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

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Abstract

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

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

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).

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

Past studies have analyzed smallholders' perception of climate change in relation to determinants for 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 in climatic conditions and pursue tree planting as one of multiple main adaptation strategies. Belay et 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, Belay et al. (2022) analyze Ethiopian smallholders' uptake of at least one climate smart agricultural practice, such as agroforestry, conditional on their awareness of climate change. Thinda et al. (2020) analyze how South African smallholder farmers choose to adopt multiple climate change adaptation strategies, including insurance uptake, migration and tree planting. In the Ugandan context, Atube et al. (2021) analyzed determinants of smallholders' adoption of diverse adaptation strategies including tree planting. In open focus group discussions in Kedougou, Senegal, Papa et al. (2020) further reveal that smallholders recognize the various ecosystem services, agroforestry practices offer and use agroforestry as a strategy to adapt to climate change. While these studies examine smallholders' perceptions of climate change and their general adoption of agroforestry as one of several adaptation strategies, we do not know much about the rationale of smallholders planting trees and selecting tree species, particularly in response to climate change. Further, climate change drives context specific environmental stressors (IPCC 2020) to agricultural practices that might encourage different adaptation strategies. Smallholders' tree species selection within their tree planting decisions, as detailed adaptation strategy of production intensification and/or diversification in relation to locally relevant climate change effects, remains unexplored.

In this paper, we thus address the following questions: Do smallholders in the Sahel region plant trees on their farmland as an adaptation strategy to their perception of local climate change effects? Additionally, do they select fertilizer and/or fruit tree species for planting as an adaptation strategy, 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 relevant climate change effects and their detailed agroforestry-based adaptation strategies beyond mere adoption. Therefore, we distinguish between the potential adaptation strategies of food production intensification and diversification by categorizing tree species according to those objectives as fertilizer or fruit trees.

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

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 smallholders in the Sudano-Sahelian climate zones across the Sahel region are facing severe threats due to the effects of climate change (Mbow et al. 2020a; Yobom and Le Gallo 2021). Average annual temperatures are increasing, rainy seasons are becoming shorter, heavy rainfalls occur more frequently, groundwater levels fluctuate greatly and soils are becoming more saline (Biasutti 2019; Mbow et al. 2020a; Yobom 2020; Ascott et al. 2022; Ba et al. 2023; Sambou et al. 2024b). While the integration and tree management on farmland have been practiced for centuries in Senegal and other Sahelian countries (Parton et al. 2004; Cotillon et al. 2021), agroforestry is increasingly recognized and promoted by policymakers and researchers as a promising approach for both mitigating and adapting to climate change in this region (Sissoko et al. 2011; Diallo et al. 2020). However, agroforestry practices still need to be expanded in Senegal and other Sahelian countries to meet land restoration targets formulated by e.g. the Great Green Wall initiative or the African Forest Landscape Restoration (Grovermann et al. 2023; Karambiri et al. 2023; UNCCD 2024).

