ADHENO Integrated Rural Development Association

Impact Assessment Report

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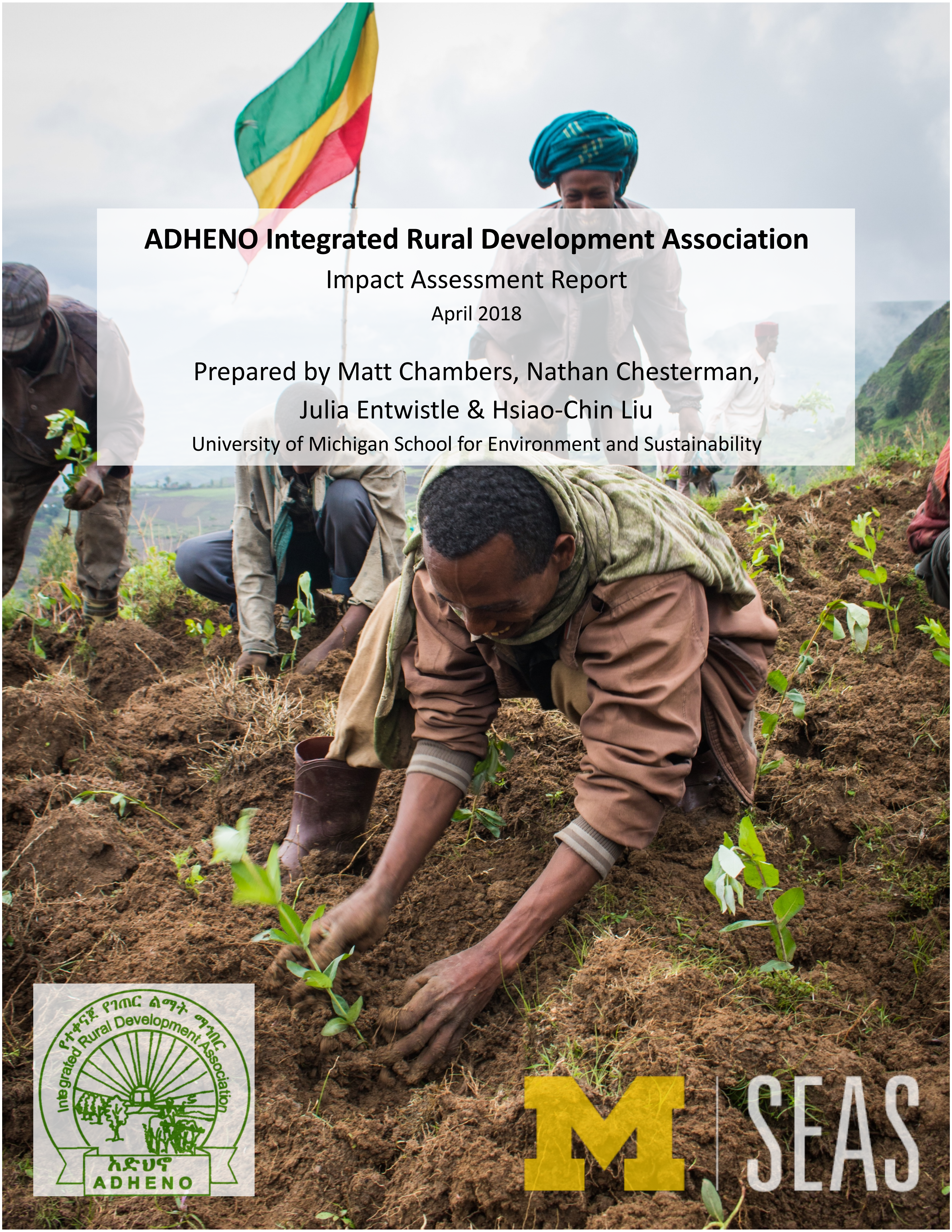

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Executive Summary

ADHENO Integrated Rural Development Association is an Ethiopian non-governmental organization (NGO) that implements rural development programs aimed at improving subsistence farmer livelihoods and rehabilitating soil, native plant biodiversity, and other environmental resources in the North Shewa Zone. In this evaluation, we studied the impacts of ADHENO's farmer training and area closure programs. We used a household survey, propensity score matching analysis, and time-series satellite imagery analysis to evaluate farmer trainings. We used ecological plot sampling in area closures and control areas (sites selected for comparison with vegetation in area closures) to evaluate the area closure program.

Farmer trainings

ADHENO farmer trainings cover seven topics related to soil conservation and sustainable agricultural practices. These include: (i) fertilizer application; (ii) intercropping; (iii) use of improved seeds; (iv) digging trenches and other water runoff mitigation; (v) terracing; (vi) planting soil to stabilize vegetation; and (vii) irrigation.

Who is participating in ADHENO farmer trainings, and do they use the methods?	● ADHENO has a high reach with farmer trainings – 424 of 488 households surveyed participated in at least one training. ● Farmers that attend trainings are highly likely to implement soil conservation farming methods. Farmers who participated in trainings used the methods of improved seeds, planting soil stabilizing vegetation, intercropping, and trenching (and other water runoff mitigation methods) more than those who did not attend trainings. The percentage of farmers reporting use of a method were higher for participating than non-participating farmers for improved seeds (44% higher), stabilizing vegetation (24%), intercropping (40%), and trenching (28%). ● For farmers that attended more than one training on intercropping, terracing, and trenching, additional training increased the likelihood of using the practice.
What are the livelihood outcomes from farmer trainings?	● Farmers who participated in trainings did not have higher crop productivity than non-participating farmers. ● Farmers that participated in trainings had a higher average yearly income from farming than non-participants of 6311 Ethiopian Birr or about $275 USD. The average reported income from farming across groups was 8913 Ethiopian Birr or about $387 US Dollars (USD).
What are the land-use outcomes from farmer trainings?	● Villages with higher participation rates in farmer trainings did not have any higher or lower land-use intensity over time, compared

with villages that had lower participation rates.

Area Closures

ADHENO works with groups of farmers to reach agreements to convert commonly-held grazing or farming land into area closures, which are areas in which grazing or plant harvesting activities are prohibited. ADHENO also raises seedlings and carries out a Tree *Gudifecha*, or seedling plantation and adoption program in area closures to restore native vegetation and biodiversity.

What is the role of area closures in restoring plant biodiversity and vegetation structure?

- In Goshebado Kebele alone, ADHENO has facilitated conversion of 12 hectares into area closures.
- Area closures have high plant biodiversity, with 71 unique tree, shrub, herb, and succulent plant species identified. Of these, species area closures provide habitat for 25 species not found in the control areas outside of area closures.
- For all layers of vegetation – tree, sapling, shrub, herb, and succulent – area closures have higher species abundance and diversity than control areas. Area closures also have higher basal area and plant height than control areas.
- In areas where ADHENO has supported plantation activities, exotic plantation species are associated with lower species abundance in the understory, while native plantation species have a higher understory species abundance.

How well are area closures enforced, and what is the impact on biodiversity?

- There are a high number of livestock trails and trees with stumps inside area closures, indicating that community stakeholders are not properly enforcing or following area closure boundaries.
- Control areas had a higher proportion of trees with stumps and coppicing than area closures, suggesting that people still use plants outside area closures at a higher rate.
- Inside area closures, the presence of livestock trails is associated with a greater number of species in the understory, while the presence of stumps is associated with slightly lower biodiversity.

Conclusion

ADHENO Integrated Rural Development Association has a positive impact on farming practices, agricultural livelihoods, and biodiversity conservation in the North Shewa Zone. There are ways to improve these programs to increase positive impacts on farmers and biodiversity, and we make recommendations below.

1. Introduction

We were solicited by ADHENO Integrated Rural Development Association (hereafter ADHENO) to perform an evaluation of their programs to identify areas of effectiveness and make recommendations for future projects. We began working with ADHENO in February 2017 and conducted fieldwork from May - August, 2017. We focused our data collection in the Goshebado and Metkoriya kebeles in the North Shewa Zone near Debre Berhan. Our fieldwork focused on evaluating two ADHENO programs: (a) farmer trainings, and (b) ecological restoration through area closure and tree plantation activities. These programs are described in further detail below.

We employed a mixed-methods approach in this evaluation. We a) administered a household survey to measure participation in ADHENO development interventions, and identify benefits and gaps in livelihood improvement and farmer training programs; b) conducted ecological sampling in area closures to determine the impact of the area closure and Tree *Gudifecha* program on biodiversity and vegetation structure; and c) utilized satellite imagery and land-use change analysis to identify trends in land-use intensity attributable to ADHENO over time.

1.1 Primary Research Questions

Our initial overarching research questions were: 1) what is the impact of ADHENO programs on the lives of rural farmers? and 2) are ADHENO projects affecting landscape wide changes in land use intensity?

Following fieldwork and preliminary analysis of our data, we narrowed our research questions:

i. What is the role of farmer trainings in mediating short-term farmer behavior change?
ii. Is adoption of farming methods associated with improved income and livelihoods, and a reduction of intensity of land-use?
iii. Are ADHENO area closures effectively restoring ecological functions of degraded areas?

1.2 Importance

Over two-thirds of the sub-Saharan African population relies on agriculture for their primary income.[1] This is the case for approximately 85 percent of Ethiopians.[2] However, the natural resources that these farmers depend on are at risk from overuse and climate change. Forty-six percent of Africa is at risk of desertification, with over 8.2 million square kilometers of land classified as medium or high risk.[3] Reductions in soil quality, soil erosion, and erratic rainfall all

[1] World Bank (1996) *Toward Environmentally Sustainable Development in Sub-Saharan Africa. A World Bank Agenda*. The World Bank, Washington, DC.
[2] Food and Agriculture Organization. (2018). "FAO.org." *FAO in Ethiopia, Food and Agriculture Organization of the United Nations*. www.fao.org/ethiopia/fao-in-ethiopia/ethiopia-at-a-glance/en/.
[3] Reich, P. F., Numbem, S. T., Almaraz, R. A., & Eswaran, H. (2001). Land resource stresses and desertification in Africa. *Agro-Science*, 2(2).

contribute to significant reductions in smallholder farm productivity[4] that in turn create income shortages as well as reduced nutrition,[5] resulting in a poverty trap. Many farmers lack access to knowledge and resources to mitigate soil erosion. Farmers intensify land use as they attempt to compensate for reduced productivity, resulting in additional soil degradation and deepening the poverty trap. A key mechanism pursued to help break the poverty trap is providing farmers with knowledge and access to resources to improve soil quality and increase crop yields.[6]

The approach of engaging farmers in training has been implemented in many contexts and by a variety of actors. Identifying the appropriate means of delivering this knowledge presents a unique challenge in sub-Saharan Africa, given varying political and economic context across the continent.[7] Despite expressed support of extension programs,[6] many African governments are subject to structural changes and shifting political wills that limit the availability of resources to support such initiatives.[8] This has also led to changes in the structure of agricultural services for many countries, which have become more decentralized or privatized.[9] Furthermore, government extension has traditionally focused exclusively on increasing productivity and often neglects livelihood goals of programs, including increasing incomes and reducing vulnerability.[10] Increasingly, non-governmental organizations (NGOs) are emerging as important actors with great potential to provide knowledge transfer initiatives to rural smallholder farmers.[11] In contrast to government sponsored initiatives, which typically feature a 'top down' approach focused on technology transfer, the NGOs often take a more 'bottom up' or grassroots approach.[10] NGOs have achieved success in soliciting donor support due to their greater flexibility, cost effectiveness, and community engagement.[12] Demand for agricultural services is being met by

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[4] Altieri, M. A., & Koohafkan, P. (2008). *Enduring farms: climate change, smallholders and traditional farming communities* (Vol. 6). Penang: Third World Network (TWN).
[5] Fan, S., Brzeska, J., Keyzer, M., & Halsema, A. (2013). *From subsistence to profit: Transforming smallholder farms* (Vol. 26). Intl Food Policy Res Inst.
[6] Sachs, J., McArthur, J. W., Schmidt-Traub, G., Kruk, M., Bahadur, C., Faye, M., & McCord, G. (2004). Ending Africa's poverty trap. *Brookings papers on economic activity*, *2004*(1), 117-240.
[7] Davis, K., Nkonya, E., Kato, E., Mekonnen, D. A., Odendo, M., Miiro, R., & Nkuba, J. (2012). Impact of farmer field schools on agricultural productivity and poverty in East Africa. *World Development*, *40*(2), 402-413.
[8] Christoplos, I., & Kidd, A. (2000). Guide for monitoring, evaluation and joint analyses of pluralistic extension support. *Guide for monitoring, evaluation and joint analyses of pluralistic extension support.*
[9] Faure, G., Desjeux, Y., & Gasselin, P. (2012). New challenges in agricultural advisory services from a research perspective: a literature review, synthesis and research agenda. *The Journal of Agricultural Education and Extension*, *18*(5), 461-492.
[10] Farrington, J., Christoplos, I., Kidd, A., & Beckman, M. (2002). Extension, poverty and vulnerability: the scope for policy reform. Final report of a study for the Neuchâtel Initiative.
[11] Davis, K., & Place, N. (2003). Non-governmental organizations as an important actor in agricultural extension in semiarid East Africa. *Journal of International Agricultural and Extension Education*, *10*(1), 31-36.
[12] Kanyinga, K. (1993). The social-political context of the growth of nongovernmental organisations in Kenya. In Gibbon, P. (Ed.), Social change and economic reform in Africa. Uppsala, Finland: Nordiska Afrikainstitutet.

NGOs that can fill this void in rural and marginalized areas that have needs that cannot be addressed by private actors seeking profit, or by government actors seeking affordability.[13]

1.3 Ethiopian Context

Subsistence agropastoralist communities in the Ethiopian Highlands typically make their living by raising crops and livestock for their own consumption, and less so for market sales. However, soil erosion and biodiversity loss, exacerbated by the gradual clearing of vegetation from the landscape and increasingly erratic rainfall due to climate change, have emerged as significant threats to farmer livelihood security[14]. Significant areas of previously fertile land in the country have become unproductive in recent years due to nutrient depletion and soil erosion.[15] Ethiopia's economy is largely driven by agriculture, and greater farm level productivity is necessary to meet the food needs of the country's population. Ethiopia faces high levels of poverty; in 2011, approximately 30 percent of the population lived on less than $1.25 (U.S. dollar purchasing power parity).[16] Ethiopian agriculture faces a high risk from climate change, especially from changes in precipitation intensity and quantity. Even marginal changes to climate challenge the well-being of the Ethiopian agricultural sector.[17] Shiferaw and Holden found that although soil erosion and nutrient depletion are among the most pressing environmental issues facing Ethiopia, there are low levels of awareness of the issues and the costs of potential losses in future productivity are not internalized by smallholder farmers.[18]

1.4 Project Area Background

ADHENO's activities are located in the North Shewa Zone of the Amhara Region of Ethiopia. All research was performed in the Goshebado (1,159 households) and Metkoriya (540 households) kebeles (Figure 1.1). (Kebeles represent the smallest administrative unit in Ethiopia). These communities rely heavily on natural resources for their livelihoods. Most are subsistence farmers, and depend on seasonal rainfall, soil, and forest resources to support themselves. The natural ecosystem of the Central Highlands is Eastern Afromontane forest, one of the most

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[13] Omolo, E. O., Sanders, J. H., McMillan, D. E., & Georgis, K. (2001). Agricultural technology for the semiarid African horn. Country study: Kenya. IGAD/INTSORMIL/USAID-RESDO. Lincoln, Nebraska: INTSORMIL.

[14] Shiferaw, B., & Holden, S. T. (1998). Resource degradation and adoption of land conservation technologies in the Ethiopian highlands: a case study in Andit Tid, North Shewa. *Agricultural economics, 18*(3), 233-247.

[15] Adimassu, Z., Langan, S., & Johnston, R. (2016). Understanding determinants of farmers' investments in sustainable land management practices in Ethiopia: review and synthesis. *Environment, development and sustainability*, *18*(4), 1005-1023.

[16] World Bank Group. (2015). Ethiopia Poverty Assessment 2014. Retrieved from https://openknowledge.worldbank.org/handle/10986/21323.

[17] Deressa, T. T., & Hassan, R. M. (2009). Economic impact of climate change on crop production in Ethiopia: evidence from cross-section measures. Journal of African economies, ejp002.

[18] Shiferaw, B., & Holden, S. (1999). Soil erosion and smallholders' conservation decisions in the highlands of Ethiopia. *World development*, *27*(4), 739-752.

threatened forest biomes in the world.[19] The degradation of these forests has been associated with increased water scarcity, soil erosion, and desertification, making life in the Ethiopian Highlands increasingly untenable.[20]

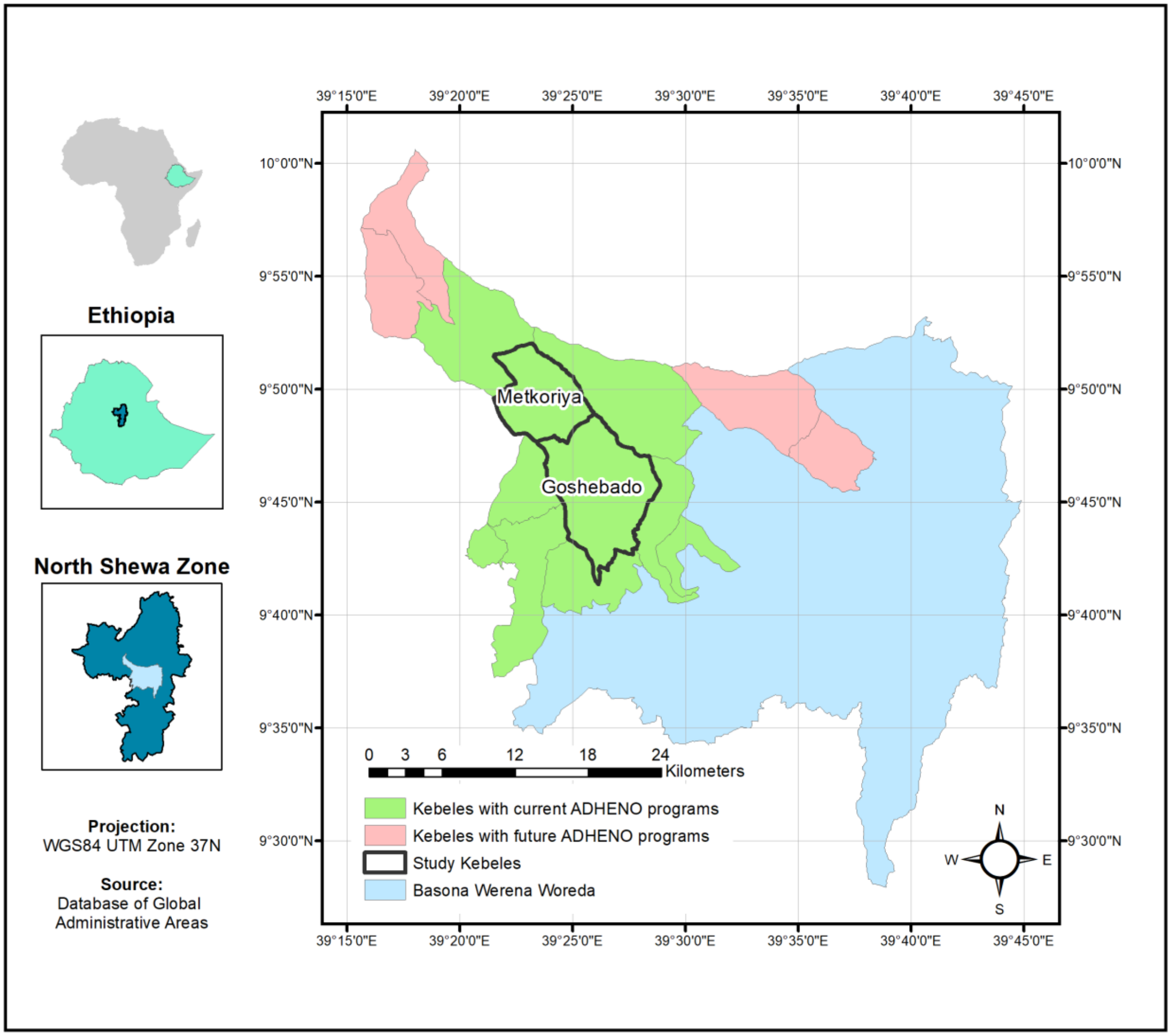

Figure 1.1. Map of ADHENO activity and the evaluation study areas within the North Shewa Zone in Ethiopia.

