Applying geospatial methods to assess and validate the uptake of fertilizer trees and fodder shrubs in Zambia

Prepared for The Standing Panel on Impact Assessment
CGIAR Independent Science and Partnership Council
Final Report - July 31^{st}, 2017

Tor-Gunnar Vågen, Patricia Masikati, Brian Chiputwa
Makui Parmutai, Steve Franzel and Karl Hughes (ICRAF)
Michael Jacobson (Penn State University)
Elias Kuntashula and Robert Nhlane (University of Zambia)
Federica Alfani (FAO) and Aslihan Arslan (FAO/IFAD)

Contents

Selected Key Findings 1

Summary 2

1 Background and introduction to the study 4
1.1 Fodder shrubs and fertilizer trees in Zambia . . . 4
1.1.1 *Faidherbia albida* natural systems. . . . 6

2 Methods 7
2.1 Field surveys . . . 7
2.1.1 Biophysical surveys . . . 7
2.1.2 On-farm surveys . . . 10
2.1.2.1 Farm survey design and sampling . . . 10
2.2 Use of existing data . . . 14
2.2.1 Rural Agricultural Livelihoods Survey (RALS) . . . 14
2.3 Remote sensing analysis . . . 15
2.3.1 Mapping the distribution of *Faidherbia albida* . . . 16
2.3.1.1 Model accuracy . . . 16
2.4 Assessment of the role of CGIAR research on uptake of fertilizer trees in Zambia . . . 16

3 Results 17
3.1 Tree species diversity and density . . . 17
3.2 Occurence of *Faidherbia albida* . . . 17
3.3 Mapping the occurence of *Faidherbia albida* . . . 18
3.4 Adoption (uptake) of fertilizer trees in Zambia . . . 26
3.4.1 Summary of findings from the Rural Agricultural Livelihoods Survey . . . 26
3.4.2 On-farm surveys to assess uptake of *Faidherbia albida* . . . 29
3.4.2.1 Household characteristics of sampled farmers by province . . . 29
3.4.2.2 Comparing remote sensing based predictions of *Faidherbia albida* and on-farm survey results . . . 31
3.4.3 Attribution to ICRAF/CGIAR . . . 34
3.4.3.1 ICRAF Operations in Zambia: 1986-2006 . . . 34
3.4.3.2 Post ICRAF Period: 2007-present . . . 34

Appendix A: Adoption Issues (including comments from interviews) 36

Appendix B: Institutions and Individuals Contacted 38

#

Selected Key Findings

- Geospatial methods can be used to predict the occurence of *Faidherbia albida* in Zambia with high levels of accuracy.
- The resulting maps show the distribution of *Faidherbia albida* across the study area and can be used to assess uptake, or spread, of the species across the country.
- Assessments of where farmers source their *Faidherbia albida* seedlings from show that projects and/or NGOs are important sources of planting materials, followed by government extension, neighbors, fiends and relatives.
- Farmers also reported to have received agroforestry training from projects and/or NGOs mainly, followed by extension officers, government agencies and farmer to farmer programs.
- ICRAF leaving in 2006 created a void of agroforestry activities across Zambia and there is currently very little uptake based on the agroforestry technologies developed and promoted by ICRAF.

Summary

We explored the potential of geospatial methods, and in particular remote sensing, for mapping the distribution of *Faidherbia albida*, which is a key agroforestry species in Zambia that also occurs naturally across many parts of the country. More than 200 species of trees were identified during field surveys in late 2016 and from March to May 2017, with almost 90 different tree species occurring in agricultural fields. *Faidherbia albida* was among the most common species in agricultural fields, along with a number of other species occuring naturally in Miombo woodlands in the region. These results show that farmers in Zambia tend to leave trees in their fields, or in some cases allow seedlings to naturally regenerate, generally favouring nitrogen fixing trees such as *Faidherbia albida* or Miombo species such as *Brachystegia spp* or *Combretum molle*.

The results of the study show that the occurence of *Faidherbia albida* can be predicted with good accuracy levels using Landsat 8 satellite imagery and field data on the presence/absence of this fertilizer tree species. When we validated these models against data from on-farm HH surveys and fertilizer tree inventories, results showed that we were able to seperate fields with high prevalence of *Faidherbia albida* from thos with very few or no trees with reasonable accuracy as well. These findings show that geospatial methods do indeed hav high potential for mapping of key agrforestry species, and hence also for assessing uptake of fertilizer trees across larger areas. The same approaches could be applied to other agroforestry species, including fodder trees and shrubs. However, due to their rather limited occurence in Zambia, we focused on *Faideherbia albida* in the current study.

On-farm surveys covering three districts in Lusaka and Eastern provinces, showed that the main sources of *Faidherbia albida* seedlings for farmers were from government extension and projects and/or NGOs such as CFU, CASU and World Vision. Private nurseries alongside friends and neighbors were also reported to be important sources. These findings correspond well with those reported in the Rural Agricultural Livelihoods Survey carried out in 2015 by FAO and national partners in Zambia. They also confirmed the importance of *Faidherbia albida* as a fertilizer tree species for farmers in Zambia.

ICRAF was very active in Zambia for about 20 years (1986-2006). However, today, and even in the recent past, there has been very little adoption or uptake of fertilizer trees that ICRAF introduced into Zambia. If one was assessing attribution in the late 1990s or early 2000s, one would have found direct evidence of ICRAF work. Today, the fact that adoption is very low and that ICRAF had not been working in Zambia directly since 2006 suggests that little if any fertilizer tree uptake can be directly attributed to ICRAF, and one can reject the hypothesis. However, there is no doubt that ICRAF laid the foundation for fertilizer tree activity in the country, so indirectly any such activity can be traced back. The lack of agroforestry activities in Zambia, specifically fertilizer tree uptake, is clearly shown by a search of the CAB abstracts database. Figure 0.1 shows a clear distinction in the number of publications and articles produced between 1986 and 2006 (when ICRAF was active in the Zambia) and from 2006 to now.