2.2 Assessing perceptions of climate change effects

Measuring smallholders’ perceptions of climate change is inherently complex, as the concept is broad and encompasses processes that extend beyond the human lifespan (UN 2025). In previous climate change adaptation studies, smallholders’ climate change perception has typically been elicited by assessing their perception of locally relevant environmental stressors, such as rainfall variability, extreme weather events or poor soil fertility, or changes in rainfall patterns, which are known to be driven by climate change. Mertz et al. (2009) and Papa et al. (2020) for instance, assess Senegalese smallholders perceptions of e.g. intensive rainfalls and inundations or short rainy seasons in relation to their adaptation strategies. Bessah et al. (2021) and Umar (2024) respectively link Ghanaian and Nigerian smallholders’ perceptions of, for instance, poor soil fertility or changes in rainfall patterns to their adaptation strategies. Likewise, Belay et al. (2017), Belay et al. (2022), and Chemeda et al. (2023), assess Ethiopian smallholders’ perception of e.g. rainfall variability to understand their related adaptation strategies. Mertz et al. (2009) and Zougmoré et al. (2023) further point out that smallholders knowledge and perception of climate change effects is consistent with meteorological data. The perceptions of environmental stressors thus serve as tangible indicators for the perception of climate 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 al. (2016), Biasutti (2019) and Gaetani et al. (2020) describe that rainy seasons are becoming shorter and heavy rains are occurring more frequently due to climate change. In their studies, Diack et al. (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) state that groundwater levels in the Sahel region are highly variable and sensitive to climate change. Smallholders perception of land degradation, shortening rainy seasons, occurrence of heavy rains, salinization of soils and lowering groundwater levels as challenges for their cropping activities therefore 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 Basin from December 2022 to January 2023. During this period, we conducted a household survey, gathering information from 606 smallholder farmer households. The three regions were selected as they are part of the Sudano-Sahelian climate zone within the Groundnut Basin, as for instance described by Ricome et al. (2017). We selected households following a multi-stage random sampling approach, for which we randomly selected five communes within each region of our study. We then randomly selected two villages within each commune. Our team of eleven enumerators was trained over three days preceding the data collection. During the survey, the enumerators conducted one-on-one 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 22 randomly selected households per village. During the interviews, smallholders were asked a range of socio-demographic questions, along with questions about their agricultural practices, as well as their 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 previously described environmental stressors that are driven through climate change in the context of 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 were used to verify whether smallholders were aware of and perceived the listed environmental stressors as challengers for their cropping activities. The smallholders' responses to this survey question have been utilized to compute distinct binary variables for smallholders' perception of respective climate change effect for our study. To gather information on smallholders' tree planting decisions for our study, we inquired whether they had planted trees on their land within the three years preceding our data collection and, if so, which specific tree species they had chosen to plant. The three-year recall period for tree planting activities was chosen because trees typically begin to realize their potential benefits, such as improving soil fertility or groundwater levels, only around three years after being planted (Mercer 2004; Coulibaly et al. 2017). By excluding trees planted more than three years ago, we ensure 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 for our study are provided in English in Appendix A.

For our study, we replaced values above the 99th percentile in continuous variables, such as age, 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 analysis. Through this imputation approach we are more likely to underestimate economic and statistical relationships in our estimations than overestimating them (Sullivan et al. 2021). Missing values in the continuous variables were replaced with the mean of the respective variable. Jadhav et al. (2019) suggest that this imputation method is appropriate when less than 1% of the variables' observations are missing, as is the case in our data.

2.4 Definition of fertilizer and fruit tree species

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

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

To analyse smallholders' selection of tree species for planting to adapt their food production system to climate change effects, we grouped the tree species that our respondents reported to have planted in the past three years into two categories: fertilizer trees and fruit trees. The categorization as fertilizer or fruit trees is based on information for respective tree species provided by World Agroforestry, as well as relevant literature on the properties of respective species (See Table 1). Tree species that have been shown to fix nitrogen in soils or enhance soil fertility and crop yields in other specific ways are classified as fertilizer trees, following e.g. Ajayi et al. (2005). If tree species provide edible fruits, they are classified as fruit trees. For most tree species reported by respondents in our dataset, we found evidence that they either produce edible fruits or have specific properties to improve soil fertility. If tree species were found to provide fruits and potentially enhance soil fertility, such as the multipurpose tree species *Tamarindus indica* (Mansingh et al. 2021), they were classified based on their primary use as indicated 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 species often provide simultaneously (Orwa et al. 2009). Tree species reported by respondents that neither have specific fertilizing properties nor produce edible fruits are therefore not categorized in our study, even though they likely provide other non-edible products and values (Orwa et al. 2009). Similarly, trees that were planted but whose species the respondents did not know will not be specifically addressed in our analysis of tree species selection, as we assume they were not planted to achieve species-specific benefits.

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

Tree Species	Fertilizer Tree	Fruit Tree	Source
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

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

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

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

Heckman models have commonly been used in agroforestry research to model conditional decisions and control for selection bias. Beyene et al. (2019), for instance, apply a Heckman model to estimate the agroforestry adoption decision and extent among farmer households in Ethiopia. In the first stage, they use a probit regression to model adoption decisions, followed by a second stage OLS regression to estimate the area of land devoted to agroforestry practices, conditional on smallholders having decided to adopt. Asrat and Simane (2018) estimate Ethiopian farmers' decision to adapt to climate change, conditional on their perception of changes in climatic conditions using two probit regressions within a Heckman selection model. Similarly, Kangai et al. (2021) employ a Heckman model with two probit regressions to model Kenyan smallholder farmers climate change adaptation decision conditional on their perception of climate change. Thinda et al. (2020) use a similar double hurdle model to estimate smallholder farmers' adoption of climate change adaptation strategies in South Africa. In the first stage, 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 how many 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 years using the following probit regression model:

$$Y_i^* = \beta_0 + \beta_1 CP_i + \beta_2 Z_i + \beta_3 R + \beta_4 IV + \varepsilon_i \tag{1}$$