The people in these kebeles are predominantly agropastoralists in the Amhara ethnic group. The kebele landscape is characterized by a central high plateau surrounded by steep escarpments, with a more gently sloping valley below. Agriculture is predominantly carried out on the plateau and near homesteads in the valley, though there is some cultivation on the

[19] Critical Ecosystem Partnership Fund. (2012). “Ecosystem profile: Eastern Afromontane biodiversity hotspot.” Accessed from: www.cepf.net.

[20] Tolessa, T., Senbeta, F., & Kidane, M. (2017). The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. *Ecosystem Services*, *23*, 47–54.

escarpments. For the most part, livestock graze in areas on the escarpment that are not under cultivation.

1.5 ADHENO's Role

To alleviate issues facing farmers in the Highlands, ADHENO, an Ethiopian non-profit, has conducted ecological restoration and economic empowerment programs in the North Shewa Zone since 2003.[21] ADHENO's programs focus on improving the lives of rural poor, preserving resources that form the foundation of farmer livelihoods, and restoring plant biodiversity and soil health. Besides improving the resilience of ecological systems, ADHENO's ecological restoration program is also intended to help communities adapt to changing environmental conditions.[22] ADHENO's projects include: farmer trainings, tree plantings, seedling adoption (Tree *Gudifecha* - payment for seedling survival), clean water projects, beekeeping, school construction, and women's savings groups.[23] Taken together, these programs aim to provide North Shewa farmers with improved access to resources and decision-making capacity, and increased autonomy over their livelihoods and environment (Figure 1.2). To effectively scale out the programs to additional rural sub-districts, as based on ADHENO's 2nd Five Year Strategic Plan, a comprehensive evaluation of program effectiveness is critical.

1.5.1 Farmer Trainings

ADHENO works to improve smallholder agricultural productivity and soil quality by training farmers in soil conservation farming methods and increasing farmer access to resources and knowledge. Trainings focus on several topics:

- Terracing
- Trenching and other water runoff mitigation practices
- Use of improved seeds
- Appropriate application of fertilizer
- Planting vegetation to stabilize soil
- Irrigation
- Intercropping

To implement these trainings, ADHENO field staff coordinate with local government agricultural extension officers. Training sessions are held by invitation only, have a maximum size of 40 farmers, and generally last 3-5 days. ADHENO and agricultural extension agents select farmers for the sessions based on the applicability of the training to their needs, as well as an informal qualitative assessment of their work ethic. In this study, we sought to understand the impacts of farmer trainings on (a) uptake of soil conservation strategies; (b) agricultural productivity and livelihoods; and (c) intensity of land-use over time.

[21] ADHENO Integrated Rural Development. (2017) “ADHENO.” Accessed from: http://adheno.org/.
[22] ADHENO Integrated Rural Development. (2017) “ADHENO Background.” Accessed from: http://adheno.org/background.html.
[23] ADHENO Integrated Rural Development. (2017) “ADHENO Current Projects.” Accessed from: http://adheno.org/current.html.

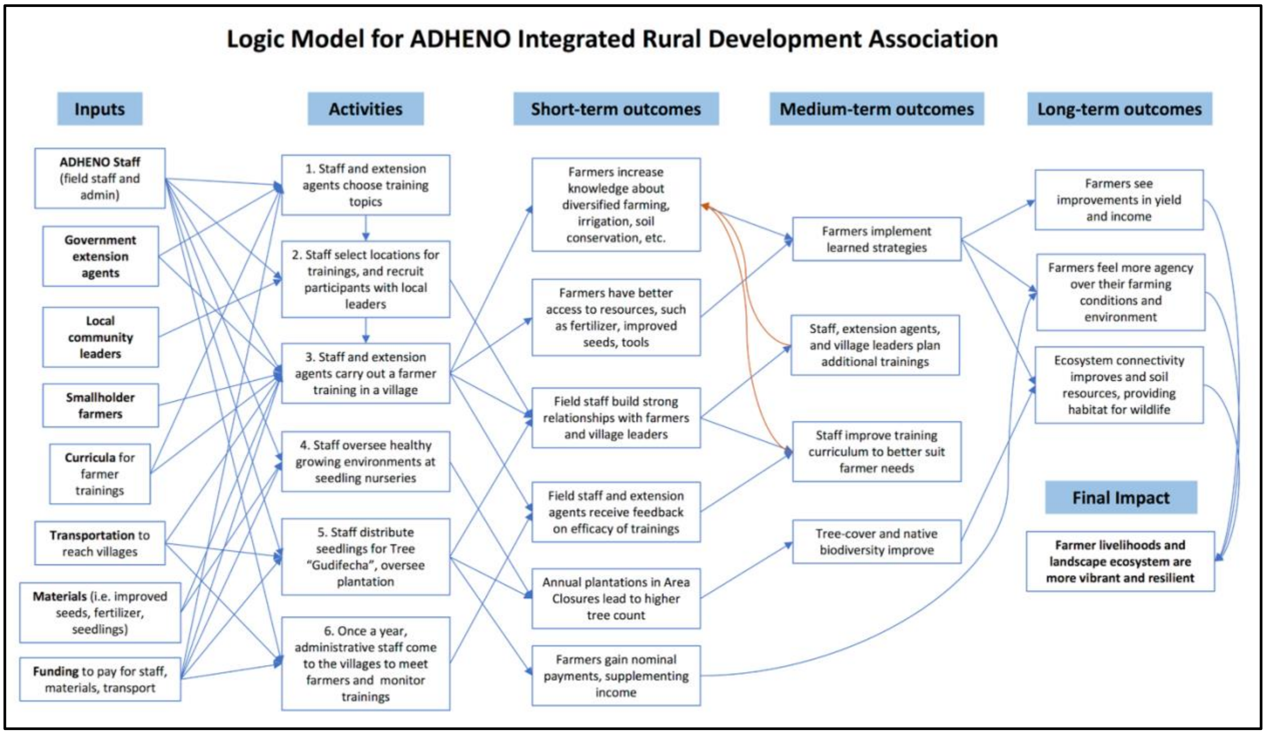

Figure 1.2. Logic model of ADHENO farmer training and ecological restoration programs. This model represents the intended short, medium, and long-term outcomes of various ADHENO inputs and activities. The intended final impact is that farmer livelihoods and landscape ecosystem are more vibrant and resilient because of the various trainings and activities.

1.5.2 Area closures and Tree *Gudifecha*

ADHENO has mobilized communities to form agreements to cease grazing and biomass extraction in some communally-held lands. It refers to these areas as "area closures." Area closures are constructed on land that is considered particularly vulnerable to soil erosion. In addition to ceasing grazing and harvesting in area closures, ADHENO sponsors a yearly event for farmers to plant seedlings in area closures and pays farmers one Ethiopian Birr for each surviving seedling. There are five area closures in Goshebado, totaling 12.1 hectares under protective management (Table 1.1).

We sought to understand the role of area closures and plantation activities in restoring floral biodiversity and vegetation structure. However, presence of livestock dung, livestock trails, and stumps inside area closures suggests that grazing and biomass extraction persist. Thus, we also sought to determine whether biodiversity and vegetation structure are impacted by lax enforcement and continued livestock and human pressure. Specifically, we asked: (a) compared to control sites, do area closures have higher biodiversity and more complex vegetation structure; (b) is there a difference in livestock pressure and biomass extraction between area closures and control sites; and (c) within area closures, does the relative density of livestock pressure and biomass extraction predict patterns in biodiversity and vegetation density.

Table 1.1. Area closures established by ADHENO in Goshebado Kebele

Area closure name	Year established	Size (hectares)
Ater Meda	2011	2.89
Ater Meda Emmanuel Church	2014	0.13
Aregay Tsabel	2016	0.21
Berkumas	2007	3.76
Saint Emmanuel Church	2003	5.14

2. Methods

2.1 Household Survey

2.1.1 Survey design

We administered a quantitative and adaptive survey to measure key variables related to farmer practices and outcomes. To test the degree to which ADHENO activities have impacted livelihoods, we collected information on demographics, farming strategies, crop yields, land holdings, income, participation in tree adoption programs, education, and health. Surveys were collected by a team of five Ethiopian enumerators who were native Amharic speakers, the primary language of all survey participants. Data were collected using Qualtrics Survey Software on Android smartphones. The enumerators had no connection to ADHENO and no incentive was offered to survey participants.

The survey consisted of 25-127 questions and was structured to prompt follow-up questions based on survey responses and the activities in which respondents had participated. Survey respondents that had participated in ADHENO programs were redirected to answer additional questions about their perceptions and experiences with those programs. Surveys lasted between 15 minutes to over an hour, depending on the level of participation in ADHENO activities and the variety and extent of the respondents' farming activities. The survey tool was initially designed in English and was translated into Amharic by an English professor at Debre Berhan University. Prior to collecting survey data, the translation was verified by another native Amharic speaker who is fluent in English. We also made minor revisions to the survey based on enumerator feedback after field testing the survey, focusing on ease of use and any community-specific issues with the survey questions.

2.1.2 Study population and sampling method

All project participants were living in the Goshebado or Metkoriya kebeles at the time we administered the survey, in June-August 2017. We selected these two kebeles because ADHENO has the longest history there and has undertaken the most activities, when compared with other kebeles. These kebeles were also accessible by road, enabling us to collect significantly more surveys than if we were to work in more remote kebeles. There were approximately 1,700 households in the project area, 449 of which were surveyed.

To ensure adequate representation of households, we grouped all villages in both kebeles into those that have received or not received the training intervention. Then, we randomly selected villages from each stratum to focus sampling efforts which accounted for 265 out of 449 project participants. We also included a convenience sample to recruit an additional 184 respondents to participate in our survey. The majority of respondents were surveyed in the market town of the kebele, at community events such as religious festivities, or in central village of sub-kebeles. Participants were recruited in one of the following manners: 1) sub-kebele leaders collected heads of households to meet at central locations in their respective villages or the central hub of the kebele, 2) enumerators visited households in selected villages, and 3) respondents were recruited by the enumerators while walking down the only road through the kebele. All respondents were self-selecting in that no specific households were targeted, or rejected, for participation in the survey. Surveys from households from other kebeles were discarded prior to analysis. Surveys were administered in May through August, 2017. Prior to use, our research was approved by the University of Michigan Institutional Review Board.

2.1.3 Analytical methods

Analysis was done using statistical a software package (STATA 15.0). The main variables of interest were the number of ADHENO-sponsored farmer trainings attended by the respondent and the impact on crop productivity, use of farming methods, and income from farming. More details about the statistical models and analytical process are included below in Appendix A.

2.2 Ecological Sampling

2.2.1 Study and control site selection

The study was conducted in June and early July 2017. We collected vegetation data in the three area closures that were larger than 1 hectare and were established over three years ago. These area closures included Saint Emmanuel, Berkumas, and Ater Meda, established in 2003, 2007, and 2013, respectively (Table 1.1, Figure 2.1). Vegetation structure is heterogeneous throughout area closures due to the patchy nature of pre-existing vegetation and ADHENO plantation activities. Livestock grazing and biomass extraction are forbidden inside area closures. ADHENO plantation and tree *gudifecha* activities were carried out in all three area closures. The planted species consisted of both indigenous and exotic species, including *Acacia abyssinica*, *Acacia saligna*, *Cordia africana*, *Cupressus lusitania*, *Dovyalis abyssinica*, *Eucalyptus globulus*, *Grevillea robusta*, *Hagenia abyssinica*, *Juniperus procera*, *Olea africana*, *Podocarpus falcatus*, and *Sesbania sesban*.

To determine the restorative effect of area closures and plantation activities, we conducted systematic vegetation sampling in area closures, and in control areas outside each area closure. To determine control areas for vegetation sampling, we ascertained land-use in each area closure prior to its establishment from ADHENO field staff. We then constructed a 150 m buffer around each closure, and selected areas within these buffers in which land-use most closely matched the original state of the area closure, hereafter referred to as control areas.

2.2.2 Vegetation sampling

We collected vegetation data using a stratified plot sampling method, with 10 x 10 meter plots used to record species and measure the diameter at breast height (DBH) of adult trees (≥ 2 cm DBH or ≥ 2 m in height), and the number of stumps and livestock trails. We constructed one 5 x 5 meter subplot in a random corner of each 10 x 10 meter plot to measure sapling DBH (≤ 2 cm DBH), and record species of saplings, shrubs, herbs, and succulents with height greater than 15 cm. These plot sizes were selected given the dense vegetation structure and steep topography of closures, which presented challenges to constructing larger plots. Plots were constructed along transects at 25 m intervals. Transects began near the edge of area closures or control areas to maximize the length of the transect. Due to the steepness of the survey areas, transect direction was set along the topographical contour. For each area closure or control area, additional transects were established parallel to the first, at a distance of 25 m.

Across the three area closures and associated control areas, a total of 121 sample plots were surveyed, with 61 plots inside closures and 60 within control areas (Figure 2.1). The number of plots constructed at each area closure and control area was determined such that each plot represented 0.2 hectares. Plants were identified to the species level by the National Herbarium of Ethiopia at Addis Ababa University. Specimens that could not be determined to the species level were identified to the family level. All species were categorized into corresponding plant forms, including adult trees, saplings, shrubs, herbs, and succulent plants.

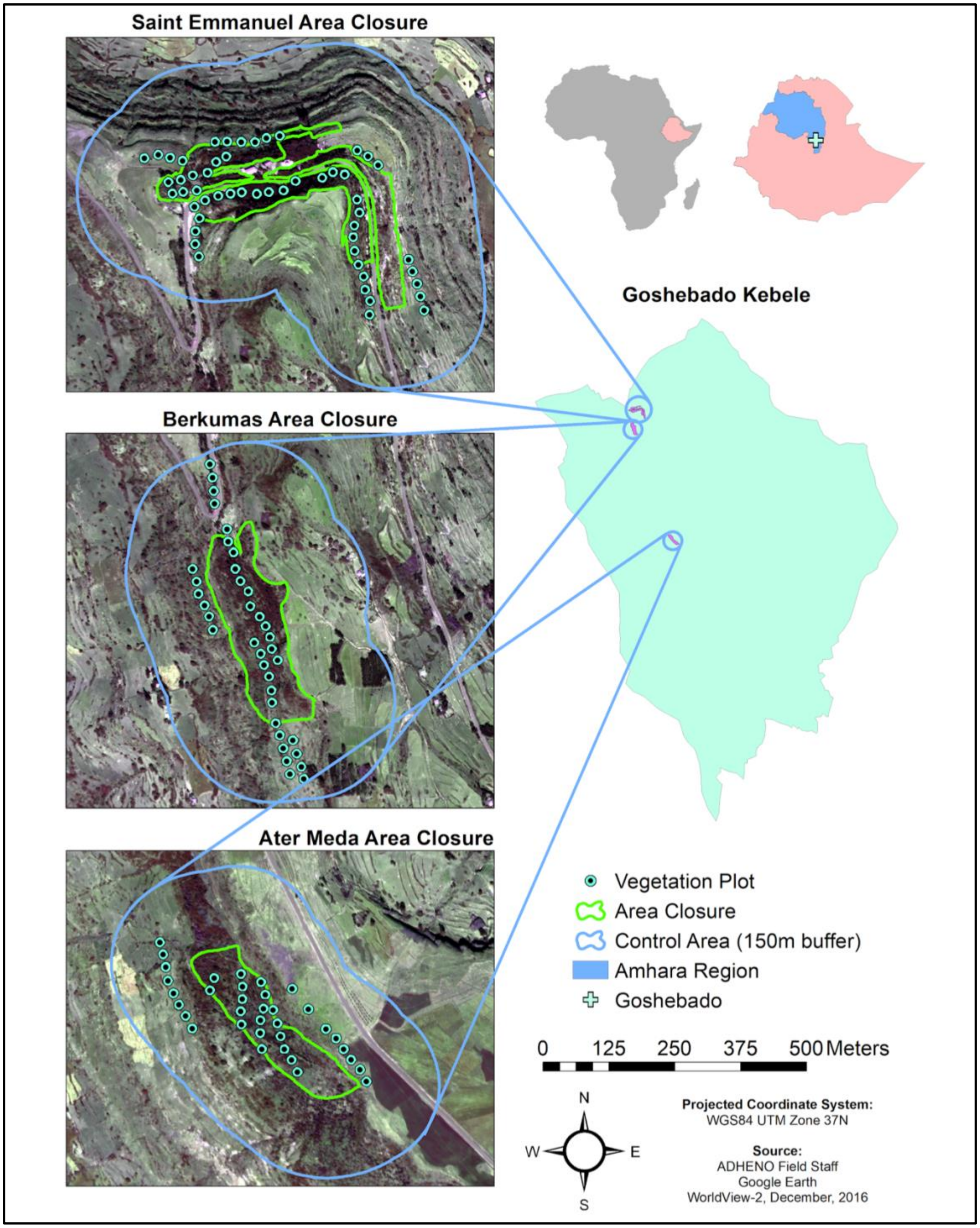

Figure 2.1. Map of Goshebado kebele showing the three sampled area closures, control areas, and vegetation plots. Area closures are overlaid onto WorldView-2 satellite imagery.

2.3 Land-use Intensity

To determine whether village-level participation in ADHENO farmer trainings was associated with land-use intensification over time, we used high-resolution (< 2m) satellite images to classify land-use/land-cover (LULC) over time and modeled changes in land-use intensity within village areas. Land-use intensification and extensification are defined as an increase and decrease in land-use intensity over time, respectively. See Table 2.1 for descriptions of different land-use intensity classifications. Due to extreme patchiness of the landscape, characterized by smallholder farm plots interspersed with eucalyptus woodlots and patches of pasture and shrubland on escarpments, we used an object-based approach for this analysis. Multispectral images were available from December 2007 and November 2016, providing a nine-year window over which to assess land-use intensification and extensification. November and December fall during a dry season harvest period, creating significant heterogeneity in the appearance of agriculture and vegetation across the landscape. Both images provided 100 percent coverage of the Goshebado kebele, a 72 km^2 area, and had 0 percent cloud cover. All image analysis was carried out in ERDAS Imagine by Hexagon Geospatial and ArcGIS Desktop 10.5. More information about the methods used in this analysis are included below in Appendix B.

Table 2.1. Land-use intensity and associated land-cover classifications and descriptions[24,25]

Land-use intensity level	Land-cover class name	Description
1 - Low intensity	Woodland	Land not used for agriculture, with vegetation cover between 20-100%
	Water	All sources of open water – primarily found in rivers in the valleys delineating Goshebado kebele from neighboring kebeles
2 - Low-medium intensity	Eucalyptus Plantation	Identified by orthogonal tracts of dense vegetation, surrounded by very little vegetation or settlements
3 - Medium intensity	Shrubland/ grassland	Land not used for agriculture, with vegetation cover between 1-20%
	Bare soil	Land not used for agriculture with 0% vegetation cover
4 - High-medium intensity	Smallholder Agriculture	Patchwork of farm plots with low density of settlements
5 - High intensity	Rural settlement	High density of settlement and impervious surface
Other	No data	Shadows and other regions for which land-cover was impossible to discern

[24] Delelegn, Y. T., Purahong, W., Blazevic, A., Yitaferu, B., Wubet, T., Göransson, H., & Godbold, D. L. (2017). Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-14128-y

[25] Eggen, M., Ozdogan, M., Zaitchik, B. F., & Simane, B. (2016). Land cover classification in complex and fragmented agricultural landscapes of the Ethiopian highlands. *Remote Sensing*, *8*(12). https://doi.org/10.3390/rs8121020

3. Results

3.1 Survey

3.1.1 Descriptive results

Of the 449 households surveyed, 100 percent cited farming as their primary or secondary source of income. All but one household reported their ethnicity as Amharic. The majority of survey respondents (77 percent) were male. Seventy-five percent of households reported participating in one or more ADHENO farmer training. Descriptive survey results for key variables of interest are presented in Table 3.1. Income from farming is reported in Ethiopian Birr; at the time of this study the conversion rate was approximately 1 US Dollar to 23 Ethiopian Birr. Descriptive results concerning farmer trainings and practices among surveyed households is presented in Figure 3.1.