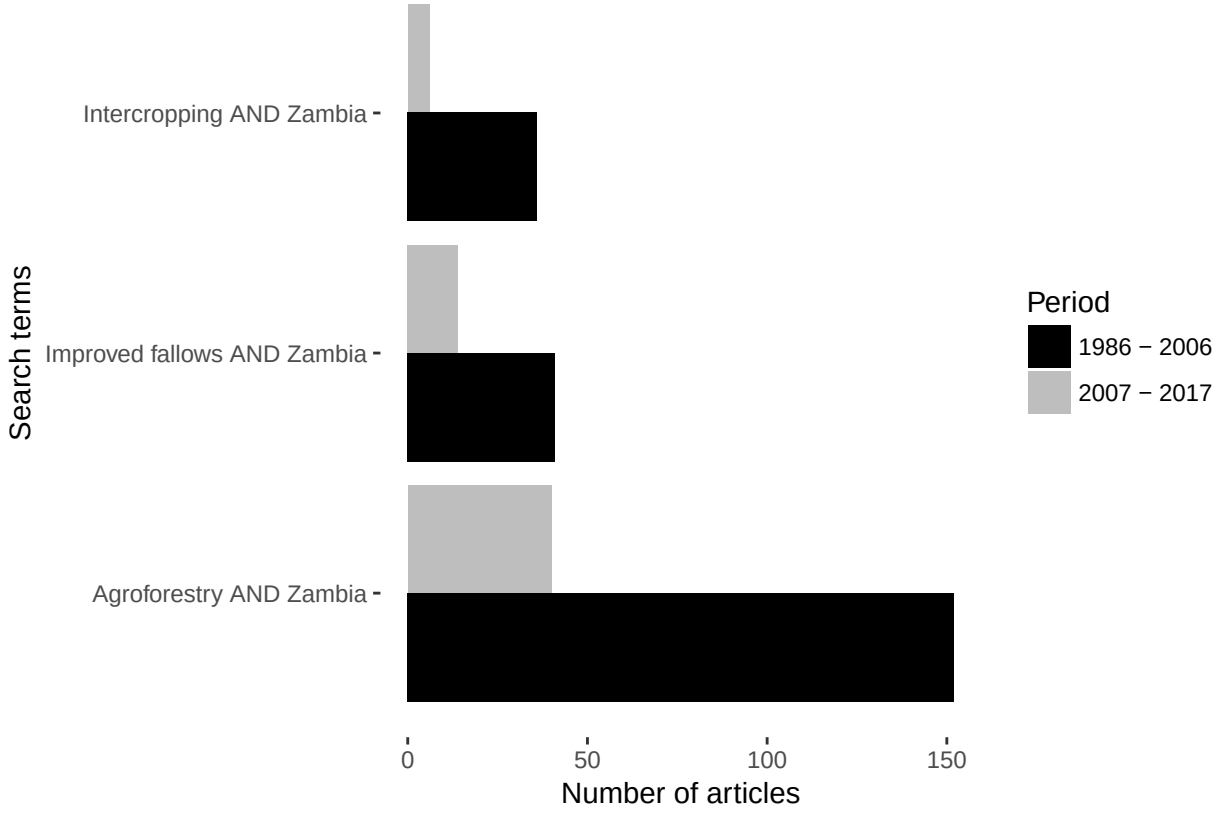

Figure 0.1: AB abstracts key word search for agroforestry articles in Zambia between 1986 and 2017.

1 Background and introduction to the study

The project "Applying geospatial methods to assess and validate the uptake of fertilizer trees and fodder shrubs in Zambia" was developed to explore the potential of remote sensing combined with systematically collected ground reference information to assess the distribution of common agroforestry species. Zambia was used as a case study, with the modeling and mapping of agroforestry tree species focusing primarily on *Faidherbia albida*. Biophysical field surveys were conducted in late 2016 and from April 2017. The late start to field surveys in 2017 was caused by an unusually wet rainy season, leading to extensive flooding in parts of the country.

> "The project has two main phases: (1) Field surveys to conduct species inventories for parts of Zambia known to have adoption of agroforestry practices, based on a review of availabe literature and (2) surveys of farms to assess the uptake and use of commonly promoted agroforestry practices. In addition, a"process tracing" approach was applied to assess linkages between agroforestry uptake and CGIAR/ICRAF activities in Zambia. The rationale for this approach is that tree detection alone is insufficient for assessing the uptake of agroforestry practices; rather, integrated methods that capture both the trees and land use systems (e.g., why farmers plant the trees) are needed."

1.1 Fodder shrubs and fertilizer trees in Zambia

Fertilizer trees were introduced into Zambia as an intentional agroforestry system to overcome soil fertility problems and save on costly mineral fertilizers. The systems ICRAF introduced were called "improved fallows" and were intended to shorten traditional bush fallows for soil replenishment (i.e. Chitemene or shifting cultivation). Fertilizer tree activity was mainly in the Eastern Province emanating from work done at the Msekera Research Station near Chipata. The species ICRAF focused on were *Gliricidia sepium*, *Sesbania sesban*, *Leucaena leucocephala*, *Tephrosia vogelii*, and *Cajanus cajan* (Pigeon pea). Numerous research papers, training materials, leaflets, and pamphlets on improved fallow benefits, species descriptions, and other production information were produced by ICRAF staff at the research station. On-farm research followed by heavy promotion was carried out by ICRAF and project partners. Adoption rates of 21% were reported during this period in the Eastern Province and over 60,000 farmers were reached and made aware. Multi-purpose fodder shrubs and trees such as *Gliricidia sepium* and *Leucaena leucocephala*, which have been widely adopted in for example Kenya have had more limited uptake in Zambia[1]. However, a number of projects have been promoting both fodder trees and shrubs, and fertilizer trees in Zambia, with a significant amount of research conducted for example at the Msekera Regional Research Station in Chipata.

While studies over the last 30 years have demonstrated significant potential of for example two- or three-year Sesbania fallows in restoring soil fertility and increasing maize yields, the extent to which farmers are adopting or taking up these practices is often not well understood. Franzel et al. (2002)[2] reported that *Sesbania sesban* and *Tephrosia vogelii* performed well in eastern Zambia, while other species such as *Cajanus cajan* performed poorly, highlighting the importance of introducing the right types of agroforestry species. Phiri et al. (2004)[3] reported a wide range in

[1] Simbaya, J., 2002. POTENTIAL OF FODDER TREE/SHRUB LEGUMES AS A FEED RESOURCE FOR DRY SEASON SUPPLEMENTATION OF SMALLHOLDER RUMINANT ANIMALS, in: Proceedings of the Final Review Meeting of an IAEA Technical Co-Operation Regional AFRA Project. International Atomic Energy Agency, Cairo, Egypt, pp. 69–76.

[2] Franzel, S., Phiri, D., Kwesiga, F., 2002. Trees on the Farm: Assessing the Adoption Potential of Agroforestry Practices in Africa, in: Franzel, S., Scherr, S.J. (Eds.), Trees on the Farm: Assessing the Adoption Potential of Agroforestry Practices in Africa. CAB International, New York, NY, p. 189.

[3] Phiri, D., Franzel, S., Mafongoya, P., Jere, I., Katanga, R., Phiri, S., 2004. Who is using the new technology? the association of wealth status and gender with the planting of improved tree fallows in Eastern Province, Zambia. Agric. Syst. 79, 131–144. doi:10.1016/S0308-521X(03)00055-6

terms of farmers planting improved fallows in eastern Zambia, ranging from 11% in Fisi to 54% in Kasauka, with an average for the study area of 29%. Exposure to the technology was hypotesized to be the most important determinants of uptake, including in the form of farmer training centres, on-farm trials, and farmer visits to research stations. Despite its potential, "improved fallow" systems are virtually non-existent in Zambia today.

One of the key soil constraints in eastern Zambia is nitrogen (N) deficiency, which has resulted in declines in soil fertility and productivity in this region, particularly under continuous monocrops such as maize (*Zea mays*). The use of short-duration tree fallows has received much attention in these areas, including species such as *Sesbania sesban*, has been promoted as a technology to restore soil fertility[4]. The reason for integrating nitrogen fixing trees with crops is for soil fertility replenishment. The trees "fix" nitrogen (N) from the air through rhizobia in their root nodules. This combines with N from the soil to eventually accumulate in tree biomass during growth. The biomass (leaves and twigs) is then cut (coppiced) and added to soil during land preparation. Unlike instantaneous effects of mineral fertilizers, the fertilizer tree systems take time to show their effect. Data from Msekera Research Station show that one hectare of fertilizer trees can fix up to 150 kg N/ ha to crops, i.e., an equivalence of between ten and fourteen bags (25-kg size) of formulated inorganic (urea) fertilizer. Other benefits from fertilizer tree systems can include ecosystem services and income from sale of forest products such as fuelwood. One can classify three main types of fertilizer tree systems in Zambia:

1. Improved fallows
2. Permanent intercropping and relay/simultaneous intercropping
3. *Faidherbia albida* species growing naturally in farming systems, also known as Farmer Managed Natural Regeneration (FMNR).

In improved fallows, crops are grown sequentially with fertilizer trees, which are grown for one or a few seasons (depending on practice, location, and species). Improved fallows were introduced to Zambia in the late 1970s through a NORAD-funded Soil Productivity program at the Misafmu Research Station in the Northern Province. In the mid-1980s, agroforestry research was shifted to Msekera Research Station in the Eastern Province. *Gliricidia sepium*, *Sesbania sesban*, *Leucaena leucocephala*, *Tephrosia vogelii*, and *Cajanus cajan* (Pigeon pea) were the main species utilized in the fallow systems. Preferred species by farmers were Tephrosia and Cajanus, since they are good seeders, require less fallow time, are easy to manage and coppice, and can provide income (Tephrosia (for seed) and Cajanus (for food)).

