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No. 21

A fruitful endeavor: Smallholders' climate change adaptation strategies through tree species selection for planting

> Luisa Müting Oliver Mußhoff

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1 Abstract

2 In the African Sahel region, arable land is being increasingly threatened by the implications of climate 3 change. Agroforestry offers opportunities to adapt to these challenges by enhancing ecological 4 resilience and food production through intensification and/or diversification by integrating fertilizer 5 and/or fruit trees. While previous studies have explored agroforestry adoption broadly, little is known 6 about how smallholders' tree species selection aligns with their perceptions of climate change. This 7 study investigates whether Senegalese smallholders plant trees and how they select fertilizer and/or fruit 8 tree species to adapt their food production to perceived climate change effects. Using survey data from 9 606 smallholders in the Senegalese Groundnut Basin, we grouped reported tree species into fertilizer 10 and fruit tree categories and applied a Heckman regression model for our analysis. Our results show 11 that resource constraints, such as limited access to wells, secure land tenure, agroforestry knowledge, 12 or financial resources are main barriers to tree planting. Climate change perceptions, however, affect 13 species selection, with fruit trees likely being selected when for instance land degradation or shortened 14 rainy seasons are perceived as threats. The perception of soil salinization discourages fertilizer and fruit 15 tree planting. Policy efforts should focus on improving resource access, promoting salt-tolerant tree species, and encouraging smallholders to integrate both, fertilizer and fruit trees into cropping systems 16 17 to enhance intensification and diversification of food production as holistic adaptation strategy to 18 climate change effects.

19 *Keywords*: Climate change adaptation; Agroforestry; Tree species selection; Land restauration;

20 Smallholders; Sahel

21 JEL codes: Q12, Q19, Q23; Q54

1. Introduction

In the African Sahel region, the majority of the populations' livelihood and food security depends on small scale farming and thus on natural resources that have been increasingly threatened by the implications climate change (Mbow et al. 2020b; UNCCD 2024). Developing and promoting agricultural practices that not only mitigate climate change but also provide smallholder farmers with tools to adapt their food production systems to it, is thus a priority in international and local policy discourse and intervention design (Mbow et al. 2020a). In this context, agroforestry, the management of trees in agricultural systems, has been found to enhance both objectives (Cardinael et al. 2021).

29 An increase of tree cover, for instance through tree planting, enhances climate change mitigation by 30 sequestering carbon from the atmosphere and storing it in the soil (Cardinael et al. 2021). Additionally, 31 agroforestry systems have been found to simultaneously enhance the resilience of production systems 32 to weather extremes such as high temperatures, strong winds, droughts or heavy rainfall through 33 improved water-holding capacity of soils (Chirwa et al. 2007), reduced surface temperatures, 34 evapotranspiration and enhanced water use efficiency (Wu and Wang 2024), or erosion control (van 35 Ramshorst et al. 2022). Agroforestry practices have also been shown to enhance smallholders' livelihoods and livelihood resilience to climate change by offering a range of potential benefits (Quandt 36 37 et al. 2017; Mbow et al. 2020a; Mbow et al. 2014; Lasco et al. 2014). The integration of trees into crop 38 production systems has for instance the potential to intensify and/or diversify smallholders' food 39 production, depending on the selection of fertilizer and/or fruit tree species (Chen et al. 2018).

40 Past studies have analyzed smallholders' perception of climate change in relation to determinants for 41 their adoption of agroforestry as one of multiple climate change adaptation strategies in Sub-Saharan Africa. Tambo and Abdoulaye (2013) for instance, show that Nigerian smallholders perceive changes 42 43 in climatic conditions and pursue tree planting as one of multiple main adaptation strategies. Belay et 44 al. (2017) and Chemeda et al. (2023) investigate Ethiopian smallholders' perception of climate change and drivers of their adoption of diverse adaptation strategies including tree planting. In a later study, 45 46 Belay et al. (2022) analyze Ethiopian smallholders' uptake of at least one climate smart agricultural 47 practice, such as agroforestry, conditional on their awareness of climate change. Thinda et al. (2020) 48 analyze how South African smallholder farmers choose to adopt multiple climate change adaptation 49 strategies, including insurance uptake, migration and tree planting. In the Ugandan context, Atube et al. 50 (2021) analyzed determinants of smallholders' adoption of diverse adaptation strategies including tree 51 planting. In open focus group discussions in Kedougou, Senegal, Papa et al. (2020) further reveal that 52 smallholders recognize the various ecosystem services, agroforestry practices offer and use agroforestry 53 as a strategy to adapt to climate change. While these studies examine smallholders' perceptions of 54 climate change and their general adoption of agroforestry as one of several adaptation strategies, we do 55 not know much about the rationale of smallholders planting trees and selecting tree species, particularly

56 in response to climate change. Further, climate change drives context specific environmental stressors 57 (IPCC 2020) to agricultural practices that might encourage different adaptation strategies. 58 Smallholders' tree species selection within their tree planting decisions, as detailed adaptation strategy 59 of production intensification and/or diversification in relation to locally relevant climate change effects, 60 remains unexplored.

61 In this paper, we thus address the following questions: Do smallholders in the Sahel region plant trees 62 on their farmland as an adaptation strategy to their perception of local climate change effects? 63 Additionally, do they select fertilizer and/or fruit tree species for planting as an adaptation strategy, 64 reflecting an aim to intensify and/or diversify food production? Our study provides a novel perspective on agroforestry for climate change adaptation by examining smallholders' perceptions of locally 65 relevant climate change effects and their detailed agroforestry-based adaptation strategies beyond mere 66 67 adoption. Therefore, we distinguish between the potential adaptation strategies of food production 68 intensification and diversification by categorizing tree species according to those objectives as fertilizer 69 or fruit trees.

70 Understanding whether and how smallholders select tree species for planting to use agroforestry to 71 adapt to climate change effects is crucial for assessing their livelihood strategies in the context of 72 climate change. Learning about smallholders' decisions and aims within agroforestry practices, would 73 further support policies and interventions in tailoring agroforestry practices to their specific needs, 74 preferences and strategies. With agroforestry being a key practice promoted in the Sahel region to 75 mitigate and adapt smallholder farms to climate change, understanding smallholders' tree planting 76 decisions concerning agroforestry as climate change adaptation strategy is crucial for policy and 77 intervention design. Moving beyond the analysis of general agroforestry adoption as a climate change 78 adaptation strategy, our research generates novel insights that support the development of holistic 79 climate change adaptation strategies to enhance food production through both intensification and diversification by strategically developing smallholders' agroforestry practices. 80

2. Materials and Methods

2.1 Study area

Our research focuses on smallholder farmers in the Senegalese Groundnut Basin. Senegal is located in the western Sahel, and the Groundnut Basin is largely located within the Sudano-Sahelian climate zone (Ricome et al. 2017), which is characterized by annual precipitation rates of 500 to 900 mm (FAO 2002). Within the Sudano-Sahelian climate zones across the Sahel region, including the Senegalese Groundnut Basin, the primarily smallholding farmers produce mainly groundnuts as cash crop with millet, maize and/or sorghum as food crops in mainly rainfed production systems (Georges et al. 2016; Jellason et al. 2021; Yobom and Le Gallo 2021). The agricultural production systems of those 88 smallholders in the Sudano-Sahelian climate zones across the Sahel region are facing severe threats due 89 to the effects of climate change (Mbow et al. 2020a; Yobom and Le Gallo 2021). Average annual 90 temperatures are increasing, rainy seasons are becoming shorter, heavy rainfalls occur more frequently, 91 groundwater levels fluctuate greatly and soils are becoming more saline (Biasutti 2019; Mbow et al. 92 2020a; Yobom 2020; Ascott et al. 2022; Ba et al. 2023; Sambou et al. 2024b). While the integration 93 and tree management on farmland have been practiced for centuries in Senegal and other Sahelian 94 countries (Parton et al. 2004; Cotillon et al. 2021), agroforestry is increasingly recognized and promoted 95 by policymakers and researchers as a promising approach for both mitigating and adapting to climate 96 change in this region (Sissoko et al. 2011; Diallo et al. 2020). However, agroforestry practices still need 97 to be expanded in Senegal and other Sahelian countries to meet land restoration targets formulated by 98 e.g. the Great Green Wall initiative or the African Forest Landscape Restoration (Grovermann et al. 99 2023; Karambiri et al. 2023; UNCCD 2024).

2.2 Assessing perceptions of climate change effects

100 Measuring smallholders' perceptions of climate change is inherently complex, as the concept is broad 101 and encompasses processes that extend beyond the human lifespan (UN 2025). In previous climate 102 change adaptation studies, smallholders' climate change perception has typically been elicited by 103 assessing their perception of locally relevant environmental stressors, such as rainfall variability, 104 extreme weather events or poor soil fertility, or changes in rainfall patterns, which are known to be 105 driven by climate change. Mertz et al. (2009) and Papa et al. (2020) for instance, assess Senegalese 106 smallholders perceptions of e.g. intensive rainfalls and inundations or short rainy seasons in relation to 107 their adaptation strategies. Bessah et al. (2021) and Umar (2024) respectively link Ghanaian and 108 Nigerian smallholders' perceptions of, for instance, poor soil fertility or changes in rainfall patterns to 109 their adaptation strategies. Likewise, Belay et al. (2017), Belay et al. (2022), and Chemeda et al. (2023), 110 assess Ethiopian smallholders' perception of e.g. rainfall variability to understand their related 111 adaptation strategies. Mertz et al. (2009) and Zougmoré et al. (2023) further point out that smallholders 112 knowledge and perception of climate change effects is consistent with meteorological data. The 113 perceptions of environmental stressors thus serve as tangible indicators for the perception of climate 114 change effects.

For our study, we follow this approach by assessing smallholders' perceptions of locally relevant climate change related environmental stressors as indicators for their perceptions of climate change effects. This approach allows us to capture smallholders' lived experiences with climate change effects, even if they themselves do not explicitly attribute these stressors to climate change. The climate change related environmental stressors, relevant in our study context, have been identified in past studies. Mbow et al. (2020a), Yobom (2020) or Benjaminsen (2021) for instance, highlight that climate change is driving the degradation of arable land in the Sahel region, including the Senegalese Groundnut Basin. Sylla et 122 al. (2016), Biasutti (2019) and Gaetani et al. (2020) describe that rainy seasons are becoming shorter 123 and heavy rains are occurring more frequently due to climate change. In their studies, Diack et al. 124 (2015), Sambou et al. (2016) and Ba et al. (2023) name the salinization of soils as a major pressing issue in Senegal, driven by climate change. Additionally, Ascott et al. (2022) and Podgorski et al. (2024) 125 126 state that groundwater levels in the Sahel region are highly variable and sensitive to climate change. 127 Smallholders perception of land degradation, shortening rainy seasons, occurrence of heavy rains, 128 salinization of soils and lowering groundwater levels as challenges for their cropping activities therefore 129 serve as indicators for their perception of climate change effects.