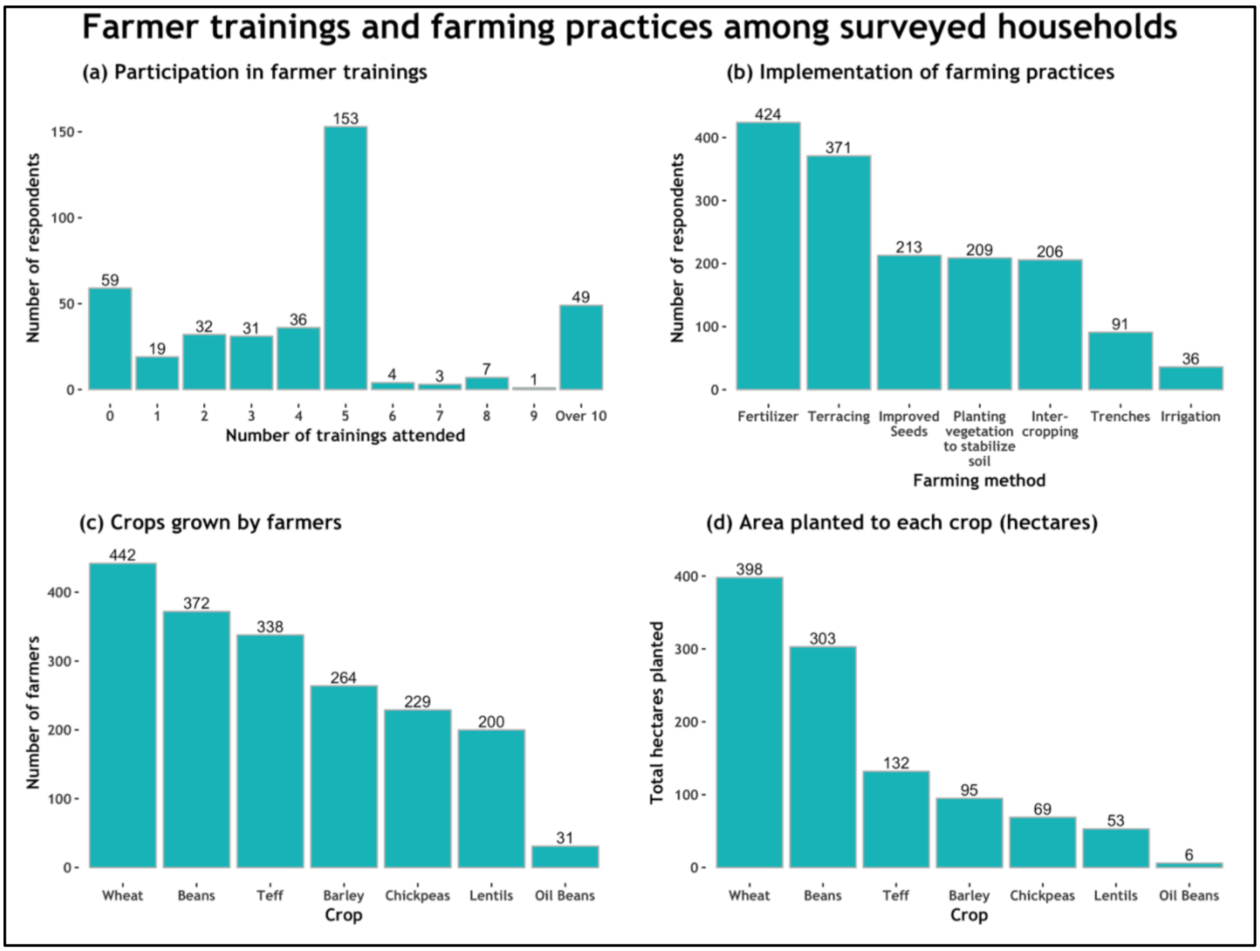

Figure 3.1. Farmer trainings and farming practices among surveyed households showing (a) the number of trainings farmers reported attending, (b) the number of farmers that reported implementing different farming methods, (c) the number of farmers that reported growing different crops, and (d) the total planted area of each of crop grown by surveyed farmers.

Table 3.1. Descriptive results for key variables of interest

Variable	Mean	Standard Deviation	Median
Farmer Trainings Attended in Previous 5 Years	4.5	3.6	5
Income from Farming[a]	8913	7746	8000
Land in *Timads*[b]	6.2	2.9	6
Male Head of Household Age	51	13.1	50
Female Head of Household Age	44	12.0	44
Household Size	5.1	2.0	5

[a]Farmers reported their income in Ethiopian Birr; the exchange rate to USD was 23:1 at the time of this study.
[b]Farmers reported land-holdings in the local unit of area measurement, the *timad.* One *timad* is equivalent to approximately 0.25 hectares.[26]

3.1.2 Crop productivity

There was no significant relationship between crop productivity and whether a respondent attended one or more farmer training sessions. Reference Appendix A for more information.

3.1.3 Use of farming methods

Analysis of the relationships between participation in ADHENO farmer trainings and self-reported use of the farming methods taught in the trainings yielded a significant effect for 4 out of 7 methods: intercropping, improved seeds, use of vegetation to stabilize soil, and trenches and other water runoff mitigation (Table 3.2). All coefficients were positive, with the exception that irrigation was negative. The results were not significant for fertilizer use. The positive significant relationship between participation in training and the use of terracing, intercropping, improved seeds, use of vegetation to stabilize soil, and trenches and other water runoff mitigation indicates that attendance in ADHENO farmer training sessions is correlated with adoption of the farming strategies presented in the trainings. A positive difference-in-means value represents the amount of increase in use of the method for treatment over the control

[26] Shiferaw, B., Holden, S., & Aune, J. (2001). Population pressure and land degradation in the Ethiopian highlands: a bio-economic model with endogenous soil degradation. In *Economic Policy and Sustainable Land Use* (pp. 73-92). Physica, Heidelberg.

group; for example, farmers who participate in training are 40% more likely to use intercropping than farmers who do not attend training.

Results were significant for use of terracing, intercropping, and trenches and other water runoff mitigation, indicating that attendance in multiple trainings was associated with the use of these methods. Results were not significant for the remaining methods, indicating one training may be sufficient for those methods with a positive coefficient, which are improved seeds and use of soil stabilizing vegetation.

Table 3.2. Results of PSM probit regression of Farmer Trainings Attended (0/1) & Use of a Method (0/1) and Rosenbaum bounds test (listed as gamma)

Method	**Means**			**SE**	**Prob > chi2**	**ATT t-stat**	**rbounds gamma<.05**
	Treatment group	**Control group**	**Difference in means**				
Fertilizer	0.976	0.956	0.021	0.064	0.002	0.32	no significance
Terracing	0.898	0.761	0.137	0.119	0.002	1.14	1.8
Improved Seeds	0.567	0.119	0.447	0.097	0.002	4.63***	7.3
Vegetation	0.590	0.341	0.249	0.091	0.002	2.74**	2.1
Intercropping	0.519	0.113	0.406	0.070	0.002	5.82***	4.8
Trenches	0.283	0.00	0.283	0.026	0.002	10.74***	30.6
Irrigation	0.058	0.137	-0.078	0.116	0.002	-0.67	no significance
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001							

We used a two-sample t-test to compare the mean numbers of training sessions attended by those who participated in one or more sessions with the use of farming methods (Table 3.3). The coefficient represents the difference in mean number of trainings attended by the treatment group(1) and control group(0). Results were significant for use of terracing, intercropping, and trenches and other water runoff mitigation, indicating that attendance in multiple trainings was associated with the use of these methods. Results were not significant for the remaining methods, indicating one training may be sufficient for those methods with a positive coefficient, which are improved seeds and use of soil stabilizing vegetation.

Table 3.3. Results of two-sample t-test comparing Numbers of Farmer Trainings Attended (non-participants eliminated) with Use of Farming Methods (0/1).

Farming Method	**Coefficient (mean1 - mean0)**	**Standard Error**	**95% Confidence Interval**		**Pr(T < t) diff < 0**
Fertilizer	-0.747	1.782	3.591	-5.085	0.655
Terracing	1.429	0.415	2.257	0.600	0.0005***
Improved Seeds	0.586	0.370	1.313	-0.142	0.057
Vegetation	0.500	0.354	1.196	-0.195	0.079
Intercropping	0.917	0.355	1.616	0.218	0.005**
Trenches	1.547	0.493	2.524	0.569	0.001**
Irrigation	-0.764	0.804	0.908	-2.436	0.824
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001					

3.1.4 Income from farming

Regressing the dummy variable representing attendance at any farmer trainings with self-reported income from farming over the past year showed indicated that attendance at farmer trainings is correlated with higher income from farming (Table 3.4). Results from this propensity score matching analysis show that the treatment group (i.e., those attending a training session) had on average an income that was higher by 6311 Ethiopian Birr, or about $275 USD, compared to the control group. The average reported income from farming across groups was 8913 Ethiopian Birr or about $387 USD.

Table 3.4. Results of PSM probit regression of Farmer Trainings Attended (0/1) & Income in Ethiopian Birr from Farming and Rosenbaum bounds test (listed as gamma)

	Means			**SE**	**Prob > chi2**	**ATT t-stat**	**rbounds gamma <.05**
	Treatment group	**Control group**	**Difference in means**				
Income from Farming	10328.64	4017.36	6311.28	1161.09	0.0003	5.44***	2.8
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001							

3.2 Ecological Results

3.2.1 Descriptive results

The site conditions of control areas include farm lands, grazing pastures, and *Eucalyptus globulus* woodlots. A total of 77 unique species were identified out of 7,693 vegetation samples (Table 3.5; see Appendix D for full inventory). Several species are considered rare due to the fact that few individuals were found in the study area. More species exist in area closures; however, six species were found only in control areas.

Table 3.5. Species richness (the total number of unique species) in each area closure and control area, and the number of common species shared in both areas.

	Area closure	Control Area	Common species
Saint Emmanuel	44	27	23
Berkumas	48	35	28
Ater Meda	39	20	14
Total (77)	71	46	40

3.2.2 Vegetation composition

Species abundance, density, richness, and diversity are significantly higher in area closures than in control areas while species evenness is not (Figure 3.2). Controlling for the impact of terrain variables on vegetation composition, only slope and aspect have significant positive and negative influence, respectively, on species abundance (Table 3.6), and solar radiation is associated with lower species richness and diversity. In all these analyses, the presence of area closure was still the most significantly associated with species abundance, richness, and diversity.

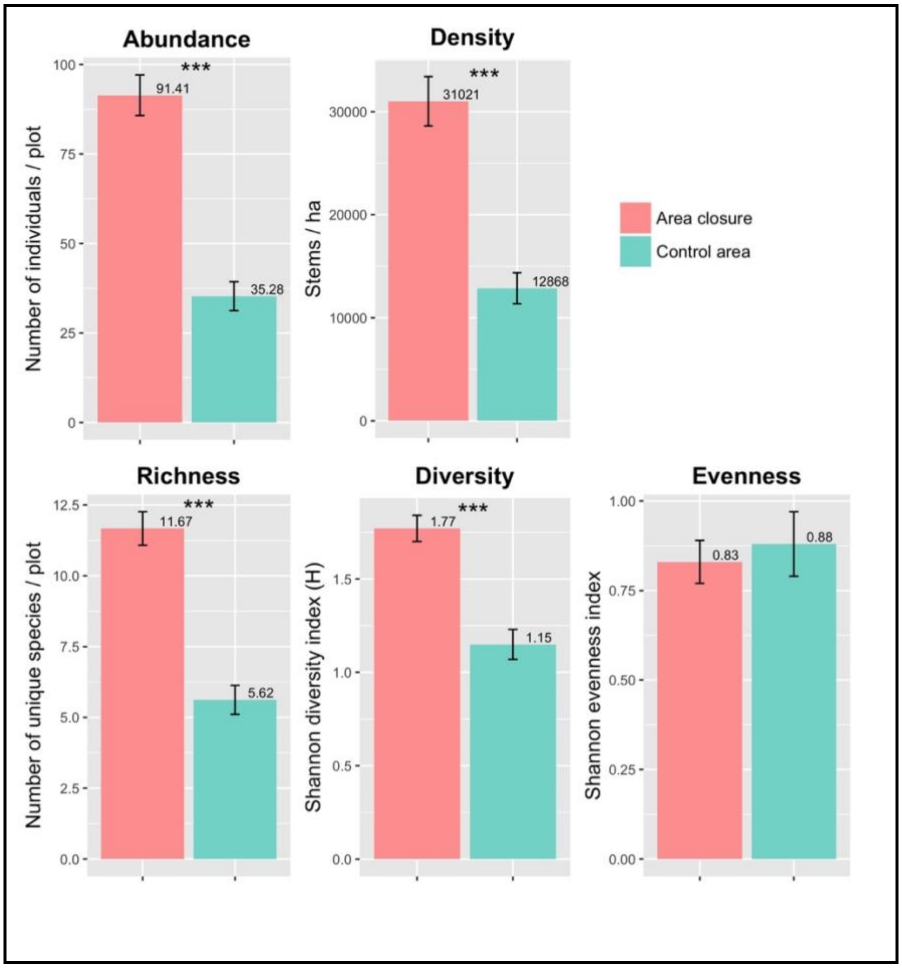

*Figure 3.2. Comparison of species abundance, density, richness, diversity, and evenness between area closures and control areas. (*** significant difference, ** moderate difference, * slight difference)*

Table 3.6. Association between terrain features and establishment of area closures on species abundance, richness, evenness, and diversity.

	Abundance	Richness	Evenness	Diversity
Slope	+*			
Elevation				
Aspect	–**			
Wetness				
Solar radiation		–*		–**
Distance to road				
Area closure	+***	+***		+***

Note: + positive effect; – negative effect
*** significant effect, ** moderate effect, * slight effect

3.2.3 Vegetation structure

The number of individuals in each plant form are higher in area closures than in control areas (Figure 3.3). Species diversity is higher in area closures for all vegetation stand structures except herbs (Figure 3.4). The characteristics of different plant categories, including basal areas of adult trees, sapling heights, and understory (the aggregation of shrubs, herbs, and succulents) heights, are average higher in area closures compared to control areas (Figure 3.5).

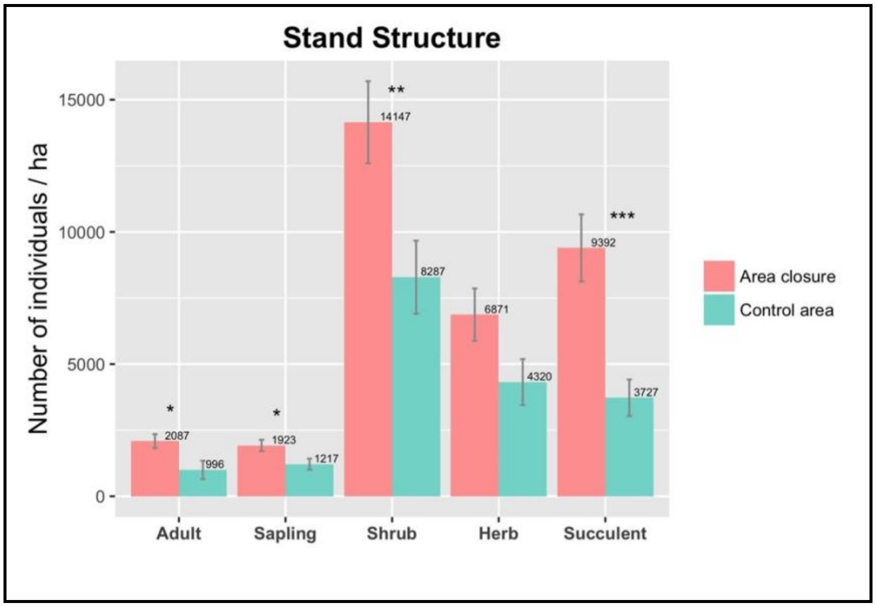

*Figure 3.3. Condition of stand structures and comparison of species abundance of each plant form between area closures and control areas. (*** highly significant difference, ** significant difference, * moderately significant difference)*

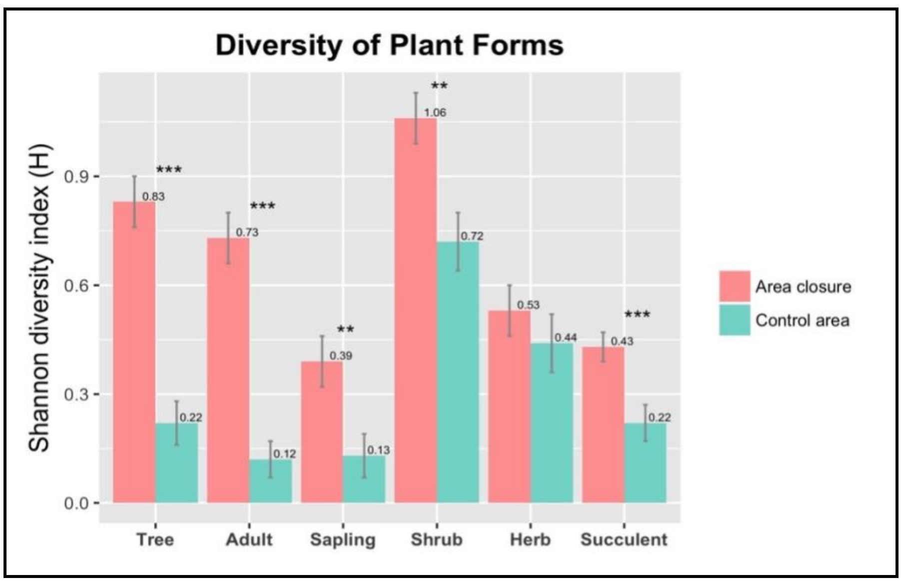

*Figure 3.4. Comparison of species diversity of each plant form between area closures and control areas. The tree category includes both adult trees and saplings. (*** highly significant difference, ** significant difference, * moderately significant difference)*

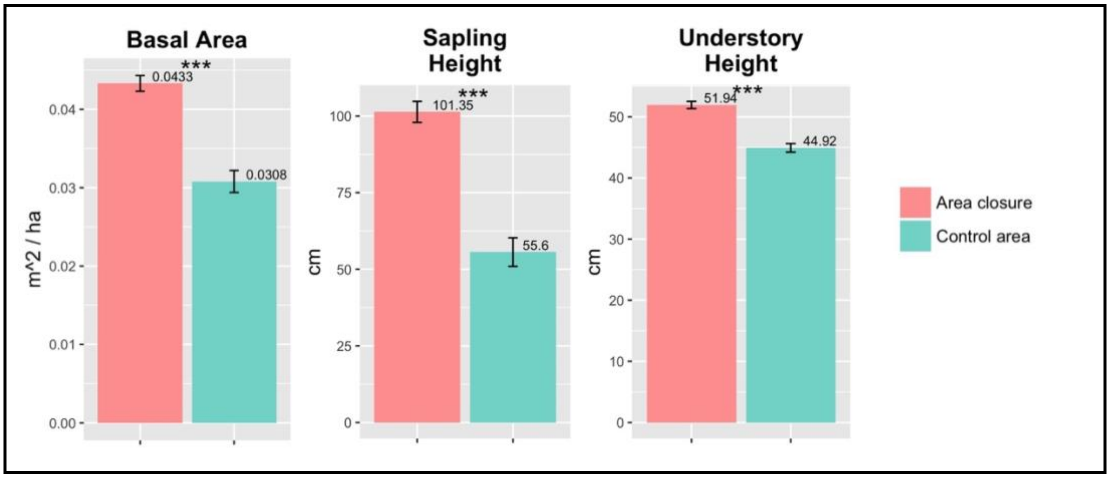

*Figure 3.5. Comparison of basal area of adult trees, sapling height, and understory height between area closures and control areas. (*** highly significant difference, ** significant difference, * moderately significant difference)*

3.2.4 Impact of planted species

The number of introduced species, *Eucalyptus globulus* and *Cupressus lusitanica,* have a highly significant negative association with understory abundance (Table 3.7). The indigenous species, *Acacia abyssinica*, is significantly associated with higher understory abundance. Although *Acacia saligna* and *Juniperus procera* have positive contribution to understory abundance, the impact is not statistically significant.

Table 3.7. Association between number of planted adult tree species and understory abundance. Understory includes shrubs, herbs, and succulents.

