ICAE 2024

32nd International Conference of Agricultural Economists
2-7 August 2024 | New Delhi | India

Dark clouds building up over trees? A simulation-based assessment of smallholder acacia investment in Ethiopia

Habtamu Yismaw[1,*], Christian Troost[1], Thomas Berger[1]

[1]Land Use Economics (490d), Hans Ruthenberg Institute, University of Hohenheim.
**Corresponding author email: h.demilewyismaw@uni-hohenheim.de*

Abstract

This study simulates the economic effects of acacia diseases on smallholder farmers in the Upper Nile basin of the Ethiopian highlands, utilizing agent-based simulation analysis. Acacia, introduced in the 1990s, has become integral to the local agroforestry, enhancing soil fertility and providing significant economic benefits. However, recent outbreaks of acacia diseases threaten these gains. Our simulations suggest that income effects will be severe if the diseases make acacia production completely unprofitable. If interventions like fungicide applications and genetically robust seedlings are able to effectively counteract the diseases, acacia production will remain profitable even with the increased costs to apply these measures. However, they will most likely only partly compensate for the income losses, especially because of an expected delay until they can be introduced. The remaining income loss will still be substantial within the first 4-8 years after the disease outbreak.
Our findings emphasize the necessity of timely and strategic management practices to support agricultural resilience. The study underscores the importance of innovative agricultural practices and targeted interventions to enhance the financial sustainability of smallholder farmers facing environmental challenges. Further research is needed to explore the role of acacia in soil fertility improvement, its impact on subsequent crop yields, potentially exacerbating interaction effects with interannual crop yield and price variability, and a detailed representation of livestock production activities. Additionally, the potential of off-farm work as an adaptation strategy warrants deeper investigation.

JEL Codes: Q150, Q120, Q180

1. Introduction

The upper Nile basin of the Ethiopian highlands has seen an unprecedented conversion of smallholder croplands to exotic Acacia tree woodlots in the past decades (Wondie et.al. 2018, Amare et al 2022). Acacia, originally from Australia and known there as *wattle*, was introduced to the region in the 1990s as a multi-purpose tree for short-rotation forestry to improve rural livelihoods and land use practices (Sawyer 1993). Indeed, several studies confirmed profitability of acacia-based agroforestry systems (e.g., Nigussie et al., 2020) and showed enhanced soil fertility on woodlots by reducing soil acidity and erosion (Amare et al., 2022; Berihun et al., 2019; Kindu et al., 2006). In particular in the Awi zone of the Ethiopian highlands, acacia woodlots have thus become an attractive investment option for smallholders who were formerly producing annual crops on low-yielding acidic soils (Abay et al., 2022). In addition to increasing their farm incomes, the expansion of woodlots in Awi established a charcoal value chain that has created additional off-farm employment opportunities reducing the need of seasonal migration as casual laborers (Mekonnen et al., 2017) to other parts of the country (Nigussie et al., 2021).

However, dark clouds are building up on the horizon threatening the robustness and sustainability of smallholder investment into acacia in the near future (Andaregie et al., 2020). Farm households need to adapt to increasing climate variability that is affecting their self-sufficiency in crop and livestock production and food security (Berger et al., 2017). Wattle pest, rust and soil-borne pathogens have recently been found to cause widespread defoliation, reduced growth, and even death of the trees (Lawson et al., 2023). Farmers reported that these plant health issues make seedling production almost impossible in the area and severely affect their tree harvest. Research into acacia pest and disease management is ongoing but it is not clear yet by how much this may increase variable costs of acacia production.

Our papers assesses these threats to smallholder agroforestry systems in Ethiopia by means of agent-based simulation analysis. The question addressed is to what degree smallholders farmers can be expected to cope with a enduring prevalence of acacia diseases in the longer run especially considering the temporary lock-in when committing scarce household resources to acacia production. Analysis of the benefits of investment in woodlots in comparison with annual crops and livestock systems requires counterfactual analysis at the farm household level. We build on the agent-based modeling approach of Berger et al. (2017) and extend it with new survey data collected from Awi zone in 2018. Interactive model validation with local experts is employed to check model response and robustness in out-of-sample experiments. To ensure that overall valid results are derived from uncertainty simulation analysis, the recently established KIA protocol for model validation as described in Troost et al., (2023) is followed.

The remainder of the paper is organized as follows. Section 2 describes data and methods including simulation experiment design and model validation results. Section 3 presents our simulation results. Section 4 discusses and interprets results and limitations of our study. The final section concludes with key findings and suggests areas for future research.

2. Data and Methods

To answer our research questions we employ farm-level agent-based simulation and we follow the protocol by Troost et al. (2023) to justify our modeling choices and methods. That means we first explain our modeling context, then justify our structure-based model selection before we explain our strategy for model refinement and validation by comparison to empirical data.

2.1 Modeling context

2.1.1. Study area and data sources

The study area for this paper is the Awi zone of the Amhara region located in the Upper Nile Basin of the Ethiopian Highlands. The farming system is part of the Western Highland Maize Mixed Farming System (WHMFS) dominated by a cool/sub-humid agro-ecological zone with an average elevation of 1,340 meters above sea level (ranging from 528m – 3,145m) (Amede et al., 2017; Ebabu et al., 2018). The average annual rainfall is 2454 mm (Yibeltal et al., 2019). Agriculture in the Awi subsystem of the WHMFS is dominated by smallholder farmers who practice an integrated crop, livestock and tree perennial production. Teff, potatoes, finger millet, wheat, and barley are the common crops grown whereas acacia, bamboo and eucalyptus are the trees grown by smallholders (Nigussie et al., 2021). Farmers also keep horses, mules, cattle, sheep and chicken (Sultan et al., 2018).

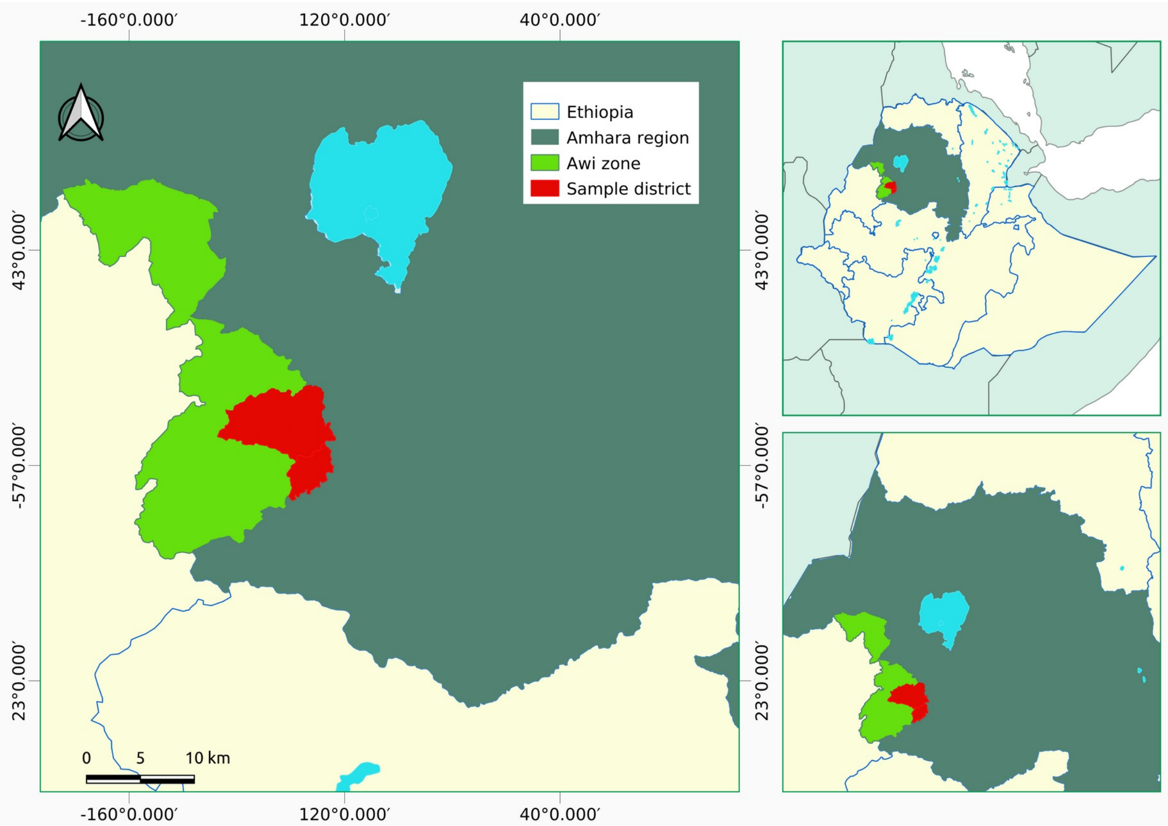

Figure 1. Sample area of the 2018 survey. (Source: shape files to create the study area map are abstained from https://ethiopia.africageoportal.com)

The data sources for this paper are a comprehensive farm household survey and focus group discussions undertaken in 2018 in Fagita Lekoma district (main acacia growing hot-spot) of Awi zone. We use detailed plot-level information to describe and predict smallholder behavior in the agent-based model. In addition, we use data from expert interviews in 2021 and 2023 on a recent outbreak of acacia diseases that motivated and shaped the simulation experiments reported upon in this article.