2.3 Data collection and cleaning

Our data collection took place in the regions Fatick, Kaolack and Kaffrine in the Senegalese Groundnut 130 131 Basin from December 2022 to January 2023. During this period, we conducted a household survey, 132 gathering information from 606 smallholder farmer households. The three regions were selected as they 133 are part of the Sudano-Sahelian climate zone within the Groundnut Basin, as for instance described by 134 Ricome et al. (2017). We selected households following a multi-stage random sampling approach, for 135 which we randomly selected five communes within each region of our study. We then randomly 136 selected two villages within each commune. Our team of eleven enumerators was trained over three 137 days preceding the data collection. During the survey, the enumerators conducted one-on-one 138 interviews in Wolof, a local language of Senegal, at each respondent's homestead and documented their answers in French. With each enumerator conducting two interviews per village, we aimed to survey 139 140 22 randomly selected households per village. During the interviews, smallholders were asked a range 141 of socio-demographic questions, along with questions about their agricultural practices, as well as their 142 knowledge, and practices related to agroforestry. Additionally, smallholders were asked about problems they encounter in their cropping activities. Among the set of predefined answer options, we listed the 143 144 previously described environmental stressors that are driven through climate change in the context of 145 the Sahel region and potentially affect smallholders cropping activities. Before conducting the survey, informal discussions were held with smallholders in the Senegalese Groundnut Basin. These exchanges 146 147 were used to verify whether smallholders were aware of and perceived the listed environmental stressors 148 as challengers for their cropping activities. The smallholders' responses to this survey question have 149 been utilized to compute distinct binary variables for smallholders' perception of respective climate 150 change effect for our study. To gather information on smallholders' tree planting decisions for our study, 151 we inquired whether they had planted trees on their land within the three years preceding our data 152 collection and, if so, which specific tree species they had chosen to plant. The three-year recall period 153 for tree planting activities was chosen because trees typically begin to realize their potential benefits, 154 such as improving soil fertility or groundwater levels, only around three years after being planted 155 (Mercer 2004; Coulibaly et al. 2017). By excluding trees planted more than three years ago, we ensure 156 that the planted trees are unlikely to have influenced e.g. soil fertility, groundwater levels or salinization

and thus smallholders' perceptions of those climate change effects. The survey questions relevant forour study are provided in English in Appendix A.

159 For our study, we replaced values above the 99th percentile in continuous variables, such as age, 160 agricultural income or household size, with the 99th percentile value, following an approach outlined by Frey (2018) and Sullivan et al. (2021). This method prevents extreme outliers from skewing the 161 162 analysis. Through this imputation approach we are more likely to underestimate economic and statistical 163 relationships in our estimations than overestimating them (Sullivan et al. 2021). Missing values in the 164 continuous variables were replaced with the mean of the respective variable. Jadhav et al. (2019) suggest 165 that this imputation method is appropriate when less than 1% of the variables' observations are missing, 166 as is the case in our data.

2.4 Definition of fertilizer and fruit tree species

167 Agroforestry systems can provide different livelihood benefits, depending on the tree species included. 168 Certain tree species enhance soil fertility, for instance by fixing nitrogen in soils (Fall et al. 2012) or by 169 increasing soil biomass and organic carbon (Sambou et al. 2024a). Such species, referred to as fertilizer 170 trees (Ajayi et al. 2005), have been shown in various studies to intensify crop production when 171 integrated and managed within cropping systems. For instance, Coulibaly et al. (2017) show that the 172 adoption of fertilizer trees enhances smallholders' maize production in Malawi. Similarly, Amadu et al. 173 (2020) find increases in maize yields related to the adoption of fertilizer trees in Malawi. Leroux et al. 174 (2022b) show a positive association of proximity to a fertilizer tree species and millet yields in Senegal. 175 These studies demonstrate that integrating fertilizer trees into agroforestry systems contributes to 176 improving smallholders' food security through production intensification.

177 Additionally, certain tree species produce edible products, such as fruits, allowing smallholders to 178 diversify their food production by incorporating fruit cultivation into their cropping systems. Production 179 diversification, as an adaptation strategy, enhances resilience and reduces risk in the face of climate 180 change (Sthapit and Scherr 2012; Mulwa and Visser 2020). Past research further demonstrates how 181 agroforestry systems that include fruit trees contribute to food security and dietary diversity. Admasu 182 and Jenberu (2022) for instance, show how the adoption of apple-based agroforestry systems in Ethiopia 183 enhanced smallholders' income and food security. In their structured literature review, Beleta and 184 Gondore (2022) find that edible tree products contribute to food security in Ethiopia. Muthuri et al. 185 (2023) argue that the integration of fruit trees enhances smallholder's food security and dietary diversity 186 in the context of East Africa. Similarly, Jansen et al. (2020) show that the integration of fruit trees can 187 contribute to smallholders' uptake of critical micronutrients.

188 To analyse smallholders' selection of tree species for planting to adapt their food production system to 189 climate change effects, we grouped the tree species that our respondents reported to have planted in the

190 past three years into two categories: fertilizer trees and fruit trees. The categorization as fertilizer or 191 fruit trees is based on information for respective tree species provided by World Agroforestry, as well 192 as relevant literature on the properties of respective species (See Table 1). Tree species that have been 193 shown to fix nitrogen in soils or enhance soil fertility and crop yields in other specific ways are classified 194 as fertilizer trees, following e.g. Ajavi et al. (2005). If tree species provide edible fruits, they are 195 classified as fruit trees. For most tree species reported by respondents in our dataset, we found evidence 196 that they either produce edible fruits or have specific properties to improve soil fertility. If tree species 197 were found to provide fruits and potentially enhance soil fertility, such as the multipurpose tree species 198 Tamarindus indica (Mansingh et al. 2021), they were classified based on their primary use as indicated 199 in the literature. Since our study focuses on the adaptation of food production to climate change effects, we do not consider the potential medical, cultural, or material values and products that different tree 200 201 species often provide simultaneously (Orwa et al. 2009). Tree species reported by respondents that 202 neither have specific fertilizing properties nor produce edible fruits are therefore not categorized in our 203 study, even though they likely provide other non-edible products and values (Orwa et al. 2009). 204 Similarly, trees that were planted but whose species the respondents did not know will not be 205 specifically addressed in our analysis of tree species selection, as we assume they were not planted to 206 achieve species-specific benefits.

| Tree Species | Fertilizer | Fruit | Source |
|--------------------------|------------|-------|--|
| | Tree | Tree | |
| Acacia albida | yes | no | Orwa et al. 2009; Ajayi et al. 2011; Sileshi et al. 2014 |
| Acacia adansonii | yes | no | Orwa et al. 2009; Ajayi et al. 2011; Sileshi et al. 2014 |
| Acacia senegal | yes | no | Ajayi et al. 2011; Nygren et al. 2012; Sileshi et al. 2014 |
| Adansonia digitata | no | yes | Orwa et al. 2009; Meinhold and Darr 2021 |
| Anacardium occidentale | no | yes | Orwa et al. 2009; Adiga et al. 2020 |
| Annona muricata | no | yes | Orwa et al. 2009; Patel and Patel 2016 |
| Anogeissus leiocarpa | no | no | Orwa et al. 2009; Ouédraogo et al. 2013 |
| Azadirachta indica | yes | yes | Orwa et al. 2009; Islas et al. 2020 |
| Balanites aegyptiaca | no | yes | Orwa et al. 2009; Tesfaye 2015 |
| Borassus flabellifer | no | yes | Orwa et al. 2009; Jerry 2018 |
| Bridelia micrantha | no | yes | Maroyi 2017 |
| Carica papaya | no | yes | Da Silva et al. 2007; Orwa et al. 2009 |
| Casuarina equisetifolia | yes | no | Orwa et al. 2009; Nygren et al. 2012; Sileshi et al. 2014 |
| Citrus medica | no | yes | Orwa et al. 2009; Chhikara et al. 2018 |
| Citrus reticulata | no | yes | Orwa et al. 2009; Lu et al. 2019 |
| Combretum glutinosum | yes | no | Jacobson 2017 |
| Combretum micranthum | no | no | Olajide et al. 2003; Tine et al. 2021 |
| Cordyla pinnata | yes | no | Orwa et al. 2009; Sambou et al. 2024 |
| Detarium senegalense | no | yes | Dossa et al. 2020; Dassou et al. 2023 |
| Eucalyptus camaldulensis | no | no | Orwa et al. 2009; Sabo & Knezevic 2019 |
| Euphorbia balsamifera | no | no | Kamba and Hassan 2010; Kindt et al. 2021 |
| Ficus thonningii | yes | yes | Orwa et al. 2009; Dangarembizi et al. 2013; Oyelere et |
| | | | al. 2021 |
| Guiera senegalensis | yes | no | Dossa et al. 2009; Bayala et al. 2022 |
| Mangifera indica | no | yes | Orwa et al. 2009; Goldschmidt 2013; Sthapit et al. 2012 |
| Musa acuminata | no | yes | Sthapit et al. 2012 |
| | | | |

Table 1. Categorization of the tree species reported by our respondents into fertilizer and fruit trees based on existing literature.

| Parkinsonia aculeata | no | yes | Cochard and Jackes 2005; Orwa et al. 2009 |
|-------------------------|-----|-----|--|
| Piliostigma reticulatum | yes | no | Bright et al. 2017; Jacobson 2017; Félix et al. 2018 |
| Psidium guajava | no | yes | Orwa et al. 2009; Sthapit et al. 2012 |
| Tamarindus indica | yes | yes | Orwa et al. 2009; Chimsah et al. 2020; Mansingh et al. |
| | | | 2021 |
| Ziziphus mauritiana | no | yes | Orwa et al. 2009; Palejkar et al. 2012; Bado et al. 2021 |

2.5 Econometric analysis

207 To understand whether and how smallholders utilize agroforestry as a means of adapting to climate 208 change, we examine if their perception on various climate change effects as challenges to their cropping 209 activities influences their tree-planting activities, as well as their choice of tree species for planting over 210 the past three years. Based on the assumption of smallholders being rational and informed decision-211 makers that aim to increase their utility (Cascetta 2009), we expect smallholders to plant fertilizer and/or 212 fruit tree species for their purpose of increasing soil fertility and crop productivity or producing fruits 213 respectively. Therefore, planting fertilizer trees is an indicator for smallholders aiming for production 214 intensification, while smallholders' decision to plant fruit trees shows their aim for production 215 diversification.

216 A Heckman model is employed to model tree planting and fertilizer selection and/or fruit tree species. 217 The Heckman model consists of two stages. In the first stage, a probit regression typically estimates a 218 binary outcome and accounts for selection bias, enabling the second stage to conditionally model a 219 subsequent outcome, which could be binary or continuous (Heckman 1979; Asrat and Simane 2018). 220 In our case, it is necessary to control for self-selection bias induced through the smallholder's decision 221 to plant trees, which is modelled in the first stage. In the second stage, the tree species selection is 222 modelled conditional on this initial decision, with fertilizer and/or fruit trees choices treated as two 223 interdependent binary outcomes.

224 Heckman models have commonly been used in agroforestry research to model conditional decisions 225 and control for selection bias. Beyene et al. (2019), for instance, apply a Heckman model to estimate 226 the agroforestry adoption decision and extent among farmer households in Ethiopia. In the first stage, 227 they use a probit regression to model adoption decisions, followed by a second stage OLS regression to 228 estimate the area of land devoted to agroforestry practices, conditional on smallholders having decided 229 to adopt. Asrat and Simane (2018) estimate Ethiopian farmers' decision to adapt to climate change, 230 conditional on their perception of changes in climatic conditions using two probit regressions within a 231 Heckman selection model. Similarly, Kangai et al. (2021) employ a Heckman model with two probit 232 regressions to model Kenyan smallholder farmers climate change adaptation decision conditional on 233 their perception of climate change. Thinda et al. (2020) use a similar double hurdle model to estimate 234 smallholder farmers' adoption of climate change adaptation strategies in South Africa. In the first stage, 235 they employ a probit regression model to account for smallholders deciding to adopt no adaptation

- strategy, while in the second stage, they employ a Poisson regression to conditionally analyze howmany strategies smallholders adopt. Our analysis is grounded in these studies.
- In the first stage of our Heckman model we estimate how smallholder's perceptions of climate change effects influence their decision to plant at least one tree of any species on their farmland in the past three
- 240 years using the following probit regression model:

$$Y_i^* = \beta_0 + \beta_1 C P_i + \beta_2 Z_i + \beta_3 R + \beta_4 I V + \varepsilon_i$$
(1)

241 where Y_i^* denotes the marginal utility smallholder *i* attributes to planting trees, which informs the binary 242 decision of tree planting in the past three years Y_i , represented as follows:

$$Y_i = \begin{cases} 1 \ if \ Y_i^* > 0 \\ 0 \ if \ Y_i^* \le 0 \end{cases}$$
(2)