	Status	Effect	Function
Eucalyptus globulus	Introduced	**–***	
Cupressus lusitanica	Introduced	**–***	
Acacia saligna	Introduced		Soil conservation
Juniperus procera	Indigenous		
Acacia abyssinica	Indigenous	**+***	Soil conservation

Note: + positive effect; – negative effect
*** highly significant effect, ** significant effect, * moderately significant effect

3.2.5 Human and livestock impacts

There are a total 309 and 81 stumps counted in area closures and control areas, respectively. The stumps comprise 15 species in area closures; 4 of those species are also present in the control areas. Two *Allophylus abyssinicus* and *Croton macrostachyus* individuals were found with over 20 stumps on one tree. Despite this, control areas had a higher proportion of trees that were found with stumps (Figure 3.6). Tree saplings are cut down only in control areas. The number of animal trails has a moderately significant positive association with species abundance, and the number of stumps has a moderately significant negative association with species diversity.

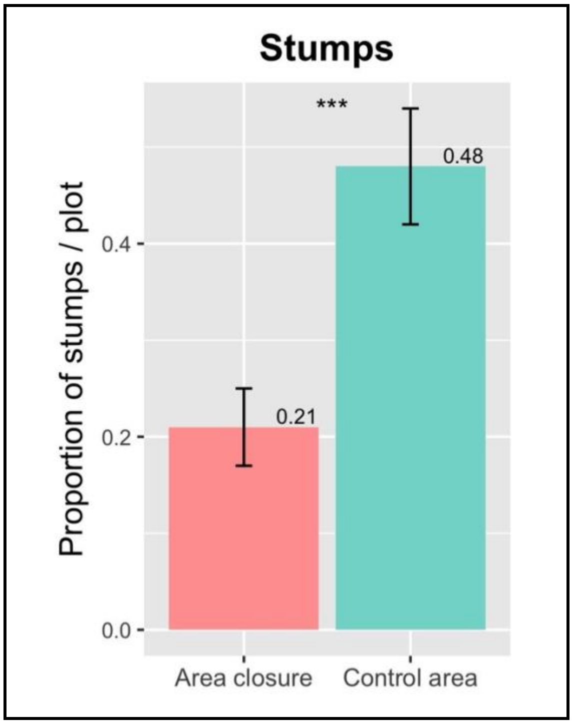

*Figure 3.6. Comparison of the proportion of cutting trees between area closures and control areas. (*** highly significant difference, ** significant difference, * moderately significant difference)*

3.3 Land-use Intensity

3.3.1 Descriptive results

On average, 63.38% of the land-use within delineated village area remained the same over time (n = 28, sd = 6.72; Figures 3.7 and 3.8). In contrast, the average rate of land-use intensification in village areas was 14.47% (n = 28, sd = 6.98; Figures 3.7 and 3.8), and the average rate of extensification was 21.85% (n = 28, sd = 7.94; Figures 3.7 and 3.8). Meanwhile, participation in farmer training sessions was high, with an average of 70% participation in at least one session across villages, though there was substantial variation between villages (n = 28, sd = 18.56; Figures 3.7 and 3.8).

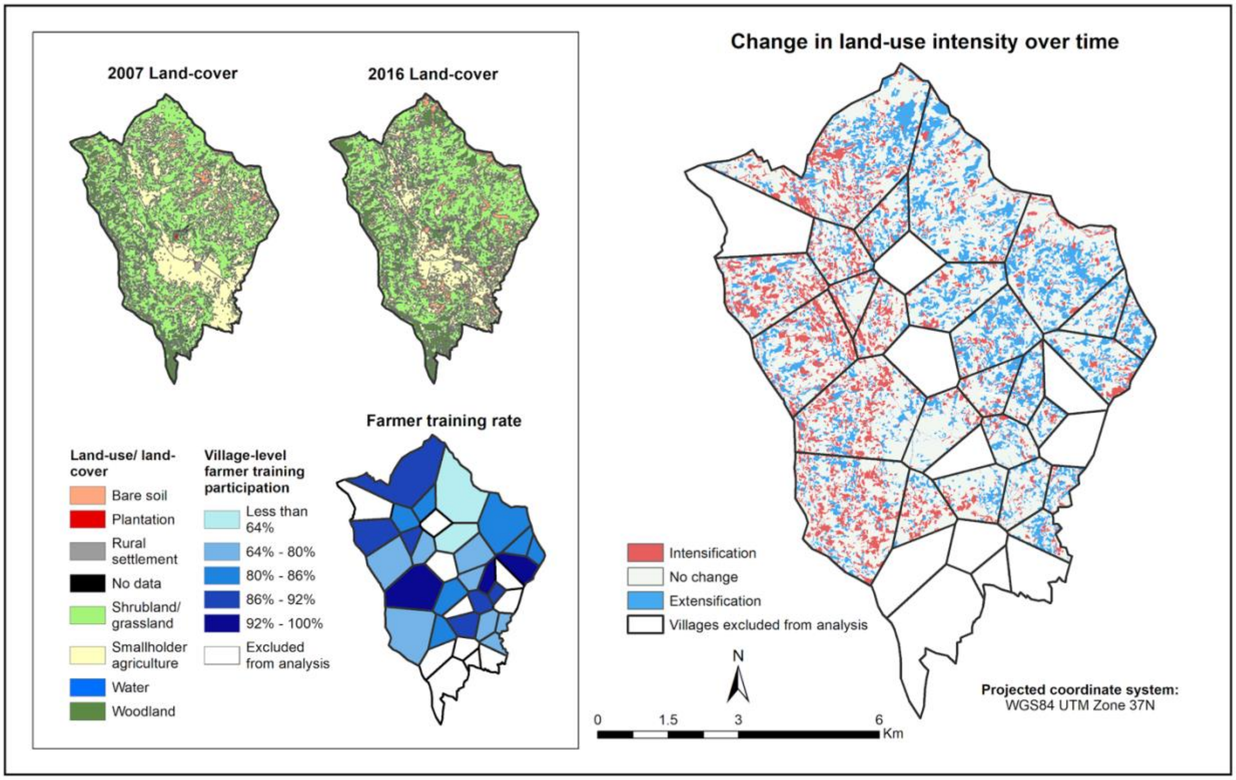

Figure 3.7. Classified land-use/land-cover for 2007 and 2016, participation rate in farmer trainings, and change in land-use intensity over time in Goshebado Kebele. Land-cover classification was based on KOMPSAT-2 imagery from November 2007 and WorldView-2 imagery from December 2016. Village boundaries were estimated as Thiessen polygons calculated from village centerpoints. Villages were excluded from analysis if fewer than 15% of households were surveyed.

3.3.2 Predictors of land-use change at the village-level

Linear models of intensification and extensification rates indicated that the rate of participation in any farmer training was not significantly associated with rate of land-use change at the village level (intensification: p = 0.89; extensification: p = 0.14). However, land-use change was significantly associated with other variables in the model (intensification: R^2 = 0.68; extensification: R^2 = 0.55; Table 3.8). Land-use intensification was positively predicted by slope, such that each percent increase in slope predicted a 0.46% increase in intensification (p = 0.001). Land-use extensification was positively associated with average land holdings and distance from ecological restoration sites, such that each additional hectare owned predicted an additional 2.74% land-use extensification (p = 0.049), and each kilometer of distance from ecological restoration sites predicted an additional 2% of land-use extensification (p = 0.03). Shapiro-Wilks tests indicated that the assumption of homoscedasticity held (intensification: p = 0.52; intensification: p = 0.08). For more in depth results, reference Appendix B.

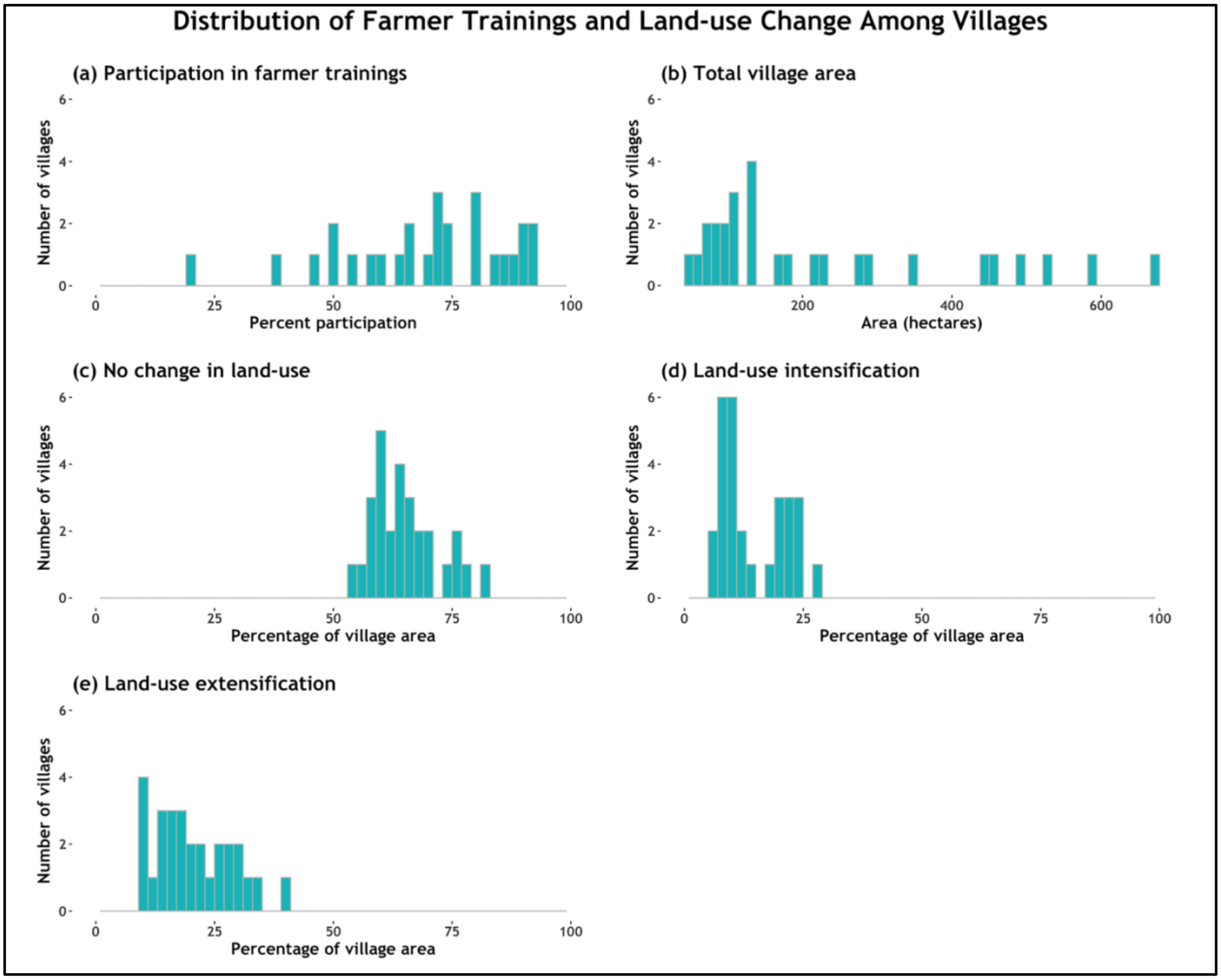

Figure 3.8. Distribution of participation in farmer trainings (a), total area (b), and land-use change dynamics (c, d, e) among villages.

Table 3.8. Linear model results of land-use change at the village level. Beta coefficients are reported with significance levels, and standard errors in parentheses.

	Dependent Variable	
	Rate of Intensification	Rate of Extensification
Participation in farmer trainings	-0.009 (0.063)	-0.131 (0.087)
Participation in ecological restoration program	-0.029 (0.168)	0.385 (0.230)
Average land holdings	-1.488 (0.950)	**2.73*** **(1.305)**
Average income	0.000 (0.000)	0.000 (0.000)
Average education	4.218 (3.376)	-0.654 (4.636)
Number of households	0.067 (0.072)	-0.095 (0.098)
Slope	**0.463**** **(0.120)**	-0.073 (0.164)
Distance from town	-0.007 (0.004)	0.004 (0.006)
Distance from ecological restoration sites	-0.029 (0.168)	**0.003*** **(0.001)**
Constant	10.912 (9.521)	0.657 (13.074)
Observations	28	28
R^2	0.680	0.554
Adjusted R^2	0.520	0.332
Residual Std. Error (df = 18)	4.762	6.538
F Statistic (df = 9; 18)	4.243	2.488
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001		

4. Discussion

Summary of results

Our analysis of survey responses in villages where ADHENO offered farmer training shows that farmer participation in training has a significant predictive relationship with adoption of soil conservation farming methods. Farmer participation in training also significantly predicts higher income from agriculture among participant households compared to households that did not participate in training, however, participation is not associated with improved agricultural productivity. Although farmer participation predicts behavior and livelihood changes, our analysis of land-use change reveals no association between village level rates of participation in farmer training and land-use changes at either the village or the pixel level. These findings have implications for the effectiveness of farmer trainings as a community development and soil conservation interventions. Our analysis also found that area closures have 25 more unique species than selected control sites, and have more robust vegetation structure. Area closures are not well enforced, given the presence of livestock trails and tree stumps, yet these appear to have minimal impacts on vegetation health.

Use of farming methods

The significant positive relationship between participation in training and the use of intercropping, improved seeds, soil stabilizing vegetation, and trenches and other water runoff mitigation practices indicates that attendance at ADHENO farmer trainings is correlated with adoption of these farming strategies. The use of fertilizer may not be significant in this analysis due to its widespread use in the study area. Of 449 respondents, 423 reported using fertilizer, indicating that it is not a method that requires a specialized training to implement as may be the case with the other methods. However, we did not include questions on our survey concerning quantity of fertilizer used or the timing of fertilizer application. Conversely, irrigation was the least utilized of all the methods with only 36 respondents reporting irrigating. Irrigation may also be the costliest of the methods to implement. The large investment required, and logistical issues may prevent lower income farmers from adopting the method. The cost prohibitive nature may also partially explain the negative relationship between irrigation and participation. Additionally, the overall low adoption of irrigation is possibly a result of the topography and hydrology of the kebeles. Many program participants live on the top of a plateau or on the slopes. Wells are not common in the area and there are very few springs and creeks during the dry season. The primary method of irrigation is through the creation of water catchment basins to collect water during the rainy season.

Of the methods with a positive relationship to any farmer training, terracing, intercropping, and trenches are significantly correlated with attendance at more training sessions, suggesting that more trainings have a positive predictive relationship with utilization of these methods. Improved seeds and planting vegetation were not positively correlated with attendance at more training sessions. This could indicate that a single training session is adequate to encourage and educate farmers to adoption those methods and that increased training sessions are not beneficial for increased adoption. Because respondents' use of the methods was self-reported there is no measure of how well respondents are implementing what they are learning in the trainings.

Crop productivity

Participation in farmer trainings was not found to be significantly associated with the productivity of the seven most common crops. Analysis of this relationship was limited in several capacities. We did not collect information on the amount of time between attendance at a training and the start of growing season. How well or to what extent farmers implement the methods was not evaluated. Also, it is possible that some methods take time to rebuild soil health and, therefore, positive changes in yields would not be expected for several years.

Income from farming

Participation in farmer training was found to be related to higher income from farming. Despite this relationship, the farmers who attended training were not found to have significantly higher crop productivity. This may suggest that higher income from farming is not a result of the methods adopted from trainings, but an indication of the characteristics of farmers who attend trainings. These farmers were selected by ADHENO and agricultural extension agents from the local government for the trainings based partially on an informal qualitative assessment of their work ethic. This may result in a selection of farmers who were experiencing a certain level of success prior to the trainings which would bias a comparison of average income from farming of the two groups.

The analysis did not consider land area used for crops or types of crops grown. It is possible that farmers who participated in the trainings farm on larger areas, and therefore have a higher income from farming. They may also be more reliant on farming as their primary income source. This could partially explain motivation to attend trainings.

Impact of area closures and planted species

The implementation of plantation programs and area closures are effective at restoring and increasing the biodiversity and vegetation structure. Although a few terrain features show slight association with vegetation composition, whether the establishment of area closures or not is the key factor that has significant positive impacts on vegetation composition. Although several rare species were surveyed in the vegetation sampling, the species evenness index is still high, 0.83 and 0.88 out of 1.00 in area closures and control areas, respectively. Despite the high value of species evenness in area closures, there are 38 species for which fewer than 10 individuals were surveyed in area closures. This indicates that area closures have the function to conserve rare species. Non-indigenous plantation species, *Eucalyptus globulus* and *Cupressus lusitanica* have significant negative association with understory species abundance while indigenous plantation species, *Acacia abyssinica*, has a positive association with the understory plant abundance. Both *Acacia abyssinica* and *Acacia saligna* have the important function of soil conservation, which can stabilize soil and prevent erosion. Although *Acacia saligna* is an introduced species with no positive association with understory abundance, its soil conservation function has the potential to benefit vegetation growth. Indigenous *Juniperus procera* also shows the potential positive effect on understory vegetation though the effect is not statistically significant.

Impact of human and livestock in area closures

Although there were far more stumps and more species that had been cut inside area closures, area closures had a lower proportion of trees cut compared to control areas. This may be because trees are more abundant and diverse in area closures. The presence of stumps and livestock trails in the area closures demonstrated that area closures do not strictly prevent from human and livestock disturbance. Livestock trails are positively associated with species abundance. This may be explained by the fact that livestock tend to graze in the areas with more vegetation. There is no association between livestock and species richness, diversity, and evenness. Although the number of stumps in a plot has slight negative association with species diversity, there is no association between stumps and other vegetation indices including species abundance, richness, and evenness. The results indicate that area closures are resilient to some degree of human and livestock disturbance.

Land-use change

We found no evidence of a relationship between rate of participation in farmer trainings within villages and rates of land-use change at the village level or at the pixel level. This is true for intensification and extensification. Nonetheless, our results show that land use has not remained the same over time. In the average Goshebado village, 63% of land area remained the same over time, while 14% of area intensified and 23% of area extensified. Additionally, rate of land-use change differed across villages (Figures 3.7 and 3.8).

Three potential explanations account for the lack of association between farmer trainings and land-use change. One may be data limitations. Our survey recorded attendance at farmer trainings over the last five years, but to mitigate recall bias, we did not ask farmers how many participations they attended in each year. Additionally, due to the sparse distribution of households and farm plots, we conducted many surveys in central locations and were thus unable to conduct land-use change analysis based on the locations of plots farmed by surveyed households. We approximated village boundaries with Thiessen polygons, but these may be poor indicators of the areas managed by the interviewed farmers. Furthermore, ADHENO has worked for a long time with farmers in some areas of Goshebado, and has begun working with other communities more recently, yet we were not able to obtain records of when new communities were included in training efforts. Thus, it was not possible to include the starting date of ADHENO's farmer trainings in each village area as a fixed effect in the models.

The second potential reason for the lack of association between trainings and land-use change may be related to the farmer trainings themselves. The training sessions conducted by ADHENO focus on strategies to increase agricultural production and conserve soil in the context of the farm plot, yet our analysis sought to use these trainings to explain overall land-use change across the kebele. Broad changes in land use are not influenced solely by decisions farmers make in how to manage their plots. In fact, in both time periods, a large proportion of Goshebado was grazing land. These grazing lands represent multiple levels of land-use intensity, given that grazing places pressure on vegetation and soil resources, which are both important for maintaining soil quality and ecosystem services. Shrubland/grassland and bare soil represent a relatively high level of land-use intensity, as most of the vegetation has been removed, creating risks for soil quality. Grazing occurs in woodlands (author observation; I. Fikre, personal communication), but the higher level of vegetation indicates that ecosystem services and soil quality is higher in these areas. Thus, it appears that livestock management practices and commons governance have important implications on land-use intensity in Goshebado. Currently, ADHENO farmer trainings and other rural development programs do not address livestock management, although ADHENO's ecological restoration program aims to improve ecosystem services in communal grazing lands.