2.2 Structural model choice

2.2.1 Research questions

The research questions we intend to address with farm-level agent-based simulation are:

- How do acacia diseases affect land use and income of smallholder farmers?
- What would be the effect of potential plant health measures (application of fungicide and use of disease resistant seedlings) on smallholder farmers income assuming enduring presence of the diseases? Would they make it feasible and profitable for smallholder farmers to maintain acacia production in such a situation?

Answering these research questions requires an output-focused analysis to understand the behavioral response of smallholders in different scenarios. Data for a statistical analysis are limited: The acacia disease outbreak started happening only recently so that full surveys have not yet been conducted and possible remedies have not been implemented on the ground. Still, structural knowledge on agronomic and agroeconomic conditions of farming in the area is good, even though not complete. Input data on the incidence and damage of diseases is not yet fully available, but plausible scenarios can be constructed from first observations and worst-case considerations and expert interviews. The conclusions we draw from our simulation experiments, therefore, hold for the current acacia-based agroforestry system and are conditional on the scenarios we set. The unit of analysis (resolution) is at individual farm household level.

2.2.2. Structural model selection:

The target situation we want to simulate entails fundamental changes compared with the observed situation, so observed behavior of farmers, observed incomes and relationships between conditions, actions and outcomes cannot simply be extrapolated or estimated as statistical functions, i.e. direct generalization is not possible. Rather anticipation of future behavior needs to be build on structural understanding of farming conditions and decision-making. As a result, we need a theory/structure-driven approach in which parameters are derived from system knowledge rather than estimations. The model formulation must include the following features to be consistent with qualitative system knowledge:

- *Whole-farm modeling* is necessary to understand the profitability of production options such as acacia compared with alternatives given multiple interrelationships between production activities including use of fixed and intermediate resources like land, labor, cash, manure and household demands on food security (Berger et al., 2017; Berger & Schreinemachers, 2006; Mössinger et al., 2022). Moreover, there are opportunity costs and indivisibilities that cannot be reflected in partial budgeting or simple gross margin analysis. Whole-farm modeling must include arable cropping, livestock, financial and consumption balances of the household as far as it affects production.
- *Coping with uncertainty:* apart from the unanticipated disease events we explicitly analyze here, farmers have to cope with recurrent variability such as annual crop diseases, drought, hail, frosts, price volatility and other shocks.
- *Multi-period decision:* Acacia production involves an investment decision (Nigussie et al., 2020) with cash inflows only occurring after some time. Seedlings of acacia are planted along with annual crops in the first year, and with pasture in the second year. Earliest at the end of the fourth year, farmers cut the trees, make charcoal and sell it to distributors or final consumers (Nigussie et al., 2021). Investment in acacia (similar to livestock), hence, constitutes a multi-year planning problem. Given the uncertainty of crop yields, prices and

other shocks, farmers need to consider multiple possible outcomes (states of nature) and their inter-temporal effects in their planning. When investing in perennial crops (and livestock), they are binding resources temporarily and need to survive 'bad' years without any harvest possibly losing these assets.

- *Dynamic simulation:* given that our focus of analysis is on unanticipated events over time, comparative-static optimization is not enough, we need a dynamic simulation model in which farmer agents take decisions and are confronted with possibly unanticipated events before taking their next decisions.
- *Interactions between farmer agents:* due to the establishment of a whole value chain based on acacia charcoal production, impacts on acacia production on farms might affect many other actors in the chain and cause feedback to smallholders. In principle, it would be possible to model this by adding interactions between farm agents, however, this is out of scope of the analysis presented in this article and will be pursued in the future. Possible feedback are considered here exogenously in scenarios and uncertainty analysis.

We addressed these requirements by choosing a dynamic farm-level agent-based simulation model, in which farm agent decisions are modeled as mixed integer programming problems with a 15-years agent planning horizon and explicit risk management, which we implemented using the MPMAS software (Schreinemachers & Berger, 2011; Mössinger et al. 2022). All simulations were run on the high-performance computing facilities (bwHPC) from the state of Baden-Württemberg in Germany.

2.2.3. New features in the farm-level agent-based model

While this paper builds on the modeling approach developed by Berger et al. (2017) it extends and adapts it in both scope and methodology: We focus on a new study area with a tree-based farming system and apply multi-period investment modeling, and incorporate ex ante multi-period risk management using a discrete stochastic programming formulation with different states of nature representing weather, crop disease and price variability. Ex-ante multi-period risk management is simplified here compared with full stochastic-dynamic formulation in that agents use the expected values over all states of nature at the end of one period as a starting point for the subsequent period, rather than a fully laid out decision tree.
Depending on their resources, farmer agents can use savings, crop storage, livestock, forestry investments, and hedging by crop diversification) for ex-ante adaptation to variability. Ex post, agents can respond to anticipated variability and unanticipated events by dissaving, consuming less or selling livestock and grain from storage.
The agent objective function reflects prioritization among multiple goals: The farm agents' main goals are to satisfy their minimum demand for food and cover other non-food minimum expenditures and ensure feasibility of follow-up production,under all anticipated states of nature. Once these main goals are fulfilled, agents maximize expected household income (see also Marohn et al. 2023 for a similar approach). Farmer agents' decisions are constrained by their resource base, household labor, production and off-farm employment options, market access, human and social capital, and cultural constraints on labor and consumption.

2.3 Strategy to reduce model uncertainty by comparison to empirical observations

The key consideration for the required precision and accuracy in our modeling context (Troost et al. 2023) is whether it accurately represents the threshold (in terms of expected yields and prices) at which acacia becomes unprofitable and it will not be chosen by smallholder farmers anymore. This threshold results endogenously from the opportunity cost created by not choosing alternative production activities instead. The result of the agents' comparison of net benefits between acacia and other production options is reflected in the optimal solution when solving this decision problem for each agent individually: if acacia is part of the optimal solution, it is preferred over other options, at least for some of the farm area.

Figures 2 show empirical validation results of agents' land use decisions for acacia tree crops and annual crops (aggregated). The distributions for both acacia and annual crops show similar pattern for the first simulation periods and confirms the overall consistency of simulation results and survey data. The visible right shift in both distributions (larger area overall) is explained by rounding of crop areas to discrete plot units in the model and by a prevalence of intercropping between acacia and annuals in the simulations, a phenomenon that was not reliably measured in the survey.

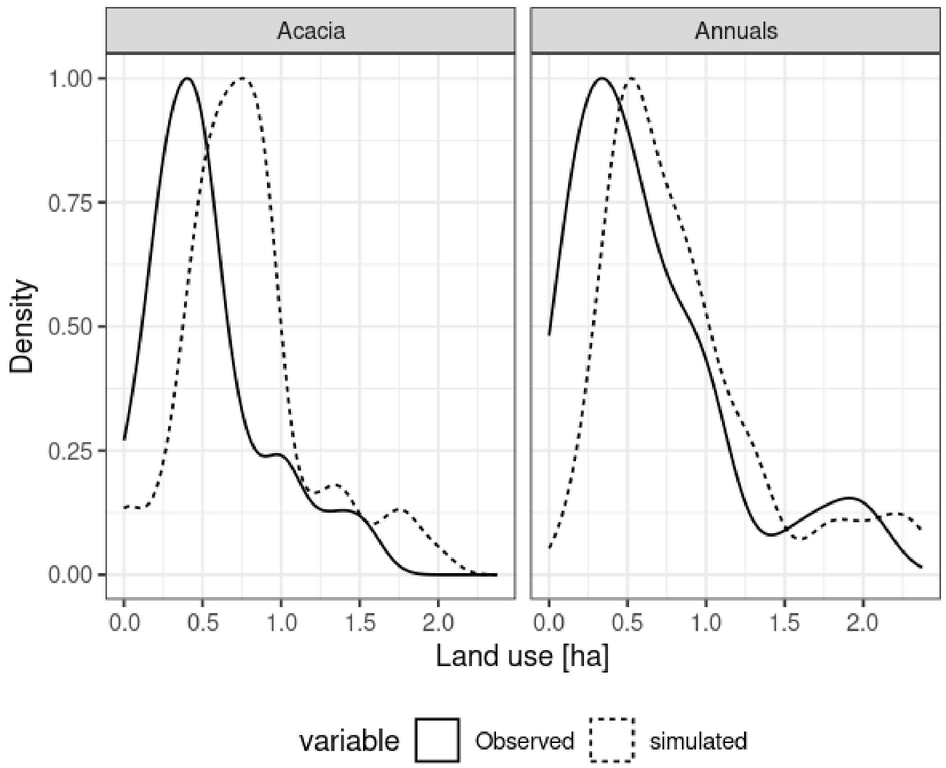

Figure 2. Comparison of acacia and annual crop area between validation run and observations in the 2018 survey.