In the second stage of our model, we employ a multivariate probit model to jointly estimate the decision to plant fertilizer tree species and/or fruit tree species, reflecting whether smallholders' climate change adaptation strategy is one of intensification or diversification in relation to food production, or both. We estimate the multivariate probit model using maximum likelihood estimation among smallholders that planted trees within the past three years as follows:

$$T_{is}^{*} = \gamma_{s0} + \gamma_{s1}CP_i + \gamma_{s2}Z_i + \gamma_{s3}R + \lambda_i + \varepsilon_{is}$$
(3)

where T_{is}^* represents the marginal utility that smallholder *i* attributes to planting tree species category s, namely, fertilizer and fruit trees. The marginal utility for planting tree species category *s* informs the decision T_{is} to plant at least one tree of the respective category as follows:

$$T_{is} = \begin{cases} 1 \ if \ T_{is}^* > 0 \\ 0 \ if \ T_{is}^* \le 0 \end{cases}$$
(4)

251 In both regression models, *CP_i* represents our indicators for smallholders' perception of climate change 252 effects, specifically their perceptions of land degradation, shortening rainy seasons, occurrence of heavy 253 rains, salinization of soils and lowering groundwater levels as challenges to their cropping activities. Z_i is a vector of control variables, including household characteristics such as the respondent's age, 254 255 agricultural income, education, gender and household size. Those variables have been identified to 256 determine agroforestry adoption in previous studies focusing on agroforestry adoption as Amare and 257 Darr (2020), Arslan et al. (2022), or Kpoviwanou et al. (2024) show in their structured literature 258 reviews. We further control for agroforestry experience, agroforestry knowledge, the practice of farmer 259 managed natural regeneration (FMNR) within the past three years, and access to subsidized seedlings. 260 Agroforestry experience is a count variable of the number of trees per hectare smallholders had on their 261 agricultural land prior to the three-year tree-planting period. By including this variable in our regression 262 model, we account for the possibility that smallholders decide to plant trees based on habit or prior 263 experience, rather than their perception of climate change effects. Agroforestry knowledge has 264 previously been identified as one of the main determinants in the smallholders' adoption decision 265 (Amare and Darr 2020; Arslan et al. 2022; Kpoviwanou et al. 2024). As well as this the access to subsidized seedlings might have financially incentivised agroforestry uptake (Kpoviwanou et al. 2024) 266 267 and the selection of specific tree species. We thus control for their effect on tree planting decisions and 268 tree species selection. FMNR is an alternative pathway for smallholders to integrate trees into their 269 production system (Reij and Garrity 2016; Karambiri et al. 2023). We therefore control for smallholders 270 integrating trees differently than through planting.

R represents commune fixed effects that account for spatial climatic or institutional differences, which
may simultaneously influence the decision to plant trees, the selection of tree species and smallholders'
perception of climate change effects (Kuyah et al. 2019; Sambou et al. 2024b). One of the commune
variables is excluded from our regressions to serve as reference for the remaining commune dummies.

275 In the first regression stage, IV refers to our instrumental variables. According to, e.g., Briggs (2004), 276 Schwiebert (2015), and Beyene et al. (2019), the inclusion of instrumental variables in the first-stage 277 probit regression of a Heckman model, which introduce exogenous variation into the selection process, 278 helps improve identification of the selection equation beyond the functional form assumptions of the 279 error term distribution. Valid instruments satisfy the exclusion restriction for the second-stage equation 280 if they are correlated with the decision modeled in the first regression stage but not with the outcome 281 variable of the second-stage regression (Coulibaly et al. 2017; Beyene et al. 2019). For our study, we 282 selected smallholders' formal land ownership and access to a well as instruments. These factors have 283 been shown to constrain agroforestry adoption in our study context (Cotillon et al. 2021; Arslan et al. 284 2022; Huntington and Shenoy 2021) but are not expected to influence the selection of tree species once 285 the decision to plant trees has been made.

286 Secure land tenure has been found to generally affect smallholders' decision to adapt to climate change. 287 However, it does not appear to play a statistically significant role in the selection of specific adaptation 288 strategies, such as crop intensification or diversification through increased input use (Yegbemey et al. 289 2013; Murken and Gornott 2022). As rainfall in our study region is limited to a few months per year, 290 and tree seedlings require year-round watering to mature (Cotillon et al. 2021) until they can draw water 291 from deeper soil depths (Bargués Tobella et al. 2017), access to a well is expected to constrain the 292 decision to plant trees in our study context. Prior studies suggest that water scarcity may favor the 293 selection of more drought-tolerant crop species (Kurukulasuriya and Mendelsohn 2007; Bozorgi et al. 294 2020). Water availability may therefore similarly favor the selection of tree species that, once mature, are more drought-tolerant and require less water input. However, the fertilizer and fruit tree species 295 296 observed in our study region are mostly endemic and thus adapted to semi-arid climatic conditions. 297 Slight variations in drought tolerance occur among both fertilizer and fruit tree species (Orwa et al.

2009). Therefore, having access to a well is not expected to influence the selection of either fruit or 299 fertilizer tree species, other than through the general decision to plant trees. By using smallholders' 300 formal land ownership and access to a well as instruments, we thus introduce exogenous variation in 301 tree planting decisions that is independent of species selection, thereby improving model identification 302 (Beyene et al. 2019).

For both regression stages, ε_i denotes the stochastic error term and is assumed to be independently distributed across smallholders. In the second stage multivariate probit regression, ε_{is} is assumed to be correlated across tree species categories, accounting for smallholders' selection of either tree species category to be jointly influenced by unobserved factors. ε_{is} is assumed to follow a multivariate normal distribution.

308 In the second stage regression model, λ_i denotes the inverse Mills ratio, which accounts for the 309 probability that respondents have decided to plant trees and thus controlling for selection bias in this 310 regression stage. We calculate the inverse Mills ratio for each respondent using the following formula:

$$\lambda_{i} = \frac{\phi \left(\beta_{0} + \beta_{1} C P_{i} + \beta_{2} Z_{i} + \beta_{3} R\right)}{\phi \left(\beta_{0} + \beta_{1} C P_{i} + \beta_{2} Z_{i} + \beta_{3} R\right)}$$
(5)

With $\phi(.)$ denoting the probability density function and $\Phi(.)$ representing the cumulative distribution function, both calculated from our first-stage probit regression model and estimating the probability that smallholders decided to plant trees in the past three years. For the interpretation of the results, we estimate the marginal effects of our independent variables to understand how changes in these variables influence the probabilities of both planting trees and selecting fertilizer trees or fruit trees.

3. Results

3.1 Descriptive results

316 The descriptive statistics (Table 2) of our indicators for smallholders' perception of the different local 317 climate change effects show that the changing climate does not go unnoticed by smallholders in the Senegalese Groundnut Basin. Several of our respondents perceive those climate change effects as 318 319 problematic for their cropping activities. The degradation of land is perceived as problematic by about 320 82% of the smallholders and the increasing frequency of heavy rain events was reported by about 29% 321 of the smallholders (Figure 1) as problematic to their cropping activities. The salinization of soils and 322 shortening rainy seasons are perceived as problematic for arable farming by about 26% and 24% of the 323 respondents respectively. The lowering of groundwater levels has been perceived by about 9% of 324 smallholders as posing problems for their cropping activities. The proportions of smallholders 325 perceiving those climate change effects further does not differ much between those who planted trees 326 and those who did not within the past three years.



Figure 1. Proportion of smallholders perceiving different climate change effects as problematic for their cropping activities (N=606).

Table 2. Descriptive statistics

| | Description | Total (N = 606) | Adopters (N= 117) | Non-Adopters (N= 489) | Mean differences |
|---|---|------------------------|------------------------|--------------------------|---------------------|
| | | Mean | Mean | Mean | |
| Outcome variables | | | | | |
| Tree planting | Smallholder having planted trees on their agricultural land within the past three y_{ears} (1-yes) | 0.193 | | | |
| Fruit tree | Smallholder having planted fruit tree species within the past three years (1=yes) | 0.097 | 0.513 | | |
| Fertilizer tree | Smallholder having planted fertilizer tree species within the past three years (1=yes) | 0.064 | 0.333 | | |
| Climate change perception | | | | | |
| Heavy rain events | Smallholder perceiving heavy rain events as problematic for their agricultural activities (1=ves) | 0.287 | 0.359 | 0.270 | -0.089* |
| Land degradation | Smallholder perceiving land degradation as problematic for their agricultural activities (1=ves) | 0.817 | 0.769 | 0.828 | 0.059 |
| Lowering groundwater | Smallholder perceiving lowering groundwater levels as problematic for their agricultural activities (1=yes) | 0.092 | 0.085 | 0.094 | 0.009 |
| Salinization of soils | Smallholder perceiving salinization of soils as problematic for their agricultural activities (1=ves) | 0.257 | 0.291 | 0.249 | -0.041 |
| Shortening rainy season | Smallholder perceiving shortening rainy seasons as problematic for their agricultural activities (1–yes) | 0.236 | 0.282 | 0.225 | -0.057 |
| Household characteristics | | | | | |
| A ge of household head | Age of household head in years | 50 892 (14 301) | 49 136 (11 951) | 51 313 (14 788) | 2 176 |
| Agricultural income | Household income generated from agricultural activities in the past year in 10 000 CFA | 21.338 (28.529) | 28.215 (33.730) | 19.692 (26.918) | -8.523*** |
| Female household head | Dummy for female headed household (1=ves) | 0 193 | 0.111 | 0.213 | 0 102** |
| Formal education | Dummy for household head having participated in formal education at least at the primary school level (1–yes) | 0.190 | 0.239 | 0.178 | -0.061 |
| Household size | Number of household members (people who shared meals and home during the past 6 months) | 14.288 (7.751) | 13.410 (7.525) | 14.498 (7.797) | 1.087 |
| Agroforestry controls | | | | | |
| Agroforestry knowledge | Smallholders self-assessed knowledge of agroforestry, measured on a scale from 1 to 5 | 2.548 (1.356) | 3.564 (1.282) | 2.305 (1.257) | -1.259*** |
| FMNR practice | Dummy for smallholder having managed naturally regrowing tree seedlings in the past three years | 0.190 | 0.376 | 0.145 | -0.231*** |
| Prior agroforestry practice Subsidized seedlings | Number of trees per hectare prior to the three-years planting period Dummy for smallholder having received tree seedlings for free or at a subsidized price | 2.160 (4.536) 0.216 | 1.565 (2.535) 0.325 | 2.302 (4.886) 0.190 | 0.736 -0.135*** |
| Instrumental variables | | | | | |
| Formal land ownership | Dummy for smallholder holding formal land ownership (1=yes) | 0.073 | 0.128 | 0.059 | -0.069*** |
| Well access | Dummy for smallholder having access to a well (1=yes) | 0.653 | 0.795 | 0.620 | -0.175*** |
| Commune dummies | | | | | |

| Diagane Barka | Dummy for household residing in the commune of Diagane Barka (1=yes) | 0.071 | 0.085 | 0.067 | -0.018 |
|--------------------------|---|----------------------|-----------------------|--------------------|---------|
| Dianké Souf | Dummy for household residing in the commune of Dianké Souf (1=yes) | 0.064 | 0.043 | 0.070 | 0.027 |
| Diokoul | Dummy for household residing in the commune of Diokoul (1=yes) | 0.058 | 0.094 | 0.049 | -0.044* |
| Diossong | Dummy for household residing in the commune of Diossong (1=yes) | 0.072 | 0.068 | 0.074 | 0.005 |
| Fimla | Dummy for household residing in the commune of Fimla (1=yes) | 0.066 | 0.085 | 0.061 | -0.024 |
| Kahi | Dummy for household residing in the commune of Kahi (1=yes) | 0.053 | 0.043 | 0.055 | 0.012 |
| Keur Maba | Dummy for household residing in the commune of Keur Maba (1=yes) | 0.068 | 0.077 | 0.065 | -0.011 |
| Keur Mboucki | Dummy for household residing in the commune of Keur Mboucki (1=yes) | 0.071 | 0.034 | 0.080 | 0.046* |
| Mbadakhoune | Dummy for household residing in the commune of Mbadakhoune (1=yes) | 0.070 | 0.077 | 0.070 | -0.009 |
| Ndiébel | Dummy for household residing in the commune of Ndiébel (1=yes) | 0.064 | 0.026 | 0.074 | 0.048* |
| Nguelou | Dummy for household residing in the commune of Nguelou (1=yes) | 0.071 | 0.077 | 0.070 | -0.007 |
| Ouadiour | Dummy for household residing in the commune of Ouadiour (1=yes) | 0.069 | 0.085 | 0.065 | -0.020 |
| Paos Koto | Dummy for household residing in the commune of Paos Koto (1=yes) | 0.061 | 0.043 | 0.065 | 0.023 |
| Passi | Dummy for household residing in the commune of Passi (1=yes) | 0.071 | 0.077 | 0.070 | -0.007 |
| Taiba Niassene | Dummy for household residing in the commune of Taiba Niassene (1=yes) | 0.071 | 0.085 | 0.070 | -0.018 |
| New doubt desire and use | anted in non-adhesis Man differences and their statistical similiance man | active at all main a | A Annatas A atominita | damata statistical | .::f: |

Standard deviations are reported in parenthesis. Mean differences and their statistical significance were estimated using t-tests; Asterisks denote statistical significance: *** p<0.01, ** p<0.05, * p<0.1

In our sample, about 19% of our respondents indicated to having planted trees on their farmland within the past three years. Out of the smallholders who planted trees, about 51% have decided for fruit tree species and about 33% have decided to plant fertilizer tree species. Figure 2 shows the proportions of

- 330 smallholders who selected fruit tree species, fertilizer tree species, other types of trees or combinations
- of those species, after deciding to plant trees. We find that approximately 14% of respondents who
- 332 planted trees within the past three years chose to plant both fertilizer and fruit tree species.



