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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

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

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

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

34 Past experimental field studies in the context of the Sahel region, as structurally reviewed by e.g. Sinare et al.  
35 (2015), demonstrate in more detail, that specific tree species in agroforestry systems potentially increase the  
36 yields of groundnuts or millet, while others might have detrimental effects on crop yields. Adinya et al. (2010),  
37 for instance, find a positive association of agroforestry systems with trees of the species *Leuceana leucocephala*  
38 and groundnut yields in Nigeria. In the context of the Senegalese Groundnut Basin, Louppe et al. (1996) detect  
39 lower groundnut yields in vicinity of *Faidherbia albida* trees compared to control areas, while Rouspard et al.  
40 (2020) find increased millet yields in agroforestry systems with *Faidherbia albida* trees. Bright et al. (2021)  
41 find increased millet yields in a groundnut and millet agroforestry system with trees of the species *Guiera*  
42 *senegalensis*. Bright et al. (2017) also find a positive association between the presence of the shrub *Piliostigma*  
43 *reticulatum* on experimental fields in Senegal and yields of groundnuts and millet. In another experimental  
44 agroforestry system in Senegal however, Goudiaby et al. (2020) find a statistically significant decrease of  
45 groundnut yields if intercropped with trees of the species *Eucalyptus camaldulensis* compared to control fields.  
46 Fadl and Sheikh (2010) also find lower yields of groundnut, sesame and roselle in an agroforestry system with  
47 *Acacia senegal* trees as compared to the control fields in an experiment situated in Sudan. While such a research  
48 design provides in depth insights into the relationships between agroforestry practices and yields over time, they  
49 are limited to the specific experimental sites and agroforestry systems, and do not reflect real-life scenarios of  
50 smallholders' agricultural systems and their management. As agroforestry systems have been found to be  
51 particularly heterogeneous in the Sudano-Sahelian climate zone (Ndao et al. 2021), evidence derived from  
52 experimental fields to those systems is difficult to generalize.

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

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

69 species diversity. Third, we expect that different tree species relate differently to soil fertility and yield outcomes  
70 due to their individual species-specific characteristics.

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

## 2. Materials

### 2.1 Study area

77 Our study is located in the Senegalese Groundnut Basin, which lies within the Sudano-Sahelian climate zone of  
78 the Sahel region. The Sudano-Sahelian climate is characterized by annual precipitation rates of 500 mm to 900  
79 mm (FAO 2002) and stretches along the Sahelian climate zone from West to East Africa, bordering the Sahara  
80 Desert to the south (Yobom and Le Gallo 2021). The regions' economy relies on agricultural production of the  
81 mainly smallholding farmers (Baoua et al. 2021; FAO 2024), with groundnuts being the main export good  
82 (Georges et al. 2016; Bakoye et al. 2019; OEC 2021). Next to groundnuts, smallholders in the Sudano-Sahelian  
83 climate zone mainly produce millet and maize (Georges et al. 2016; Yobom and Le Gallo 2021). Agricultural  
84 production is mainly rainfed, and the agricultural season thus aligns with the rainy season from July to October  
85 (Cotillon et al. 2021). The Groundnut Basin is the main agricultural region of Senegal, making up about 70%  
86 of the country's arable land (Faye and Du 2021). In recent decades, the effects of climate change pose a severe  
87 threat to the agricultural production systems of smallholders in the Sahel region (Mbow et al. 2020). While  
88 managing trees on agricultural land is a traditional practice in this region (Parton et al. 2004; Cotillon et al.  
89 2021), agroforestry has been promoted in recent decades as one of the most promising natural regeneration  
90 practices in this context (Diallo et al. 2020). Groundnut, millet, and maize cropping systems are suitable for the  
91 integration of agroforestry (Diallo et al. 2020). Predominant agroforestry tree species in the Senegalese  
92 Groundnut Basin are *Faidherbia albida* and *Cordyla pinnata* (Sambou et al. 2024b), with *Faidherbia albida*  
93 primarily found in the northern regions and *Cordyla pinnata* mainly located in the southern parts of the  
94 Groundnut Basin (Leroux et al. 2022b).