The two main types of intercropping are: 1) permanent intercropping (alley cropping) where rows of trees are spaced between rows of crops, and 2) relay or simultaneous intercropping where the trees are grown along with the crop on the same plot. In these latter systems, the crop outgrows the tree and, after crop harvest, the tree continues to grow and is coppiced before the next cropping season. All the species noted above can be used in intercropping. Gliricidia is preferred for permanent intercropping due to its growth, branch form, and biomass production. Sesbania and Tephrosia are preferred for relay intercropping due to their fast-growing nature. Faidherbia has become of interest in recent years in permanent alley systems. Albeit relatively slow growing, Faidherbia requires less labor (no coppicing) and, due to reverse phenology, does not compete for light with crops during the growing season. Faidherbia takes 10-15 years to be fully functional and effective in providing soil benefits according to the CFU manual.

[4]Kwesiga, F.R., Franzel, S., Place, F., Phiri, D., Simwanza, C.P., 1999. Sesbania sesban improved fallows in eastern Zambia: Their inception, development and farmer enthusiasm. Agrofor. Syst. 47, 49–66. doi:10.1023/a:1006256323647

1.1.1 *Faidherbia albida* natural systems.

Faidherbia albida is found naturally in certain parts of Zambia, especially in the eastern and southern regions (e.g., Tonga). A study conducted by Fagg (1992)[5] reported that the largest (natural) populations of *Faidherbia albida* in Zambia were found on alluvial soils in the fringes and surrounding areas of the Kafue flats. A survey conducted by Pullen (1974)[6] indicated that *Faidherbia albida* farmed parkland covered approximately 770 km^2 in the Kafue Plains. Found more in low-lying riverine and valley areas, it has long been used by farmers as part of their farming systems. Generally, farmers would leave trees to grow naturally in the fields as they recognized their nitrogen fixing ability. Recent interest, especially from work in West Africa, is for Farmer Managed Natural Regeneration (FMNR) where farmers tend and intentionally manage Faidherbia on the farms. Faidherbia requires minimal labor inputs and historically, Faidherbia has specific characteristics that fit current practices compared to other technologies. Today, some farmers are more interested in allowing natural recruitment of Faidherbia on farms.

Satellite remote sensing is increasingly recognized as a cost-effective approach for the mapping of tree species abundance and composition. However, in order for such assessments to provide accurate results, it is critical that appropriate field sampling designs are used. Also, defining the population of concern is important to reduce uncertainties in the modeled outputs. Several studies have demonstrated the application of remote sensing to the mapping of species distributions in landscapes, either through analysis of the phenology of different species or through the use of the spectral characteristics of the vegetation canopy cover, or in some cases a combination of both of these approaches. However, many such assessments are limited to the local scale and relatively few assessments have been made across larger landscapes. In the current study we explore the application of remote sensing, using data from the Landsat 8 platform, to map the distribution of *Faidherbia albida* in the Southern, Central/Lusaka and Eastern provinces of Zambia.

[5] Fagg, C.W. 1992. Germplasm collection of Faidherbia albida in eastern and southern Africa. Pages 19-24 in Faidherbia albida in the West African semi-arid tropics: proceedings of a workshop, 22-26 Apr 1991, Niamey, Niger (Vandenbeldt, R. J., ed.). Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics; and Nairobi, Kenya: International Centre for Research in Agroforestry.

[6] Pullen, R.A. 1974. Farmed parkland in Zambia. Zambian Geographical Association Magazine 26.17 pp.

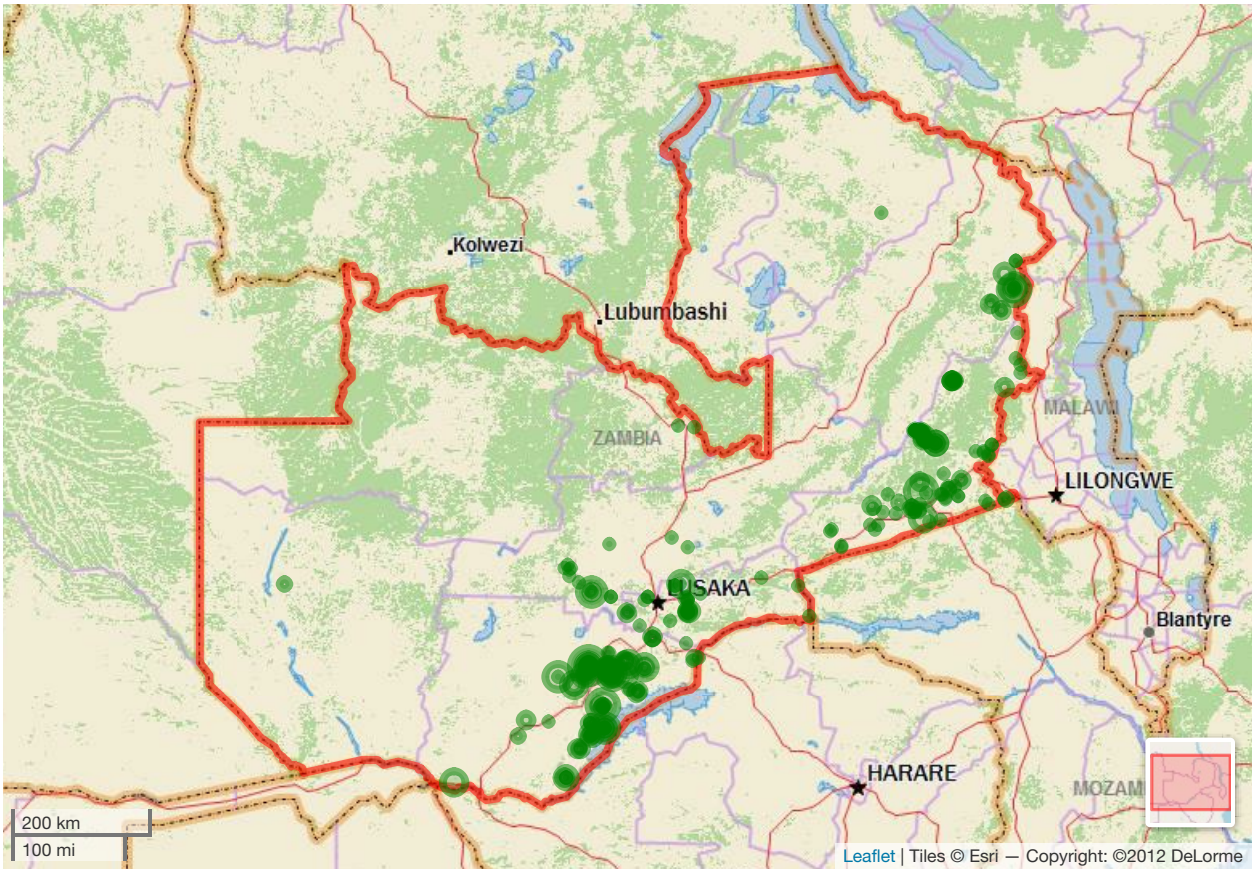

Figure 2.1: Map showing the distribution of HHs surveyed as part of the Rural Agricultural Livelihoods Survey in Zambia reporting to have planted *Faidherbia albida* on their farms. The size of the circles show number of trees reported.

2 Methods

2.1 Field surveys

2.1.1 Biophysical surveys

Given the very limited use of agroforestry in large parts of Zambia, and the limited resources available for the current study, we prioritized the Central (Lusaka), Southern and Eastern provinces. These are also the parts of the country reported to have most *Faidherbia albida* in the RALS survey conducted in 2015, as snown in the map in Figure 2.1.