Figure 2. Proportions of smallholders who selected fruit tree species, fertilizer tree species, and/or other types of tree species after deciding to plant trees (N=117).

333 Smallholders who planted trees within the past three years chose a variety of specific fertilizer or fruit 334 tree species, as well as tree species that neither yield fruits nor have been found to specifically enhance 335 soil fertility or crop yields. Figure 3 shows the proportions of smallholders who selected the different 336 specific tree species after having decided to plant trees. While about 30% of the smallholders who 337 decided to plant trees reported planting trees with unknown species, approximately 22% selected Acacia 338 albida, and another 22% chose Mangifera indica. Those two tree species, followed by Citrus medica, 339 Ziziphus mauritiana, Anacardium occidentale, Carica papaya, and Acacia adansonii are the most 340 frequently selected tree species for planting in our sample.



Figure 3. Proportion of smallholders who selected specific tree species within the categories of fruit, fertilizer and other tree species (N=117).

<u>3.2 Econometric results</u>

341 Our regression results (Table 3) provide more detailed information on the relationship between 342 smallholders' perceptions of climate change effects and their decision to plant trees, as well as their 343 subsequent selection of fertilizer and/or fruit trees for planting. The analysis shows that while the decision to plant trees is not statistically significantly related to our indicators for smallholders' 344 345 perceptions of different climate change effects, the marginal changes in the likelihood of having decided 346 to plant trees within the past three years for all of our climate change perception indicators are positive. 347 For smallholders who have decided to plant trees, however, the estimates for several of our climate 348 change indicators are statistically significant in their tree species selection for planting. Different than 349 for the initial decision to plant trees, smallholders' perception of land degradation, salinization of soils 350 and shortening rainy seasons exhibits statistical significance for selecting fruit tree species. While the perception of land degradation and shortening rainy seasons relates to increases in smallholders' 351 352 likelihood to have selected fruit tree species, smallholders' perception of a salinization of their soils 353 relates to a decreased likelihood to have selected fruit trees for planting. Other than for the selection of 354 fruit trees for planting, smallholders' climate change perception indicators do not statistically significantly increase smallholders' likelihood to select fertilizer trees for planting. On the contrary, 355 356 smallholders' perception of heavy rain events or a salinization of soils as posing problems for their agricultural activities exhibit a statistically significant negative relationship with smallholders' 357 358 likelihood of having selected fertilizer tree species for planting.

Table 3. Regression results

| | Tree planting | | Frui | Fruit tree | | zer tree |
|---|------------------------|-------------------------|-------------------------|-------------------------|------------------------------|--------------------------|
| | Coefficient | Marginal effect | Coefficient | Marginal effect | Coefficient | Marginal effect |
| Climate change perception | | | | | | |
| Heavy rain events | 0.253 (0.173) | 0.053 | -0.039 (0.415) | -0.016 | -0.618* (0.366) | -0.207 |
| Land degradation | 0.097 (0.182) | 0.020 | 1.625*** (0.475) | 0.648 | -0.517 (0.328) | -0.173 |
| Lowering groundwater | 0.123 (0.252) | 0.026 | -0.395 (0.533) | -0.158 | 0.140 (0.473) | 0.047 |
| Salinization of soils | 0.034 (0.171) | 0.007 | -2.169*** (0.615) | -0.865 | -0.801** (0.347) | -0.268 |
| Shortening rainy season | 0.143 (0.175) | 0.030 | 1.666*** (0.466) | 0.664 | 0.253 (0.394) | 0.085 |
| Household characteristics | | | | | | |
| Age of household head | -0.017*** (0.005) | -0.004 | -0.002 (0.018) | -0.001 | 0.012 (0.014) | 0.004 |
| Agricultural income | 0.003 (0.002) | 0.001 | -0.028*** (0.010) | -0.011 | -0.001 (0.005) | -0.000 |
| Female household head | -0.051 (0.205) | -0.011 | 2.852*** (0.993) | 1.138 | -0.682 (0.550) | -0.229 |
| Formal education | 0.108 (0.185) | 0.023 | -1.157** (0.450) | -0.461 | -0.164 (0.386) | -0.055 |
| Household size | 0.006 (0.010) | 0.001 | 0.093*** (0.036) | 0.037 | 0.002 (0.023) | 0.001 |
| Agroforestry controls | | | | | | |
| Agroforestry knowledge | 0.388*** (0.058) | 0.081 | -0.579* (0.307) | -0.231 | -0.263 (0.250) | -0.088 |
| FMNR practice | 0.558*** (0.157) | 0.116 | -0.936** (0.442) | -0.373 | -0.754* (0.400) | -0.252 |
| Prior agroforestry practice | -0.041** (0.021) | -0.009 | 0.009 (0.057) | 0.003 | -0.035 (0.092) | -0.012 |
| Subsidized seedlings | 0.318** (0.159) | 0.066 | -1.073* (0.592) | -0.428 | 0.453 (0.401) | 0.152 |
| Instrumental variables | | | | | | |
| Formal land ownership | 0.666*** (0.252) | 0.139 | | | | |
| Well access | 0.318* (0.163) | 0.066 | | | | |
| Lambda | | | -3.108** (1.221) | | -0.583 (0.805) | |
| (Conditional) Observations | 606 | | 117 | | 117 | |
| Robust standard errors in paren | theses; Asterisks deno | te statistical signific | ance: *** p<0.01, ** p< | (0.05, * p<0.1; Commune | e-level fixed effects and in | ntercept are included in |
| the models but not reported for brevity; The correlation coefficient (atrho21) of the multivariate probit regression is not statistically significant at the 1%, 5% or 10% level. | | | | | | |

359 Although a smallholders' perception of climate change effects does not appear to drive their decision 360 to plant trees across our sample, other factors seem relevant for this decision. An older household head, 361 for example, statistically significantly negatively relates to the households' likelihood to have planted trees within the past three years. Smallholders' knowledge of agroforestry, receipt of subsidized tree 362 363 seedlings, and engagement in FMNR within the past three years are statistically significantly associated 364 with an increased likelihood of tree planting. However, if smallholders had more trees per hectare prior 365 to the three-year tree planting period, they were statistically significantly less likely to plant additional 366 trees. Our estimates for or instrumental variables, households having access to a well and formal land 367 ownership, show statistical significance in enhancing the likelihood of tree planting.

While the selection of tree species statistically significantly depends on smallholders' perception of 368 several climate change effects, we additionally identified several other factors influencing the selection 369 370 of tree species. Higher agricultural income statistically significantly relates to a decline in the likelihood 371 of selecting fruit tree species. Our estimates for the relationship between the household head being 372 female, and the household having selected fruit tree species for planting are statistically significantly 373 positive. Respondents who attended formal education seem statistically significantly less likely to select 374 fruit tree species. Furthermore, a larger household size is statistically significantly associated with a 375 higher likelihood of selecting fruit trees. Respondents who reported more knowledge on agroforestry 376 and smallholders who received subsidized tree seedlings were statistically significantly less likely to 377 select fruit tree species for planting. The selection of fertilizer tree species is not statistically 378 significantly related to any of those factors. While the provision of subsidized seedlings appears to 379 encourage the planting of fertilizer trees, this relationship is not statistically significant. Only 380 households that practiced FMNR in the past three years were found to be statistically significantly less 381 likely to select either fertilizer or fruit trees.

382 <u>3.3 Robustness checks</u>

383 We conducted several robustness checks to verify the reliability of our results. First, to test the 384 robustness of our fertilizer and fruit tree species categorization, we additionally estimated smallholder 385 farmers' tree species selection in a case where tree species that both improve soil fertility and provide 386 edible fruit were included in both categories (Appendix B.1). Second, we conducted a multivariate 387 probit analysis when selecting fertilizer and/or fruit tree species for planting, without accounting for 388 selection bias (Appendix B.2), to assess the robustness of our estimates through the Heckman model. 389 Third, we estimated two separate Heckman models, each using individual probit regressions to estimate 390 fertilizer and fruit tree species selection independently (Appendix B.3), to evaluate the robustness of 391 our joint estimation in the second stage of our Heckman model. According to Certo et al. (2016), the 392 statistical significance of the coefficient for the lambda variable in our second-stage regression results 393 further confirms the suitability of the Heckman model for our analysis. The statistical significance of 394 the coefficients of our instrumental variables, estimated in the first-stage regression, support the validity 395 of our chosen instruments.

4. Discussion

396 While previous studies, such as those by Belay et al. (2017), Atube et al. (2021), Belay et al. (2022), or 397 Chemeda et al. (2023), find that tree planting is one of multiple climate change adaptation approaches 398 of smallholders, our findings reveal a different pattern. Even though smallholders in our sample 399 perceive the different climate change effects as problematic for their cropping activities, our estimates 400 for the tree planting decision of smallholders show that none of our perception indicators of the climate 401 change effects is statistically significantly related to smallholders' decision to plant trees. Smallholders' tree planting decision seems rather constrained by a potential lack of crucial resources for agroforestry 402 403 practices, such as access to water, secure land tenure, agroforestry knowledge or subsidies.

404 Notably, formal land ownership and access to a well, which serve as instrumental variables in our study, 405 seem to be key constraints to agroforestry uptake and extension through tree planting. This finding 406 aligns with our expectations, given that access to water during the dry season is necessary to manage 407 agroforestry systems in the Sahel region (Cotillon et al. 2021) and secure land ownership has previously 408 been detected to condition agricultural innovations adoption (Arslan et al. 2022; Kpoviwanou et al. 409 2024).

410 The positive relationship between knowledge on agroforestry and smallholders' likelihood to have 411 planted trees within the past three years aligns with the findings of Amare and Darr (2020), Arslan et 412 al. (2022), and Kpoviwanou et al. (2024). In their structured reviews on agroforestry adoption literature, 413 they find knowledge on agroforestry to be an important driver for adoption. Receiving subsidized tree 414 seedlings also appears to incentivize smallholders' decision to plant trees, a relationship that aligns with 415 established knowledge on the effects of agricultural subsidies (Sucker 2021; Ahmad et al. 2023). Our 416 indicator of prior agroforestry practice, the number of trees per hectare before the three-year planting 417 period, suggests that habit or experience in managing agroforestry systems does not drive smallholders' 418 decisions to plant trees. Instead, it appears to align with the findings from Papa et al. (2020), who, in focus group discussions with Senegalese smallholders, observed that a major concern in their tree 419 420 planting decisions is the potential competition for nutrients between trees and crops.