### 2.2. Data collection and cleaning

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

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

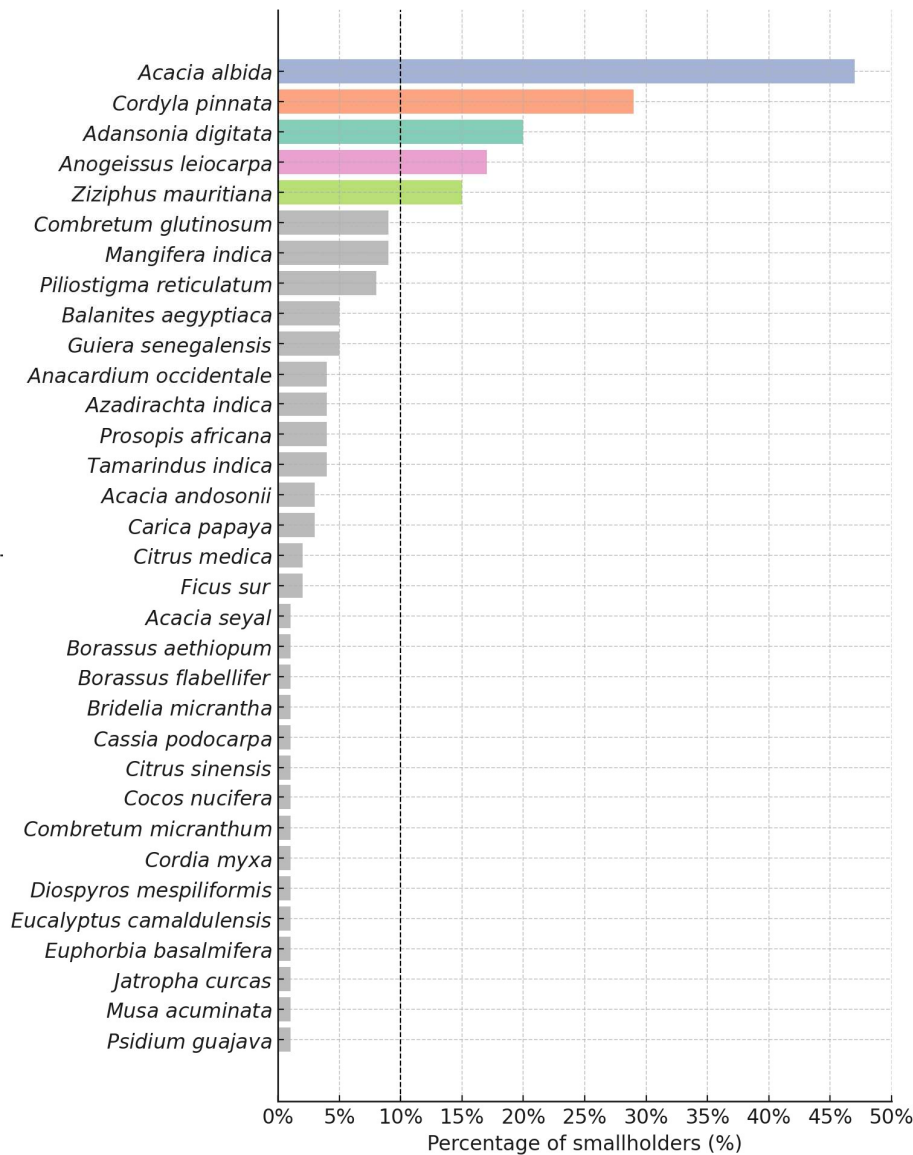
### 2.3. Most prevalent tree species in our data