Sampling clusters were stratified to cover these provinces, excluding protected areas, and sampling plots were randomly located around each cluster centroid. Figure 2.2 shows the locations of sampling clusters. Sampling plots building on the Land Degradation Surveillance Framework (LDSF) were used, each plot having an area of 1,000 m^2 (i.e. the same spatial support as the LDSF), and all tree and shrub species were identified (scientific and/or local/common name), counted and measured (DBH and height) within each sampling plot. In addition, basic plot characterisation was conducted, including land use, vegetation structure (following the LCCS), assessments of erosion, landform and other plot

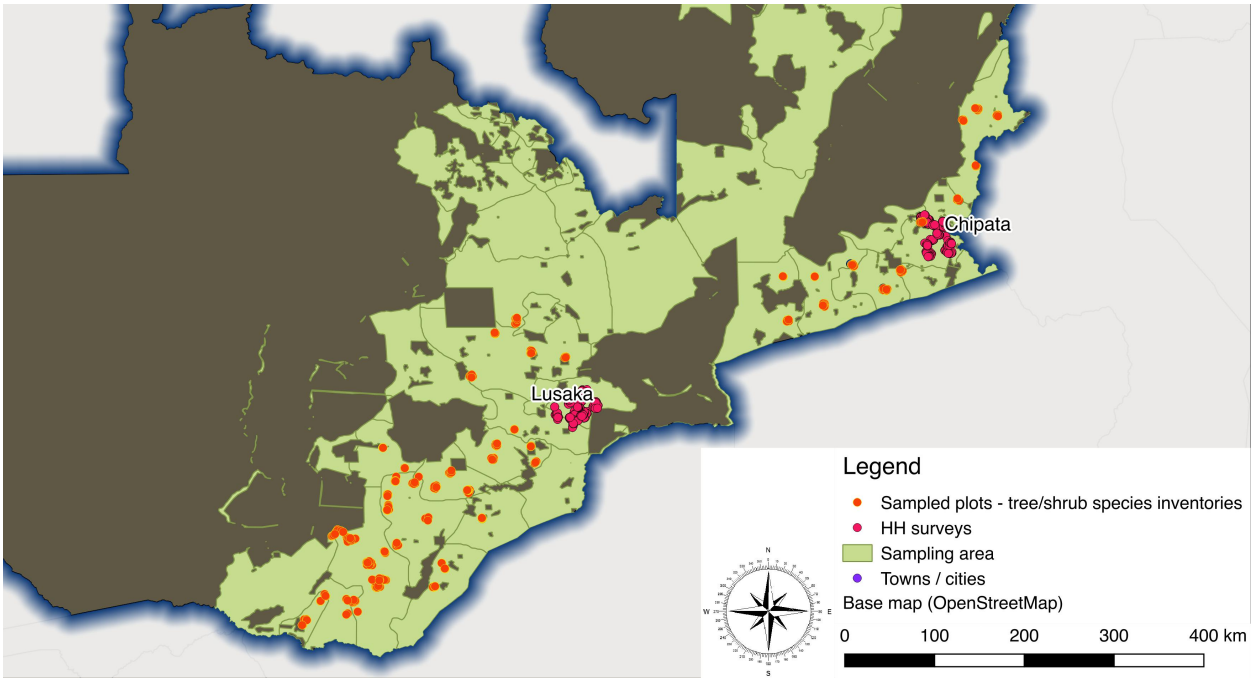

Figure 2.2: Map showing the locations of sampling clusters sampled using a stratified random sampling design.

properties

An Open Data Kit (ODK) data-entry app was developed for the biophysical survey (Figure 2.3), and was applied during the field surveys. Data collected in the field was uploaded to a database on a server hosted by ICRAF whenever the field team had access to mobile data networks or WiFi connectivity. A database was developed for storage of the field data.

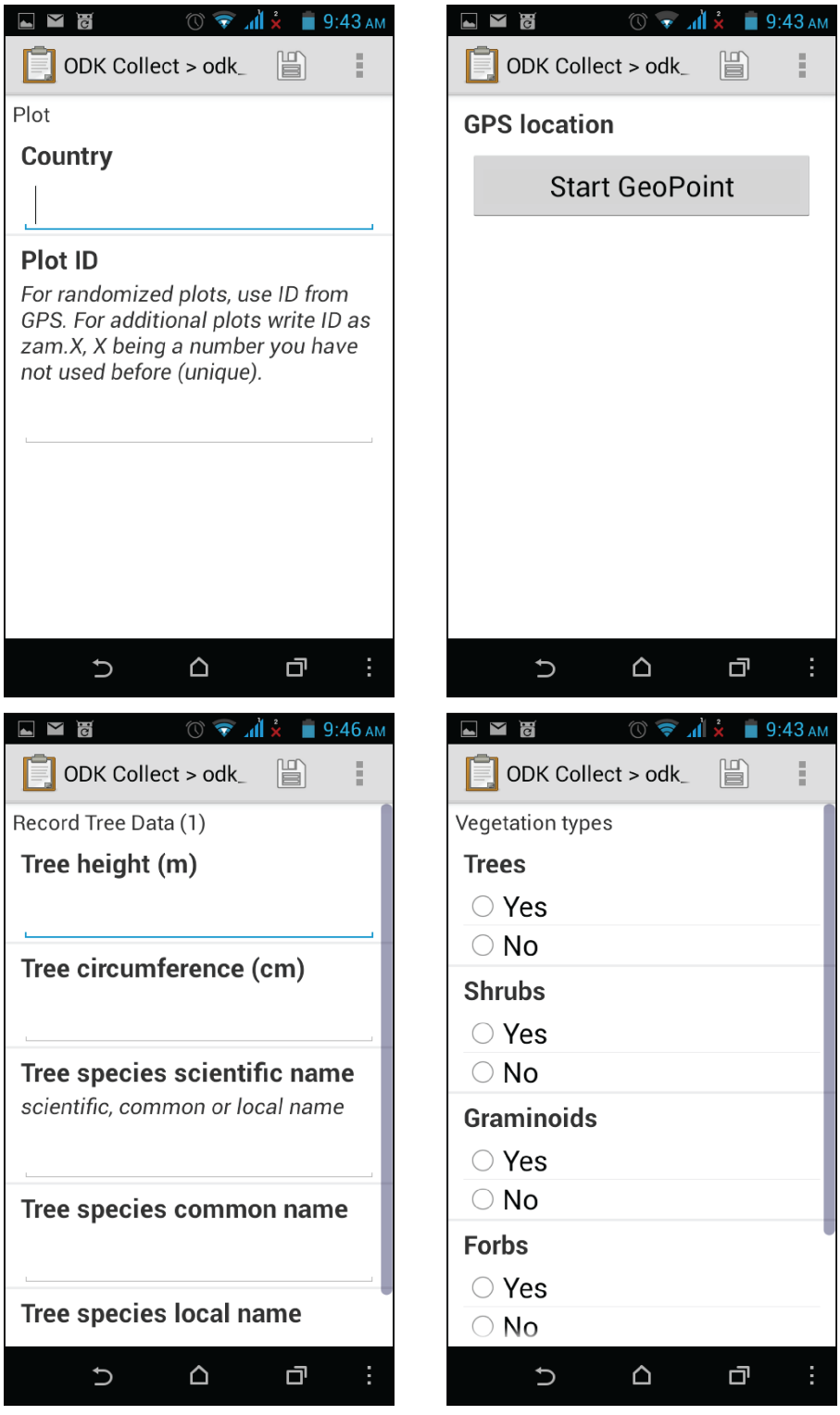

Figure 2.3: Screenshots showing elements of the ODK data-entry app that was developed for and used in the biophysical field surveys.

2.1.2 On-farm surveys

On-farm surveys were conducted to assess the uptake and use of commonly promoted agroforestry practices in the study regions, and as part of a validation exercise against the predicted distribution of *Faidherbia albida* based on remote sensing (i.e. geospatial methods). A total of 550 farmers in Lusaka and the Eastern Province were surveyed over the period March to June, 2017 (Figure 2.4 and Figure **??**).

Within Lusaka province, two districts namely Chongwe and Rufunsa were selected for this study. Both of the districts surveyed in Lusaka lie to the east of the capital. Chongwe District has a population of approximately 148,000 and is about 35 km from Lusaka. The district is considered rural to peri-urban with families living in homesteads and relying on subsistence farming. The main source of livelihood for most families is agriculture and charcoal production. On average, the area receives between 800 and 1000 mm of rainfall per year. Chongwe is predominantly a farming area populated with mostly subsistence farmers growing maize, but also cash crops including groundnuts, cotton, and beans. The average cultivated land ranges from 0.5 to 4 hectares. For administrative and operational purposes, Chongwe is divided into 5 zones and these zones are further divided into 28 agricultural camps. The camps are administrative geographical units created by the Ministry of Agriculture for convenience in the administration of extension services. Each camp on average has 1,691 households[7]. A total of 9 camps were involved in this study. The camps that were sampled and surveyed included; Kampekete, Katoba, Lukoshi, Lwimba, Mulalika, Mwalumina, Njolwe, Palabana and Shelleni agricultural camps.