A third potential explanation for the lack of apparent relationship between farmer trainings and land-use change is that this program may have been unable to generate an agricultural transition yet. Under an agricultural transition, if farmers can sustainably intensify agricultural production to satisfy food needs with less land, they may cease to convert land to agricultural use, and perhaps put some farmland to less intensive uses.[27] Woodlots, popular in the Ethiopian highlands, are an example of land-use extensification. *Eucalyptus globulus* is a popular woodlot species in Ethiopia for fuelwood and carpentry due to the resilience and value of the species. *E. globulus* trees are planted at a median density of approximately 3,000 stems per hectare, and with an adult tree fetching approximately $3 USD within ten years, the ability to devote land to woodlots may be transformational for rural livelihoods in Ethiopia.[28] In the case of ADHENO, the goal of farmer trainings is to mitigate losses in soil nutrient levels and soil erosion, improve soil organic matter, and provide farmers with more robust yields. Our survey results have shown that for most farming methods, farmers that participate in just one training are significantly more likely to practice these methods than those that have not attended trainings. These findings present promising results that suggest a land-use transition may be possible if ADHENO continues its programs in Goshebado and expands trainings to underserved communities in the area.

5. Recommendations

Expand farmer trainings to more villages and more participants

Our results show that most farmer training topics have significant impacts on agricultural practices. Farmers that attend trainings on improved seeds, trenches, stabilizing soil with vegetation, intercropping, and terracing are highly likely to utilize those methods. Additionally, farmers that attend trainings have higher incomes than farmers that do not attend trainings. These findings suggest that ADHENO trainings improve farmers' knowledge on alternative farming methods, and provide them with the necessary resources to implement the practices. The findings also suggest that ADHENO trainings predict improved livelihoods from agricultural activities. Our results show that this is the case even when farmers have attended just one training. Due to this, *we suggest that ADHENO carries out trainings in additional villages to increase the number of farmers with access to ADHENO trainings.*

[27] Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. Annals of Botany, 114(8), 1571–1596. https://doi.org/10.1093/aob/mcu205

[28] Jagger, P., & Pender, J. (2000). The role of trees for sustainable management of less-favored lands: The case of Eucalyptus in Ethiopia. Washington, D.C.

Address grazing practices in farmer trainings

Land-use intensity is a useful lens through which to consider conservation of soil resources, especially given the role that vegetation plays in stabilizing soil. The fact that farmers are likely to plant vegetation to stabilize soil if they attend trainings suggests that additional farmer trainings can reduce land-use intensity beyond the farm. Livestock grazing is likely a factor that prevents regrowth of vegetation, and a reduction in land-use intensity on a broad scale. Thus, *we recommend that ADHENO develops a new farmer training topic to address grazing practices*.

Utilize mixed-species plantation strategy

Currently, numerous areas within area closures are dedicated to the plantation of a single tree species. In cases where this species is non-indigenous, notably *Eucalyptus globulus* and *Cupressus lusitanica,* there is lower plant abundance in the understory. *We suggest that ADHENO implements a mixed-planting strategy to plant useful woodlot species in the same areas as indigenous and soil-conserving species such as Juniperus procera*, *Acacia abyssinica,* and *Acacia saligna.*

Improve process and enforcement in area closure agreements

Despite area closures being ostensibly dedicated solely to conservation, we found substantial grazing and biomass extractions taking place. Areas that were more accessed by livestock (indicated by number of trails in a plot) had equal biodiversity to areas that were less grazed by livestock. However, areas with more biomass extraction (indicated by the number of stumps) had lower species diversity. Thus, it appears that use of area closures has mixed effects on vegetation in these areas. To ensure preservation of biodiversity in area closures, and to maintain trust between all community stakeholders in area closures, *we recommend that ADHENO holds annual or semi-annual meetings with all stakeholders for each area closure to reaffirm commitment to area closures.*

Create resource-use plans for established area closures

Additionally, the mixed biodiversity effects of grazing and tree cutting in area closures suggest that area closures are resilient to low level use by community members. Thus, to ensure that area closure stakeholders gain benefits from the conservation of area closures, *we recommend that ADHENO works with area closure stakeholders to develop sustainable utilization plans, in which all stakeholders have an equal share of benefits, and harvesting is maintained at a sustainable level.*

It is possible that the three area closures we evaluated are resilient to sustained use because of their age, and frequent tree plantations. Thus, *we recommend that ADHENO develops resource-use plans for new area closures only after they have been established for several years.*

6. Conclusions

This study has demonstrated that farmer trainings in ADHENO's project area in the North Shewa are strongly associated with the implementation of practices included in the training sessions and have a strong positive association with increased income from agriculture. Over the time during which these trainings took place, there was no noticeable relationship between farmer trainings and land-use change, despite land-use change occurring broadly across the landscape. These results suggest that land-use intensity is influenced by a broad range of factors besides agricultural practices adopted on smallholder farms. Most farmers in Goshebado are agropastoralists, and given the relationship between grazing and pressure on soil resources, a potential area for expansion of farmer training programs may be to address grazing practices. Such training would have to consider the fact that grazing practices are enmeshed in complex seasonal shifts and communal pasture governance, and behavioral change in relation to grazing practices may be more difficult for farmers to implement compared to crop cultivation. Nonetheless, the association between farmer trainings and agricultural income suggests that land-use may change as farming livelihoods continue to improve.

Area closures and tree *gudifecha* are effective at conserving biodiversity, as evidenced by 25 species found inside area closures that could not be found in the control areas. Area closures had higher biodiversity and more robust vegetation structure and composition indices, compared to control sites. This has implications on health for a number of rare species found in the Ethiopian Highlands, including the Ethiopian wolf, gelada monkey, and numerous bird species. If area closures are successful at restoring biodiversity, improved ecosystem connectivity may bring more wildlife and ecosystem services back to Goshebado. Additionally, we found that while area closures are not well enforced, human and livestock pressure had minimal impact on vegetation structure and composition. This suggests that there are opportunities for ADHENO to begin creating plans with community stakeholders to begin collaborative management and sustainable extraction from the area closures.

Overall, ADHENO activities have very strong associations with improved farming practices and ecological outcomes. This is positive for farmers in Goshebado. Because ADHENO programs have worked in the past, an increase in ADHENO trainings in certain topics and in tree *gudifecha* activities will continue to improve livelihoods and ecological services for future generations.

Appendices

Appendix A. Household Survey Methods and Results

Variable management and analytical methods

The main variables of interest were whether the respondents attended any ADHENO-sponsored farmer training sessions and, if so, how many, and the crop productivity, farming methods used, and income from farming for each of those households. The number of sessions attended by surveyed households ranged from 0-30. Statistical analysis was completed using STATA 15.0.

We generated a dummy variable representing any training, or no training, to represent the treatment and control groups and used probit regression models to evaluate the relationship between participation in farmer training and each outcome variable. Propensity score matching of demographic and geographic variables was used to compare participating and non-participating households to account for confounding differences between villages. Propensity score matching (PSM) helps to estimate the effect of a treatment by accounting for differences between the treatment and control groups that could predict both receiving the treatment and the outcome. The following variables were used to match treatment and control groups: total amount of land used for farming, ages of the male and female heads of household, household size, and whether the farm was located on the plateau, valley, or slope. The output of PSM includes the average treatment effect on the treated (ATT), which represents the observable average difference of everyone in the treatment group receiving training versus no one in the treatment group receiving training.[29] The estimated effect of the treatment is show in the difference in means. We estimated the impact of participation in multiple training sessions on farming methods only, by first removing respondents who had attended 0 trainings were removed from the analysis. A two-sample t-test was used to compare the number of trainings attended, 1-30, by the dummy variables for use of farming methods. The sensitivity of all PSM models was tested using the Rosenbaum bounds test.

Outcome variables represented productivity, farming methods, and income from farming. We generated a crop productivity variable for seven crops: wheat, beans, barley, teff, lentils, chickpeas, and oil beans. For each household we divided the total reported weight of the crop yield by the total reported land area used for growing. We tested the farming methods fertilizer, terracing, improved seeds, planting vegetation for soil stabilization, intercropping, trenches and water runoff mitigation, and irrigation. We generated a dummy variable for self-reported use of each of these methods. Finally, we calculated reported household income from farming activities over the past year.

[29] Li, M. (2012). Using the Propensity Score Method to Estimate Causal Effects: A Review and Practical Guide. *Organizational Research Methods,* 1-39. doi: 10.1177/1094428112447816

Descriptive results

Of the 449 households surveyed, 100 percent cited farming as their primary or secondary source of income. All but one household reported their ethnicity as Amharic. Most survey respondents (77 percent) were male. Seventy-five percent of households reported participating in one or more ADHENO farmer training. Descriptive survey results for key variables of interest are presented in Table A-1. Income from farming is reported in Ethiopian Birr; at the time of this study the conversion rate was approximately 1 US Dollar to 23 Ethiopian Birr.

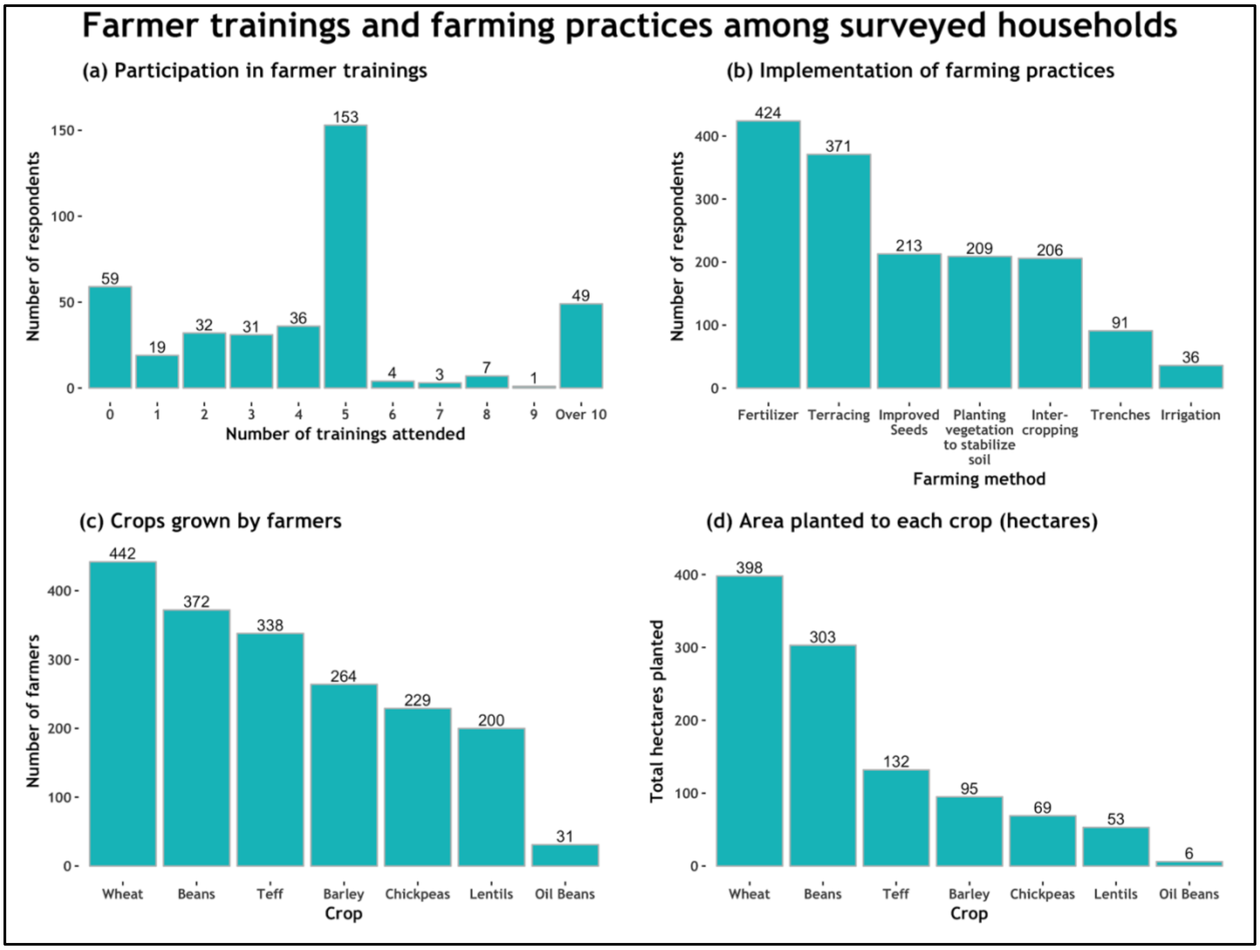

Figure A-1. Farmer trainings and farming practices among surveyed households showing (a) the number of trainings farmers reported attending, (b) the number of farmers that reported implementing different farming methods, (c) the number of farmers that reported growing different crops, and (d) the total planted area of each of crop grown by surveyed farmers.

Table A-1. Descriptive results for key variables of interest

Variable	Mean	Standard Deviation	Median
Farmer Trainings Attended in Previous 5 Years	4.47	3.6	5
Income from Farming[a]	8913	7745.7	8000
Land in *Timads*[b]	6.2	2.9	6
Male Head of Household Age	51	13.1	50
Female Head of Household Age	44	12.0	44
Household Size	5.1	2.0	5

[a]Farmers reported their income in Ethiopian Birr; the exchange rate to USD was 23:1 at the time of this study.
[b]Farmers reported land-holdings in the local unit of area measurement, the *timad.* One *timad* is equivalent to approximately 0.25 hectares.[30]

Crop productivity

There was no significant relationship between crop productivity and whether a respondent attended one or more farmer training sessions (Table A-2). The sample size for oil beans was not sufficiently large to perform a matching analysis.

[30] Shiferaw, B., Holden, S., & Aune, J. (2001). Population pressure and land degradation in the Ethiopian highlands: a bio-economic model with endogenous soil degradation. In *Economic Policy and Sustainable Land Use* (pp. 73-92). Physica, Heidelberg.

Table A-2. Results of PSM probit regression of Farmer Trainings Attended (0/1) & Crop Productivity. The ATT t-statistic denotes statistical significance of the effect, with a value ≥1.95 indicating 95% confidence.

Crop	Means			SE	Prob > chi2	ATT t-stat
	Treatment group	Control group	Difference in means			
Wheat	252.73	250.82	1.90	41.89	0.001	0.05
Beans	216.61	218.61	-2.00	87.17	0.003	-0.02
Teff	178.15	160.95	17.20	43.54	0.005	0.40
Barley	211.52	172.94	38.58	45.50	0.02	0.85
Chickpeas	150.24	157.03	-6.79	38.36	0.24	-0.18
Lentils	138.15	113.16	24.99	69.62	0.01	0.36
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001						

Use of farming methods

Analysis of the relationships between participation in ADHENO farmer trainings and self-reported use of the farming methods taught in the trainings yielded a significant effect for 4 out of 7 methods: intercropping, improved seeds, use of vegetation to stabilize soil, and trenches and other water runoff mitigation (Table A-3). All coefficients were positive, with the exception that irrigation was negative. The results were not significant for fertilizer use. The positive significant relationship between participation in training and the use of terracing, intercropping, improved seeds, use of vegetation to stabilize soil, and trenches and other water runoff mitigation indicates that attendance in ADHENO farmer training sessions is correlated with adoption of the farming strategies presented in the trainings. A positive difference-in-means value represents the amount of increase in use of the method for treatment over the control group; for example, farmers who participate in training are 40% more likely to use intercropping than farmers who do not attend training.

The Rosenbaum bounds test was used to determine the sensitivity of the results to hidden bias, or unaccounted for self-selection of the participants to the treatment group. Gamma values were tested at 0.1 increments. The highest value before gamma exceeded the upper bound of .05 significance level for each method is shown in Table A-3. These values range from 1.8 for use of terracing to 30.6 for use of trenches. This can be interpreted to mean that effects of training on matched households would have to differ (because of unobserved variables) from the predicted effect by 1.8 to 30.6 times for unobserved variables to invalidate the significance of the relationship between farmer trainings and use of terracing or trenches, respectively.

Table A-3. Results of PSM probit regression of Farmer Trainings Attended (0/1) & Use of a Method (0/1) and Rosenbaum bounds test (listed as gamma)

Method	Means			SE	Prob > chi2	ATT t-stat	rbounds gamma<.05
	Treatment group	Control group	Difference in means				
Fertilizer	0.976	0.956	0.021	0.064	0.002	0.32	no significance
Terracing	0.898	0.761	0.137	0.119	0.002	1.14	1.8
Improved Seeds	0.567	0.119	0.447	0.097	0.002	4.63***	7.3
Vegetation	0.590	0.341	0.249	0.091	0.002	2.74**	2.1
Intercropping	0.519	0.113	0.406	0.070	0.002	5.82***	4.8
Trenches	0.283	0.00	0.283	0.026	0.002	10.74***	30.6
Irrigation	0.058	0.137	-0.078	0.116	0.002	-0.67	no significance

Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001

We used a two-sample t-test to compare the mean numbers of training sessions attended by those who participated in one or more sessions with the use of farming methods (Table A-4). The coefficient represents the difference in mean number of trainings attended by the treatment group(1) and control group(0). Results were significant for use of terracing, intercropping, and trenches and other water runoff mitigation, indicating that attendance in multiple trainings was associated with the use of these methods. Results were not significant for the remaining methods, indicating one training may be sufficient for those methods with a positive coefficient, which are improved seeds and use of soil stabilizing vegetation.

Table A-4. Results of two-sample t-test comparing Numbers of Farmer Trainings Attended (zeros eliminated) with Use of Farming Methods (0/1).

Farming Method	**Coefficient (mean1 - mean0)**	**Standard Error**	**95% Confidence Interval**		**Pr(T < t) diff < 0**
Fertilizer	-0.747	1.782	3.591	-5.085	0.655
Terracing	1.429	0.415	2.257	0.600	0.0005***
Improved Seeds	0.586	0.370	1.313	-0.142	0.057
Vegetation	0.500	0.354	1.196	-0.195	0.079
Intercropping	0.917	0.355	1.616	0.218	0.005**
Trenches	1.547	0.493	2.524	0.569	0.001**
Irrigation	-0.764	0.804	0.908	-2.436	0.824
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001					

Income from farming

Regressing the dummy variable representing attendance at any farmer trainings with self-reported income from farming over the past year showed indicated that attendance at farmer trainings is correlated with higher income from farming (Table A-5). Results from this propensity score matching analysis show that the treatment group (i.e., those attending a training session) had on average an income that was higher by 6311 Ethiopian Birr, or about $275 USD, compared to the control group. The average reported income from farming across groups was 8913 Ethiopian Birr or about $387 USD.

Table A-5. Results of PSM probit regression of Farmer Trainings Attended (0/1) & Income from Farming and Rosenbaum bounds test (listed as gamma)

	Means			**SE**	**Prob > chi2**	**ATT t-stat**	**rbounds gamma <.05**
	Treatment group	**Control group**	**Difference in means**				
Income from Farming	10328.64	4017.36	6311.28	1161.09	0.0003	5.44***	2.8
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001							

Appendix B. Land-use Intensity Methods and Results

Land-use Intensity using remote sensing

To answer the question of whether ADHENO farmer trainings impacted land-use intensification over time, we used remote sensing to classify land-use/land-cover (LULC) over time. Due to extreme patchiness of the landscape, characterized by smallholder farm plots interspersed with eucalyptus woodlots and patches of pasture and shrubland on escarpments, we used very high-resolution satellite imagery (< 2m pixels) and an object-based approach for this analysis. Multispectral images were available from December 2007 and November 2016, providing a nine-year window to assess land-use intensification and extensification. November and December fall during a dry season harvest period, creating significant heterogeneity in the appearance of agriculture and vegetation across the landscape. Both images provided 100 percent coverage of the Goshebado kebele, a 72 km^2 area, and had 0 percent cloud cover. This analysis was carried out in ERDAS Imagine by Hexagon Geospatial and ArcGIS Desktop 10.5.

Image preprocessing

The 2007 image was captured by the Korea Multi-Purpose Satellite (KOMPSAT-2) system, which contains bands in the blue, green, red, and near-infrared spectrum, as well as a panchromatic band. Panchromatic imagery is captured in 1m pixels, while multispectral imagery is captured in 4m pixels. The 2016 image was captured by WorldView-2, and contained panchromatic imagery at 0.5m pixels and 4-band multispectral imagery at 1.3m pixels. Both images were orthorectified with a 30m SRTM digital elevation model. The KOMPSAT-2 multispectral imagery was pan-sharpened to increase the multispectral resolution to 1m, then resampled to 1.3m pixels to standardize pixel size between the two images. All image preprocessing was conducted with ERDAS Imagine.