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

128 For our analysis, we focus on three agroforestry measures, (a) tree quantity per hectare, (b) tree species diversity,  
129 and (c) the quantities per hectare of the most prevalent tree species in our data. Tree quantity per hectare is a  
130 ratio of total number of trees to the hectares of land. Tree species diversity reflects the total number of different  
131 tree species reported by respondents. The most prevalent tree species in our data are those reported by at least  
132 10% of smallholders in our sample. Figure 1 displays the tree species reported by smallholders, highlighting the  
133 most prevalent species in our sample. The frequent reporting of *Faidherbia albida*, *Adansonia digitata*,



134 *Anogeissus leiocarpa* and *Ziziphus mauritiana* aligns with the studies by Leroux et al. (2020) and Ndao et al.  
 135 (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.

136 Almost half of our sampled households reported having trees of the species *Faidherbia albida*. Due to its reverse  
 137 phenology, *Faidherbia albida* trees increase soil fertility by adding biomass to the soil during the rainy season  
 138 in the Sudano-Sahelian climate zone (Mokgolodi et al. 2011). Furthermore, soils under the canopies of  
 139 *Faidherbia albida* trees have shown higher levels of organic carbon and total nitrogen compared to soils outside  
 140 the canopies (Stephen et al. 2020). While *Faidherbia albida* trees fix nitrogen in soils, the nitrogen-fixing  
 141 capacity of this species is comparatively low. In a field experiment, Ndoye et al. (1995) for instance compared  
 142 the nitrogen-fixing capacity of different *Acacia* species and found relatively low levels of nitrogen-fixation for  
 143 *Faidherbia albida* trees compared to other species such as *Acacia seyal* and *Acacia senegal*. However,

144 *Faidherbia albida* trees can adapt to different climatic conditions and soil types (Sambou et al. 2024b). While  
145 multiple studies, such as Roupsard et al. (2020), or Leroux et al. (2022a, 2022b) find a beneficial relationship  
146 between *Faidherbia albida* parklands and millet productivity, scarce evidence, such as the study of Louppe et  
147 al. (1996), suggests a detrimental relationship between this tree species and groundnut yields. Next to  
148 *Faidherbia albida*, *Codyla pinnata* is one of the main agroforestry tree species in Senegal (Sambou et al. 2024b).  
149 This tree species is mainly known for its nitrogen-fixing capacities (Sambou et al. 2024b). Being a deciduous  
150 tree species, *Codyla pinnata* trees shed their leaves and contribute to soil fertility through increased biomass.  
151 Unlike *Faidherbia albida* trees however, *Codyla pinnata* trees do not shed their leaves at the beginning of the  
152 agricultural season but during the dry season (Samba 2001). *Adansonia digitata*, commonly known as Baobab,  
153 is one of the most important agroforestry tree species across the Sahel region, primarily providing food, fodder,  
154 and medicine (Kalinganire 2022). *Adansonia digitata* also holds substantial cultural importance and plays an  
155 essential role in various cultural ceremonies (Meinhold and Darr 2021). However, *Adansonia digitata* does not  
156 have any specific soil fertility-enhancing characteristics (Kyndt et al. 2009; Meinhold and Darr 2021). Also  
157 *Anogeissus leiocarpa* is a deciduous tree species that sheds its leaves during the dry season, thereby contributing  
158 to soil organic matter and increasing soil fertility (Seghieri et al. 2012). While *Anogeissus leiocarpa* is not a  
159 nitrogen-fixing species, Mesele and Huising (2024) find increased nitrogen and carbon content in the soils under  
160 its stand in the Opara forest reserve in Nigeria. *Ziziphus mauritiana* is an evergreen species (Orwa et al. 2009;  
161 Seghieri et al. 2012). The species is non-native to Senegal (Orwa et al. 2009) but rather common in our  
162 respondents agroforestry systems. As this tree species is very heat and drought resistant, it is grown to protect  
163 soils and crops from heat and erosion (Orwa et al. 2009). In their experimental study in Niger, Bado et al. (2021)  
164 show a positive association of *Ziziphus mauritiana* in millet and cowpea agroforestry systems with organic  
165 carbon and nitrogen levels in the soil, even though *Ziziphus mauritiana* is not a nitrogen-fixing tree species  
166 (Palejkar et al. 2012).