The conclusions that can be drawn from this comparison are, however, limited for two reasons:
(1) They confirm that acacia is profitable enough to be chosen by agents to the extent observed in reality, but the distance to the profitability threshold, i.e. how much profitability could decrease before acacia is not chosen anymore, cannot be tested.
(2) Comparing dynamic simulation results with observed survey results at a given snapshot in time cannot test the model's dynamic validity and is prone to overfitting. To complement the comparison to survey data, we conducted an interactive validation experiment with farming experts in Ethiopia to ensure that simulated agents incomes and the thresholds for acacia benefits are realistic.

Following the methodology applied in Mössinger et al. (2022)and Troost (2015), an important part of interactive model validation is a kind of Turing test that checks for the plausibility of simulation results. Our Ethiopian farm experts were provided with data for five farm household types: large farm-size farmers, high-labor capacity farmers, farmers with the largest livestock nedowments, as well as relatively better-off and worse-off farmers. (Type 1 to 5 in Figure 3).

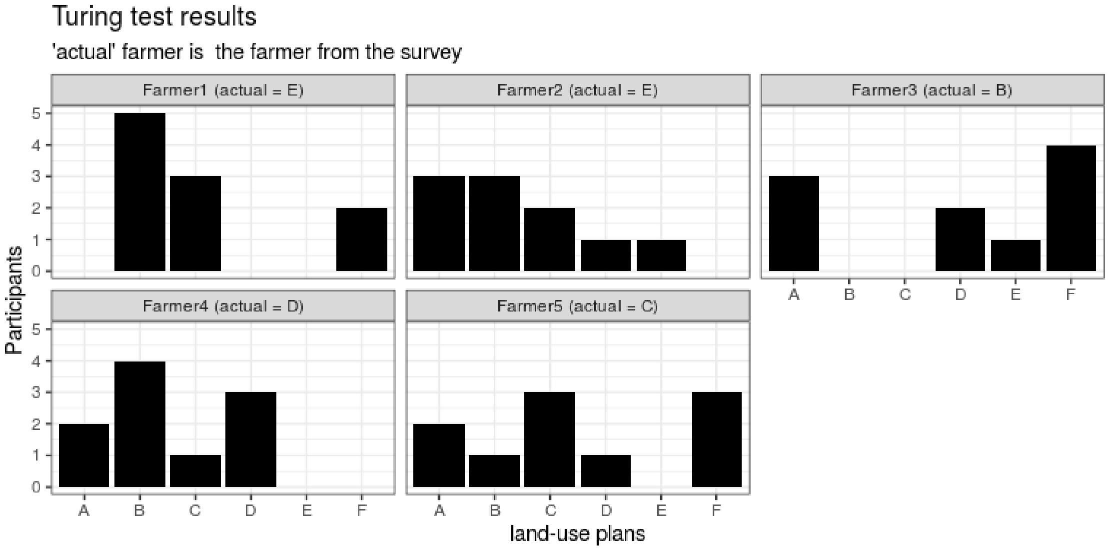

Figure 3. Results of the Turing tests performed with local agricultural experts for a face validation of the agent-based model. Indicates how many participants guessed the presented results indicated by the letter was the one taken from an actual farm observation and not simulated.

For each farmer type, five simulations were run with several parameter combinations and the major land-use decisions in addition to the actual land-use as taken from the survey. Experts were then asked to compare the simulated and observed data and choose one of the six options they thought was an actual farmer from the survey. Not being able to discriminate between simulated and observed farmer decision was then interpreted as a indication of model realism.

As shown in Figure 3, most of the experts' (86%) chose simulated land-use plans instead of the actual farmer from the survey. Only in 7 out of 50 choices the actual farmer's plan was correctly identified. We, therefore, concluded that our modeling approach successfully stood expert scrutiny and can be considered realistic.

2.4 Design of scenario and uncertainty analysis

2.4.1. Outcome variables

In this study, scenarios with and without plant health measures against acacia disease are critically evaluated to ascertain their impacts on discretionary income, a key metric for assessing economic resilience among farmers. Discretionary income is the appropriate measure for agent's income especially when a substantial portion of income goes to food and basic non-food items.

2.4.2.Scenarios and experimental design

Four scenarios have been devised to address the research questions, with each simulation commencing in the baseline year of data collection, 2018. These scenarios are predicated on initial reports received from farmers in 2020, which have been instrumental in shaping the simulation parameters and management interventions explored in the study.

No acacia disease: assuming stable acacia yields; a continuation of the situation before the outbreak of acacia diseases.

Acacia disease: Starting from 2021 acacia plantations are continuously affected by diseases, older trees yielding less biomass and with younger acacia trees dying, which effectively makes the establishment of new acacia plantations impossible. The scenario assumes that farmer agents reduce their yield expectations by half in the first year after occurrence of the disease and to zero from the second year onward.

Acacia disease and fungicide application: assuming disease occurrence as in the acacia disease scenario, but from 2025 onward fungicides become available to effectively combat the disease. This intervention completely mitigates the disease's impact but introduces additional costs and labor requirements, affecting the net discretionary income of farmers.

Acacia disease and robust seedlings: assuming a similar disease occurrence as the AD scenario, but genetically resistant seedlings become available in 2025, which have a higher price than the old seedlings, but completely mitigate the threat of the disease.

Comparing these scenarios illuminates the varying degrees of financial impact resulting from different levels of investment in acacia cultivation and management. By analyzing scenarios with and without investment in disease management, the study identifies the potential for targeted interventions to alleviate the economic consequences of acacia diseases. Moreover, contrasting these with the baseline of no disease intervention allows for a clearer evaluation of the effectiveness and financial viability of each management strategy in sustaining or enhancing discretionary income under fluctuating market conditions and ongoing environmental challenges.

In all scenarios, prices and yields have been kept constant throughout the simulation periods (while they vary between the different repetitions of the uncertainty sample). This is a simplification that helps to highlight the dynamics as caused by the scenarios and will be relaxed in future in-depth analysis.

2.4.3. Uncertainty analysis

To corroborate robustness of simulation experiment results, uncertainty analysis was carried out following the approach by Troost & Berger, (2015) and Berger et al. (2017). Sobol's quasi-random sequence method was applied to select samples from the full factorial space and determine the number of model repetitions required in our simulation experiments (Tarantola et al., 2012).

A total of 15 model variables and parameters were included in the uncertainty analyses; they capture the major model uncertainties related to annual crop and tree crop yields, livestock outputs, farm-gate sales prices, agricultural input prices and key financial parameters (interest rates, inflation rates and agents' time preferences). As Figure 4 shows, 20 model repetitions were sufficient to converge to stable averages in agent discretionary income.