Image classification

We classified LULC for each image using an eight-category classification based on a system developed for the Ethiopian Highlands by Eggen et al.,[31] and refined for the Goshebado context with on-the-ground observations (Table B-1). Specifically, we added a class for Eucalyptus plantation, due to the livelihood importance of woodlots in this region, and removed the wetland class, due to the lack of wetlands. Images were classified by classifying and extracting all objects within each land-cover classes using ERDAS Objective, an object-based image analysis package in ERDAS Imagine. ERDAS Objective segments an image into spatial objects and enables the user to employ machine-learning algorithms to discriminate between land-cover features according to pixel values and object characteristics. For this process, we adapted an approach previously used to extract trees from WorldView-2 satellite imagery.[32] Prior to the extraction of classes in ERDAS Objective, we digitized the rural settlement and masked it out of the image, as there is only one densely settled area in Goshebado.

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[31] Eggen, M., Ozdogan, M., Zaitchik, B. F., & Simane, B. (2016). Land cover classification in complex and fragmented agricultural landscapes of the Ethiopian highlands. *Remote Sensing*, *8*(12). https://doi.org/10.3390/rs8121020

[32] Chepkochei, L. C. (2011, November). Object-oriented image classification of individual trees using Erdas Imagine objective: case study of Wanjohi area, Lake Naivasha Basin, Kenya. In *Proceedings of the Kenya Geothermal Conference, Nairobi, Kenya* (Vol. 2123).

Table B-1. Land-use intensity and associated land-cover classifications and descriptions[33,34]

Land-use intensity level	Land-cover class name	Description
1 - Low intensity	Woodland	Land not used for agriculture, with vegetation cover between 20-100%
	Water	All sources of open water – primarily found in rivers in the valleys delineating Goshebado kebele from neighboring kebeles
2 - Low-medium intensity	Eucalyptus Plantation	Identified by orthogonal tracts of dense vegetation, surrounded by very little vegetation or settlements
3 - Medium intensity	Shrubland/ grassland	Land not used for agriculture, with vegetation cover between 1-20%
	Bare soil	Land not used for agriculture with 0% vegetation cover
4 - High-medium intensity	Smallholder Agriculture	Patchwork of farm plots with low density of settlements
5 - High intensity	Rural settlement	High density of settlement and impervious surface
Other	No data	Shadows and other regions for which land-cover was impossible to discern

For a target LULC class, we identified a set of training pixels using landscape features that fell within the class and identified pixels that fell outside the target class as background pixels for the model to ignore. We applied these data to train a Single Feature Probability pixel classifier, which calculated the probability that each pixel was in a target LULC class. We then performed an unsupervised object-based segmentation using the ERDAS FLS Image Segmentation tool to

[33] Delelegn, Y. T., Purahong, W., Blazevic, A., Yitaferu, B., Wubet, T., Göransson, H., & Godbold, D. L. (2017). Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-14128-y

[34] Eggen, M., Ozdogan, M., Zaitchik, B. F., & Simane, B. (2016). Land cover classification in complex and fragmented agricultural landscapes of the Ethiopian highlands. *Remote Sensing*, *8*(12). https://doi.org/10.3390/rs8121020

specify desired levels of homogeneity of size, texture, shape, and pixel value for output objects. The minimum mapping unit for FLS segmentation was 30m. Following FLS segmentation, the model used previously calculated pixel probability to calculate the probability that each segment fell within the target class. The model then calculated vector geometry parameters for all objects, including area, perimeter, rectangularity, and eccentricity of polygon outlines. We then identified training objects, which the model used to calculate the vector parameters for all objects and the probability that each object fell within the target class. The probability from pixel and object-based calculations were then combined, providing a total probability measure for each object. We then applied a probability filter to reduce the likelihood that the final feature class contained incorrectly classified objects. Classified objects were then masked out of the image to ensure no pixels were classified twice. We repeated this process to sequentially extract all LULC classes for both images, until there were few remaining unclassified pixel clusters.

Following the classification in ERDAS Objective, classification was migrated to ArcGIS Desktop. A trained observer classified all unclassified polygons larger than the minimum mapping unit and merged all LULC classes into one shapefile. A topology was applied to this layer to identify gaps and remove overlaps between polygons. The ArcGIS Eliminate tool was then used to dissolve all remaining unclassified pixel clusters into the largest neighboring polygon. The fully classified scene was then converted into a thematic raster. This process was carried out for both the 2007 KOMPSAT-2 and 2016 WorldView-2 images, as shown in Figure B-1.

We conducted accuracy assessments for the classified images using a unique set of test pixels for each image that were manually classified by a trained observer, using the original satellite image for reference. Test pixels were distributed using a random stratified sampling technique, with each class receiving a minimum of 30 test pixels. We calculated producer and user accuracy for each LULC class; overall kappa was 0.77 for the KOMPSAT-2 image, and 0.86 for the WorldView-2 image.

Classification of land-use intensity and change detection

Following the land-cover classification, we aggregated LULC classes to broader categories of intensity of land-use based on previous studies of historic land-cover and land-use impacts on soil stability and nutrient levels (reference Table B-1). Geological evidence reveals that the Ethiopian highlands were forested before an increase in agricultural pressure upon the landscape beginning 2,000 to 3,000 years ago,[35] indicating that woodland reflects the lowest intensity of land-use among the LULC classes present in Goshebado. Eucalyptus plantation represents low-medium land-use intensity. Plantations have better soil stability and levels of soil organic carbon relative to agricultural and pastoral land;[36] however, plantations have more acidic soil compared to forests and periodic harvests in plantations contribute to lower nutrient

[35] Darbyshire, I., Lamb, H., & Umer, M. (2003). Forest clearance and regrowth in northern Ethiopia during the last 3000 years. *Holocene*, *13*(4), 537–546. https://doi.org/10.1191/0959683603hl644rp

[36] Delelegn, Y. T., Purahong, W., Blazevic, A., Yitaferu, B., Wubet, T., Göransson, H., & Godbold, D. L. (2017). Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-14128-y

levels compared to forests.[37] Shrubland/grassland and bare soil were designated as medium land-use intensity, as they likely reflect areas used for grazing livestock. Grazing land represents frequent low-intensity nutrient removal from soils, resulting in intermediate soil stability and nutrient levels that are between woodland and farmland.[38,39] Agricultural lands were designated high-medium intensity, due to the pressure on soil organic matter and soil stability caused by the farming of annual crops.[40] Rural settlement represents the most intense land-use, given the propensity for urbanization to fragment ecosystems and add to impervious surface.[41] The different land-use intensity classes, names, and levels are included in Table B-1.

Variable management and statistical analysis of land-use intensity changes

Pixel-level spatial variable preparation

Change in land-use intensification was determined by subtracting land-use intensity for 2007 from land-use intensity for 2016. The resulting raster was reclassified into two separate binary rasters with 1.3m cells representing intensification over time (no change and extensification = 0; intensification = 1) or extensification over time (no change and intensification = 0; extensification = 1). We created rasters for spatial covariates using a 30m SRTM digital elevation model to calculate slope as percent rise and path distance from the market town. We also calculated Euclidean distance from sites where ADHENO carries out ecological restoration projects to control for any spillover from these sites. To match the resolution of covariate rasters, we aggregated land-use change rasters to two 30m rasters, where cells represented the presence of intensification (1 = any intensification within a 30m zone; 0 = no intensification) and extensification (1 = any extensification within a 30m zone; 0 = no extensification).

Village-level survey variable preparation

We aggregated information from household surveys to the village level for independent variables. The primary variable of interest was participation in farmer trainings, which we calculated as a proportion of surveyed households within a village that participated in any trainings. For covariates, we calculated the proportion of surveyed households that participated in ADHENO ecological restoration programs, and averages for village income, land holdings, and level of education. The number of households in each village was obtained from census sheets held by local agricultural extension agents, and was included as a covariate.

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[37] Liang, J., Reynolds, T., Wassie, A., Collins, C., & Wubalem, A. (2016). Effects of exotic Eucalyptus spp. plantations on soil properties in and around sacred natural sites in the northern Ethiopian Highlands. *AIMS Agriculture and Food*, *1*(2), 175–193. https://doi.org/10.3934/agrfood.2016.2.175

[38] Delelegn, Y. T., Purahong, W., Blazevic, A., Yitaferu, B., Wubet, T., Göransson, H., & Godbold, D. L. (2017). Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-14128-y

[39] Yimer, F., Ledin, S., & Abdelkadir, A. (2007). Changes in soil organic carbon and total nitrogen contents in three adjacent land use types in the Bale Mountains, south-eastern highlands of Ethiopia. *Forest Ecology and Management*, *242*(2–3), 337–342. https://doi.org/10.1016/j.foreco.2007.01.087

[40] Delelegn, Y. T., Purahong, W., Blazevic, A., Yitaferu, B., Wubet, T., Göransson, H., & Godbold, D. L. (2017). Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-14128-y

[41] Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., ... & George, P. (2001). The causes of land-use and land-cover change: moving beyond the myths. *Global environmental change*, *11*(4), 261-269.

To make these variables spatially explicit, we recorded coordinates for all surveyed villages (n = 37) using Google Earth, through consultation with ADHENO field staff. We then generated Thiessen polygons from village coordinates, and joined the survey and census data with all pixels within these polygons. The result was a dataset that associated demographic and spatial variables with each land-use intensity datapoint.

Modeling land-use intensity changes

We used RStudio Version 1.1.442 to conduct statistical analysis. To determine whether farmer trainings predicted any landscape-level trends in land-use change, we used linear models to test whether there was a significant linear relationship between farmer trainings and rate of land-use change at the village level. To avoid undersampling bias, we filtered out villages for which we had surveyed fewer than 15% of households, leaving 28 villages for the analysis. We calculated the percent of village area that intensified and extensified over time, using the 1.3m land-use change raster. We then fit a linear model to the data, using farmer training participation as the independent variable. We controlled for number of households, average slope, distance to the town, education, income, land holdings, and participation in the ADHENO ecological restoration program.

To determine the role of farmer trainings in predicting land-use change at the pixel level, we built two logit models. The first model predicted the presence of intensification and the second predicted the presence of land-use extensification within a 30m zone. For each model, land-use was the dependent variable, and rate of village participation in farmer trainings as the primary independent variable. We also included the aforementioned geographic and demographic variables as covariates. The covariate for slope was not normally distributed; thus, we performed a square root transformation to create a normal distribution. We included village as a fixed effect to account for any omitted variables that might influence land-use intensity, and to account for the hierarchical data structure. We performed Monte-Carlo (MC) simulations of spatial autocorrelation utilizing the Global Moran's I statistic and found a high degree of spatial autocorrelation for land-use intensity (intensification: 999 MC simulations, p-value = 0.001; extensification: 999 MC simulations, p-value = 0.001). To control for this spatial autocorrelation, we clustered standard errors from each logit model at the village level.

Descriptive results

Total area and participation in farmer trainings varied significantly between villages. On average, 63.38% of village area land-use remained the same over time (n = 28, sd = 6.72; Figure B-1). In contrast, the average rate of land-use intensification was 14.47% (n = 28, sd = 6.98; Figure B-1), and the average rate of extensification was 21.85% (n = 28, sd = 7.94; Figure B-1). Meanwhile, participation in farmer trainings was high, with an average of 70% participation across villages, though there was substantial variation between villages (n = 28, sd = 18.56; Figure B-1).

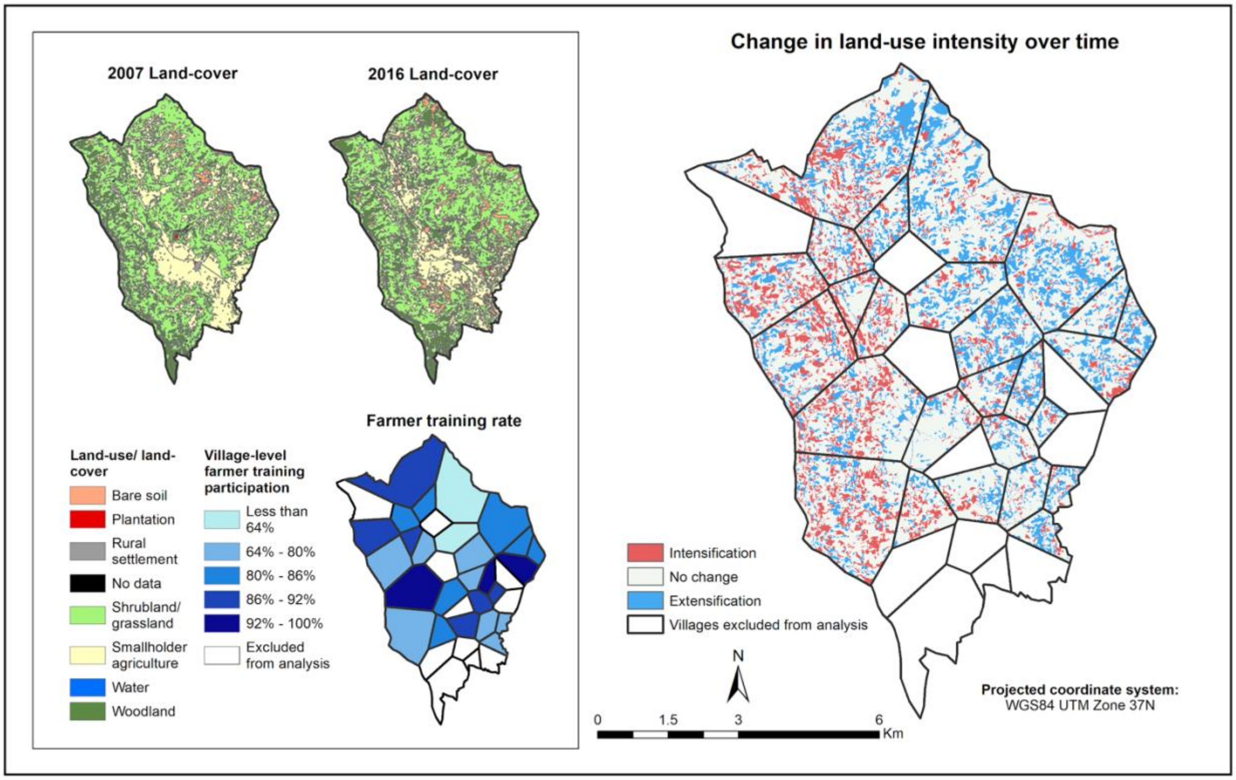

Figure B-1. Classified land-use/land-cover for 2007 and 2016, participation rate in farmer trainings, and change in land-use intensity over time in Goshebado Kebele. Land-cover classification was based on KOMPSAT-2 imagery from November 2007 and WorldView-2 imagery from December 2016. Village boundaries were interpolated with Thiessen polygons from village centerpoints. Villages were excluded from analysis if fewer than 15% of households were surveyed.

Predictors of land-use change at the village-level

We tested fixed-effects linear models to determine the role of farmer trainings and other covariates in predicting trends in land-use change across villages. Linear models were first tested with variance inflation factors to remove any collinear variables, and Shapiro-Wilks tests were performed on model residuals to test the assumption of homoscedasticity (intensification: $p = 0.52$; intensification: $p = 0.08$). Linear models of intensification and extensification rates indicated that participation in farmer trainings was not significantly associated with rate of land-use change at the village level (intensification: $p = 0.89$; extensification: $p = 0.14$). However, land-use change was significantly predicted by other variables in the model (intensification: $R^2 = 0.680$; extensification: $R^2 = 0.554$; Table B-2). Land-use intensification was positively predicted by slope, such that each percent increase in slope predicted a 0.46% increase in intensification ($p = 0.001$). Land-use extensification was positively predicted by average land holdings and distance from ecological restoration sites, such that each additional hectare owned predicted an additional 2.74% land-use extensification ($p = 0.049$), and each meter of distance from ecological restoration sites predicted an additional 0.002% of land-use extensification ($p = 0.03$).

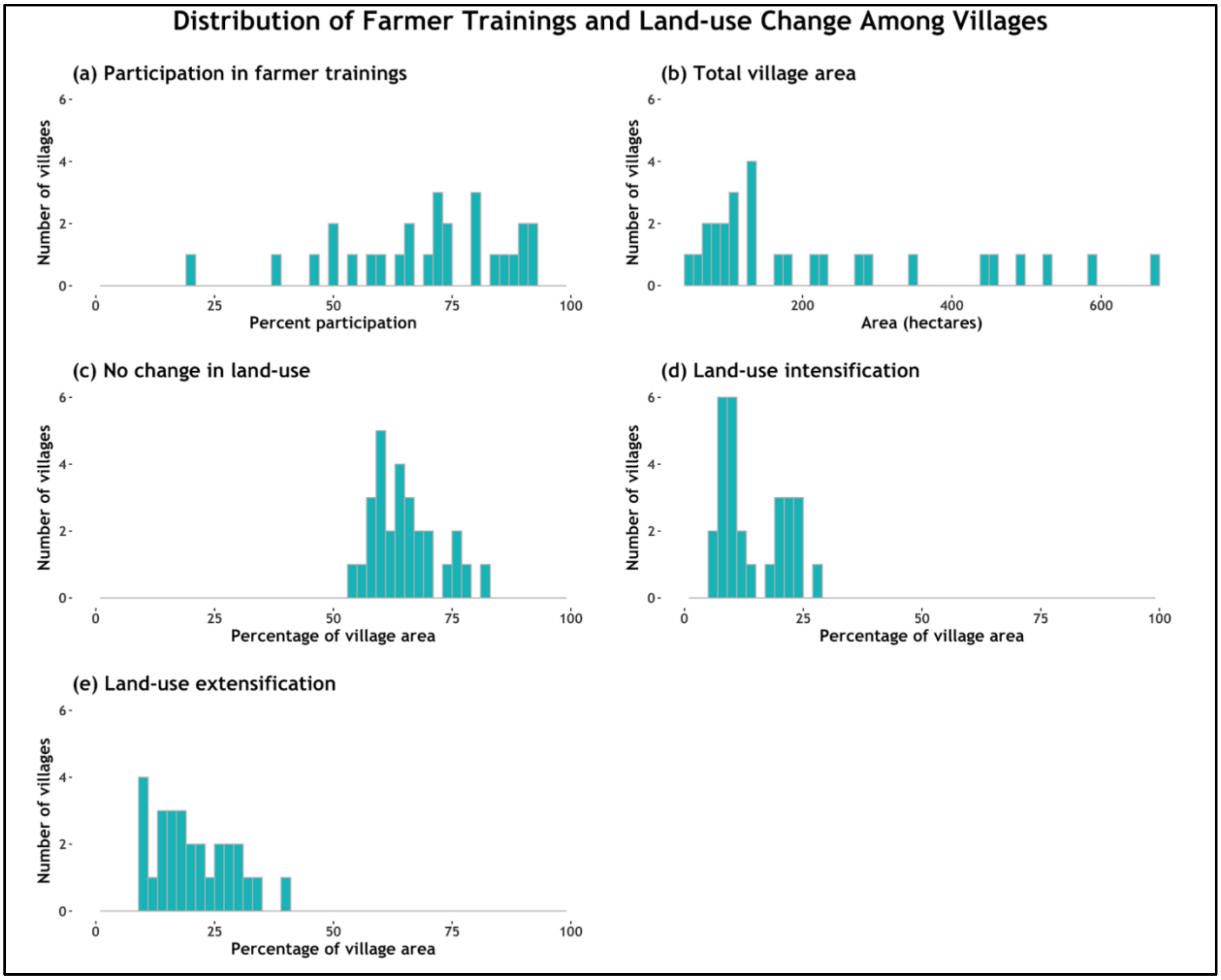

Figure B-2. Distribution of participation in farmer trainings (a), total area (b), and land-use change dynamics (c, d, e) among villages.

Table B-2. Linear model results of land-use change at the village level. Beta coefficients are reported with significance levels, and standard errors in parentheses. Land-use intensification rate is positively predicted by increasing slope at the village level, while land-use extensification is positively predicted by land-holdings and distance from ecological restoration sites.