421 Our results suggest that smallholders, who have access to the necessary resources for planting and 422 managing trees strategically select fruit tree species to adapt to climate change effects, particularly land 423 degradation and shortening rainy seasons, by diversifying their food production. Similarly, 424 diversification of food production through crop diversification has been found to be a key adaptation 425 strategy for smallholders in e.g. Ethiopia (Asrat and Simane 2018), Ghana (Antwi-Agyei et al. 2021), 426 or Senegal (Papa et al. 2020). Our findings of smallholders likely selecting fruit tree species as climate427 change adaptation strategy corresponds to those findings.

428 In contrast, our findings do not indicate that smallholders' perceptions of climate change effects enhance 429 the selection of fertilizer trees. Consequently, fertilizer trees do not seem to be specifically utilized as a 430 climate change adaptation tool to intensify food production. On the contrary, the perception of heavy 431 rain events and a salinization of soils appears to discourage the selection of fertilizer tree species for 432 planting. However, as Coulibaly et al. (2017), Amadu et al. (2020) and Leroux et al. (2022b) 433 demonstrate, integrating fertilizer trees can improve soil fertility and enhance food security outcomes 434 trough increased crop yields. Our results therefore indicate that smallholders in the Senegalese 435 Groundnut Basin have not yet exploited the potential of planting fertilizer trees as a climate change 436 adaptation strategy. Policymakers and intervention designs should therefore focus on communicating about the advantages of fertilizer trees, as well as promoting diverse agroforestry systems that 437 438 incorporate multiple tree species serving different purposes, such as enhancing soil fertility and 439 providing edible fruits. Furthermore, although the positive relationship between the provision of tree 440 seedlings and the planting of fertilizer trees is not statistically significant, interventions that include the 441 subsidized provision of fertilizer tree seedlings could still be a promising pathway at enhancing fertilizer 442 tree planting.

Our finding that smallholders perceiving soil salinization as a challenge for their cropping activities are less likely to select either fruit trees or fertilizer trees for planting may be attributed to the unfavorable conditions saline soils create for tree growth (Dagar and Minhas 2016). However, as e.g. Behera et al. (2015), Dagar and Minhas (2016) or Banyal et al. (2017) point out, agroforestry has the potential to reclaim saline soils and provide food and non-food tree products, if saline-tolerant tree species, such as *Acacia nilotica, Casuarina equisetifolia, Tamarindus indica* or *Eucalyptus camaldulensis* are integrated.

450 Additionally, smallholders appear to practice FMNR alongside tree planting, suggesting that both 451 pathways of agroforestry uptake and upscaling are likely practiced jointly. This contrasts with 452 perspectives such as those of Reij and Garrity (2016) and Bonye (2024), who treat FMNR as an 453 approach opposing tree planting in agroforestry uptake. Our additional finding that smallholders who practiced FMNR within the past three years were less likely to select fertilizer or fruit tree species, 454 455 might suggest that those smallholders adopted fertilizer or fruit tree species through FMNR rather than planting and consequently selected other tree species to plant additionally to their FMNR practices. 456 457 Abasse et al. (2023) for instance state that e.g. Faidherbia albida, one of the main fertilizer tree species 458 in Senegal (Leroux et al. 2022b), is commonly expanded through FMNR. While Reij and Garrity (2016) 459 call for a shift from tree planting to FMNR to achieve restoration targets, our results suggest that both 460 pathways for integrating trees into agroforestry systems are practiced jointly. Moreover, selecting tree species for planting depends on this combined practice of FMNR and tree planting. We would thus
suggest to promote the joint practice of both tree planting and FMNR, as also e.g. Hadgu et al. (2019)
propose.

In general, a higher tree species diversity enhances ecological resilience of production systems to e.g. weather shocks or pests (Sow et al. 2020; Messier et al. 2022), and multiple different tree species can coexist in agroforestry systems and provide various ecosystem services synergistically (Leroux et al. 2022a). Therefore, the joint selection of fertilizer trees, fruit trees, and other tree species for tree planting would enhance smallholders' holistic climate change adaptation, combining intensification with the diversification of food production, offering synergistic benefits.

5. Conclusion

470 Our study examines the relationship between smallholders' perception of different climate change 471 effects as complicating arable farming in the Sudano-Sahelian climate and their adaptation strategies 472 through agroforestry practices in the context of the Senegalese Groundnut Basin. We go beyond 473 previous studies on climate change adaptation, which identify tree planting as one of multiple climate 474 change adaptation practices of smallholders in Sub-Saharan Africa, and additionally investigate 475 smallholders' selection of fertilizer and/or fruit tree species for planting, as a strategy to intensify and/or 476 diversify their food production in response to climate change effects. Employing a Heckman model, we 477 modelled smallholders' decisions to plant trees as well as their tree species selection for planting, within 478 a three-year period preceding our data collection.

479 Our findings indicate that most of the smallholders perceive one or the other climate change effect as 480 posing problems for their cropping activities. Among the various climate change effects in the study 481 region, the largest number of smallholders identified land degradation as a challenge to their cropping 482 activities, followed by heavy rain events, soil salinization and shorter rainy seasons. The initial decision 483 to plant trees, however, appears to be rather constrained by limited access to essential resources for 484 agroforestry practices, such as access to water, secure land tenure, agroforestry knowledge or financial 485 resources, than determined by the perception of different climate change effects. Once smallholders 486 decided to plant trees though, we find that their tree species selection for planting does depend on their 487 perception of different climate change effects. Smallholders are more likely to select fruit tree species 488 if they perceive land degradation or shorter rainy seasons as challenges to their cropping activities. 489 Selecting fertilizer trees is not positively associated to the perception of the different climate change 490 effects and the perception of heavy rain events and salinization of soils even discourages the planting 491 selection process for fertilizer trees. Smallholders thus rather utilize tree planting to diversify than to 492 intensify their food production in the face of climate change. Future policy design should primarily 493 focus on enhancing smallholders' access to crucial resources, such as water, secure land tenure, 494 information and financial resources to facilitate agroforestry adoption as a climate change adaptation

495 tool. Additionally, as fertilizer trees hold great potential to maintain and restore soil fertility, efforts 496 should focus on promoting the selection of fertilizer trees for planting within cropping systems, 497 particularly in response to specific climate change effects, such as the widely perceived issue of land 498 degradation. Overall, policy makers should aim to enhance the integration of both fertilizer and fruit 499 tree species, to support a holistic climate change adaptation, enhancing intensification and 400 diversification of smallholders' food production

501 Further, about 26% of our respondents perceive soil salinization as problematic for their crop production 502 and this perception discourages them from selecting either fertilizer or fruit trees for planting. In this 503 context, policy makers could promote a selection of specific tree species, such as *Tamarindus indica*, 504 that are adaptable to saline soils, reduce salinization and potentially provide fruits. With the increasing 505 salinization of soils due to climate change, particularly in the western Sahel, further research specifically 506 focusing on the potential of specific tree species and agroforestry systems to counteract soil salinization 507 and provide additional ecosystem services would be valuable. Such research could help establish a 508 comprehensive knowledge base for policymakers to promote the broader adoption of agroforestry in 509 the context of soil salinity and enhance the suitability of agroforestry systems for mitigating soil 510 salinization and delivering ecosystem services.

511 We also find that FMNR is likely practiced jointly with tree planting to integrate trees, and this joint 512 practice influences the selection of tree species for planting. Future research is needed to gain a better 513 understanding of the detailed interdependences of tree planting and FMNR, such as tree species 514 selection for FMNR or tree planting if jointly practiced. It could also be valuable to investigate in greater 515 detail which ecosystem services, among the many that different tree species in agroforestry systems can 516 provide beyond soil fertilization and fruit production, drive smallholders' tree species selection. 517 Additionally, exploring which potential ecosystem services of trees could enhance smallholders' climate change adaptation at the local level but remain underutilized, and understanding the reasons for 518 519 their underutilization, would provide useful insights for the strategic promotion and selection of tree 520 species for agroforestry practices.

521

522 Statements and Declarations

523 <u>CRediT authorship contribution statement</u>

- 524 Luisa Müting: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation,
- 525 Data Curation, Writing Original Draft, Writing Review & Editing, Visualization; Oliver Mußhoff:
- 526 Writing Review & Editing, Supervision, Project administration, Funding acquisition
- 527 <u>Funding</u>
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- 530 Declaration of Competing Interest
- 531 The authors have no competing interests to declare that are relevant to the content of this article.

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538 Data availability

- 539 Data will be made available on request.
- 540 Declaration of Generative AI and AI-assisted technologies in the writing process
- 541 During the preparation of this work, the authors utilized ChatGPT 3.5 to enhance the article's readability
- 542 and assist in creating the figures. After using this tool/service, the authors reviewed and edited the
- 543 content as needed and take full responsibility for the content of the publication.

Appendix A Survey questions

Table A. Survey questions

| Variable | Survey Question | Answer Option | Potential additional Construction of Variable |
|---|---|---|---|
| Tree planting | Have you planted trees on your agricultural land in the past three years? | Yes/ No | |
| Fruit tree Fertilizer tree | How many different tree species have you planted on this land? | Number | The reported tree species have been categorized as fertilizer or fruit tree species based on World |
| | Please name the tree species that you planted on your agricultural land in the past three years. | Text | previous studies. |
| Heavy rain events Land degradation Lowering groundwater levels Salinization of soils Shortening rainy season | What problems do you encounter in your cropping activities? | □ Soil degradation (e.g., fertility loss, erosion) □ Market access (e.g., distance or poor infrastructure) □ Soil salinization (e.g. salt accumulation in soil) □ Shortening rainy seasons (e.g., delayed onset or early end of rain season) □ Heavy rains (extreme rain events) □ Decline in groundwater levels (e.g., wells drying up or reduced water table) □ Competition for land use with sedentary herders (e.g., overlapping land needs with settled livestock farmers) □ Competition for land use with nomadic herders (e.g., conflicts over grazing areas with migrating livestock herders) □ Low market prices for crops (e.g., reduced income due to poor crop prices) □ Low labour availability (e.g., difficulty hiring workers during peak agricultural seasons) □ Others (<i>Text</i>) □ Refused to answer | This survey question serves as a base to compute our binary climate change perception indicators. If a smallholder reported a specific effect of climate change as problematic for their cropping activities, their response was coded as '1'. If they did not report perceiving that effect, their response was coded as '0'. For our analysis, each climate change effect is thus captured using a separate binary variable. |

| Age of household head | How old are you? | Number | |
|--------------------------------|---|---|--|
| Agricultural income | The following question is ask household cultivates. | ed for each crop the | |
| | How much income did your household generate from the last seasons' harvest of <i>crop n</i> in CFA. | Number | The income generated from each crop and each type of livestock have been summed together. |
| | The following question is asked livestock the household owns. | d for each type of | |
| | How much income did your household generate from <i>livestock n</i> in CFA in the last year? | Number | |
| Female household head | Enumerators noting respondent | ts' sex | |
| Formal education | Are you currently or have you ever been to school? | Yes/No | |
| Household size | How many members are currently living in your household (including yourself)? (<i>i.e. lived and</i> shared meals with you over the past 6 months.) | Number | |
| Agroforestry knowledge | How much do you know about agroforestry? | Likert Scale: 1(nothing) – 5(very much) | |
| FMNR practice | Have you cultivated naturally regrown tree seedlings on the land you use for farming in the last three years? | Yes/No | |
| Prior agroforestry practice | How many trees grow on the land you use for farming?? | Number | The number of trees planted and the number of trees that have grown back naturally in the last three years were deducted from the total number of trees currently growing on the respondents' farmland. |
| Subsidized seedlings | Has an organization ever given you tree seedlings free of charge or at a subsidized rate? | Yes/No | |
| Formal land ownership | Do you have a certificate of ownership for your farmland? | Yes/No | |
| Well access | Do you have access to a well to draw water? | Yes/No | |