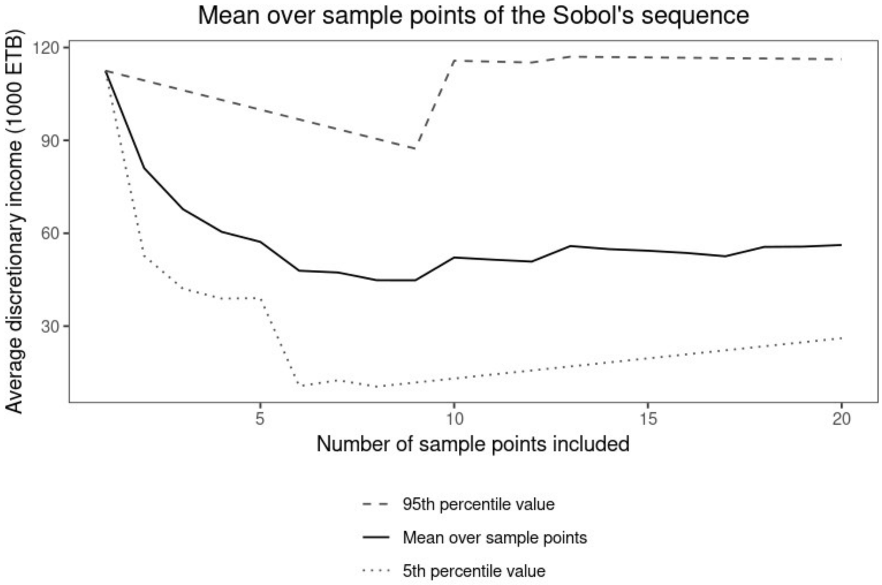

Figure 4. Convergence of averaged discretionary income over the repetitions of the uncertainty sample.

3. Simulation results

Land use

Before comprehensively analyzing the income effects of disease and plant health measures, we firstly take a look at the trajectory of land use decisions of a single selected farm agent in one repetition of the uncertainty sample in order to illustrate the dynamics in the simulations (Figure 5).

Initially, traditional crops dominate, with potatoes covering 55-60% of the land use. Barley, maize, and wheat collectively occupy about 10-15%, while acacia is grown on 30% of the farm agent area (including intercropping). This situation reflects a well-established integration of agroforestry practices prior to any disease impact.

At the outbreak of acacia diseases in period 3 in the AD scenario, the agent first reacts by replanting the lost acacia plantation of age two and younger leading to a slight increase in acacia area. After that acacia production is phased out and not taken up again as the agent loses also the replacement planting and realizes the persistent nature of the disease. In the scenario introducing fungicide application, which begins in period 7, the agent adopts this plant health measure and starts reinvesting in acacia to reach an acacia area share that is only slightly below pre-outbreak levels (20-25%), though with a more pronounced cyclic pattern of investment and sales due to the sharp restart on a large share of its area at the same time. A very similar pattern is observed in the scenario that introduces robust seedlings. As a first result, we can conclude that it is still profitable for this agent to produce acacia, when plant health measures are necessary to allow for tree survival.

Figure 5. Trajectories of land use for a selected agent across simulation periods for the different scenarios in a selected repetition of the uncertainty sample.

Trajectories of discretionary income under acacia disease and remedies

The disease and land use dynamics exemplarily described in the previous section are reflected in the dynamics of discretionary income of agents over time. Figure 6 shows the average discretionary incomes of the lower, middle and upper income thirds of the agent population over time (mean over the uncertainty sample for each simulation period).

While the absolute agent incomes differ, the dynamics are very similar among the three income thirds. In the initial 4 years before the disease outbreak, incomes are the same in all four scenarios and are determined by the acacia investment cycle with higher sales incomes from a larger share of older trees at the very beginning. Incomes start to diverge between the no disease scenario and the scenarios with diseases at the beginning of year 5, when the effect of the disease first leads to about 36%-41% lower discretionary incomes due to lower sales revenues for the harvested acacia trees planted at the beginning of the simulation.[1]

In the 'acacia disease' scenario without plant health measures, agents have a stable income level from then onward as they then choose a constant pattern of annual crop production (and actual prices and yields have been kept constant across the simulation). In the first years after the outbreak, in the 'no disease' scenario, the discretionary income is in some cases even lower than in the 'with disease' scenario as the replanting of acacia leads to a reduced income from annual crops

1 Note: Crop and acacia sales occur at the beginning of a period in the model, so that the discretionary income recorded in simulation period 5 corresponds to the results of the land use decisions in period 4. This has to be kept in mind when comparing figures 5 and 6. Also recall that figure 5 shows the trajectory of one agent, while figure 6 averages over many agents

until the next generation of acacia trees has matured and leads to a new revenue peak. In the two scenarios with plant health measures, the dynamics are similar as in the no disease scenario, only that the revenue peak is delayed by two years, reflecting the two year gap in which acacia production was not possible. Due to the brisk stop and restart of acacia production the planting cycle is more pronounced as it would usually have been and the peak is considerably higher than in the 'no disease' scenario in these two scenarios. (Lower third: by 57%, resp. 54%, Middle third: by 42%, resp. 39%, Upper third: by 33%, resp. 32%.)[2] While the dynamics are the same with fungicide or robust seedlings, the peak is slightly higher with fungicides. The remainder of the simulation horizon then shows a restart of a new five year cycle oscillation, with a 2 year phase shift between the 'no disease' and the 'disease with plant health measures' scenarios, even if the second peak for the latter is not covered in the simulation horizon anymore.

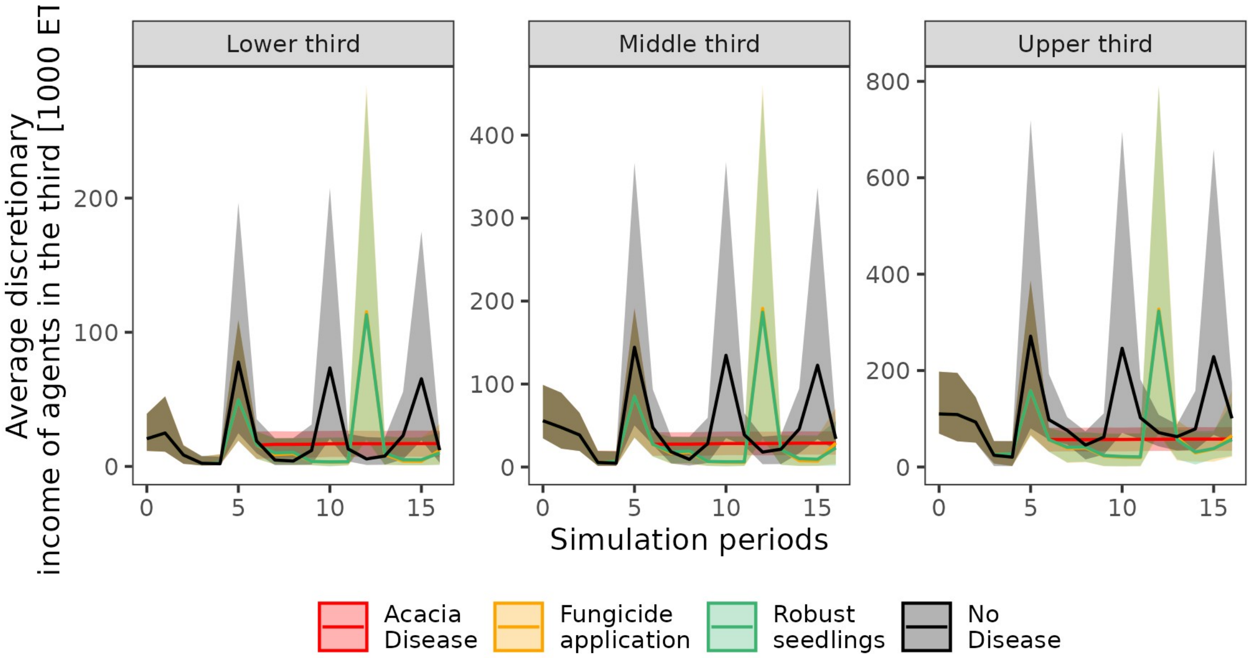

Figure 6. Trajectory of average discretionary income in the lower, middle, and upper income thirds of the agent population over the simulation periods by scenarios. (The graph depicts the average discretionary income over all agents in the respective third. The solid line indicates the mean of this value over the repetitions of the uncertainty sample, the shaded area indicates the range between the 5th and 95th percentile of this value over the uncertainty sample.)

Effect of acacia disease and plant health measures on average discretionary income of agents

The cyclic nature of the acacia investments and especially the shift in phasing in the scenarios with disease and plant health measures compared with the 'no disease' scenario makes taking a balance of the income effects of the acacia disease and plant health scenarios over time challenging. In addition, it needs to be emphasized that the phasing of the cycle is not exactly the same for each agent and plantation, as there are different age structures at the beginning of the simulation and also the speed of replanting after the introduction of plant health measures differs. Here we decided to use the average discretionary income between period 5 and 12 (outbreak of disease until first peak revenue from acacia produced with plant health measures) for comparison between the scenarios.

Figure 7 indicates the percentage change in discretionary income caused by the acacia disease outbreak in this time frame averaged over the simulation years and all repetitions of the uncertainty sample for each agent (change from 'no disease' to 'acacia disease' scenario).