Rufunsa district came into existence in 2012 when it was declared as a district by the current Government of Zambia. Until then, the district was part of Chongwe. As of the 2001 Zambian Census, the district was not yet in place as it was still part of Chongwe district. It is estimated to have a population of about 45,000 people. The main economic stay of the local people in Rufunsa is subsistence farming and hunting. The camps that were sampled and surveyed in Rufunsa districts are Nyangwena and Mwachilele.

The Eastern Province lies between the Luangwa River and borders with Malawi to the East and Mozambique to the South. The province covers about 51,476 km^2 and is divided into eleven districts (Figure **??**) and is characterised by a flat to gently rolling landscape with altitudes ranging from 900 to 1,200 m above sea level. Rainfall is unimodal with about 85% falling in four months, December through March. Average air temperatures range from 15° to 18°C during June-July and 21° to 26°C during September-October. Population density varies between 25 and 40 persons per km^2. About half of the farmers practice ox cultivation, the others cultivate by hand-hoe. Land tenure is mostly traditional with most farmers acquiring land through inheritance. Average cropped land ranges between 1.1 and 1.6 ha for hoe cultivators, and 2.3 to 4.3 ha for ox cultivators. Maize is the most important crop in the area accounting for about 60% to 80% of total cultivated area. Other crops include sunflower, groundnuts, cotton and exotic vegetables. The sampled district for this study in eastern province was Chipata district which also houses the provincial capital for the province.

2.1.2.1 Farm survey design and sampling

The sampling procedure was mostly informed by the predicted maps of *Faidherbia albida* occurrences from remote sensing. The maps were presented to a number of key informants from the Ministry of Agriculture (Chongwe, Kafue and Chipata Districts) and Conservation Agriculture Scaling Up (CASU) Project Officers in Lusaka and Chipata Districts who assisted in drawing up the sampling frames. Based on the maps, all the camps in the two provinces

[7] Chompola and Kaonga (2016),'Adoption of Conservation Agriculture in Zambia - The Case of Chongwe', Sustainable Development, 79

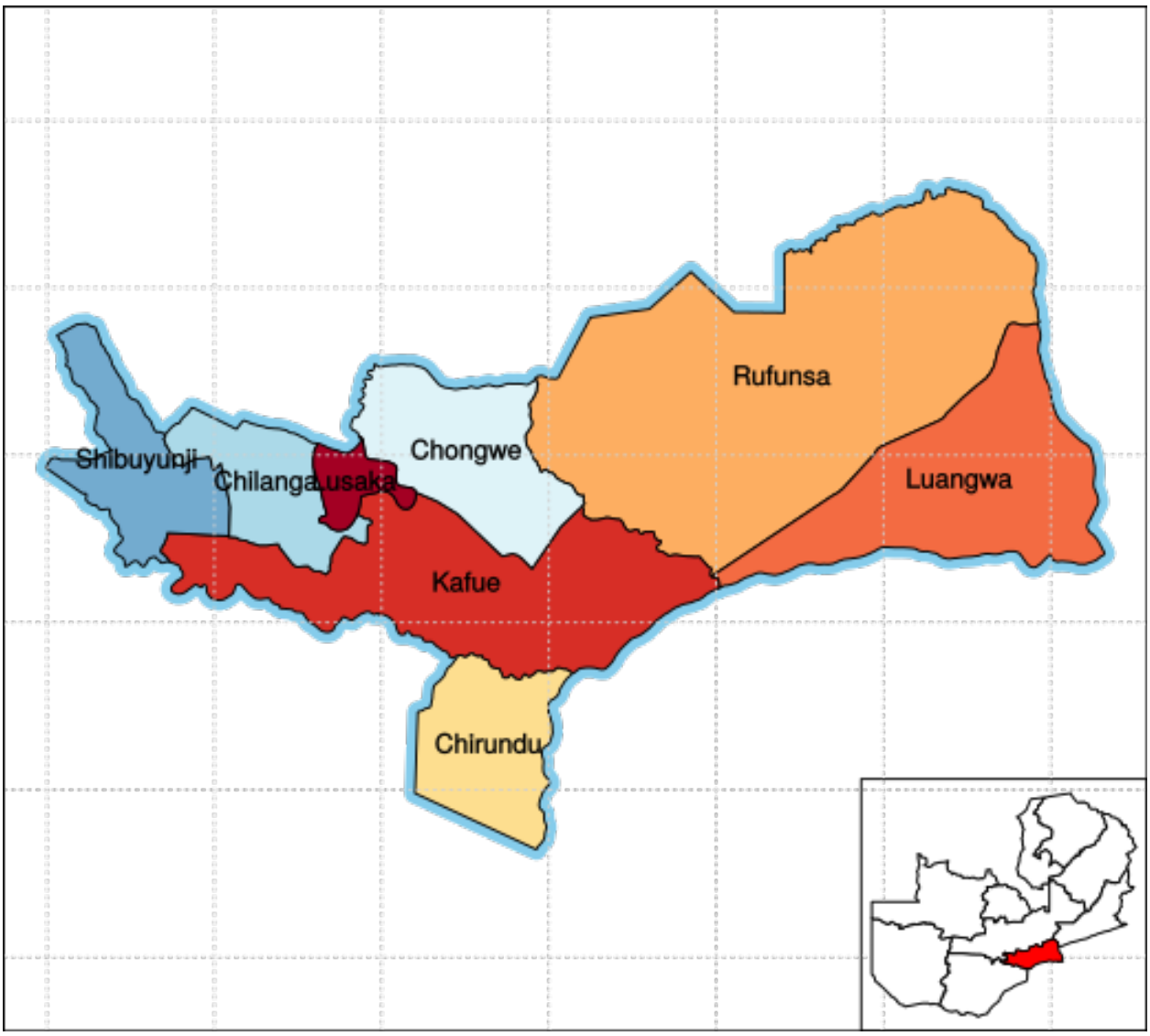

Figure 2.4: Map of Lusaka province showing its districts

could be classified into one of three categories low, medium and high prevalence of *Faidherbia albida*. Based on sampling frames populated during key informant interviews, farmers to be interviewed were randomly sampled. The respondents were mainly household heads. Figure 2.6 shows one of the sampled farms with HH location, as well as locations of georeferenced *Faidherbia albida* trees.

2.1.2.1.1 Data collection process

The data collection process followed for the farm inventory survey is summarized in Figure 2.7. It started off with the design of a structured survey form or questionnaire that captured the main indicators of choice in this study. More specifically, the form captured key indicators that related to fertilizer tree adoption. In addition, the form also elicited information on household demographics and socioeconomic characteristics, asset ownership, crop and livestock production, food consumption and sales, adoption of natural resource management (NRM) practices.