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

$$Y_i = \begin{cases} 1 \text{ } if \text{ } Y_i^* > 0 \\ 0 \text{ } if \text{ } Y_i^* \leq 0 \end{cases} \tag{2}$$

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:

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

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:

$$T_{is} = \begin{cases} 1 \text{ } if \text{ } T_{is}^* > 0 \\ 0 \text{ } if \text{ } T_{is}^* \leq 0 \end{cases} \tag{4}$$

In both regression models, CP_i represents our indicators for smallholders' perception of climate change effects, specifically their perceptions of land degradation, shortening rainy seasons, occurrence of heavy 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, agricultural income, education, gender and household size. Those variables have been identified to determine agroforestry adoption in previous studies focusing on agroforestry adoption as Amare and Darr (2020), Arslan et al. (2022), or Kpoviwanou et al. (2024) show in their structured literature reviews. We further control for agroforestry experience, agroforestry knowledge, the practice of farmer managed natural regeneration (FMNR) within the past three years, and access to subsidized seedlings. Agroforestry experience is a count variable of the number of trees per hectare smallholders had on their agricultural land prior to the three-year tree-planting period. By including this variable in our regression model, we account for the possibility that smallholders decide to plant trees based on habit or prior experience, rather than their perception of climate change effects. Agroforestry knowledge has previously been identified as one of the main determinants in the smallholders' adoption decision (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) and the selection of specific tree species. We thus control for their effect on tree planting decisions and tree species selection. FMNR is an alternative pathway for smallholders to integrate trees into their production system (Reij and Garrity 2016; Karambiri et al. 2023). We therefore control for smallholders 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.

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

Secure land tenure has been found to generally affect smallholders' decision to adapt to climate change. However, it does not appear to play a statistically significant role in the selection of specific adaptation strategies, such as crop intensification or diversification through increased input use (Yegbemey et al. 2013; Murken and Gornott 2022). As rainfall in our study region is limited to a few months per year, and tree seedlings require year-round watering to mature (Cotillon et al. 2021) until they can draw water from deeper soil depths (Bargués Tobella et al. 2017), access to a well is expected to constrain the decision to plant trees in our study context. Prior studies suggest that water scarcity may favor the selection of more drought-tolerant crop species (Kurukulasuriya and Mendelsohn 2007; Bozorgi et al. 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 observed in our study region are mostly endemic and thus adapted to semi-arid climatic conditions. 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 fertilizer tree species, other than through the general decision to plant trees. By using smallholders' formal land ownership and access to a well as instruments, we thus introduce exogenous variation in tree planting decisions that is independent of species selection, thereby improving model identification (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.

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

$$\lambda_i = \frac{\phi\ (\beta_0 + \beta_1 CP_i + \beta_2 Z_i + \beta_3 R)}{\Phi(\beta_0 + \beta_1 CP_i + \beta_2 Z_i + \beta_3 R)} \tag{5}$$

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

The descriptive statistics (Table 2) of our indicators for smallholders' perception of the different local 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 problematic for their cropping activities. The degradation of land is perceived as problematic by about 82% of the smallholders and the increasing frequency of heavy rain events was reported by about 29% of the smallholders (Figure 1) as problematic to their cropping activities. The salinization of soils and shortening rainy seasons are perceived as problematic for arable farming by about 26% and 24% of the respondents respectively. The lowering of groundwater levels has been perceived by about 9% of smallholders as posing problems for their cropping activities. The proportions of smallholders perceiving those climate change effects further does not differ much between those who planted trees and those who did not within the past three years.