Appendix B Robustness checks

Table B.1 Results of Heckman regression with Ficus thonningii, Tamarindus indica, and Azadirachta indica categorized as both fertilizer and fruit trees.

| | Tree planting | Fruit tree | Fertilizer tree |
|--|---|--|--|
| | Coefficient | Coefficient | Coefficient |
| Climate change perception | | | |
| Heavy rain events | 0.253 (0.173) | -0.004 (0.415) | -0.654* (0.372) |
| Land degradation | 0.097 (0.182) | 1.653*** (0.468) | -0.616* (0.329) |
| Lowering groundwater | 0.123 (0.252) | -0.521 (0.514) | 0.385 (0.451) |
| Salinization of soils | 0.034 (0.171) | -2.280*** (0.623) | -0.670* (0.343) |
| Shortening rainy season | 0.143 (0.175) | 1.688*** (0.463) | 0.193 (0.388 |
| Household characteristics | | | |
| Age of household head | -0.017*** (0.005) | 0.001 (0.019) | 0.005 (0.014) |
| Agricultural income | 0.003 (0.002) | -0.030*** (0.010) | 0.001 (0.005) |
| Female household head | -0.051 (0.205) | 2.823*** (0.911) | -0.167 (0.518) |
| Formal education | 0.108 (0.185) | -1.183** (0.487) | -0.311 (0.378) |
| Household size | 0.006 (0.010) | 0.096*** (0.036) | -0.003 (0.024) |
| Agroforestry controls | | | |
| Agroforestry knowledge | 0.388*** (0.058) | -0.600* (0.322) | -0.247 (0.249) |
| FMNR practice | 0.558*** (0.157) | -0.978** (0.459) | -0.691* (0.392) |
| Prior agroforestry practice | -0.041** (0.021) | 0.011 (0.057) | -0.060 (0.105) |
| Subsidized seedlings | 0.318** (0.159) | -1.102* (0.607) | 0.382 (0.392) |
| Instrumental variables | | | |
| Formal land ownership | 0.666*** (0.252) | | |
| Well access | 0.318* (0.163) | | |
| Lambda | | -3.262** (1.277) | -0.412 (0.789) |
| (Conditional) Observations | 606 | 117 | 117 |
| Robust standard errors in parentheses | ; Asterisks denote statistical significance | e: *** p<0.01, ** p<0.05, * p<0.1; Commune-le | evel fixed effects and intercept are included in |
| the models but not reported for brevit | y; The correlation coefficient (atrho21) o | f the multivariate probit regression is not statisti | cally significant at the 1%, 5%, or 10% level. |

Table B.2 Results of multivariate probit regression on tree species selection, without correction for selection bias.

| | Fruit tree | Fertilizer tree |
|--|---|--|
| Climate change percention | Coefficient | Coefficient |
| Chinate change perception | 0.240 (0.202) | 0.024 (0.222) |
| Heavy rain events | 0.240 (0.203) | -0.024 (0.222) |
| Land degradation | 0.528** (0.261) | -0.155 (0.201) |
| Lowering groundwater levels | -0.056 (0.300) | 0.191 (0.284) |
| Salinization of soils | -0.451** (0.220) | -0.473** (0.231) |
| Shortening rainy season | 0.613*** (0.189) | 0.286 (0.212) |
| Household characteristics | | |
| Age of household head | -0.021*** (0.006) | -0.012** (0.006) |
| Agricultural income | -0.002 (0.003) | 0.004* (0.002) |
| Female household head | 0.286 (0.248) | -0.120 (0.260) |
| Formal education | -0.074 (0.201) | -0.029 (0.230) |
| Household size | 0.019 (0.011) | 0.012 (0.012) |
| Agroforestry controls | | |
| Agroforestry knowledge | 0.398*** (0.071) | 0.198*** (0.065) |
| FMNR practice | 0.186 (0.201) | 0.046 (0.191) |
| Prior agroforestry practice | -0.046 (0.041) | -0.057** (0.024) |
| Subsidized seedlings | 0.294 (0.204) | 0.434** (0.176) |
| Instrumental variables | | |
| Formal land ownership | 0.745*** (0.282) | 0.576** (0.272) |
| Well access | 0.360* (0.208) | 0.365** (0.186) |
| Observations | 606 | 606 |
| Robust standard errors in parentheses: Asterisks | denote statistical significance: *** p<0.01. ** p<0.05. * r | p<0.1: Commune-level fixed effects and intercept are included in |

Robust standard errors in parentheses; Asterisks denote statistical significance: *** p<0.01, ** p<0.05, * p<0.1; Commune-level fixed effects and intercept are included in the models but not reported for brevity; The correlation coefficient (atrho21) of the multivariate probit regression is not statistically significant at the 1%, 5%, or 10% level.

Table B.3 Results of Heckman regression estimated with two separate probit models in the second stage.

| | Tree planting | Fruit tree | Fertilizer tree | | |
|--|--|---|---------------------------------------|--|--|
| | Coefficient | Coefficient | Coefficient | | |
| Climate change perception | | | | | |
| Heavy rain events | 0.253 (0.173) | -0.070 (0.407) | -0.581 (0.365) | | |
| Land degradation | 0.097 (0.182) | 1.778*** (0.516) | -0.602* (0.326) | | |
| Lowering groundwater | 0.123 (0.252) | -0.305 (0.622) | 0.368 (0.491) | | |
| Salinization of soils | 0.034 (0.171) | -2.095*** (0.575) | -0.684* (0.355) | | |
| Shortening rainy season | 0.143 (0.175) | 1.453*** (0.465) | 0.276 (0.390) | | |
| Household characteristics | | | | | |
| Age of household head | -0.017*** (0.005) | -0.008 (0.018) | -0.001 (0.014) | | |
| Agricultural income | 0.003 (0.002) | -0.021** (0.010) | 0.002 (0.005) | | |
| Female household head | -0.051 (0.205) | 2.624*** (1.006) | -0.138 (0.496) | | |
| Formal education | 0.108 (0.185) | -1.020** (0.414) | -0.307 (0.367) | | |
| Household size | 0.006 (0.010) | 0.078** (0.034) | 0.007 (0.023) | | |
| Agroforestry controls | | | | | |
| Agroforestry knowledge | 0.388*** (0.058) | -0.411 (0.281) | -0.219 (0.245) | | |
| FMNR practice | 0.558*** (0.157) | -0.682* (0.412) | -0.629 (0.390) | | |
| Prior agroforestry practice | -0.041** (0.021) | 0.021 (0.057) | -0.027 (0.051) | | |
| Subsidized seedlings | 0.318** (0.159) | -0.964* (0.554) | 0.493 (0.381) | | |
| Instrumental variables | | | | | |
| Formal land ownership | 0.666*** (0.252) | | | | |
| Well access | 0.318* (0.163) | | | | |
| Lambda | | -2.603** (1.093) | -0.252 (0.779) | | |
| (Conditional) Observations | 606 | 117 | 117 | | |
| Robust standard errors in parentheses; A | sterisks denote statistical significance: *** p< | 0.01, ** p<0.05, * p<0.1; Commune-level fixed | effects and intercept are included in | | |
| the models but not reported for brevity; The correlation coefficient (atrho21) of the multivariate probit regression is not statistically significant at the 1%, 5%, or 10% level. | | | | | |

References

- Abasse, Tougiani; Massaoudou, Moussa; Ribiou, Habou; Idrissa, Soumana; Guimbo Iro, Dan (2023):
 Farmer managed natural regeneration in Niger: the state of knowledge.
- Admasu, Tesfaye Gebeyehu; Jenberu, Amene Afework (2022): The Impacts of Apple-based
 Agroforestry Practices on the Livelihoods of Smallholder Farmers in Southern Ethiopia. In Trees,
 Forests and People 7, p. 100205. DOI: 10.1016/j.tfp.2022.100205.
- Ahmad, Sibbir; Smale, Melinda; Theriault, Veronique; Maiga, Eugenie (2023): Input subsidies and crop
 diversity on family farms in Burkina Faso. In J Agricultural Economics 74 (1), pp. 237–254. DOI:
 10.1111/1477-9552.12504.
- Ajayi, O. C.; Place, F.; Kwesiga, P.; Mafongoya, P.; Franzel, S. (2005): Impact of Fertilizer Tree
 Fallows in Eastern Zambia. A study on Impacts of Agroforestry. World Agroforestry Centre.
- Amadu, Festus O.; Miller, Daniel C.; McNamara, Paul E. (2020): Agroforestry as a pathway to
 agricultural yield impacts in climate-smart agriculture investments: Evidence from southern
 Malawi. In Ecological Economics 167, p. 106443. DOI: 10.1016/j.ecolecon.2019.106443.
- Amare, Dagninet; Darr, Dietrich (2020): Agroforestry adoption as a systems concept: A review. In
 Forest Policy and Economics 120, p. 102299. DOI: 10.1016/j.forpol.2020.102299.
- Antwi-Agyei, Philip; Wiafe, Esther Ako; Amanor, Kofi; Baffour-Ata, Frank; Codjoe, Samuel Nii Ardey
 (2021): Determinants of choice of climate change adaptation practices by smallholder pineapple
 farmers in the semi-deciduous forest zone of Ghana. In Environmental and Sustainability
 Indicators 12, p. 100140. DOI: 10.1016/j.indic.2021.100140.
- Arslan, Aslihan; Floress, Kristin; Lamanna, Christine; Lipper, Leslie; Rosenstock, Todd S. (2022): A
 meta-analysis of the adoption of agricultural technology in Sub-Saharan Africa. In PLOS Sustain
 Transform 1 (7), e0000018. DOI: 10.1371/journal.pstr.0000018.
- Ascott, M. J.; Macdonald, D.M.J.; Sandwidi, W.J.P.; Black, E.; Verhoef, A.; Zongo, G. et al. (2022):
 Time of emergence of impacts of climate change on groundwater levels in sub-Saharan Africa. In
 Journal of Hydrology 612, p. 128107. DOI: 10.1016/j.jhydrol.2022.128107.
- Asrat, Paulos; Simane, Belay (2018): Farmers' perception of climate change and adaptation strategies
 in the Dabus watershed, North-West Ethiopia. In Ecol Process 7 (1). DOI: 10.1186/s13717-0180118-8.
- Atube, Francis; Malinga, Geoffrey M.; Nyeko, Martine; Okello, Daniel M.; Alarakol, Simon Peter;
 Okello-Uma, Ipolto (2021): Determinants of smallholder farmers' adaptation strategies to the
 effects of climate change: Evidence from northern Uganda. In Agric & Food Secur 10 (1). DOI:
 10.1186/s40066-020-00279-1.