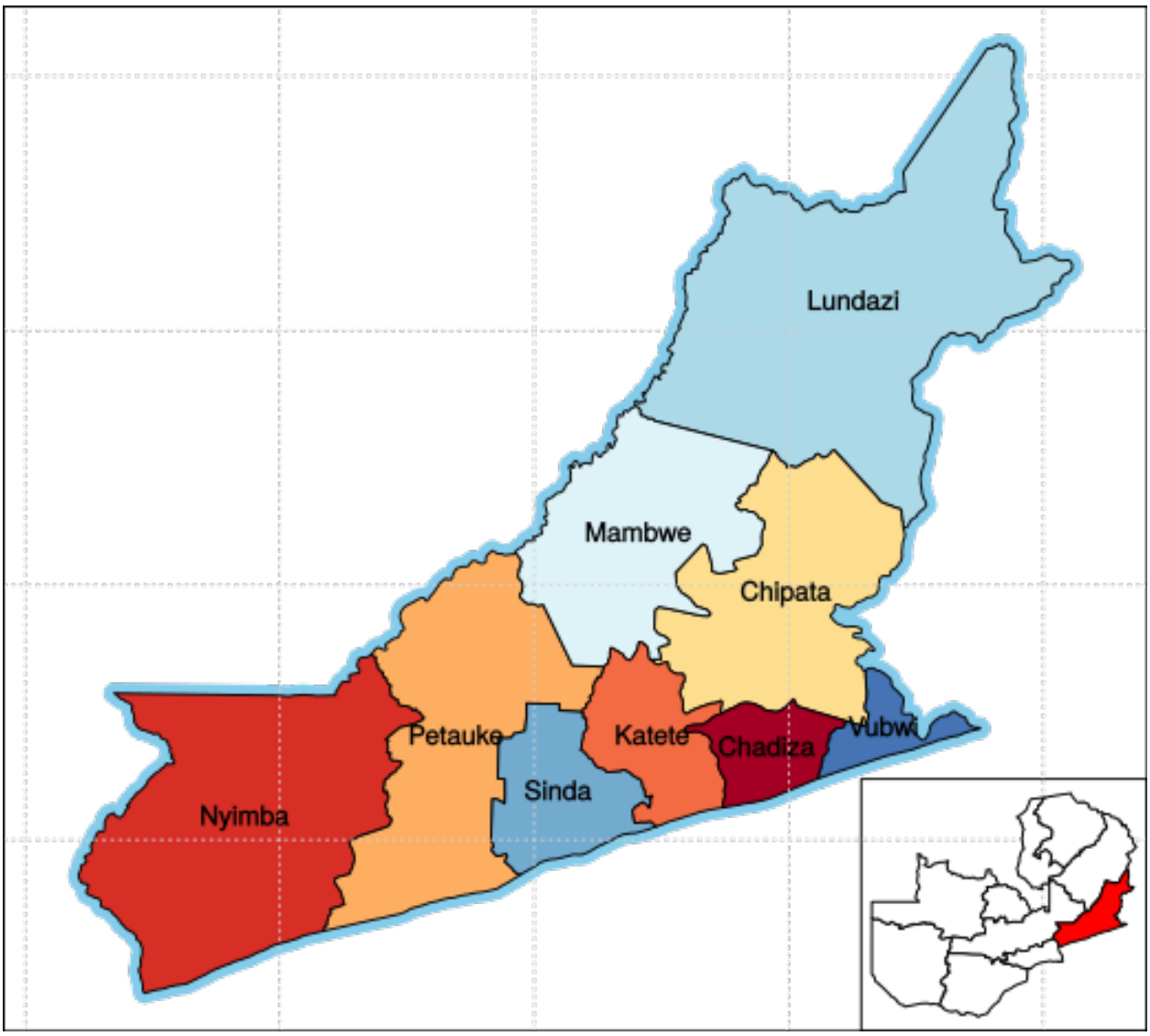

Figure 2.5: Maps of the Eastern province showing its districts

Information from farms was collected at three levels, with GPS coordinates taken (1) at the household location, (2) at the farm plot (field) and (3) of individual *Faidherbia albida* trees within the field see Figure 2.6.

The forms were uploaded to an electronic data entry system in the form of Open Data Kit (ODK)[8] and made available for download onto Android based tablets. A team of seven enumerators and one supervisor were recruited under the minimum requirement that they were local residents with a minimum of a Bachelor's Degree in an Agricultural course. This exercise was led by a team of researchers from the University of Zambia (UNZA). The enumerators participated in a one week training prior to the survey. The program included sessions on the the objectives of the on-farm surveys, the role and responsibilities of the enumerator, interviewing techniques, research ethics, conducting Computer Assisted Personal Interviews (CAPI) and the importance of randomness and bias during sampling. On the last day of the training, a field pilot to pre-test the survey instrument was conducted and the the instrument

[8]https://opendatakit.org/

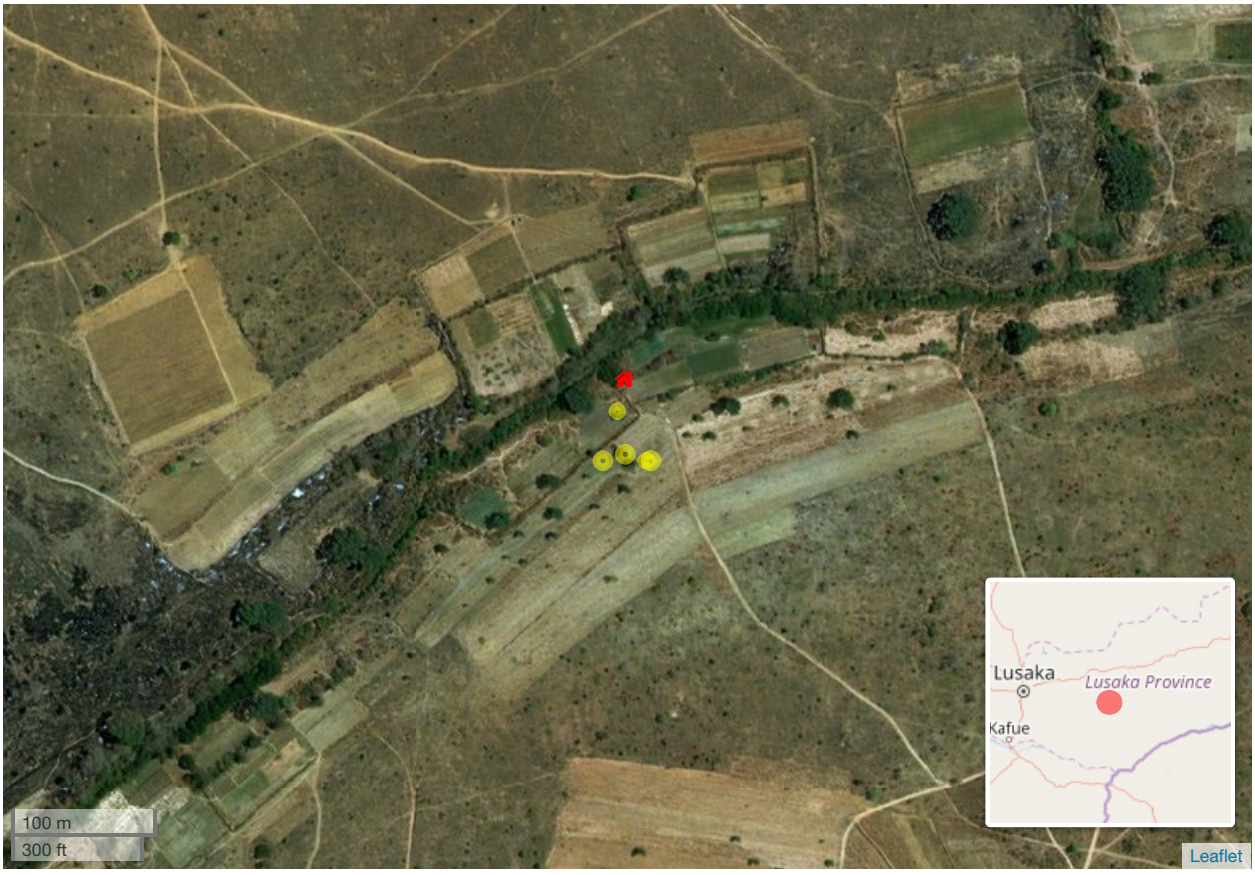

Figure 2.6: Map showing one of the farms surveyed. The red marker shows the location of the household, while the yellow circles show plot locations and locations of individual *Faidherbia albida* trees.