### 3. Econometric analysis

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

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

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

$$\ln Y_i = \beta_0 + \sum_{k=1}^K \beta_k \ln X_{ik} + \gamma_1 Z_i + \gamma_2 A Q_i + \gamma_3 A Q_i^2 + \gamma_4 A D_i + \gamma_5 A D_i^2 + \gamma_6 A D_i A Q_i + \gamma_7 C + \varepsilon_i \quad (1)$$

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

$$\ln Y_i = \beta_0 + \sum_{k=1}^K \beta_k \ln X_{ik} + \gamma_1 Z_i + \gamma_2 A S_i^\pi + \gamma_3 (A S_i^\pi)^2 + \gamma_4 C + \varepsilon_i \quad (2)$$

195 In both models,  $Y_i$  represents groundnut yield, in kg per hectare, for household  $i$ .  $X_i$  is a vector of  $k$  inputs and  
 196  $Z_i$  is a vector of socio-demographic variables.  $\varepsilon_i$  denotes the stochastic error term in our models. We selected  
 197 the input and socio-demographic control variables to include in our model (see Table 1) based on the studies of  
 198 Teuscher et al. (2015), Amadu et al. (2020a), Branca et al. (2021) and Shah et al. (2022). In the first model,  $A Q_i$   
 199 is an indicator for (a) the quantity of agroforestry trees per hectare, and  $A D_i$  represents (b) tree species diversity,  
 200 i.e. the number of different tree species growing on the land of household  $i$ . In the second model,  $A S_i^\pi$  represents  
 201 (c) the quantity per hectare of the most prevalent tree species, denoted by  $\pi$ , in our data: *Faidherbia albida*,  
 202 *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa*, and *Ziziphus mauritiana*. The squared terms of our  
 203 agroforestry indicators serve to derive information on a potential saturation in the relationship between total tree  
 204 quantity per hectare, tree species diversity and tree quantities per hectare of the tree species and groundnut  
 205 yields.  $C$  represents the commune level fixed effects, which are included in the model to account for spatial  
 206 differences in climate, environmental and institutional factors that might affect crop yield and growth of specific  
 207 tree species simultaneously (Kuyah et al. 2019; Sambou et al. 2024b). The outcome variable and the continuous

208 input variables were log-transformed employing the natural logarithm. Following Battese (1997), we added a  
209 small constant, in our case 0.01, to all zero input values before we log-transformed the variables. The other  
210 variables were included in the model without transformation.

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

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

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

#### 4. Results and discussion

##### 4.1. Descriptive statistics and variables

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

228 Table 1 shows the descriptive statistics of our groundnut yield outcome variable, our agroforestry indicators,  
229 control variables for input use and household characteristics, as well as the commune dummies used as fixed  
230 effects in our regressions. We recorded a wide variety of agroforestry systems on groundnut farms in the  
231 Senegalese Groundnut Basin. These systems included up to 50 trees per hectare of up to 7 different tree species.  
232 Specifically, smallholders reported up to 30 trees of *Faidherbia albida* and up to 14 *Cordyla pinnata* trees per  
233 hectare. The maximum number of *Adansonia digitata* trees in these agroforestry systems is 3 trees per hectare.  
234 Smallholders further reported up to 12 trees per hectare of the species *Anogeissus leiocarpa*. For *Ziziphus*  
235 *mauritiana*, the highest reported number was 2.5 trees per hectare. In these diverse systems, smallholders  
236 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
<b>Outcome variable</b>					
Groundnut yield	Groundnut yield of the 2022 agricultural season in kg per hectare	835.20	1002.15	33.33	5000.00
<b>Agroforestry variables</b>					
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 <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
<b>Production inputs</b>					
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
<b>Household characteristics</b>					
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			
<b>Commune Dummies</b>					
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