- Ba, Khadidiatou; Sambou, Hyacinthe; Ndiaye, Binette; Goudiaby, Assane (2023): Dynamics of Land
 Salinization in the Commune of Fimela (Fatick, Senegal) from 1973 to 2020. In JGIS 15 (01), pp.
 19–34. DOI: 10.4236/jgis.2023.151002.
- Banyal, R.; Rajkumar; Kumar, Manish; Yadav, R. K.; Dagar, Jagdish Chander (2017): Agroforestry for
 Rehabilitation and Sustenance of Saline Ecologies. In Jagdish Chander Dagar, Vindhya Prasad
 Tewari (Eds.): Agroforestry. Singapore: Springer Singapore, pp. 413–454.
- Bargués Tobella, A.; Hasselquist, N. J.; Bazié, H. R.; Nyberg, G.; Laudon, H.; Bayala, J.; Ilstedt, U.
 (2017): Strategies trees use to overcome seasonal water limitation in an agroforestry system in
 semiarid West Africa. In Ecohydrology 10 (3), Article e1808. DOI: 10.1002/eco.1808.
- Behera, Laxmikanta; Nayak, Manas; Patel, Dhiraji; Mehta, Abhishek; Sinha, Satish; Gunaga, Rajesh
 (2015): Agroforestry practices for physiological amelioration of salt affected soils. In J. Plant
 Stress Physiol 1 (1), p. 13. DOI: 10.5455/jpsp.2015-06-06.
- Belay, Abrham; Oludhe, Christopher; Mirzabaev, Alisher; Recha, John W.; Berhane, Zerihun; Osano,
 Philip M. et al. (2022): Knowledge of climate change and adaptation by smallholder farmers:
 evidence from southern Ethiopia. In Heliyon 8 (12), e12089. DOI: 10.1016/j.heliyon.2022.e12089.
- Belay, Abrham; Recha, John W.; Woldeamanuel, Teshale; Morton, John F. (2017): Smallholder
 farmers' adaptation to climate change and determinants of their adaptation decisions in the Central
 Rift Valley of Ethiopia. In Agric & Food Secur 6 (1). DOI: 10.1186/s40066-017-0100-1.
- Beleta, Kitessa Gemechu; Gondore, Tokuma Urgessa (2022): Edible Woody Plants Diversity and
 Potential Contribution to Food Security in Ethiopia. In International Journal of Ecotoxicology and
 Ecobiology.
- Benjaminsen, Tor A. (2021): Climate Change and Human Conflict in the Sahel. In Leonardo A. Villalón
 (Ed.): The Oxford Handbook of the African Sahel: Oxford University Press.
- Beyene, Abebe D.; Mekonnen, Alemu; Randall, Bluffstone; Deribe, Rahel (2019): Household Level
 Determinants of Agroforestry Practices Adoption in Rural Ethiopia. In Forests, Trees and
 Livelihoods 28 (3), pp. 194–213. DOI: 10.1080/14728028.2019.1620137.
- Biasutti, Michela (2019): Rainfall trends in the African Sahel: Characteristics, processes, and causes.
- In Wiley interdisciplinary reviews. Climate change 10 (4), e591. DOI: 10.1002/wcc.591.
- Bonye, Samuel Ziem (2024): Local institutions, actors and governance systems under farmer managed
 natural regeneration (FMNR) in Northwestern Ghana. In Agroforest Syst 98 (3), pp. 567–583.
 DOI: 10.1007/s10457-023-00930-3.

- Bozorgi, Mahsa; Moein, Mahsa; Nejadkoorki, Farhad; Toosi, Neda Bihamta (2020): Assessing the
 effect of water scarcity on crop selection and spatial pattern of croplands in central Iran. In
 Computers and Electronics in Agriculture 178, p. 105743. DOI: 10.1016/j.compag.2020.105743.
- Briggs, Derek C. (2004): Causal Inference and the Heckman Model. In Journal of Educational and
 Behavioral Statistics 29 (4), pp. 397–420. DOI: 10.3102/10769986029004397.
- 614 Cardinael, Rémi; Cadisch, Georg; Gosme, Marie; Oelbermann, Maren; van Noordwijk, Meine (2021): 615 Climate change mitigation and adaptation in agriculture: Why agroforestry should be part of the 616 Ecosystems & 319, 107555. DOI: solution. In Agriculture, Environment p. 10.1016/j.agee.2021.107555. 617
- Cascetta, Ennio (2009): Random Utility Theory. In Ennio Cascetta (Ed.): Transportation Systems
 Analysis, vol. 29. Boston, MA: Springer US (Springer Optimization and Its Applications), pp. 89–
 167.
- 621 Certo, S. Trevis; Busenbark, John R.; Woo, Hyun-soo; Semadeni, Matthew (2016): Sample selection
 622 bias and Heckman models in strategic management research. In Strategic Management Journal 37
 623 (13), pp. 2639–2657. DOI: 10.1002/smj.2475.
- Chemeda, Beshea Abdissa; Wakjira, Feyera Senbeta; Birhane, Emiru (2023): Determinants of
 perception of climate change and adaptation strategies of coffee-based agroforestry farmers in
 western Ethiopia. In Emerald Open Res 5, p. 5. DOI: 10.35241/emeraldopenres.14904.1.
- 627 Chen, Minjie; Wichmann, Bruno; Luckert, Marty; Winowiecki, Leigh; Förch, Wiebke; Läderach, Peter
 628 (2018): Intensification and diversification of agricultural adaptation from global to local scales. In
 629 PloS one 13 (5), e0196392. DOI: 10.1371/journal.pone.0196392.
- Chirwa, Paxie W.; Ong, Chin K.; Maghembe, Jumanne; Black, Colin R. (2007): Soil water dynamics
 in cropping systems containing Gliricidia sepium, pigeonpea and maize in southern Malawi. In
 Agroforest Syst 69 (1), pp. 29–43. DOI: 10.1007/s10457-006-9016-7.
- Cotillon, Suzanne; Tappan, Gray; Reij, Chris (2021): Land Use Change And Climate- Smart Agriculture
 In The Sahel. In Leonardo A. Villalón (Ed.): The Oxford Handbook of the African Sahel: Oxford
 University Press.
- Coulibaly, Jeanne Y.; Chiputwa, Brian; Nakelse, Tebila; Kundhlande, Godfrey (2017): Adoption of
 agroforestry and the impact on household food security among farmers in Malawi. In Agricultural
 systems 155, pp. 52–69. DOI: 10.1016/j.agsy.2017.03.017.
- Dagar, J. C.; Minhas, P. S. (2016): Global Perspectives on Agroforestry for the Management of Salt affected Soils. In Jagdish Chander Dagar, Paramjit Minhas (Eds.): Agroforestry for the

- Management of Waterlogged Saline Soils and Poor-Quality Waters, vol. 13. New Delhi: Springer
 India (Advances in Agroforestry), pp. 5–32.
- Diack, Mateugue; Diop, T.; Ndiaye, R. (2015): Restoration of Degraded Lands Affected by Salinization
 Process Under Climate Change Conditions: Impacts on Food Security in the Senegal River Valley.
 In Rattan Lal, Bal Ram Singh, Dismas L. Mwaseba, David Kraybill, David O. Hansen, Lars Olav
- Eik (Eds.): Sustainable Intensification to Advance Food Security and Enhance Climate Resilience
- 647 in Africa. Cham: Springer International Publishing, pp. 275–288.
- Diallo, Mountakha; Ndir, Khadidiatou; Diop, Amadou M.; Dieye, Bineta; Ndiaye, Saliou (2020):
 Global analysis of millet-based household farms: Characterization of the Senegalese production
 system of Niayes and Groundnut basin areas. In Afr. J. Agric. Res. 16 (8), pp. 1133–1140. DOI:
 10.5897/AJAR2019.14551.
- Fall, Dioumacor; Diouf, Diegane; Zoubeirou, Alzouma Mayaki; Bakhoum, Niokhor; Faye, Aliou; Sall,
 Saidou Nourou (2012): Effect of distance and depth on microbial biomass and mineral nitrogen
 content under Acacia senegal (L.) Willd. trees. In Journal of environmental management 95 Suppl,
 S260-4. DOI: 10.1016/j.jenvman.2011.03.038.
- 656FAO(2002):GWIESSomeDefinitions.Availableonlineat657https://www.fao.org/3/y7738e/y7738e09.htm, checked on 3/5/2024.
- Frey, Bruce B. (2018): The SAGE Encyclopedia of Educational Research, Measurement, and
 Evaluation. 2455 Teller Road, Thousand Oaks, California 91320: SAGE Publications, Inc.
- Gaetani, Marco; Janicot, Serge; Vrac, Mathieu; Famien, Adjoua Moise; Sultan, Benjamin (2020):
 Robust assessment of the time of emergence of precipitation change in West Africa. In Scientific
 reports 10 (1), p. 7670. DOI: 10.1038/s41598-020-63782-2.
- Georges, Ndiaye; Fang, Shaoyong; Beckline, Mukete; Wu, Ye (2016): Potentials of the Groundnut
 Sector towards Achieving Food Security in Senegal. In OALib 03 (09), pp. 1–13. DOI:
 10.4236/oalib.1102991.
- Grovermann, Christian; Rees, Charles; Beye, Assane; Wossen, Tesfamicheal; Abdoulaye, Tahirou;
 Cicek, Harun (2023): Uptake of agroforestry-based crop management in the semi-arid Sahel –
 Analysis of joint decisions and adoption determinants. In Front. Sustain. Food Syst. 7, Article
 1042551. DOI: 10.3389/fsufs.2023.1042551.
- Hadgu, Kiros Meles; Bishaw; Badege; Iiyama, Miyuki; Birhane, Emiru; Negussie, Aklilu et al. (2019):
 Climate-Smart Agriculture. Enhancing Resilient Agricultural Systems, Landscapes, and
 Livelihoods in Ethiopia and Beyond. World Agroforestry (ICRAF). Nairobi, Kenya.

- Heckman, James J. (1979): Sample Selection Bias as a Specification Error. In Econometrica 47 (1), p.
 153. DOI: 10.2307/1912352.
- Huntington, Heather; Shenoy, Ajay (2021): Does insecure land tenure deter investment? Evidence from
 a randomized controlled trial. In Journal of Development Economics 150, p. 102632. DOI:
 10.1016/j.jdeveco.2021.102632.
- 678 IPCC (2020): Climate Change and Land. Summary for Policymakers. IPCC.
- Jadhav, Anil; Pramod, Dhanya; Ramanathan, Krishnan (2019): Comparison of Performance of Data
 Imputation Methods for Numeric Dataset. In Applied Artificial Intelligence 33 (10), pp. 913–933.
 DOI: 10.1080/08839514.2019.1637138.
- Jansen, Merel; Guariguata, Manuel R.; Raneri, Jessica E.; Ickowitz, Amy; Chiriboga-Arroyo, Fidel;
 Quaedvlieg, Julia; Kettle, Chris J. (2020): Food for thought: The underutilized potential of tropical
 tree-sourced foods for 21st century sustainable food systems. In People and Nature 2 (4), pp. 1006–
 1020. DOI: 10.1002/pan3.10159.
- Jellason, Nugun P.; Conway, John S.; Baines, Richard N.; Ogbaga, Chukwuma C. (2021): A review of
 farming challenges and resilience management in the Sudano-Sahelian drylands of Nigeria in an
 era of climate change. In Journal of Arid Environments 186, p. 104398. DOI:
 10.1016/j.jaridenv.2020.104398.
- Kangai, Everlyn Ruth; Wemali Chitechi; James, Koske; Boaz, Waswa; Innocent, Ngare (2021):
 Determinants of climate change adaptation and perceptions among small-scale farmers of Embu
 County, Eastern Kenya. In Afr. J. Environ. Sci. Technol. 15 (4), pp. 167–178. DOI:
 10.5897/AJEST2020.2943.
- Karambiri, Mawa; Bourne, Mieke; Bayala, Jules; Ndiaye, Anna Daba; Sanogo, Diaminatou (2023):
 'Trees are not all the same' Assessing the policy and regulatory barriers to the upscaling of Famer
 Managed Natural Regeneration (FMNR) in Senegal. In Forests, Trees and Livelihoods, pp. 1–23.
 DOI: 10.1080/14728028.2023.2229355.
- Kpoviwanou, M.R.J. Houndjo; Sourou, Bienvenue Nawan Kuiga; Ouinsavi, Christine A.I. Nougbodé
 (2024): Challenges in adoption and wide use of agroforestry technologies in Africa and pathways
 for improvement: A systematic review. In Trees, Forests and People 17, p. 100642. DOI:
 10.1016/j.tfp.2024.100642.
- Kurukulasuriya, Pradeep; Mendelsohn, Robert (2007): Crop Selection. Adapting to Climage Change in
 Africa. The World Bank.
- Kuyah, Shem; Whitney, Cory W.; Jonsson, Mattias; Sileshi, Gudeta W.; Öborn, Ingrid; Muthuri,
 Catherine W.; Luedeling, Eike (2019): Agroforestry delivers a win-win solution for ecosystem