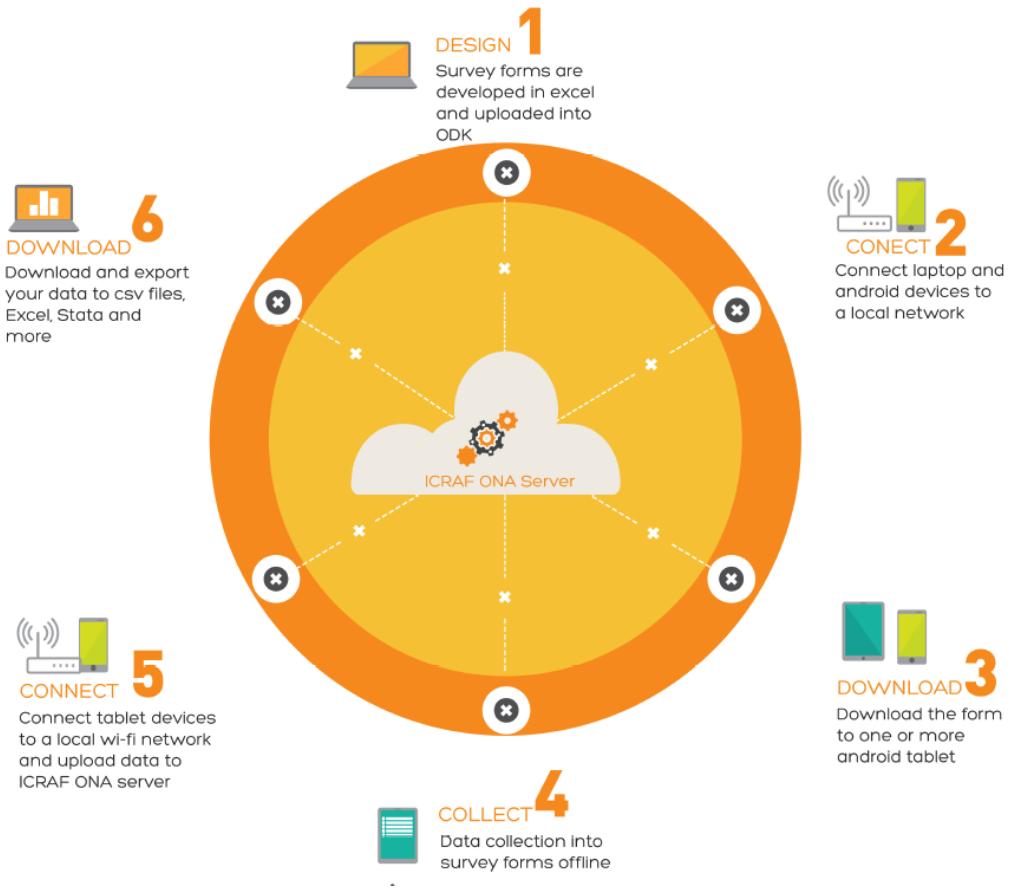

Figure 2.7: Schematic illustration of the data collection process during the farm inventory surveys

revised based on the enumerators' field experience. The data was collected over a period of three weeks, under close supervision from ICRAFs socio-economic team in collaboration with partners at UNZA. All collected data were then uploaded to the ICRAF server account hosted by ONA[9] on a daily basis by the enumerators. In order to remotely monitor and assess the quality of data in real time and ensure that the protocols were being administered correctly and individual measurements recorded accurately, the socio-economic team at ICRAF developed and used automated work-flow scripts and were in constant touch with the enumerators and the field supervisors. Upon completion of the survey, the final dataset was then downloaded and exported to different formats for further processing and analysis e.g., CSV, SPSS, R and Stata.

2.2 Use of existing data

2.2.1 Rural Agricultural Livelihoods Survey (RALS)

Data and information on the extent of agroforestry practices in Zambia from RALS[10] were used to assess the prevalence of *Faidherbia albida* based on HH surveys from across Zambia. We explored georeferenced information from

[9] www.ona.io
[10] IAPRI, 2015. Rural Agricultural Livelihoods Survey: 2015 Survey Report. Lusaka, Zambia.

Figure 2.8: Enumerator recording GPS coordinates of a Faidherbia albida tree.

the RALS survey to identify farms with various agroforestry species and compared the estimated distribution of *Faidherbia albida* to those reported in the RALS dataset. It is important to note that the RALS data did not contain the locations of farmer fields, but rather the household locations. Hence, this analysis should be considered a rough approximation at the farm level and not a validation of the estimated probabilities for *Faidherbia albida* occurence per se.

2.3 Remote sensing analysis

We used Landsat 8 satellite imagery to map the distribution of *Faidherbia albida* in the study area (Figure 2.2). The satellite images were downloaded from the Amazon cloud by accessing the s3://landsat-pds/ bucket directly and downloading scenes covering the study area over the period September 2016 through April 2017. The downloaded satellite images were calibrated to ground reflectance, cloud contamination was filtered out and overall image

quality was assessed using the the Quality Assessment (QA) band prior to the application of the imagery.

After processing and calibrating the images, reflectance values were extracted for (i) all plots sampled as part of the biophysical surveys, (ii) coordinates of individual Faidherbia trees collected in the field and (iii) coordinates of fields and indivual trees from on-farm surveys. In addition, reflectance values were extracted for a set of coordinates known to have no Faidherbia present, which represented agricultural plots and Miombo woodlands without *Faidherbia albida*.

2.3.1 Mapping the distribution of *Faidherbia albida*

Prediction models were developed using Random Forests (RF)[11] to estimate the probability of having *Faidherbia albida* in each Landsat 8 image pixel using the presence/absense of Faidherbia as the dependent variable and bands two through seven from Landsat 8 as predictors. Random Forests have a wide range of applications, including in image processing and species distribution modeling. In brief, the framework for RF models involves four main steps, where (1) a bootstrap sample is drawn with replacement, (2) a decision tree is grown for each bootstrap sample and (3) the results are summarised over all the trees. In the case of classification trees, such as in this study, the majority vote is taken across the decision trees in the forest to represent the predicted presence (or absence) of *Faidherbia albida*.

2.3.1.1 Model accuracy

There are several approaches for assessing the accuracy of classification models. The most common is to compute a simple confusion matrix. A method commonly used in medical research and in signal detection theory is the Receiver Operating Characteristic (ROC) curve, which evaluates the accuracy of a model by considering errors that are either *false positives* or *false negatives*. A *true positive* (TPF) is calculated as:

$$TPF(c) = P\{M > c|D = 1\}$$

A false positive, which is the probability that we falsely predict the occurence of Faideherbia where there is none is calculated as:

$$FPF(c) = P\{M > c|D = 0\}$$

.

In the above equations represent, *M* is the probability of *Faidherbia albida* occuring in a given plot and *D* is the binary outcome (yes/no) for observed *Faidherbia albida* presence/absence in the plot. The ROC is then a plot of the TPF against the FPF for all possible values of *c* (0 to 1) in the above equations.

2.4 Assessment of the role of CGIAR research on uptake of fertilizer trees in Zambia

We examined the influence of ICRAF-CGIAR research on uptake of fertilizer trees (leguminous nitrogen fixing trees) in Zambia using "process tracing". This is is a qualitative method which links causal relationships. This project assesses attribution of ICRAF research on fertilizer trees by tracing the progress of specific practices from the research station to the field. Using this technique, one can test a hypothesis that ICRAF-CGIAR research substantially

[11] Breiman, L., 2001. Random forests. Machine Learning 45, 35. doi:10.1023/A:1010933404324

affected fertilizer tree uptake in Zambia. The methodology uses a variety of different tests to confirm or reject the hypothesis.

In this study, three categories of evidence: direct, indirect, or no evidence were used. Direct evidence would include confirmation of current use of ICRAF in research, promotion, providing training or materials, or other such information or activities in fertilizer tree uptake. Indirect would be anecdotal or suggested evidence that ICRAF research was relevant and necessary but not sufficient to show actual on the ground uptake at present.

To trace these causal relations and evidence, a literature review along with direct interviews were carried out in Lusaka from June 27 through July 1, 2017. Lists and names of potential stakeholders and key informants were solicited from various sources. Efforts were made to contact all relevant people associated with fertilizer tree activities in Zambia. The list of those interviewed along with a description of their organizations is shown in Appendix B.