2 First value is for the fungicide scenario, second value for the robust seedlings scenario.

The result shows a consistent negative impact on income, with all agents experiencing a decrease. The mean percentage decrease over agents is approximately -30%, with a standard deviation of 5.8% over the uncertainty sample. The most affected agent saw a decrease of up to 37%, while the least affected had a decrease of about 9%. Notably, 95% of agents experienced a reduction in discretionary income exceeding 20% and for 65% of the population it exceeded 30%.

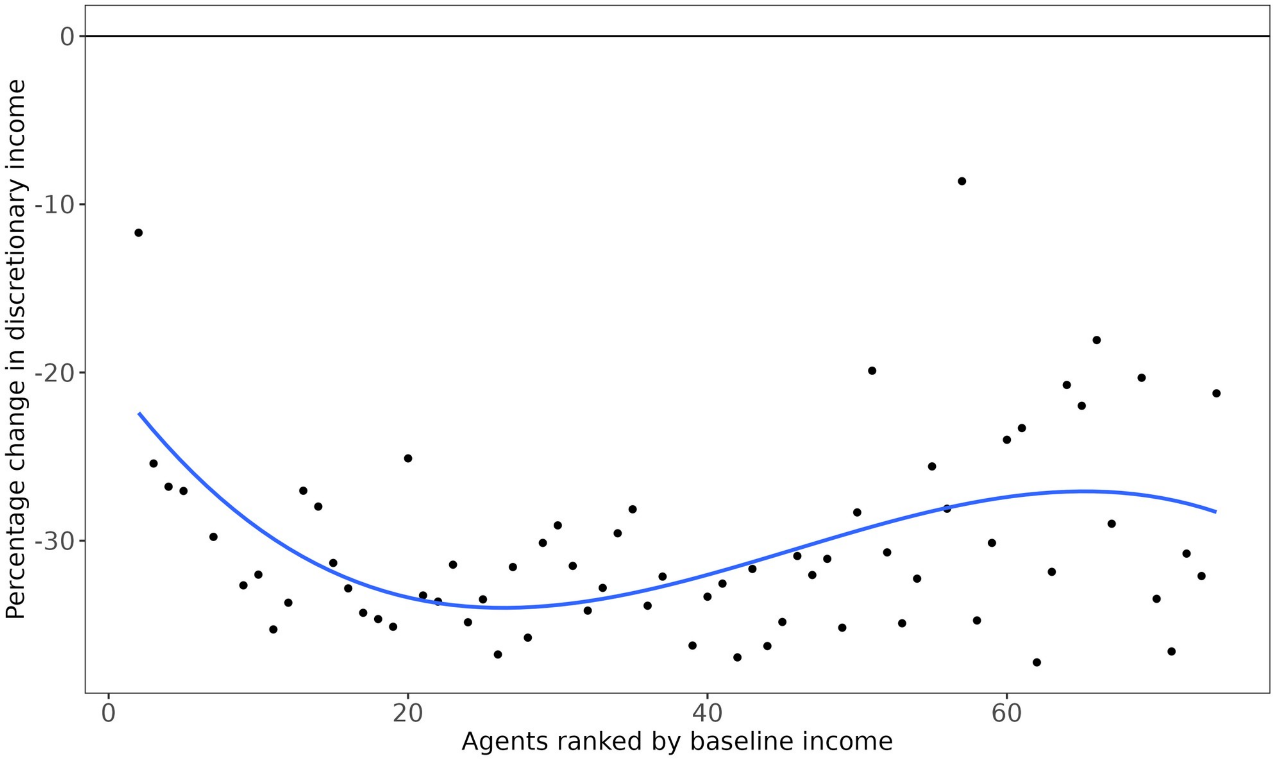

Figure 7. Effects of acacia disease on discretionary income (Percentage change in discretionary income from the no disease scenario to the acacia disease scenario averaged for each agent over all simulation years and all repetitions of the uncertainty sample.)

When we compare the effect of *fungicide application* directly against the scenario with acacia disease, the average change is a positive 25% (+/- 7.5%), suggesting that fungicide application helps mitigate a substantial part of the income loss caused by the disease. About 72% of agents benefit from fungicide application by a percentage increase of more than 20%. As Figure 8 shows, this group of agents stems from all income ranks, while the remainder, i. e. the agents that benefit by less than 20%, stems exclusively from the upper half of the income spectrum.

To check to what extent the acacia disease effect is compensated by fungicide application, Figure 9 compares the scenario with fungicide application with the no disease scenario. Similar to the scenario without plant health measures, all agents experienced a decrease in income, with an average reduction of -18% (+/- 4%). This suggests that introduction of fungicide application four years after the outbreak could reduce the loss in discretionary income by about 12 percentage points on average. Income losses are still somewhat less pronounced for lower income agents, mirroring the situation in the acacia disease scenario.

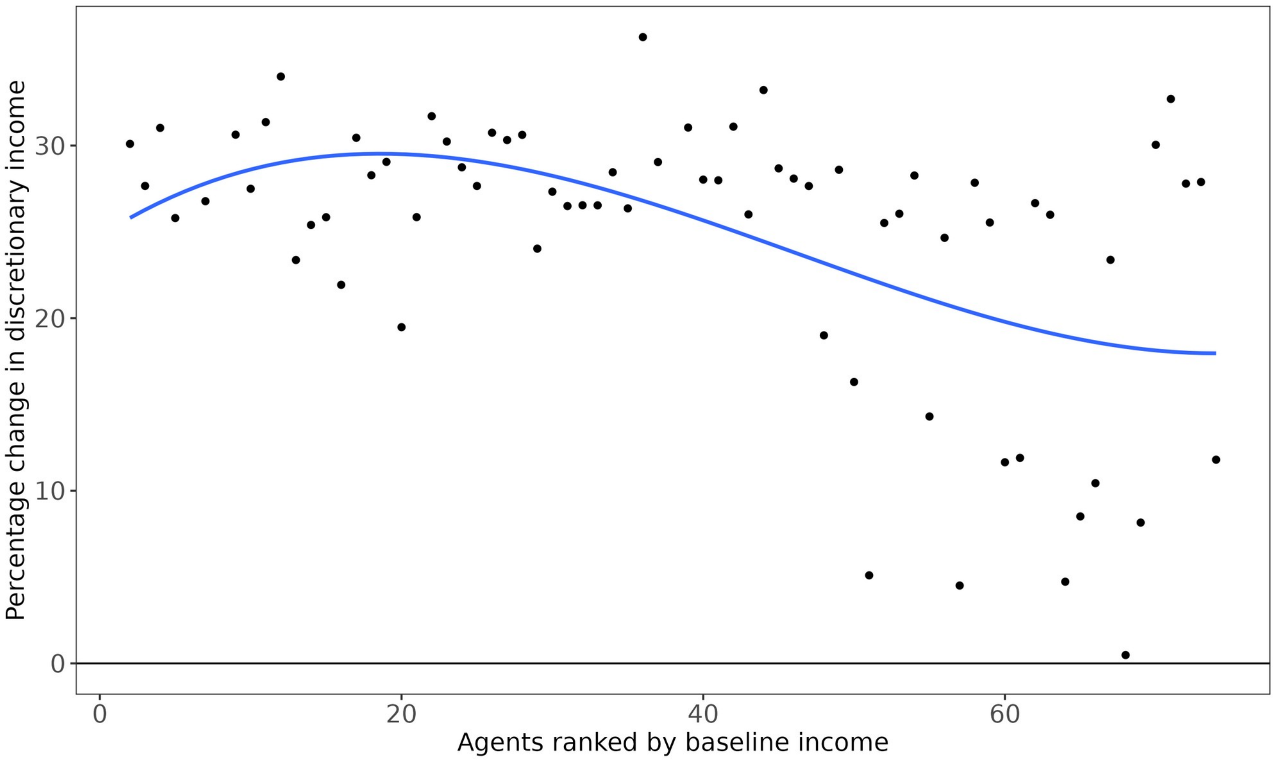

Figure 8. Effects of fungicide application on discretionary income. (Percentage change in discretionary income from the acacia disease scenario to the with fungicide application scenario averaged for each agent over all simulation years and all repetitions of the uncertainty sample.)