237 Table 2 shows the results of the OLS regression analyses, first, including the variables for (a) tree quantity per  
238 hectare and (b) tree species diversity, and second, (c) the tree quantities per hectare of the tree species *Faidherbia*  
239 *albida*, *Cordyla pinnata*, *Adansonia digitata*, *Anogeissus leiocarpa* and *Ziziphus mauritiana*. To ground our  
240 study in existing literature that examines binary agroforestry adoption and its impact on crop yield outcomes,  
241 we also ran our regression model using a binary agroforestry adoption indicator. The results are reported in  
242 Appendix B and are consistent with past studies, such as those of Coulibaly et al. (2017), Amadu et al. (2020a),  
243 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	
<b>Agroforestry variables</b>						
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
<b>Production inputs</b>						
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
<b>Household characteristics</b>						
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						

244 For our control variables, the regression results show that smallholders utilizing organic fertilizers such as  
245 manure, compost, or crop residues on their groundnut fields obtained higher groundnut yields in the 2022

246 agricultural season. On the contrary, a higher application of pesticides on fields relates negatively to groundnut  
247 yields. This might be related to pesticide use being correlated with smallholders experiencing pest infestations  
248 that adversely affect yields, which is a relationship shown by e.g. Asare-Nuamah (2022). Family labour power,  
249 hiring labour and animal labour power in form of having at least one cow, horse or donkey for agricultural work,  
250 relate positively to groundnut yields. Additionally, the utilization of improved seeds relates to slightly higher  
251 groundnut yield outcomes. We also observe that the household head being female and a higher age of the  
252 household head are negatively related to groundnut yields, whereas having obtained primary and secondary  
253 school education is positively associated with groundnut yields. The generally positive relationships of  
254 agricultural input variables and household characteristics with groundnut yields align with previous crop  
255 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

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

*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  $(exp^{marginal\ product} - 1) \cdot 100\%$ .

279 Our tree species diversity indicator provides more detailed information on the compositions of agroforestry  
280 systems. The tree species diversity variable shows a much stronger and statistically significant relationship to  
281 groundnut yields. Additional tree species on the agricultural land relate to relatively large initial percentage  
282 increases in groundnut yields per hectare. When increasing the number of tree species in the agroforestry system  
283 from the rounded sample mean of 2 to 3 tree species and holding other factors constant, we would expect a  
284 5.02% increase in groundnut yields, based on our results. The confidence interval indicates high statistical  
285 certainty for our estimated coefficient. However, the coefficient for the squared term of tree species diversity  
286 suggests that after reaching a saturation point, each additional tree species is associated with a percentage  
287 reduction in groundnut yields. The literature on the relationship between tree species diversity in agroforestry  
288 systems and crop yield outcomes is scarce. However, the results of the study by Nesper et al. (2017), the  
289 structured literature review by Kuyah et al. (2019) and the study by Leroux et al. (2022b) corroborate our  
290 findings. Nesper et al. (2017) found increased coffee bean production in agroforestry systems with higher shade  
291 tree species diversity in India. Similarly, Kuyah et al. (2019) reported that past studies observed positive crop  
292 yield effects in mixed agroforestry systems featuring both nitrogen-fixing and non-nitrogen-fixing tree species.  
293 The results of Leroux et al. (2022) suggest a positive relationship between millet yields and tree species diversity  
294 in the landscape surrounding smallholder fields in Senegal. Additionally, Soti et al. (2019) and Sow et al. (2020)  
295 demonstrate that landscape diversity can positively influence pest control, providing a pathway to enhance crop  
296 yields. Studies focusing on soil fertility in forest areas have further identified higher soil organic carbon and  
297 greater soil fauna diversity, suggesting higher soil fertility, in forests with greater tree species diversity  
298 (Korboulewsky et al. 2016; Li et al. 2019). These findings might be transferred to the agroforestry context to  
299 explain our results. The interaction term between tree quantity per hectare and tree species diversity indicates  
300 that having more trees and a greater variety of tree species in the agroforestry system enhances the positive  
301 relationship of the two indicators with groundnut yields.