	Dependent Variable	
	Rate of Intensification	Rate of Extensification
Participation in farmer trainings	-0.009 (0.063)	-0.131 (0.087)
Participation in ecological restoration program	-0.029 (0.168)	0.385 (0.230)
Average land holdings	-1.488 (0.950)	**2.73*** **(1.305)**
Average income	0.000 (0.000)	0.000 (0.000)
Average education	4.218 (3.376)	-0.654 (4.636)
Number of households	0.067 (0.072)	-0.095 (0.098)
Slope	**0.463**** **(0.120)**	-0.073 (0.164)
Distance from town	-0.007 (0.004)	0.004 (0.006)
Distance from ecological restoration sites	-0.029 (0.168)	**0.003*** **(0.001)**
Constant	10.912 (9.521)	0.657 (13.074)
Observations	28	28
R^2	0.680	0.554
Adjusted R^2	0.520	0.332
Residual Std. Error (df = 18)	4.762	6.538
F Statistic (df = 9; 18)	4.243	2.488
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001		

Predictors of land-use change at the pixel level

Following an analysis of land-use trends at the village level, we tested fixed effects logit models to predict land-use change at the pixel level, and clustered standard errors at the village level to account for spatial autocorrelation. We found no relationship between farmer trainings and land-use extensification ($p = 0.414$). We found that farmer trainings significantly predicted land-use intensification ($p = 0.012$). We built a second model to predict land-use intensification without farmer trainings to compare Aikike Information Criteria (AIC) to determine whether model fit was stronger with or without farmer trainings. We found that model fit was equivalent between the two models (AIC = 87162 for both), indicating that farmer trainings do not contribute meaningfully to a predictive model of land-use intensification. Several model covariates were significantly predictive of land-use intensification (Table B-3). We tested models with these variables removed on an individual basis, and found higher AIC for models without distance from the town (AIC = 87596), distance from ecological restoration sites (AIC = 87272), and slope (AIC = 87242), indicating that these variables all play a role in model fit. Increasing slope and distance from ecological restoration sites marginally decrease the odds of intensification, while increased distance from the town marginally increases the odds of intensification.

Table B-3. Logit Model results. Odds ratios are reported with significance levels. Intensification model 1 includes participation in farmer trainings (AIC = 87162), while Intensification model 2 does not include farmer trainings (AIC = 87162).

	Logit model odds ratios		
	Intensification (1)	Intensification (2)	Extensification
Participation in farmer trainings	**1.063***		0.95
Participation in ecological restoration program	0.993	**1.122***	1.01
Average land holdings	**8.776*****	**63.465****	0.30
Average income	1.000	**0.999***	**1.00*****
Average education	0.044	**23.656*****	1797.23
Number of households	**1.081***	**1.041***	0.90
Slope	**0.846*****	**0.846*****	1.03
Distance from town	**1.001*****	**1.001*****	1.00
Distance from ecological restoration sites	**0.999***	**1.000***	1.00
Constant	0.000***	0.000	18251.45
Observations	65527	65527	65527
AIC	87162	87162	83781
Note: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001			

Appendix C. Ecological Sampling Methods and Results

Study area

Goshebado kebele is situated at the eastern edge of Ethiopian highlands, approximately 120 km north-east from Addis Ababa, at 9˚45'10.05"N, 39˚27'3.09"E. The annual precipitation, interpolated from a nearby weather station in Debre Berhan, averages approximately 900 mm and is split between one short rainy season (March to May), a long rainy season (June to September), and a long dry season (October to February).[42] The altitude ranges from 1964 m to 2827 m and the mean annual precipitation is over 900 mm, placing the area within the moist Wenya Dega and Dega agroclimatic zones.[43]

Study and control site selection

There are five area closures in Goshebado, ranging in size from 0.13 ha to 5.14 ha. For the purpose of this study, we selected the three area closures that were larger than one hectare and were established over three years ago. These area closures included Saint Emmanuel (5.1 ha), Berkumas (3.75 ha), and Ater Meda (2.9 ha), established in 2003, 2007, and 2013, respectively. Livestock grazing and biomass extraction are forbidden inside area closures. Vegetation structure is heterogeneous throughout area closures due to the patchy nature of pre-existing vegetation and ADHENO plantation activities. All three area closures were targets for ADHENO plantation activities. The planted species consisted both indigenous and exotic species, including *Acacia abyssinica*, *Acacia saligna*, *Cordia africana*, *Cupressus lusitania*, *Dovyalis abyssinica*, *Eucalyptus globulus*, *Grevillea robusta*, *Hagenia abyssinica*, *Juniperus procera*, *Olea africana*, *Podocarpus falcatus*, and *Sesbania sesban*.

To determine the restorative effect of area closures and plantation activities, we conducted systematic vegetation sampling in area closures, and in control areas outside each area closure. To determine control areas for vegetation sampling, we ascertained land-use in each area closure prior to its establishment from ADHENO field staff. We then constructed a 150 m buffer around each area closure, and selected areas within these buffers in which land-use most closely matched the original state of area closures, hereafter referred to as control areas.

Plot sampling

We collected vegetation data using a systematic plot sampling method, with 10 x 10 meter plots used to record species and measure the diameter at breast height (DBH) of adult trees (≥ 2 cm DBH or ≥ 2 m of height). One 5 x 5 meter subplot was constructed in a random corner of each 10 x 10 meter plot to measure sapling DBH (≤ 2 cm DBH), and record species of saplings, shrubs, herbs, and succulents with height greater than 15 cm. The number of animal trails, the number of stumps and trees with stumps were recorded within each 10 meter plot. These plot sizes were selected given the dense vegetation structure and steep topography of area

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[42] Bewket, W., & Conway, D. (2007). A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia, *1477*(May), 1467–1477. https://doi.org/10.1002/joc

[43] Bekele-Tesemma, A. (1993). *Useful Trees and Shrubs for Ethiopia*. Nairobi, Kenya: Regional Soil Conservation Unit, Swedish International Development Authority.

closures, which presented challenges to constructing larger plots. Plots were constructed along transects at 25 m intervals. Transects began near the edge of area closures or control areas to maximize the length of the transect. Due to the steepness of the survey areas, transect direction was set along the topographic contour. For each area closure or control area, additional transects were established parallel to the first, at a distance of 25 m.

A total of 121 sample plots were surveyed, with 61 plots inside area closures and 60 within control areas. The number of plots constructed at each area closure and control area was decided such that each plot was representative of 0.2 hectares. Plants were identified to the species level by the National Herbarium of Ethiopia at Addis Ababa University. Specimens that could not be determined to the species level were identified to the family level. All species were categorized into corresponding plant forms, including adult trees, saplings, shrubs, herbs, and succulent plants.

Vegetation composition calculation

Species abundance, species density, species richness, species diversity, and species evenness were parameters used to assess the differences of vegetation composition between area closures and control areas. Species abundance was the number of individual plants surveyed in a plot. Species density was derived by extrapolating the number of individuals based on the plot sizes (100 m^2 or 25 m^2) to a hectare. Species richness (S) represented the total number of unique species sampled in a plot. Shannon diversity index (H) was utilized to examine species diversity because it weighs more on the changes of rare species, several of which were identified in the sampling. Shannon evenness (E) was also used to disentangle its contribution to diversity since two components (richness and evenness) were embedded in Shannon diversity index. Both Shannon diversity and Shannon evenness indices were computed at the plot level.

Vegetation structure calculation

After segregating vegetation data according to plant forms, these structural categories were used to examine plot-level vegetation structure for area closures and control areas. The abundance of each plant form was estimated by extending the amount of surveyed individuals from the plot sizes (100 m^2 or 25 m^2) to a hectare. Shannon diversity index was applied to each plant category at the plot level. Three parameters were adopted to assess the characteristics of different structural categories. The basal area of adult trees was calculated as a percentage of plot area dedicated to tree biomass, based on summing the area of all trees at breast height (π*(DBH/2)^2 per 100 m^2 plot) and extrapolated to m^2 per hectare. Sapling height was averaged within each 5 x 5 m plot and the mean height of all shrubs, herbs, and succulent plants in each 5 x 5 m plot was described as understory height.

Plantation species and understory abundance calculation

Five main planted species were used to analyze their impacts on the understory abundance. The plantation species included *Cupressus lusitanica*, *Juniperus procera*, *Eucalyptus globulus*, *Acacia saligna*, and *Acacia abyssinica*. Understory abundance represented the total number of individuals of shrub, herb, and succulent categories. A linear regression was utilized to examine the association between the number of each adult planted species and the understory abundance at the plot level.

Terrain features extraction

Terrain features of each plot, including slope, elevation, aspect, wetness, solar radiation, and distance to roads, were extracted from a 30 m SRTM digital elevation model by the ArcGIS Desktop 10.5. A multiple linear regression was used to assess the influence of terrain features and area closure establishment on vegetation composition comprising species abundance, richness, evenness, and diversity.

Human and livestock impact calculation

The number of stumps was transformed into the proportion of trees that were cut down in each plot in area closures. A multiple linear regression was utilized to evaluate the impact of the proportion of tree-cutting and the number of animal trails on vegetation composition including species abundance, richness, evenness, and diversity in area closures.

Statistical analysis

A t-test was used to detect the differences of all parameters between area closures and control areas. The assumption of normality was released due to the large sample size (> 30) and the resampling method was utilized when sample size was small. Data not conforming to equal variance were designated to Welch's t-test. A multiple linear mixed-effects model was conducted to evaluate the influence of terrain features, area closure establishment, and trail and stump occurrence on species abundance, richness, diversity, and evenness. The number of trails and stumps in area closures, presence within area closures or control areas (binary factor), and terrain features were considered as the independent variables. The models were run separately for each species abundance, richness, diversity, and evenness as the dependent variables. Area closure site was included as a random effect to account for the similarity between plots in each area closure due to the short distance between plots. The generalized linear mixed-effects model (GLM) was analyzed when residual homoscedasticity and normality were not conformed. The family of GLM was determined based on the distribution of data. RStudio 1.1.442 was used for all statistical analyses. The significance level of 0.05 was adopted in all the analysis interpretation.

Descriptive results

The site conditions of control areas include farm lands, grazing pastures, and *Eucalyptus globulus* woodlots. A total of 77 unique species were identified out of 7,693 vegetation samples (Table C-1). A multitude of species are considered as rare species due to few individuals sampled. 43 species in area closures were sampled below 20 individuals out of total 5,576 individuals (Figures C-1, C-2). 27 species in control areas were sampled below 10 individuals out of 2,117 individuals. 15 out of these 43 and 27 species are common species between area closures and control areas. More species exist in area closures, but 6 species were found only in control areas.

Table C-1. Species richness (the total number of unique species) in each area closure and control area, and the number of common species shared in both areas.

	Area closure	Control Area	Common species
Saint Emmanuel	44	27	23
Berkumas	48	35	28
Ater Meda	39	20	14
Total (77)	71	46	40

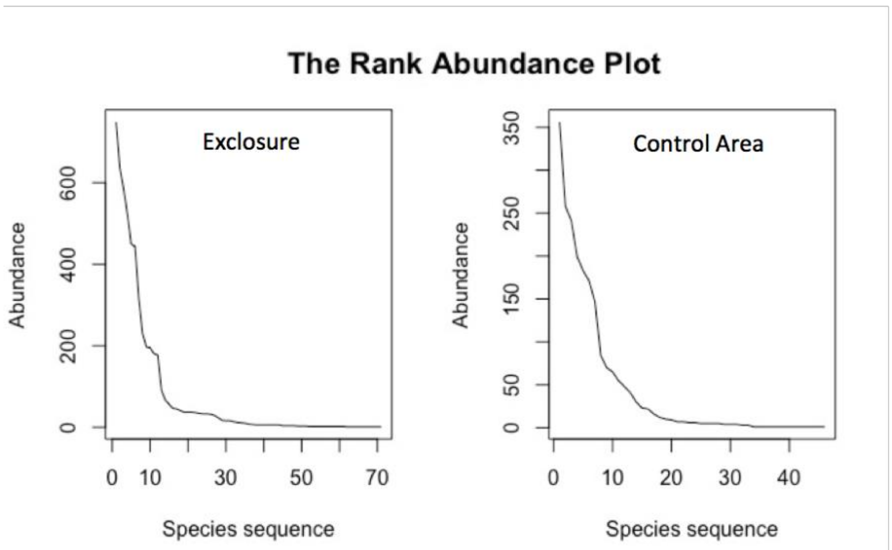

Figure C-1. The rank abundance plot shows the sequence of dominant species to rare species sampled in both area closures and control areas.

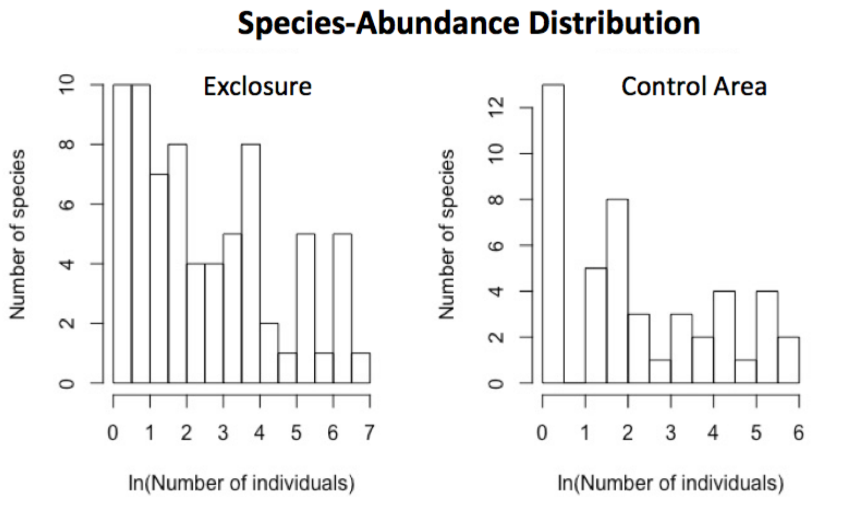

Figure C-2. The species-abundance distribution shows the number of species in each abundance category in both area closures and control areas.

Vegetation composition

Species abundance, species density, species richness, and species diversity are significantly higher in area closures than in control areas while species evenness is not (Tables C-2 and C-3). Separated by study sites, all above variables are also significantly higher in area closures compared to control areas of each site except for species diversity in Saint Emmanuel. Slope and aspect have significant positive and negative influence, respectively, on species abundance (Table C-4). Solar radiation is significantly associated with lower species richness and diversity. The factor of area closure has highly significant positive contribution to species abundance, richness, and diversity. However, species evenness is not affected by all terrain features and the factor of area closure. Additionally, elevation, wetness, and distance to roads are not statistically associated with vegetation composition.

Table C-2. T-test results for the comparison of species abundance (the number of individuals/plot) and density (stems/ha) between area closures and control areas.

Species abundance									
	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*
Saint Emmanuel	79.42	8.01	26	32.88	6.72	24	25.36 - 67.74 ***	4.42	48
Berkumas	100.25	10.55	16	36.9	7.07	20	38.36 - 88.34 ***	5.15	34
Ater Meda	100.37	11.17	19	36.88	7.57	16	34.94 - 92.05 ***	4.52	33
Total	91.41	5.67	61	35.28	4.04	60	42.33 - 69.93 ***	8.06	108.14
Species density									
	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*
Saint Emmanuel	25158	3728	26	10813	2360	24	5439.7 - 23250.68 **	3.25	41.76
Berkumas	36444	9111	16	13875	3103	20	13187.38 - 31950.12 ***	4.89	34
Ater Meda	34479	4370	19	31021	2397	16	8566.91 - 31003.48 **	3.59	33
Total	31021	2397	61	12868	1504	60	12539.96 - 23765.99 ***	6.42	100.68

Note: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$

Table C-3. T-test results for the comparison of species richness (the number of unique species/plot), diversity (Shannon-Weiner diversity index), and evenness (Shannon evenness index) between area closures and control areas.

	Area closure			Control area			95% CI for Mean Difference	*t*	*df*
Species richness									
	M	SE	n	M	SE	n		*t*	*df*
Saint Emmanuel	9.04	0.9	26	5.38	0.78	24	1.25 - 6.08 **	3.05	48
Berkumas	15	0.98	16	7.1	0.95	20	5.1 - 10.71 ***	5.72	34
Ater Meda	12.47	0.67	19	4.13	0.82	16	6.22 - 10.47 ***	8	33
Total	11.67	0.59	61	5.62	0.51	60	4.51 - 7.61 ***	7.74	119
Species diversity									
	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*
Saint Emmanuel	1.46	0.14	26	1.22	0.12	22	-0.14 - 0.61	1.26	46
Berkumas	2.12	0.08	16	1.31	0.14	20	0.49 - 1.14 ***	5.12	30.64
Ater Meda	1.89	0.06	19	0.84	0.14	15	0.74 - 1.37 ***	6.94	19.53

Total	1.77	0.07	61	1.15	0.08	57	0.4 - 0.83 ***	5.72	116
				Species evenness					
	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*
Saint Emmanuel	0.86	0.14	26	0.84	0.07	22	-0.29 - 0.34	0.14	37.09
Berkumas	0.8	0.03	16	0.82	0.13	20	-0.31 - 0.26	-0.17	19.9
Ater Meda	0.77	0.04	19	0.64	0.1	15	-0.11 - 0.36	1.1	15.93
Total	0.83	0.06	61	0.88	0.09	57	-0.26 - 0.16	-0.47	99.46
Note: * *P* ≤ 0.05, ** *P* ≤ 0.01, *** *P* ≤ 0.001									

Table C-4. Multiple linear mixed-effects regression results for the influence of terrain features and plantation on species abundance (the number of individuals/plot), richness (the number of unique species/plot), evenness (Shannon evenness index), and diversity (Shannon-Weiner diversity index). Species evenness results are shown in multiple generalized linear mixed-effects regression with Gamma family inverse link.

		Abundance		
	Coefficient	***SE***	***t***	***P***
Slope	1.4230	0.6673	2.132611	0.0352*

Elevation	0.1940	0.1397	1.389330	0.1675
Aspect	-0.1043	0.0392	-2.658611	0.0090**
Wetness	-5.5834	3.2887	-1.697772	0.0924
Solar radiation	< 0.001	0.0003	0.101152	0.9196
Distance to roads	0.1021	0.1240	0.823290	0.4121
Area closure	65.2931	7.4634	8.748388	< 0.001***

	Richness			
	Coefficient	***SE***	***t***	***P***
Slope	0.115830	0.07131	1.624330	0.1071
Elevation	0.003036	0.01243	0.244353	0.8074
Aspect	-0.002367	0.00416	-0.568271	0.5710
Wetness	0.008853	0.35225	0.025133	0.9800
Solar radiation	-0.000069	0.00003	-2.427411	0.0168*
Distance to roads	0.004777	0.01035	0.461543	0.6453
Area closure	6.796421	0.82336	8.254467	< 0.001***

Evenness

	Coefficient	***SE***	***t***	***P***
Slope	-0.012521	0.012782	-0.9795567	0.3295
Elevation	-0.001765	0.002327	-0.7581756	0.45
Aspect	-0.000541	0.000884	-0.6123297	0.5416
Wetness	0.014752	0.069251	0.2130194	0.8317
Solar radiation	0.000006	0.000005	1.0664364	0.2886
Distance to roads	0.002808	0.002082	1.3485020	0.1804
Area closure	-0.021243	0.153778	-0.1381427	0.8904

Diversity

	Coefficient	***SE***	***t***	***P***
Slope	0.010426	0.010061	1.036311	0.3024
Elevation	-0.000977	0.001806	-0.541214	0.5895

Aspect	-0.000416	0.000589	-0.705683	0.4819
Wetness	0.024225	0.048649	0.497954	0.6195
Solar radiation	-0.000012	0.000004	-3.110123	0.0024**
Distance to roads	-0.001534	0.001444	-1.062470	0.2904
Area closure	0.695492	0.114905	6.052773	< 0.001***
Note: * P ≤ 0.05, ** P ≤ 0.01, ***, P ≤ 0.001				

Vegetation structure
The number of plant individuals of each plant form are higher in area closures than in control areas (Figure C-3). All plant forms except herbs have statistically significant higher abundance in area closures compared to control areas. Both area closures and control areas contain high abundance of understory plants (the aggregation of shrubs, herbs, and succulents) compared to trees (saplings and adults) (Figure C-4). Excluded *Eucalyptus globulus* which has narrow canopy and high water-consumption rate, saplings have higher abundance than adult trees. In addition, species diversity of each plant form are average higher in area closures except herbs (Table C-5). The characteristics of different plant categories, including basal areas of adult trees, sapling heights, and understory heights, are average higher in area closures compared to control areas (Table C-6). Separated by study site, all variables above, except basal areas in Berkumas and Ater Meda, are significantly higher in area closures than control areas of each site.