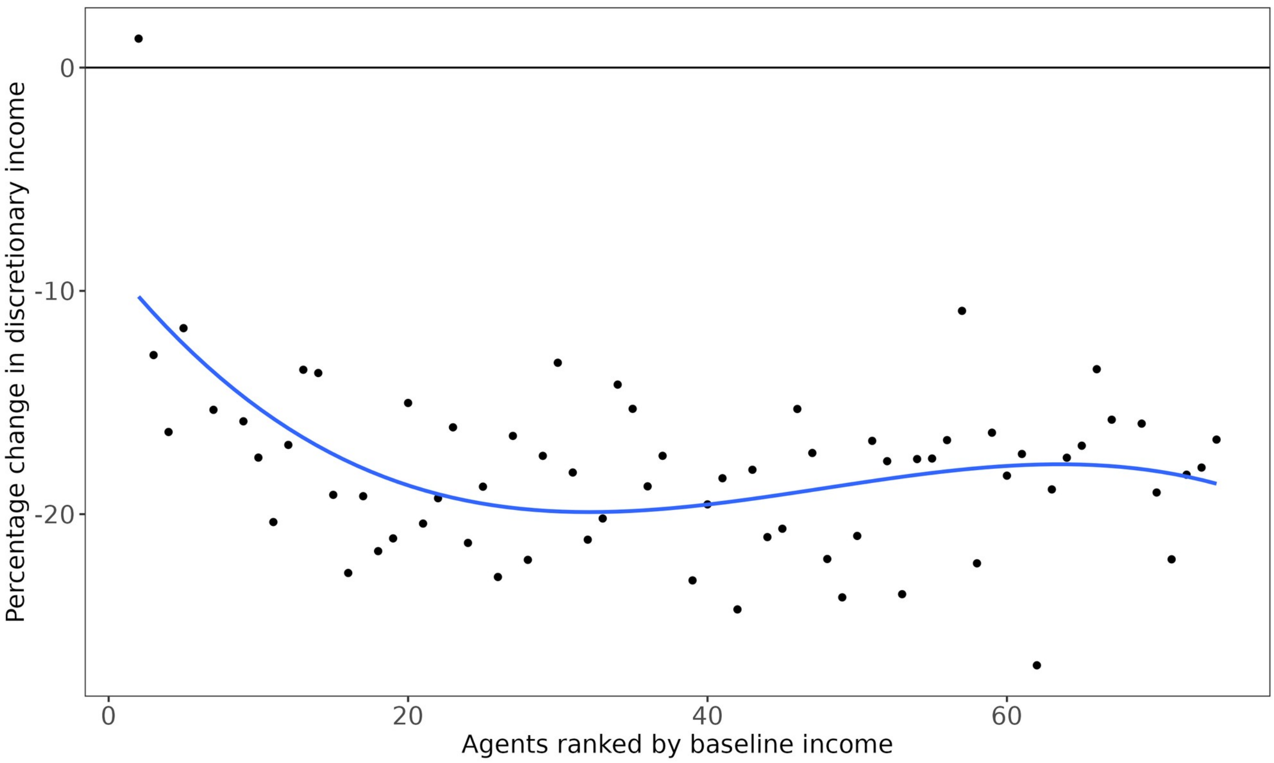

Figure 9. Effects of the acacia disease on discretionary income when mitigated by fungicide application. (Percentage change in discretionary income from the no disease scenario to the acacia disease with fungicide application scenario averaged for each agent over all simulation years and all repetitions of the uncertainty sample.)

The adoption of robust seedlings, increases discretionary incomes by 24% (+/-7.5%) on average in the time frame. As Figure 10 shows, the distribution over agents ranked by income is similar to the fungicide scenarios with 72% of agents benefiting from an increase of more than 20% and the remainder concentrated in the higher half of the income range.

When compared with the 'no disease' scenario, the situation with the introduction of robust seedlings is very similar to the fungicide scenario: Agents loose about 19% (+/-3.3%) of discretionary income in the respective time frame on average, when the acacia diseases can be mitigated by robust seedlings three years after its outbreak. The shape of the distribution over agents is again very similar to the cases with fungicide application and without any plant health measures (Figure 11).

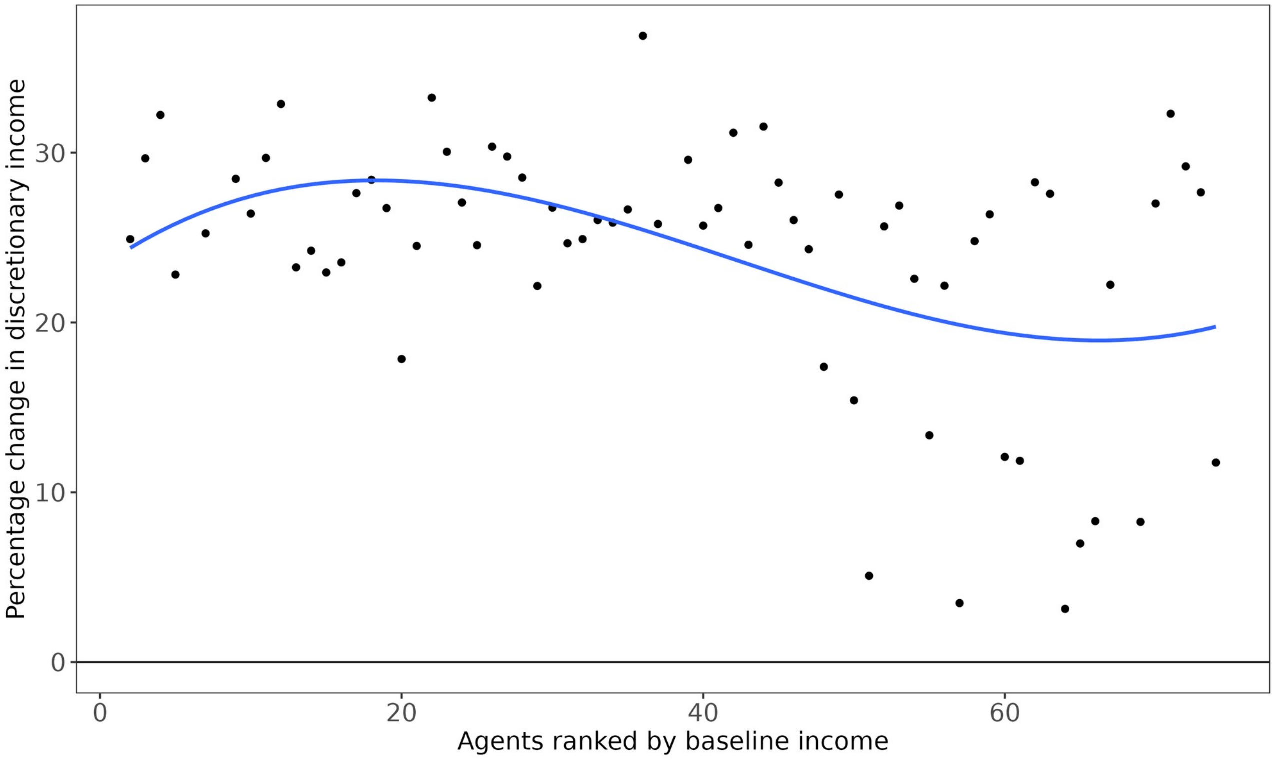

Figure 10. Effects of robust seedlings on discretionary income. (Percentage change in discretionary income from the acacia disease scenario to the acacia disease with robust seedlings scenario averaged for each agent over all simulation years and all repetitions of the uncertainty sample.)