#### 4.2.2. Quantities of the most prevalent tree species

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

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

329 For the relationship between the quantity of *Cordyla pinnata* trees per hectare and groundnut yields, we observe  
330 an initially positive association of groundnut yields. The estimated coefficients of 0.13 for *Cordyla pinnata* trees  
331 per hectare and -0.016 for the squared term of this variable, suggests that an additional *Cordyla pinnata* tree per  
332 hectare compared to the sample mean is associated with an increase in groundnut yields of 10.30%. After  
333 reaching a tipping point of *Cordyla pinnata* trees per hectare, additional trees of this species are however  
334 associated with a decrease in yields. Our results align with past experimental field studies in the Senegalese  
335 context. For instance, Samba et al. (2012) reported increased soil fertility and groundnut yields in experimental  
336 agroforestry systems featuring *Cordyla pinnata* trees, and Diatta et al. (2017) documented increased soil fertility

337 in *Cordyla pinnata* agroforestry parklands. The nitrogen-fixing capacity of this tree species and its leaf litter  
338 contribute to increased soil fertility (Sambou et al. 2024b; Samba 2001). In line with Kuyah et al. (2019), the  
339 coefficient of the squared term for *Cordyla pinnata* trees per hectare suggests competition for space and  
340 nutrients between these trees and groundnuts if the trees grow too densely.

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

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

367 Our regression results further indicate an increase in groundnut yields for additional *Ziziphus mauritiana* trees  
368 per hectare. The confidence interval for the statistical certainty of this estimate is however wider compared to  
369 tree quantities of the other tree species, ranging between -0.412 and 0.889. Based on our estimates, we would  
370 expect an increase of 2.43% for one additional *Ziziphus mauritiana* tree per hectare compared to its sample  
371 mean. The negative estimator for the squared term of tree quantities for *Ziziphus mauritiana* suggests a likely

372 decrease in groundnut yields associated with additional trees of this species after a certain quantity of these trees  
373 is reached. The confidence interval for this estimate is also rather wide and ranges from -425 to 0.211. The wide  
374 confidence intervals for our estimated coefficients indicate that the number of *Ziziphus mauritiana* trees might  
375 not be statistically related to groundnut yield outcomes in our sample, with potential yield changes varying  
376 widely. These statistically uncertain results diverge from Bado et al. (2021), who reported increased soil fertility  
377 in agroforestry systems with *Ziziphus mauritiana* trees. However, our findings might be due to *Ziziphus*  
378 *mauritiana* trees not shedding their leaves and lacking nitrogen-fixing capabilities (Palejkar et al. 2012; Seghieri  
379 et al. 2012).

#### 4.3. Limitations

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

#### 5. Conclusion

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

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

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

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

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

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

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### CRedit authorship contribution statement

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

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### Declaration of Competing Interest

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

### Data availability

450 Data will be made available at request.

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

451 During the preparation of this work, the authors utilized ChatGPT 3.5 to enhance the article's readability and  
452 assist in creating Figure 1. After using this tool/service, the authors reviewed and edited the content as needed  
453 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)	
...	
<b>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.</b>	
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
<b>Repeat for each tree species:</b>	
<b>Now, I will ask you questions about the different tree species one by one.</b>	
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
<b>Have you planted trees on the land you use for agriculture in the past three years?</b>	
How many different tree species have you planted on this land?	Number
<b>Repeat for each tree species:</b>	
<b>Now, I will ask you questions about the different tree species one by one.</b>	
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	
<b>Agroforestry dummy</b>			
Agroforestry adoption	0.306	-0.043	0.655
<b>Production inputs</b>			
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
<b>Household characteristics</b>			
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	
<b>Agroforestry variables</b>			
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
<b>Production inputs</b>			
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
<b>Household characteristics</b>			
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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