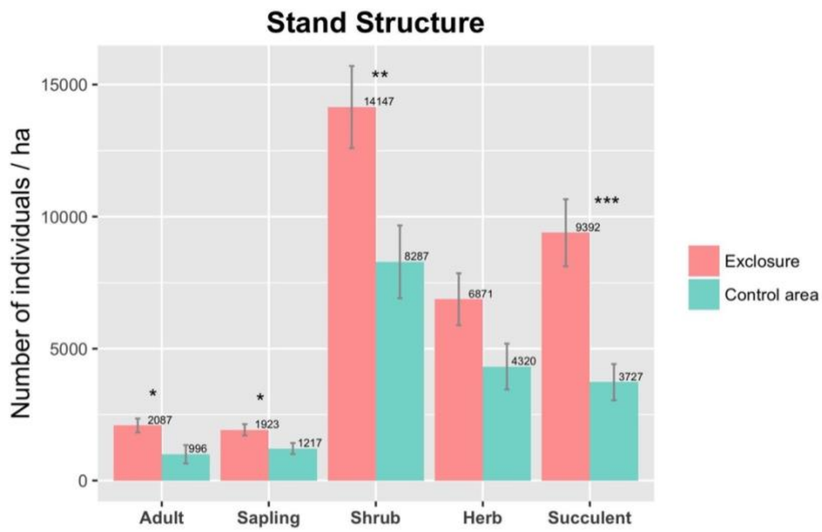

Figure C-3. The stand structure shows the comparison of the abundance of each plant form (the number of individuals/ha) between area closures and control areas.

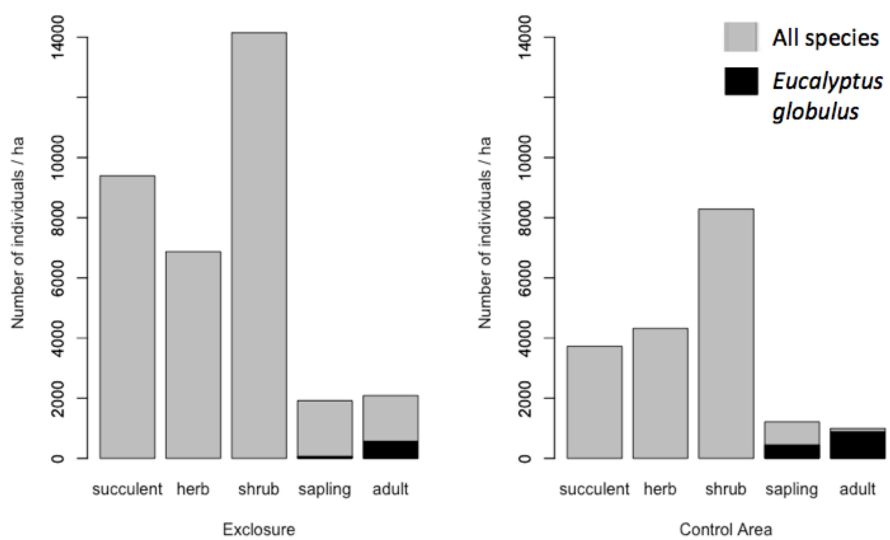

Figure C-4. The graph shows the number of individuals in each plant form and the proportion of Eucalyptus globulus in saplings and adult trees in both area closures and control areas.

Table C-5. T-test results comparing species diversity (Shannon-Weiner diversity index) for vegetation structure levels between area closures and control areas. The structure category of trees includes adult trees and saplings.

Species diversity									
	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*
Tree	0.83	0.07	59	0.22	0.06	32	0.43 - 0.78 ***	6.77	88.23
Adult tree	0.73	0.07	54	0.12	0.05	25	0.43 - 0.78 ***	7.03	76.99
Sapling	0.39	0.07	52	0.13	0.06	24	0.09 - 0.43 ***	3.01	70.57
Shrub	1.06	0.07	57	0.72	0.08	46	0.12 - 0.55 **	3.11	101
Herb	0.53	0.05	56	0.44	0.07	40	-0.08 - 0.26	1.01	94
Succulent	0.43	0.04	52	0.22	0.05	44	0.1 - 0.34 ***	3.6	94

Note: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$

Table C-6. T-test results for the comparison of basal area of adult trees (m^2/ha), sapling height (cm), and understory height (cm) between area closures and control areas.

Basal area									
	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*

Saint Emmanuel	0.0502	0.0015	573	0.0283	0.0015	186	0.0178 - 0.026 ***	10.5	577.38
Berkumas	0.0428	0.0002	191	0.0381	0.0004	59	-0.0042 - 0.0137	1.04	248
Ater Meda	0.0324	0.0013	350	0.0466	0.0037	2	-0.0391 - 0.021	-0.83	350
Total	0.0433	0.001	1114	0.0308	0.0014	247	0.0009 - 0.016 ***	7.22	503.53

Sapling height

	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*
Saint Emmanuel	98.96	4.6	119	57.19	7.88	36	23.15 - 60.39 ***	4.43	153
Berkumas	100.53	10.3	32	54.69	6.05	29	21.84 - 69.85 ***	5.12	30.64
Ater Meda	104.77	5.86	91	51.14	8.87	7	30.51 - 76.74 ***	5.05	12.22
Total	101.35	3.43	242	55.6	4.67	72	34.31 - 57.2 ***	7.9	154.82

Understory height

	Area closure			Control area			95% CI		

	M	SE	n	M	SE	n	for Mean Difference	*t*	*df*
Saint Emmanuel	47.52	0.89	1252	37.34	0.96	542	7.61 - 12.75 ***	7.76	1425.4
Berkumas	59.17	1.17	1374	52.94	1.32	650	2.79 - 9.69 ***	3.55	1599.2
Ater Meda	48.92	0.95	1455	43.03	0.18	580	2.93 - 8.86 ***	3.9	1342.3
Total	51.94	0.59	4081	44.92	0.7	1772	5.22 - 8.82 ***	7.65	4249.5

Note: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$

Impact of Planted Species

The number of introduced species, *Eucalyptus globulus* and *Cupressus lusitanica,* have a highly significant negative association with understory abundance (Table C-7). The indigenous and important soil-conserving species, *Acacia abyssinica*, is significantly associated with higher understory abundance. Although *Acacia saligna* and *Juniperus procera* have positive contribution to understory abundance, the impact is not statistically significant.

Table C-7. Generalized linear regression (GLM) and linear regression results for the influence of the number of adult plantation species on understory species abundance. The results for Eucalyptus globulus and Cupressus lusitanica are shown in GLM with Poisson family log link.

		Coefficient	***SE***	***z***	***P***	**Function**
Eucalyptus globulus	Introduced	-0.014341	0.001772	-8.093	< 0.001***	
Cupressus lusitanica	Introduced	-0.043775	0.002663	-16.44	< 0.001***	
		Coefficient	***SE***	***t***	***P***	
Juniperus procera	Indigenous	3.0484	3.8416	0.7935	0.4479	
Acacia saligna	Introduced	1.679	5.460	0.308	0.7637	Soil conservation
Acacia abyssinica	Indigenous	23.504	10.117	2.3232	0.03463*	Soil conservation
Note: * *P* ≤ 0.05, ** *P* ≤ 0.01, ***, *P* ≤ 0.001						

Human and livestock impacts

There are total 309 and 81 stumps counted in area closures and control areas, respectively. The stumps comprise 15 species in area closures and 4 species in control areas, where the 4 species are common species in both area closures and control areas. *Allophylus abyssinicus (Hochst.) Radlk* and *Croton macrostachyus Del.* have over 20 stumps on one tree. The latter species has one old tree in control areas contains 119 counted stumps itself. Lower proportion of stumps are cut down in the area closures compared to control areas (Table C-8), which are statistically significant in Saint Emmanuel, Berkumas, and the combination of all study sites. Tree saplings are cut down only in control areas. There are higher proportion of adult trees cut down in *Eucalyptus globulus* plantation areas in area closures and farm lands and pastures in control areas. However, *Eucalyptus globulus* woodlots in control areas, where most DBH of trees are small, have relatively lower proportion of tree-cutting. The number of animal trails has moderately significant positive influence on species abundance and the number of stumps has moderately significant negative effect on species diversity (Table C-9).

Table C-8. T-test results for the comparison of stumps (the proportion of stumps among trees/plot) between area closures and control areas.

	Stumps								
	Area closure			Control area			95% CI for Mean Difference		
	M	SE	n	M	SE	n		*t*	*df*
Saint Emmanuel	0.11	0.05	25	0.33	0.08	14	-0.39 - -0.09 *	-2.49	37
Berkumas	0.28	0.06	15	0.47	0.1	17	-0.44 - 0.06	-1.59	25.24
Ater Meda	0.3	0.08	16	0.78	0.09	8	-0.75 - -0.22 ***	-3.82	25
Total	0.21	0.04	59	0.48	0.06	39	-0.41 - -0.13 ***	-3.79	63.23

Note: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$

Table C-9. Multiple linear and generalized linear mixed-effects regression results for the influence of the number of livestock trails and stumps on species abundance, richness, evenness, and diversity. The results for species richness are shown with Poisson family log link and the results for species evenness are shown with Gamma family inverse link.

Abundance				
	Coefficient	***SE***	***t***	***P***
Trail	0.095353	0.04281663	2.227013	0.03*
Stump	0.005025	0.00437741	1.147908	0.2559

Richness

	Coefficient	SE	t	P
Trail	0.583991	0.3738249	1.562205	0.1239
Stump	-0.013295	0.0397561	-0.334420	0.7393

Evenness

	Coefficient	SE	t	P
Trail	-0.0029861	0.06493621	-0.045985	0.9635
Stump	0.0153363	0.00993718	1.543329	0.1284

Diversity

	Coefficient	SE	t	P
Trail	0.0387142	0.04638661	0.8346	0.4075
Stump	-0.0102746	0.00493174	-2.083355	0.0418*

Note: * P ≤ 0.05, ** P ≤ 0.01, ***, P ≤ 0.001

Appendix D. Inventory of Floral Species in Area Closures

Table D-1. Inventory of all unique floral species found in the three sampled area closures (Ater Meda, Berkumas, and Saint Emmanuel Church).

	Species	Family Name	Local Name	Size	Status	Uses	Soil conserving properties
1	Dodonaea angustifolia L.f.	Sapindaceae	Kitkita	Shrub/Tree	Indigenous	Medicinal Plant: Wound dressing, febrifuge, sore throat	Soil conservation - stabilize moving sand and prevent erosion
2	Aloe debrana Christian	Aloaceae	Ret	Succulent herb	Endemic		Soil conservation
3	Clutia abyssinica Jaub. & Spach.	Euphorbiaceae	Fiyele fej	Shrub		Medicinal Plant: Hemorrhage, cancer	
4	Allophylus abyssinicus (Hochst.) Radlk.	Sapindaceae	Embus	Tree	Indigenous	Medicinal Plant: Anthelmintic, venereal diseases	
5	Aloe pulcherrima Gilbert & Sebsebe	Aloaceae	Sette Ret	Succulent perennial herb	Endemic	Medicinal Plant	Soil conservation
6	Rhus vulgaris Meikle	Anacardiaceae		Shrub/Tree	Indigenous		
7	Lippia adoensis Hochst. ex Walp.	Verbenaceae	Kassi	Shrub	near endemic	Condiment in wot and butter	
8	Conyza sp.	Asteraceae	Atis nadid	Herb			
9	Dovyalis verrucosa (Hochst.) Warb.	Flacourtiaceae	Koshim	Shrub/Tree	Indigenous		
10	Unidentified	Unidentified		Shrub			
11	Laggera tomentosa (Sch. Bip. ex A. Rich.) Olivo & Hiern	Asteraceae		Shrub			
12	Eucalyptus globulus Labill	Myrtaceae	Nech bahir zaf	Tree	Introduced	Medicinal Plant: Febrifuge, common cold, headache, coughs	
13	Grevillea robusta R. Br.	Proteaceae		Tree	Introduced		Soil conservation

14	Bidens sp.	Asteraceae		Herb			
15	Cupressus lusitanica Mill.	Cupressaceae	Yaferenji Sid	Tree	Introduced		Mexican cypress gives only limited protection against soil erosion. Pure stands on slopes or erosion-prone sites should be underplanted with other suitable species.
16	Juniperus procera Hochst. ex Endl.	Cuperssaceae		Tree	Indigenous		
17	Vernonia amygdalina Del.	Asteraceae		Shrub/Tree	Indigenous		Soil conservation
18	Pterolobium stellatum (Forssk.) Brenan	Fabaceae		Shrub			
19	Dovyalis abyssinica (A. Rich.) Warb.	Flacourtiaceae	Koshim	Shrub/Tree	Indigenous		
20	Erythrina brucei Schwein.	Fabaceae	Korch	Tree	Indigenous	Medicinal Plant: Elephantiasis	Soil conservation
21	Conyza stricta Willd.	Asteraceae		Herb			
22	Unidentified	Unidentified		Shrub			
23	Plectranthus sp.	Lamiaceae	Doach'at	Succulent herb			
24	Rumex nervosus Vahl	Polygonaceae	Embacho	Shrub		Medicinal Plant; Condiment in butter	
25	Unidentified	Unidentified		Shrub			
26	Maytenus arbutifolia (A. Rich.) Wilczek	Celasteraceae		Shrub/Tree	Indigenous		
27	Solanum anguivi Lam.	Solanaceae		Shrub			
28	Colutea abyssinica Kunth & Bouche	Fabaceae		Shrub		Medicinal Plant: Cancer	
29	Helichrysum schimperi (Sch. Bip. ex A. Rich.) Moeser	Asteraceae		Herb			
30	Jasminum grandiflorum L.subsp. floribundum (R.Br. ex Fresen.) P.S.	Oleaceae		Climbing Shrub		Medicinal Plant: Hemorrhoids,	

	Green					conjunctivitis	
31	Rosa abyssinica Lindley	Rosaceae	Kega	Shrub/Tree	Indigenous	Medicinal Plant: Anthelmintic	
32	Anthospermum herbaceum L.f.	Rubiaceae		Herb/Shrub			
33	Acacia saligna (Liabill.) Wendl.	Fabaceae	Acacia Saligna	Tree	Introduced		Soil conservation
34	Acacia abyssinica Hochst. ex Benth	Fabaceae		Tree	Indigenous		Soil conservation
35	Vernonia leopoldi (Sch. Bip. ex Walp.) Vatke	Asteraceae		Shrub			
36	Sida schimperiana Hochst. ex A. Rich.	Malvaceae		Woody Herb		Honey bee forage	
37	Kalanchoe marmorata Bak.	Crassulaceae		Succulent perennial herb		Honey bee forage	
38	Echinops sp.	Asteraceae		Herb			
39	Osyris quadripartita Decn.	Santalaceae		Shrub/Tree		Medicinal Plant: Ulcers, Tinea versicolor	
40	Echinops sp.	Asteraceae		Shrub			
41	Cytisus proliferus L.f.	Fabaceae		Tree			Soil conservation
42	Opuntia ficus-indica (L.) Miller	Cactaceae		Succulent herb		Medicinal Plant: Hyperpigmentation	
43	Croton macrostachyus Del.	Euphorbiaceae		Tree	Indigenous		Soil conservation
44	Conyza sp.	Asteraceae		Herb			
45	Vernonia sp.	Asteraceae		Shrub			
46	Unidentified	Unidentified		Shrub			
47	Unidentified	Unidentified		Shrub			

48	Solanum sp.	Solanaceae	Shrub			
49	Leucas stachydiformis (Hochst. ex Benth.) Briq.	Lamiaceae	Shrub			
50	Aloe sp.	Aloaceae	Succulent herb			Soil conservation
51	Unidentified	Unidentified	Shrub			
52	Grewia ferruginea Hochst. ex A. Rich.	Tiliaceae	Shrub/Tree	Indigenous		
53	Unidentified	Unidentified	Shrub			
54	Echidnopsis dammanniana Sprenger	Asclepiadaceae	Succulent herb			
55	Ekebergia capensis Sparrm.	Meliaceae	Tree	Indigenous		Soil conservation
56	Grewia sp.	Tiliaceae	Shrub			
57	Abutilon sp.	Malvaceae	Shrub			
58	Leonotis ocymifolia (Burm.f) Lwarsson	Lamiaceae	Shrub		Medicinal Plant: Cancer; Honey bee forage	
59	Tephrosia pumila (Lam.) Pers.	Fabaceae	Shrub			
60	Acacia mearnsii De Wild.	Mimosaceae	Shrub/Tree	Introduced		Soil conservation
61	Hagenia abyssinica (Brace) JF. Gmel.	Rosaceae	Tree	Indigenous		Soil conservation
62	Otostegia integrifolia Benth.	Lamiaceae	Shrub		Medicinal Plant: Lung diseases; Honey bee forage	
63	Olea europaea L.subsp. cuspidata (Wall. ex G.Don) Cif	Oleaceae	Tree	Indigenous	Medicinal Plant: Tooth decay, hemorrhoids	
64	Carissa spinarum L.	Apocynaceae	Shrub			
65	Schinus molle L.	Anacardiaceae	Tree	Introduced		Soil conservation

66	Acacia melanoxylon R. Br.	Mimosaceae	Tree	Introduced		
67	Aloe sp.	Aloaceae	Succulent herb			Soil conservation
68	Plectranthus sp.	Lamiaceae	Succulent herb			
69	Solanum incanum L.	Solanaceae	Shrub			
70	Pittosporum abyssinicum Del.	Pittosporaceae	Tree			
71	Maesa lanceolata Forssk.	Myrsinaceae	Shrub/Tree	Indigenous	Medicinal Plant: Anthelmintic	
72	Discopodium penninervium Hochst.	Solanaceae	Shrub/Tree	Indigenous	Medicinal Plant: Snake bite	
73	Hypericum quartinianum A. Rich.	Hypericaceae	Shrub/Tree	Indigenous	Medicinal Plant: Stomach disorder, toothache; Honey bee forage	
74	Cyphostemma niveum (Hochst. ex Schweinf) Desc.	Vitaceae	Shrub			
75	Hibiscus sp.	Malvaceae	Shrub			
76	Argemone mexicana L.	Papaveraceae	Herb			
77	Unidentified	Unidentified	Shrub			Photo Species
78	Becium grandiflorum (Lam.) Pic.Serm.	Lamiaceae	Shrub		Honey bee forage	
79	Agave sisalana Perrine ex Engel.	Agavaceae	Succulent herb		Medicinal Plant	
80	Conyza hypoleuca A. Rich.	Asteraceae	Shrub			
81	Impatiens rothii Hook. f.	Balsaminaceae	Herb			
82	Myrsine africana L.	Myrsinaceae	Shrub			
83	Euphorbia dumalis S. Carter	Euphorbiaceae	Shrub			

84	Vernonia sp.	Asteraceae		Shrub		
85	Rhus glutinosa A. Rich.	Anacardiaceae	Embus	Shrub/Tree	Indigenous	
86	Acacia sp.	Fabaceae		Tree		
87	Vernoania sp.	Asteraceae		Shrub		
88	Unidentified	Unidentified		Shrub		
89	Dombeya torrida (J. F. Gmel.) P. Bamps	Sterculiaceae		Shrub/Tree	Indigenous	
90	Buddleja polystachya Fresen.	Loganiaceae		Tree	Indigenous	Medicinal Plant
91	Rhus retinorrhoea Oliv.	Anacardiaceae		Shrub/Tree	Indigenous	
92	Satureja punctata (Benth.) Briq.	Lamiaceae		Herb		
Additional Species in St. Emmanuel Church Forest						
93	Pterolobium stellatum (Forssk.) Brenan	Fabaceae				
94	Vernonia amygdalina Del.	Asteraceae				
95	Syzygium guineense (Willd.) DC.	Myrtaceae				
96	Podocarpus falcatus (Thunb.) R. B. ex. Mirb.	Podocarpaceae				
97	Gomphocarpus fruticosus (L.) Ait.f	Asclepiadaceae				
98	Malus sylvestris Mill.	Rosaceae				
99	Malus sylvestris Mill.	Rosaceae				

100	Prunus persica (L.) Batsch	Rosaceae	
101	Bridelia	Euphorbiaceae	
102	Persea americana Mill.	Lauraceae	
103	Millettia ferruginea (Hochst.) Bak.	Fabaceae	
104	Jacaranda mimosifolia D. Don	Bignoniaceae	
105	Melia azedarach L.	Meliaceae	
106	Pinus radiata D. Don	Pinaceae	