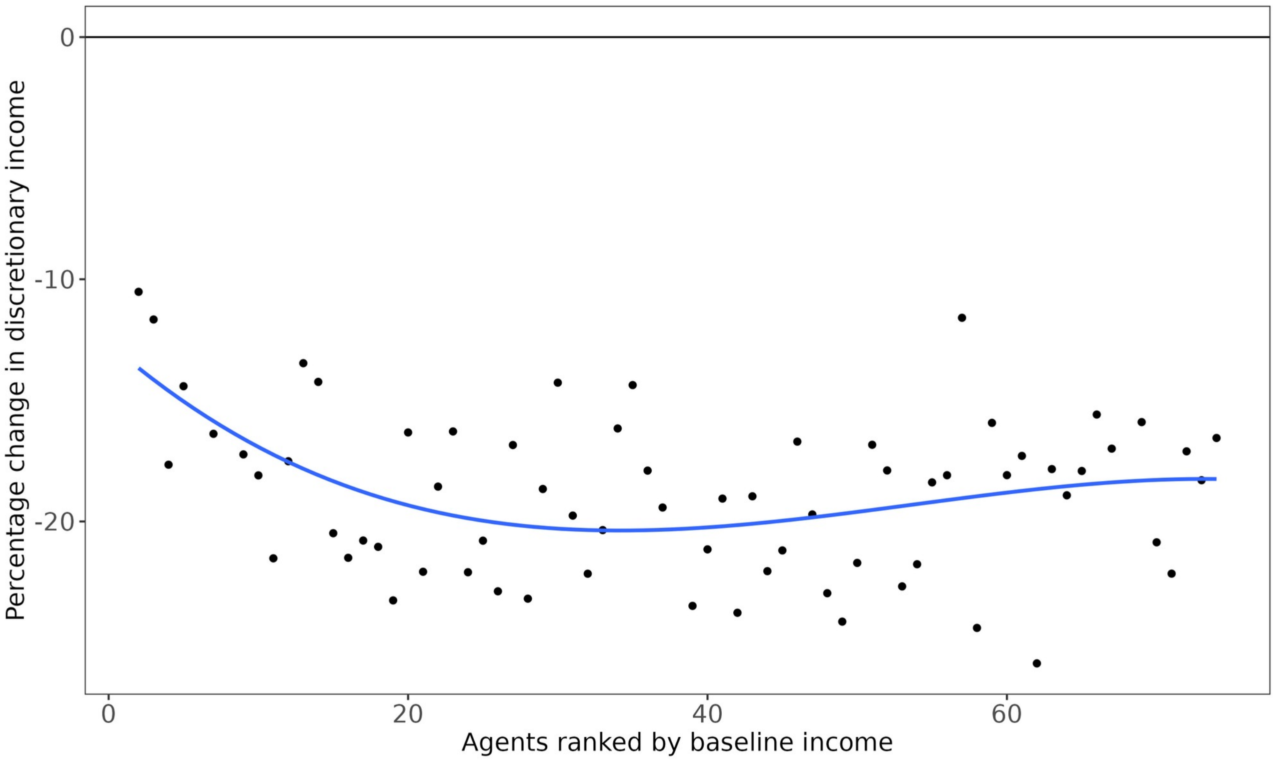

Figure 11. Effects of the acacia disease on discretionary income when mitigated by robust seedlings. (Percentage change in discretionary income from the no disease scenario to the acacia disease with robust seedlings scenario averaged for each agent over all simulation years and all repetitions of the uncertainty sample.)

4. Discussion

Our findings illustrate the potentially substantial economic repercussions of acacia diseases on discretionary income of smallholder farmers, showing a consistent negative impact across all income levels. Since acacia had developed into a highly profitable cash crop in the area, adopted by smaller and larger farmers alike, each segment, from lower to higher earners, experiences a decline in discretionary income in our simulations – underscoring the widespread economic distress caused by this agricultural challenge. This considerable economic strain can lead to scaled-back spending on non-essential goods and services, potentially catalyzing broader economic slowdowns in affected regions. The evenly distributed representation of income groups within the study ensures that these findings are broadly applicable, providing a broad view of the economic impact without skewing towards any particular demographic.

The introduction of plant health measures such as fungicide application and robust seedlings offers the potential to continue acacia production. Our simulations clearly suggest that under plausible assumptions on the farm-level costs for these measures, their application will be highly profitable and likely adopted by farmers. Certainly, this is subject to the assumption that farmers are able to gain trust in the effectiveness of these measures as we assumed here and are not completely discouraged from acacia production by the negative experience of the outbreak.

Both, plant health measures tested here would have similar effects on discretionary incomes, with fungicides offering a slightly higher benefit in our simulations. However, this difference should not be overinterpreted as the difference is small and depends largely on assumptions on input costs, which have to be considered preliminary as targeted measures have not yet been widely introduced in the area.

In our simulations, both types of plant health measures do not fully compensate for the discretionary income loss caused by the diseases, which is due to the additional cost, but even more importantly due to the hiatus of acacia production caused by their delayed introduction. We only tested one specific assumption on how long it takes to widely introduce them in the area, but we expect that a shorter, resp. longer delay would alleviate resp. exacerbate the difference to the no disease scenario.

This underlines that it is essential for policymakers and stakeholders in the agricultural sector to proactively develop strategies that enhance the economic resilience of vulnerable communities. Initiatives could include financial support programs, public research in potential risks and countermeasures before they manifest, strategic contingency plans, and efforts to diversify income sources – all aimed at mitigating the adverse effects of such unanticipated diseases and stabilizing the economic conditions of those impacted.

In our simulations, all agents were able to switch back to annual production, when diseases made acacia production infeasible. On the one hand, this is due to the risk management assumptions incorporated in the model that ensure some annual production even if a cash-oriented production option such as acacia is more profitable (even though the anticipated risks did not include the acacia disease). On the other hand, this can also be attributed to the relatively short production cycle of acacia and the fact that younger aged trees died off immediately, so that additional area was directly freed for annual production.

Limitations

While our results underline the importance of addressing acacia diseases in the Ethiopian Highlands and show how a dynamic farm-level analysis can contribute to this, we acknowledge that the analysis still contains a number of limitations, which means that our simulations should not be understood as accurate forecasts of acacia disease effects.

- While we included risk management measures to cope with interannual variability in crop prices and yields in the decision strategies of agents, we did not actually confront agents with price and yield variability – apart from the acacia disease – during the dynamic simulations. Including this interannual variability in the model is an important next step in the analysis (Berger et al. 2017; Wossen et al. 2018). In case the disease outbreak coincided with a difficult year (low crop yields, low crop sales prices, high consumption prices), this might have far more detrimental effects than observed in our present simulations, especially since acacia for a long time offered a relatively secure income that could compensate for losses in crop production.

- It has been understood from the interactive validation sessions that the soil fertility improvement achieved through acacia production is an important additional benefit of acacia production. Hence, financial analysis alone might not fully capture the long-term effect of acacia on farmers' livelihoods. To this effect, the contribution of acacia to the soil as a leguminous plant and the resultant improvement in crop yield after subsequent cycles of acacia should be taken into account in the future. This can be methodologically captured using a soil dynamics feature in MPMAS once the yield effect of improvement in the soil can be quantified This calls for further research to sharpen the effect of investment in acacia on agents in the model.

- Another important model feature that needs more expansion is livestock production. The role of livestock to farmers' livelihoods in the area is well established. Even though the income from livestock in the model is validated, the type of livestock that agents are keeping and the number of years they are keeping them in the model differs from what is happening in reality. Agents only keep cows and chickens, and they only keep them for one year. As livestock is an important adaptation and coping measure for farmers, an improved representation of livestock production activities and constraints backed by detailed data should further improve the reliability of the simulation analysis.

- Compared to crop production, acacia requires less labor during the agricultural season, which can hence be used for off-farm work. While off-farm work opportunities have been included in the model, realistically capturing off-farm job opportunities requires more empirical work and specifically capturing the repercussions of disruptions by disease outbreaks in both labor supply (more on-farm labor with increased crop production) and less labor demand downstream in the acacia-charcoal value chain requires both new model features and a better empirical basis.
- We assessed the effects on average discretionary income over a selected time frame to assess scenario differences. However, we did not yet explicitly assess food security status under all circumstances. In addition, the valuation of agroforestry investments in smallholder farm households is not well captured by average incomes and more specific performance measures will have to be evaluated.

5. Conclusions

The findings of this study provide a first understanding of the potential financial impacts of acacia diseases on smallholder farming hosueholds in the Upper Nile basin of the Ethiopian highlands, as well as the effectiveness of various plant health measures to address the diseases. The agent-based simulations anticipate significant income losses across all income levels. The introduction of fungicide applications and genetically robust seedlings can be expected to partly compensate, but these interventions alone are most likely insufficient to fully counteract the financial impacts of acacia diseases – especially because their introduction is likely to occur with some delay. The immediate adjustments and subsequent stabilization of farming practices emphasize the necessity of timely and strategic management to support agricultural resilience in advance of such disease outbreaks. These insights are crucial for informing policies and practices aimed at enhancing the financial resilience and sustainability of smallholder farmers in the face of environmental challenges.

The study highlights the role that agent-based simulation can play in the *ex ante* analysis of production and income risks in smallholder agriculture in tropical areas and should encourage research in addressing the limitations of the present study – not only for this specific case study, but to generally increase the understanding of smallholder farm economics. Specifically, this calls for further advances in (i) understanding the role of acacia in soil improvement and its impact on subsequent crop yields and in how far this is considered in farmer decision-making, (ii) the representation of actual smallholder risk management behavior in agent-based models, (iii) better capturing local labor markets and value chains, (iv) a better understanding and model representation of smallholder livestock production activities.