- services in sub-Saharan Africa. A meta-analysis. In Agron. Sustain. Dev. 39 (5). DOI:
 10.1007/s13593-019-0589-8.
- 708 Lasco, Rodel D.; Delfino, Rafaela Jane P.; Catacutan, Delia C.; Simelton, Elisabeth S.; Wilson, David 709 M. (2014): Climate risk adaptation by smallholder farmers: the roles of trees and agroforestry. In 710 Current in Environmental Sustainability 6. 83-88. DOI: Opinion pp. 711 10.1016/j.cosust.2013.11.013.
- Leroux, L.; Clermont-Dauphin, C.; Ndienor, M.; Jourdan, C.; Roupsard, O.; Seghieri, J. (2022a): A
 spatialized assessment of ecosystem service relationships in a multifunctional agroforestry
 landscape of Senegal. In The Science of the total environment 853, p. 158707. DOI:
 10.1016/j.scitotenv.2022.158707.
- Leroux, L.; Faye, N. F.; Jahel, C.; Falconnier, G. N.; Diouf, A. A.; Ndao, B. et al. (2022b): Exploring
 the agricultural landscape diversity-food security nexus: an analysis in two contrasted parklands
 of Central Senegal. In Agricultural systems 196, p. 103312. DOI: 10.1016/j.agsy.2021.103312.
- Mansingh, B. Brailson; Binoj, J. S.; Sai, N. Prem; Hassan, Shukur Abu; Siengchin, Suchart; Sanjay, M.
 R.; Liu, Y. C. (2021): Sustainable development in utilization of Tamarindus indica L. and its byproducts in industries: A review. In Current Research in Green and Sustainable Chemistry 4, p.
 100207. DOI: 10.1016/j.crgsc.2021.100207.
- Mbow, C.; Toensmeier, E.; Brandt, M.; Skole, D.; Dieng, M.; Garrity, D.; Poulter, B. (2020a):
 Agroforestry as a solution for multiple climate change challenges in Africa. In Delphine Deryng
 (Ed.): Climate change and agriculture: Burleigh Dodds Science Publishing (Burleigh Dodds series
 in agricultural science).
- Mbow, Cheikh; Halle, Mark; El Fadel, Rabih; Thiaw, Ibrahim (2020b): Land resources opportunities
 for a growing prosperity in the Sahel. In Current Opinion in Environmental Sustainability 48, pp.
 85–92. DOI: 10.1016/j.cosust.2020.11.005.
- 730 Mbow, Cheikh; Smith, Pete; Skole, David; Duguma, Lalisa; Bustamante, Mercedes (2014): Achieving 731 mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. 732 In Current Opinion in Environmental Sustainability 6, pp. 8-14. DOI: 733 10.1016/j.cosust.2013.09.002.
- Mercer, D. E. (2004): Adoption of agroforestry innovations in the tropics: A review. In Agroforest Syst
 61-62 (1-3), pp. 311–328. DOI: 10.1023/B:AGFO.0000029007.85754.70.
- Mertz, Ole; Mbow, Cheikh; Reenberg, Anette; Diouf, Awa (2009): Farmers' perceptions of climate
 change and agricultural adaptation strategies in rural Sahel. In Environmental management 43 (5),
 pp. 804–816. DOI: 10.1007/s00267-008-9197-0.

- 739 Messier, Christian; Bauhus, Jürgen; Sousa-Silva, Rita; Auge, Harald; Baeten, Lander; Barsoum, Nadia
- et al. (2022): For the sake of resilience and multifunctionality, let's diversify planted forests! In
 CONSERVATION LETTERS 15 (1), Article e12829. DOI: 10.1111/conl.12829.
- Mulwa, Chalmers K.; Visser, Martine (2020): Farm diversification as an adaptation strategy to climatic
 shocks and implications for food security in northern Namibia. In World Development 129, p.
 104906. DOI: 10.1016/j.worlddev.2020.104906.
- Murken, Lisa; Gornott, Christoph (2022): The importance of different land tenure systems for farmers'
 response to climate change: A systematic review. In Climate Risk Management 35, p. 100419.
 DOI: 10.1016/j.crm.2022.100419.
- Muthuri; C.D., Wakaba; C., Njoki (2023): Fruit Trees for Climate Change Mitigation and Adaptation
 in East Africa: Project highlights: World Agroforestry.
- Orwa, C.; Mutua, A.; Kindt, R.; Jamnadass, R.; Simons, A. (2009): Agroforestree Database. A tree
 reference and selection guide version 4.0. World Agroforestry. Available online at
 https://www.worldagroforestry.org/output/agroforestree-database.
- Papa, Chad; Nzokou, Pascal; Mbow, Cheikh (2020): Farmer Livelihood Strategies and Attitudes in
 Response to Climate Change in Agroforestry Systems in Kedougou, Senegal. In Environmental
 management 66 (2), pp. 218–231. DOI: 10.1007/s00267-020-01302-8.
- Parton, W.; Tappan, G.; Ojima, D.; Tschakert, P. (2004): Ecological impact of historical and future
 land-use patterns in Senegal. In Journal of Arid Environments 59 (3), pp. 605–623. DOI:
 10.1016/j.jaridenv.2004.03.024.
- Podgorski, Joel; Kracht, Oliver; Araguas-Araguas, Luis; Terzer-Wassmuth, Stefan; Miller, Jodie;
 Straub, Ralf et al. (2024): Groundwater vulnerability to pollution in Africa's Sahel region. In Nat
 Sustain 7 (5), pp. 558–567. DOI: 10.1038/s41893-024-01319-5.
- Quandt, Amy; Neufeldt, Henry; McCabe, J. Terrence (2017): The role of agroforestry in building
 livelihood resilience to floods and drought in semiarid Kenya. In E&S 22 (3). DOI: 10.5751/ES09461-220310.
- Reij, Chris; Garrity, Dennis (2016): Scaling up farmer-managed natural regeneration in Africa to restore
 degraded landscapes. In Biotropica 48 (6), pp. 834–843. DOI: 10.1111/btp.12390.
- Ricome, Aymeric; Affholder, François; Gérard, Françoise; Muller, Bertrand; Poeydebat, Charlotte;
 Quirion, Philippe; Sall, Moussa (2017): Are subsidies to weather-index insurance the best use of
 public funds? A bio-economic farm model applied to the Senegalese groundnut basin. In
 Agricultural systems 156, pp. 149–176. DOI: 10.1016/j.agsy.2017.05.015.

- Sambou, Antoine; Theilade, Ida; Fensholt, Rasmus; Ræbild, Anders (2016): Decline of woody
 vegetation in a saline landscape in the Groundnut Basin, Senegal. In Reg Environ Change 16 (6),
 pp. 1765–1777. DOI: 10.1007/s10113-016-0929-z.
- Sambou, Mariama; Koné, Brahima; Sambou, Simon; Niang, Fatimata; Sane, Seyni; Diatta, Malainy et
 al. (2024a): Variation of biomass carbon stock within agroforestry systems in the Senegalese
 groundnut basin. In Discov Sustain 5 (1). DOI: 10.1007/s43621-024-00208-3.
- Sambou, Mariama; Koné, Brahima; Sane, Seyni; Vodounnon, Mahunan Eric José; Diatta, Andre
 Amakobo; Diatta, Lamine et al. (2024b): Impact of climate change on the habitat range and
 distribution of Cordyla pinnata, Faidherbia albida and Balanites aegyptiaca in Senegal. In Model.
 Earth Syst. Environ. 10 (3), pp. 3137–3155. DOI: 10.1007/s40808-023-01935-8.
- Schwiebert, Jörg (2015): Estimation and interpretation of a Heckman selection model with endogenous
 covariates. In Empir Econ 49 (2), pp. 675–703. DOI: 10.1007/s00181-014-0881-z.
- Sissoko, Keffing; van Keulen, Herman; Verhagen, Jan; Tekken, Vera; Battaglini, Antonella (2011):
 Agriculture, livelihoods and climate change in the West African Sahel. In Reg Environ Change 11
 (S1), pp. 119–125. DOI: 10.1007/s10113-010-0164-y.
- Sow, Ahmadou; Seye, Djiby; Faye, Emile; Benoit, Laure; Galan, Maxime; Haran, Julien; Brévault,
 Thierry (2020): Birds and bats contribute to natural regulation of the millet head miner in tree-crop
 agroforestry systems. In Crop Protection 132, p. 105127. DOI: 10.1016/j.cropro.2020.105127.
- Sthapit, Sajal; Scherr, Sara (2012): Tropical Fruit Trees and Opportunities for Adaptation and
 Mitigation. In Bhuwon Sthapit, V. Ramanatha Rao, Sajal Sthapit (Eds.): Tropical fruit tree species
 and climate change. New Delhi: Biodiversity International, pp. 129–137.
- Sucker, Franziska (2021): Reflections on agricultural subsidies. In SSRN Journal. DOI:
 10.2139/ssrn.3925066.
- Sullivan, Joe H.; Warkentin, Merrill; Wallace, Linda (2021): So many ways for assessing outliers: What
 really works and does it matter? In Journal of Business Research 132, pp. 530–543. DOI:
 10.1016/j.jbusres.2021.03.066.
- Sylla, Mouhamadou Bamba; Nikiema, Pinghouinde Michel; Gibba, Peter; Kebe, Ibourahima; Klutse,
 Nana Ama Browne (2016): Climate Change over West Africa: Recent Trends and Future
 Projections. In Joseph A. Yaro, Jan Hesselberg (Eds.): Adaptation to Climate Change and
 Variability in Rural West Africa. Cham: Springer International Publishing, pp. 25–40.
- Tambo, Justice Akpene; Abdoulaye, Tahirou (2013): Smallholder farmers' perceptions of and
 adaptations to climate change in the Nigerian savanna. In Reg Environ Change 13 (2), pp. 375–
 388. DOI: 10.1007/s10113-012-0351-0.

- Thinda, K. T.; Ogundeji, A. A.; Belle, J. A.; Ojo, T. O. (2020): Understanding the adoption of climate
 change adaptation strategies among smallholder farmers: Evidence from land reform beneficiaries
 in South Africa. In Land Use Policy 99, p. 104858. DOI: 10.1016/j.landusepol.2020.104858.
- 807 Umar, Mohammed Bashir (2024): Climate Change Awareness, Perception, and Adaptation Strategies
 808 for Small and Marginal Farmers in Yobe State, Nigeria. In Rohitashw Kumar (Ed.): Sustainability
 809 of natural resources. Planning, development, and management. First edition. Boca Raton: CRC
 810 Press Taylor & Francis Group.
- 811UN(2025):WhatIsClimateChange?UN.Availableonlineat812https://www.un.org/en/climatechange/what-is-climate-change, checked on 1/21/2025.
- 813 UNCCD (2024): The Great Green Wall. Available online at https://www.unccd.int/our-work/ggwi,
 814 checked on 1/6/2022.
- van Ramshorst, Justus G. V.; Siebicke, Lukas; Baumeister, Moritz; Moyano, Fernando E.; Knohl,
 Alexander; Markwitz, Christian (2022): Reducing Wind Erosion through Agroforestry: A Case
 Study Using Large Eddy Simulations. In Sustainability 14 (20), p. 13372. DOI:
 10.3390/su142013372.
- Wu, Qinglin; Wang, Lan (2024): Farmland hydrological cycle under agroforestry systems and efficient
 use of water resources in the karst desertification environment. In Heliyon 10 (15), e35506. DOI:
 10.1016/j.heliyon.2024.e35506.
- Yegberney, Rosaine N.; Yabi, Jacob A.; Tovignan, Silvère D.; Gantoli, Geoffroy; Haroll Kokoye,
 Sènakpon E. (2013): Farmers' decisions to adapt to climate change under various property rights:
 A case study of maize farming in northern Benin (West Africa). In Land Use Policy 34, pp. 168–
 175. DOI: 10.1016/j.landusepol.2013.03.001.
- Yobom, Oudah (2020): Climate change and variability: empirical evidence for countries and
 agroecological zones of the Sahel. In Climatic Change 159 (3), pp. 365–384. DOI:
 10.1007/s10584-019-02606-3.
- Yobom, Oudah; Le Gallo, Julie (2021): Climate and agriculture: empirical evidence for countries and
 agroecological zones of the Sahel. In Applied Economics, pp. 1–19. DOI:
 10.1080/00036846.2021.1970710.

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