 0.254
Adansonia digitata squared	0.112	−0.146 to 0.370
Anogeissus leiocarpa	0.043	−0.187 to 0.273
Anogeissus leiocarpa squared	0.012	−0.007 to 0.030
Ziziphus mauritiana	−0.006	−0.662 to 0.650

Variables	Coefficient	95% Confidence interval
Ziziphus mauritiana squared	−0.001	−0.326 to 0.324
<i>Production inputs</i>		
Ln Family labor	0.075	−0.081 to 0.231
Hired labor	0.084	−0.138 to 0.306
Improved seeds	0.214	−0.257 to 0.684
Livestock labor power	0.054	−0.345 to 0.453
Organic fertilizer	0.343	0.026 to 0.660
Ln Pesticides (liter/ hectare)	−0.076	−0.121 to −0.030
<i>Household characteristics</i>		
Age of household head	−0.009	−0.017 to −0.002
Female household head	−0.199	−0.471 to 0.072
Primary school	0.157	−0.183 to 0.497
Secondary school	0.262	−0.174 to 0.698
R ² adjusted	0.239	
Observations		492

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

Table 11 OLS estimates for Cobb–Douglas production function parameters on groundnut yield per hectare (ln), using the Simpson diversity index as a measure of tree species diversity

Variables	Coefficient	95% Confidence interval
<i>Agroforestry variables</i>		
Tree quantity	0.023	−0.023 to −0.068
Tree quantity squared	−0.001**	−0.002 to −0.000
Simpson diversity index	0.444**	0.020 to 0.868
<i>Production inputs</i>		
Ln Family labor	0.069	−0.090 to 0.229
Hired labor	0.093	−0.118 to 0.303
Improved seeds	0.223	−0.235 to 0.682
Livestock labor power	0.024	−0.375 to 0.422
Organic fertilizer	0.320**	0.028 to 0.612
Ln Pesticides (liter/ hectare)	−0.072***	−0.116 to −0.028
<i>Household characteristics</i>		
Age of household head	−0.010***	−0.017 to −0.002
Female household head	−0.220*	−0.482 to 0.042
Primary school	0.160	−0.164 to 0.483
Secondary school	0.206	−0.207 to 0.619
R ² adjusted	0.243	
Observations		492

Robust standard errors; Intercept and commune-level fixed

effects are included in the models but not reported for brevity

Table 12 OLS estimates for Cobb–Douglas production function parameters on groundnut yield per hectare (ln), using the Shannon diversity index as a measure of tree species diversity

Variables	Coefficient	95% Confidence interval
<i>Agroforestry variables</i>		
Tree quantity	0.025	− 0.021 to 0.070
Tree quantity squared	− 0.001**	− 0.002 to − 0.000
Shannon diversity index	0.223*	− 0.015 to 0.460
<i>Production inputs</i>		
Ln Family labor	0.072	− 0.088 to 0.231
Hired labor	0.095	− 0.116 to 0.305
Improved seeds	0.224	− 0.238 to 0.686
Livestock labor power	0.023	− 0.374 to 0.419
Organic fertilizer	0.330**	0.037 to 0.624
Ln Pesticides (liter/hectare)	− 0.071***	− 0.115 to − 0.027
<i>Household characteristics</i>		
Age of household head	− 0.010***	− 0.017 to − 0.003
Female household head	− 0.225*	− 0.489 to 0.038
Primary school	0.156	− 0.167 to 0.480
Secondary school	0.196	− 0.216 to 0.607
R ² adjusted	0.241	
Observations		492

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

Table 13 OLS estimates for Cobb–Douglas production function parameters on groundnut yield per hectare (ln), including trees planted or regenerated within the past three years

Variables	Coefficient	95% Confidence interval	Coefficient	95% Confidence interval
<i>Agroforestry variables</i>				
Tree quantity	0.018	− 0.032 to 0.068		
Tree quantity squared	− 0.001	− 0.002 to 0.000		
Tree species richness	0.262	0.027 to 0.497		
Tree species richness squared	− 0.037	− 0.078 to 0.004		

Variables	Coefficient	95% Confidence interval	Coefficient	95% Confidence interval
Tree quantity x tree species richness	0.001	− 0.009 to 0.012		
Faidherbia albida			− 0.033	− 0.130 to 0.064
Faidherbia albida squared			0.002	− 0.002 to 0.005
Cordyla pinnata			0.133	− 0.007 to 0.273
Cordyla pinnata squared			− 0.016	− 0.028 to − 0.004
Adansonia digitata			− 0.146	− 0.743 to 0.450
Adansonia digitata squared			0.014	− 0.232 to 0.259
Anogeisus leiocarpa			0.106	− 0.117 to 0.330
Anogeisus leiocarpa squared			− 0.004	− 0.027 to 0.019
Ziziphus mauritiana			0.258	− 0.380 to 0.896
Ziziphus mauritiana squared			− 0.104	− 0.421 to 0.213
<i>Production inputs</i>				
Ln Family labor	0.064	− 0.093 to 0.221	0.103	− 0.054 to 0.260
Hired labor	0.074	− 0.142 to 0.291	0.118	− 0.099 to 0.335
Improved seeds	0.231	− 0.227 to 0.689	0.245	− 0.231 to 0.720
Livestock labor power	0.041	− 0.352 to 0.434	0.024	− 0.363 to 0.411
Organic fertilizer	0.281	− 0.030 to 0.592	0.434	0.131 to 0.738
Ln Pesticides (liter/hectare)	− 0.074	− 0.119 to − 0.030	− 0.068	− 0.112 to − 0.023
<i>Household characteristics</i>				

Variables	Coefficient	95% Confidence interval	Coefficient	95% Confidence interval
Age of household head	−0.009	−0.017 to −0.002	−0.010	−0.018 to −0.003
Female household head	−0.204	−0.466 to 0.059	−0.227	−0.498 to 0.043
Primary school	0.171	−0.158 to 0.499	0.149	−0.188 to 0.486
Secondary school	0.236	−0.185 to 0.656	0.189	−0.231 to 0.609
R ² adjusted	0.242		0.226	
Observations	492		492	

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

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