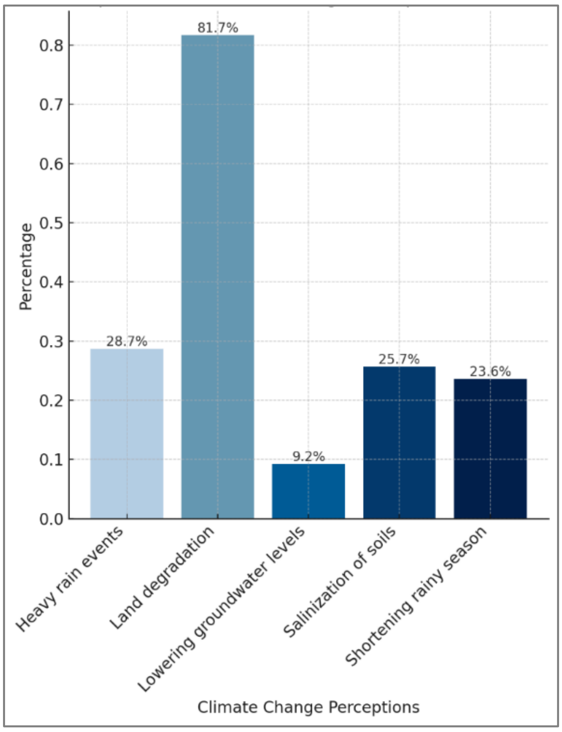

Figure 1. Proportion of smallholders perceiving different climate change effects as problematic for their cropping activities (N=606).

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 years (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=yes)	0.287	0.359	0.270	-0.089*
Land degradation	Smallholder perceiving land degradation as problematic for their agricultural activities (1=yes)	0.817	0.769	0.828	0.059
Lowering groundwater levels	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=yes)	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					
Age 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=yes)	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	Number of trees per hectare prior to the three-years planting period	2.160 (4.536)	1.565 (2.535)	2.302 (4.886)	0.736
Subsidized seedlings	Dummy for smallholder having received tree seedlings for free or at a subsidized price	0.216	0.325	0.190	-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

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 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 planted trees within the past three years chose to plant both fertilizer and fruit tree species.

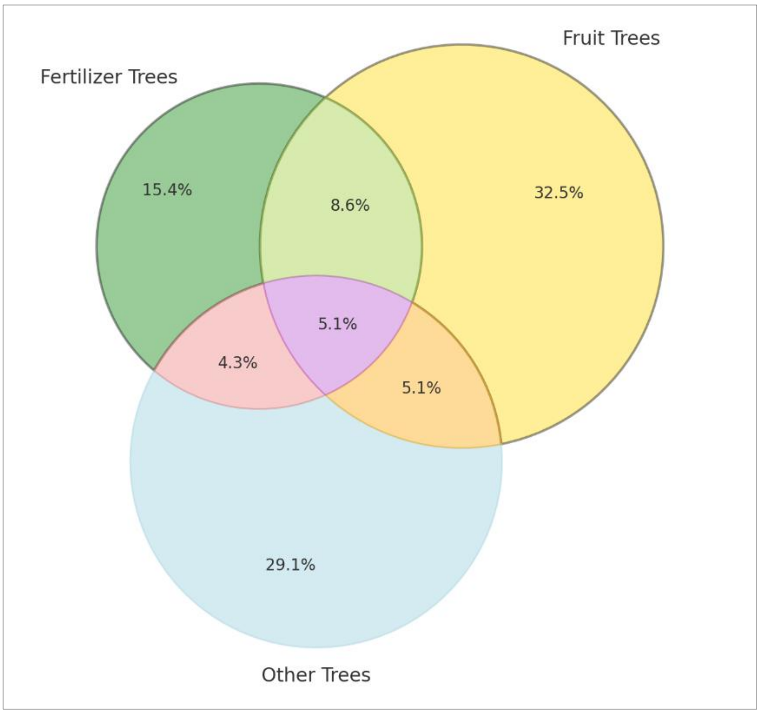

Figure 2. Proportions of smallholders who selected fruit tree species, fertilizer tree species, and/or other types of tree species after deciding to plant trees (N=117).