Overall, this research highlights the critical need for continued investment in resilient agricultural technologies and comprehensive strategies to support smallholder farmers in adapting to the challenges posed by a variety of environmental threats, for which acacia diseases are only one example.

References

Abay, K. A., Abay, M. H., Amare, M., Berhane, G., & Aynekulu, E. (2022). Mismatch between soil nutrient deficiencies and fertilizer applications: Implications for yield responses in Ethiopia. *Agricultural Economics (United Kingdom)*, *53*(2), 215–230. Scopus. https://doi.org/10.1111/agec.12689

Ajayi, O. C., Akinnifesi, F. K., Sileshi, G., & Kanjipite, W. (2009). Labour inputs and financial profitability of conventional and agroforestry-based soil fertility management practices in Zambia. *Agrekon*, *48*(3), 276–292. https://doi.org/10.1080/03031853.2009.9523827

Amare, T., Amede, T., Abewa, A., Woubet, A., Agegnehu, G., Gumma, M., & Schulz, S. (2022). Remediation of acid soils and soil property amelioration via Acacia decurrens-based agroforestry system. *Agroforestry Systems*, *96*(2), 329–342. https://doi.org/10.1007/s10457-021-00721-8

Amede, T., Auricht, C., Boffa, J.-M., Dixon, J., Mallawaarachchi, T., Rukuni, M., & Teklewold-Deneke, T. (2017). *A farming system framework for investment planning and priority setting in Ethiopia* (Technical Report TR90). https://www.aciar.gov.au/publication/technical-publications/farming-system-framework-investment-planning-and-priority-setting-ethiopia

Andaregie, A., Worku, A., & Astatkie, T. (2020). Analysis of economic efficiency in charcoal production in Northwest Ethiopia: A Cobb-Douglas production frontier approach. *Trees, Forests and People*, *2*, 100020. https://doi.org/10.1016/j.tfp.2020.100020

Berger, T., & Schreinemachers, P. (2006). Creating agents and landscapes for multiagent systems from random samples. *Ecology and Society*, *11*(2).

Berger, T., & Troost, C. (2014). Agent-based Modelling of Climate Adaptation and Mitigation Options in Agriculture. *Journal of Agricultural Economics*, *65*(2), 323–348. https://doi.org/10.1111/1477-9552.12045

Berger, T., Troost, C., Wossen, T., Latynskiy, E., Tesfaye, K., & Gbegbelegbe, S. (2017). Can smallholder farmers adapt to climate variability, and how effective are policy interventions? Agent-based simulation results for Ethiopia. *Agricultural Economics*, *48*(6), 693–706. https://doi.org/10.1111/agec.12367

Berihun, M. L., Tsunekawa, A., Haregeweyn, N., Meshesha, D. T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A. A., Sultan, D., & Yibeltal, M. (2019). Exploring land use/land cover changes, drivers and their implications in contrasting agro-ecological environments of Ethiopia. *Land Use Policy*, *87*, 104052. https://doi.org/10.1016/j.landusepol.2019.104052

Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D. T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A. A., & Yibeltal, M. (2018). Analyzing the variability of sediment yield: A case study from paired watersheds in the Upper Blue Nile basin, Ethiopia. *Geomorphology*, *303*, 446–455. https://doi.org/10.1016/j.geomorph.2017.12.020

Kindu, M., Glatzel, G., Tadesse, Y., & Yosef, A. (2006). Tree Species Screened on Nitosols of Central Ethiopia: Biomass Production, Nutrient Contents and Effect on Soil Nitrogen. *Journal of Tropical Forest Science*, *18*(3), 173–180.

Lawson, S., Healey, M., Agena, A., Regasa, K., & Beze, W. (2023). *Management of Acacia decurrens Pests and Diseases in Ethiopia* (FR2022-035. ISBN 978-1-922787-60–6). Australian Centre for International Agricultural Research (ACIAR). https://www.aciar.gov.au/project/fst-2021-162

Marohn, C., Troost, C., Warth, B., Bateki, C., Zijlstra, M., Anwar, F., Williams, B., Descheemaeker, K., Berger, T., Asch, F., Dickhoefer, U., Birner, R., Cadisch, G., (2022): Coupled biophysical and decision-making processes in grassland systems in East African savannahs - A modelling framework. Ecological Modelling, 474, 110113 https://doi.org/10.1016/j.ecolmodel.2022.110113

Mekonnen, D., Bryan, E., Alemu, T., & Ringler, C. (2017). Food versus fuel: Examining tradeoffs in the allocation of biomass energy sources to domestic and productive uses in Ethiopia. *Agricultural Economics (United Kingdom)*, *48*(4), 425–435. Scopus. https://doi.org/10.1111/agec.12344

Mössinger, J., Troost, C., & Berger, T. (2022). Bridging the gap between models and users: A lightweight mobile interface for optimized farming decisions in interactive modeling sessions. *Agricultural Systems*, *195*, 103315. https://doi.org/10.1016/j.agsy.2021.103315

Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Ayalew, Z., & Abele, S. (2020). Economic and financial sustainability of an Acacia decurrens-based Taungya system for farmers in the Upper Blue Nile Basin, Ethiopia. *Land Use Policy*, *90*, 104331. https://doi.org/10.1016/j.landusepol.2019.104331

Nigussie, Z., Tsunekawa, A., Haregeweyn, N., Tsubo, M., Adgo, E., Ayalew, Z., & Abele, S. (2021). The impacts of Acacia decurrens plantations on livelihoods in rural Ethiopia. *Land Use Policy*, *100*, 104928. https://doi.org/10.1016/j.landusepol.2020.104928

Sawyer, J. (1993). *Plantations in the Tropics: Environmental Concerns*. https://www.semanticscholar.org/paper/Plantations-in-the-Tropics%3A-Environmental-Concerns-Sawyer/dd4e2be5a13fc4cec9436b243432c4c4e30fc304

Schreinemachers, P., & Berger, T. (2011). An agent-based simulation model of human-environment interactions in agricultural systems. *Environmental Modelling and Software*, *26*(7), 845–859.

Sultan, D., Tsunekawa, A., Haregeweyn, N., Adgo, E., Tsubo, M., Meshesha, D. T., Masunaga, T., Aklog, D., Fenta, A. A., & Ebabu, K. (2018). Efficiency of soil and water conservation practices in different agro-ecological environments in the Upper Blue Nile Basin of Ethiopia. *Journal of Arid Land*, *10*(2), 249–263. https://doi.org/10.1007/s40333-018-0097-8

Tarantola, S., Becker, W., & Zeitz, D. (2012). A comparison of two sampling methods for global sensitivity analysis. *Computer Physics Communications*, *183*(5), 1061–1072. https://doi.org/10.1016/j.cpc.2011.12.015

Troost, C. (2014). *Agent-based modeling of climate change adaptation in agriculture: A case study in the Central Swabian Jura*. http://opus.uni-hohenheim.de/volltexte/2015/1035/

Troost, C., Berger, T., (2015). Dealing with Uncertainty in Agent-Based Simulation: Farm-Level Modeling of Adaptation to Climate Change in Southwest Germany. American Journal of Agricultural Economics 97: 833-854. https://doi.org/10.1093/ajae/aau076

Troost, C., Huber, R., Bell, A. R., van Delden, H., Filatova, T., Le, Q. B., Lippe, M., Niamir, L., Polhill, J. G., Sun, Z., & Berger, T. (2023). How to Keep it Adequate: A Protocol for Ensuring Validity in Agent-Based Simulation. *Environmental Modelling & Software*, *159*, 105559. https://doi.org/10.1016/j.envsoft.2022.105559

Wondie, M., & Mekuria, W. (2018). Planting of Acacia decurrens and Dynamics of Land Cover Change in Fagita Lekoma District in the Northwestern Highlands of Ethiopia. *Mountain Research and Development*, *38*(3), 230–239. https://doi.org/10.1659/MRD-JOURNAL-D-16-00082.1

Wossen, T., Berger, T., Haile, M., Troost, C. (2018)**.** Impacts of climate variability and food price volatility on household income and food security of farm households in East and West Africa. *Agricultural Systems* 163, 7-15. https://doi.org/ 10.1016/j.agsy.2017.02.006

Yibeltal, M., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D. T., Aklog, D., Masunaga, T., Tsubo, M., Billi, P., Vanmaercke, M., Ebabu, K., Dessie, M., Sultan, D., & Liyew, M. (2019). Analysis of long-term gully dynamics in different agro-ecology settings. *CATENA*, *179*, 160–174. https://doi.org/10.1016/j.catena.2019.04.013