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

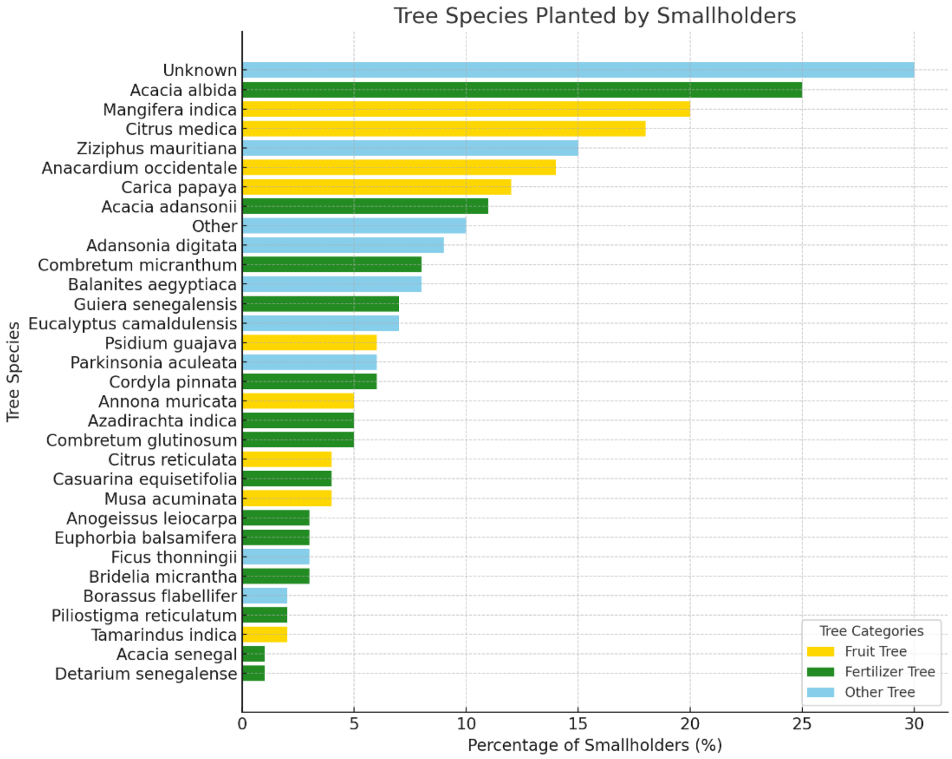

Figure 3. Proportion of smallholders who selected specific tree species within the categories of fruit, fertilizer and other tree species (N=117).

3.2 Econometric results

Our regression results (Table 3) provide more detailed information on the relationship between smallholders' perceptions of climate change effects and their decision to plant trees, as well as their 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' perceptions of different climate change effects, the marginal changes in the likelihood of having decided to plant trees within the past three years for all of our climate change perception indicators are positive. For smallholders who have decided to plant trees, however, the estimates for several of our climate change indicators are statistically significant in their tree species selection for planting. Different than for the initial decision to plant trees, smallholders' perception of land degradation, salinization of soils 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' likelihood to have selected fruit tree species, smallholders' perception of a salinization of their soils relates to a decreased likelihood to have selected fruit trees for planting. Other than for the selection of 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, 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' likelihood of having selected fertilizer tree species for planting.

Table 3. Regression results

	Tree planting		Fruit tree		Fertilizer 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 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.

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

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

3.3 Robustness checks

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

4. Discussion

While previous studies, such as those by Belay et al. (2017), Atube et al. (2021), Belay et al. (2022), or Chemeda et al. (2023), find that tree planting is one of multiple climate change adaptation approaches of smallholders, our findings reveal a different pattern. Even though smallholders in our sample perceive the different climate change effects as problematic for their cropping activities, our estimates for the tree planting decision of smallholders show that none of our perception indicators of the climate 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 practices, such as access to water, secure land tenure, agroforestry knowledge or subsidies.

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

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

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

In contrast, our findings do not indicate that smallholders' perceptions of climate change effects enhance the selection of fertilizer trees. Consequently, fertilizer trees do not seem to be specifically utilized as a climate change adaptation tool to intensify food production. On the contrary, the perception of heavy rain events and a salinization of soils appears to discourage the selection of fertilizer tree species for planting. However, as Coulibaly et al. (2017), Amadu et al. (2020) and Leroux et al. (2022b) demonstrate, integrating fertilizer trees can improve soil fertility and enhance food security outcomes trough increased crop yields. Our results therefore indicate that smallholders in the Senegalese Groundnut Basin have not yet exploited the potential of planting fertilizer trees as a climate change 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 incorporate multiple tree species serving different purposes, such as enhancing soil fertility and providing edible fruits. Furthermore, although the positive relationship between the provision of tree seedlings and the planting of fertilizer trees is not statistically significant, interventions that include the subsidized provision of fertilizer tree seedlings could still be a promising pathway at enhancing fertilizer 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.

Additionally, smallholders appear to practice FMNR alongside tree planting, suggesting that both pathways of agroforestry uptake and upscaling are likely practiced jointly. This contrasts with perspectives such as those of Reij and Garrity (2016) and Bonye (2024), who treat FMNR as an 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, 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. Abasse et al. (2023) for instance state that e.g. *Faidherbia albida*, one of the main fertilizer tree species in Senegal (Leroux et al. 2022b), is commonly expanded through FMNR. While Reij and Garrity (2016) call for a shift from tree planting to FMNR to achieve restoration targets, our results suggest that both 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

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

Our findings indicate that most of the smallholders perceive one or the other climate change effect as posing problems for their cropping activities. Among the various climate change effects in the study region, the largest number of smallholders identified land degradation as a challenge to their cropping activities, followed by heavy rain events, soil salinization and shorter rainy seasons. The initial decision to plant trees, however, appears to be rather constrained by limited access to essential resources for agroforestry practices, such as access to water, secure land tenure, agroforestry knowledge or financial resources, than determined by the perception of different climate change effects. Once smallholders decided to plant trees though, we find that their tree species selection for planting does depend on their perception of different climate change effects. Smallholders are more likely to select fruit tree species if they perceive land degradation or shorter rainy seasons as challenges to their cropping activities. Selecting fertilizer trees is not positively associated to the perception of the different climate change effects and the perception of heavy rain events and salinization of soils even discourages the planting selection process for fertilizer trees. Smallholders thus rather utilize tree planting to diversify than to intensify their food production in the face of climate change. Future policy design should primarily focus on enhancing smallholders' access to crucial resources, such as water, secure land tenure, information and financial resources to facilitate agroforestry adoption as a climate change adaptation tool. Additionally, as fertilizer trees hold great potential to maintain and restore soil fertility, efforts should focus on promoting the selection of fertilizer trees for planting within cropping systems, particularly in response to specific climate change effects, such as the widely perceived issue of land degradation. Overall, policy makers should aim to enhance the integration of both fertilizer and fruit tree species, to support a holistic climate change adaptation, enhancing intensification and diversification of smallholders' food production

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

We also find that FMNR is likely practiced jointly with tree planting to integrate trees, and this joint practice influences the selection of tree species for planting. Future research is needed to gain a better understanding of the detailed interdependences of tree planting and FMNR, such as tree species selection for FMNR or tree planting if jointly practiced. It could also be valuable to investigate in greater detail which ecosystem services, among the many that different tree species in agroforestry systems can provide beyond soil fertilization and fruit production, drive smallholders' tree species selection. 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 their underutilization, would provide useful insights for the strategic promotion and selection of tree species for agroforestry practices.

Statements and Declarations

CRediT authorship contribution statement

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

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Declaration of Competing Interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Data availability

Data will be made available on request.

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

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

Appendix A Survey questions

Table A. Survey questions

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 Agroforestry and previous studies.
	Please name the tree species that you planted on your agricultural land in the past three years.	Text	
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 (*Text*) □ 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 asked for each crop the household cultivates.**		
	How much income did your household generate from the last seasons’ harvest of *crop n* in CFA.	Number	The income generated from each crop and each type of livestock have been summed together.
	The following question is asked for each type of livestock the household owns.		
	How much income did your household generate from *livestock n* in CFA in the last year?	Number	
Female household head	Enumerators noting respondents’ 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.e. lived and 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	

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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 Coefficient	**Fruit tree Coefficient**	**Fertilizer tree 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: *** 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.2 Results of multivariate probit regression on tree species selection, without correction for selection bias.

	Fruit tree **Coefficient**	**Fertilizer tree** **Coefficient**
Climate change perception		
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, * 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 Coefficient	Fruit tree Coefficient	Fertilizer tree 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; 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.

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