3 Results

3.1 Tree species diversity and density

A total of 401 plots were sampled during the biophysical field surveys, which is somewhat short of the target of 500 plots for the project, but a satisfactory result given that only one field season was available for the study and extensive flooding during the 2017 rainy season, which rendered many areas inaccessible. A wide range of species occur in the sampled plots, with a total of 239 unique species recorded, with 88 of these found in agricultural fields. Tree densities in the randomly sampled plots ranged from 0 to 470 trees ha^{-1}, with an average tree density of 66 trees ha^{-1} overall. Tree densities were highest in woodlands on average (98 trees ha^{-1}) and lowest in grasslands, followed by shrublands and croplands (45 trees ha^{-1}).

As shown in Figure 3.2, the most commonly occuring species recorded during the field campaigns was *Brachystegia boehmii*, followed by *Combretum molle*, *Brachystegia spiciformis* and a range of species that are characteristic of Miombo systems in southern Africa. Miombo is indeed the Swahili word for Brachystegia, which is a very diverse genus in terms of the number of species. The Miombo biome covers large parts of Zambia, with Central Zambezian Miombo woodland being the most dominant ecoregion in the country. Eastern, Lusaka and Southern Zambia are characterized by Southern Miombo (Figure 3.1) and Mopane woodlands.

3.2 Occurence of *Faidherbia albida*

Faidherbia albida occurred in about 6% of the sampled field plots, but was the dominant species in croplands together with *Combretum molle*, followed by *Brachystegia boehmii* (Figure @(fig:speciesOccurenceCult)). As shown in Figure 3.2 - panel 2, *Faidherbia albida* occurs naturally in semi-natural ecosystems in Zambia. It is often abundant in riperian zones, such as those found along the Zambezi River and on alluvial soils such as in Kafue and other parts of Central, Lusaka and Eastern Zambia. It is an important fodder species for both domestic and wild animals (Figure 3.3). Where the species occurs naturally it can form dense woodlands. In cultivated areas, *Faidherbia albida* is often retained and managed by farmers after clearing of woodlands for cultivation, hence its dominance in the data collected as part of this study, if we consider only cultivated areas (Figure 3.4). In croplands that had *Faidherbia albida*, the average tree density was 15 trees ha^{-1}. About 15% of the sampled plots in cultivated areas had *Faidherbia albida*).

Figure 3.1: Photo of a typical Miombo woodland in Southern Zambia. Southern Miombo woodlands cover about 15 percent of the country and are dominated by decidious trees and shrubs, which shed their leaves in the dry season as can be seen in this photo from July 2016. Photo credit: Tor-G. Vågen

3.3 Mapping the occurence of *Faidherbia albida*

Model performance for the prediction of *Faidherbia albida* **presence** is good, with an overall accuracy for the independent testing of the model of 0.85 as shown in Table 3.1 and Figure 3.5. Model accuracy for the prediction of *Faidherbia albida* **absence** is over 93%, while model accuracy for the prediction of its **presence** is about 60%. An assessment of the relative importances of Landsat 8 bands for predicting the occurence of *Faidherbia albida* showed that bands 3, 4 and 6 were the most important independent variables in the RF model. Considering that the trees found in agricultural fields were mostly individual trees, sparsely distributed (i.e. with low density), the detection accuracy is good, but would likely improve with larger sample sizes. The ROC curve in Figure 3.5 confirms these findings, with the Area Under Curve (AUC) calculated at 0.86. This indicates that the classifier will rank a randomly chosen positive instance higher than a randomly chosen negative instance, or in other words that model performance is satisfactory for mapping the distribution of *Faidherbia albida.* An AUC value of 0.5 would have indicated that the model was performing no better than random, while a value of 1 would have indicated a "perfect" model.

Given the results above, we feel reasonably confident that the model will allow us to predict the presence of *Faidherbia albida* based on Landsat 8 with an acceptable level of accuracy.

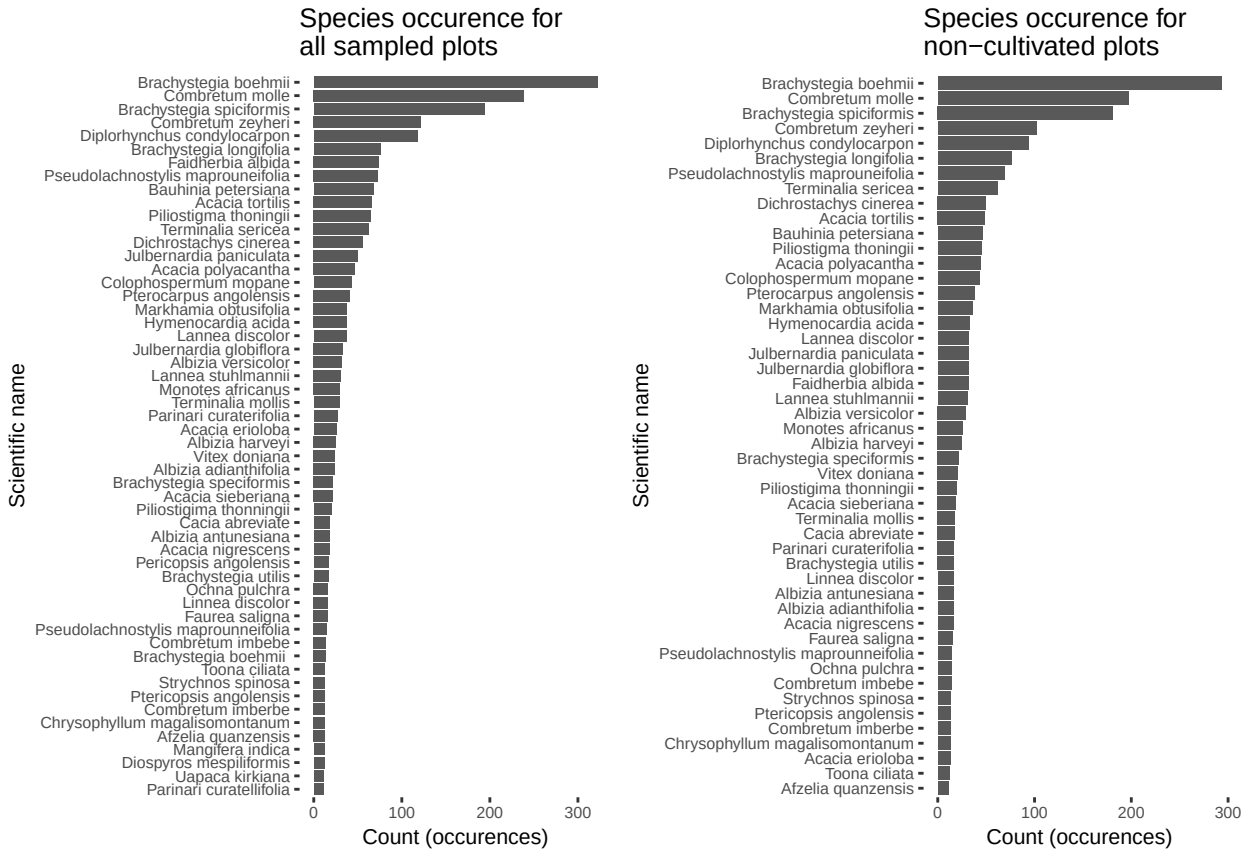

Figure 3.2: Results of tree species inventories, showing species occuring in the spatially stratified random sample of plots in South, Lusaka/Central and Eastern Zambia.

Table 3.1: Confusion matrix showing model performance for the independent (validation) test of the Faidherbia prediction model. The smaller table on the left shows measured presence (1) and absence (0) as columns and predicted presence and absence as rows.

	1	0
1	226	84
0	151	1153

	Est	LCL	UCL
Accuracy	0.85	0.84	0.87
Sensitivity	0.60	0.58	0.62
Specificity	0.93	0.92	0.94
PPV	0.73	0.71	0.75
NPV	0.88	0.87	0.90

Figure 3.3: Elephant feeding on a Faidherbia albida tree on the Zambezi River plain in Southern Zambia. Photo credit: Tor-G. Vågen

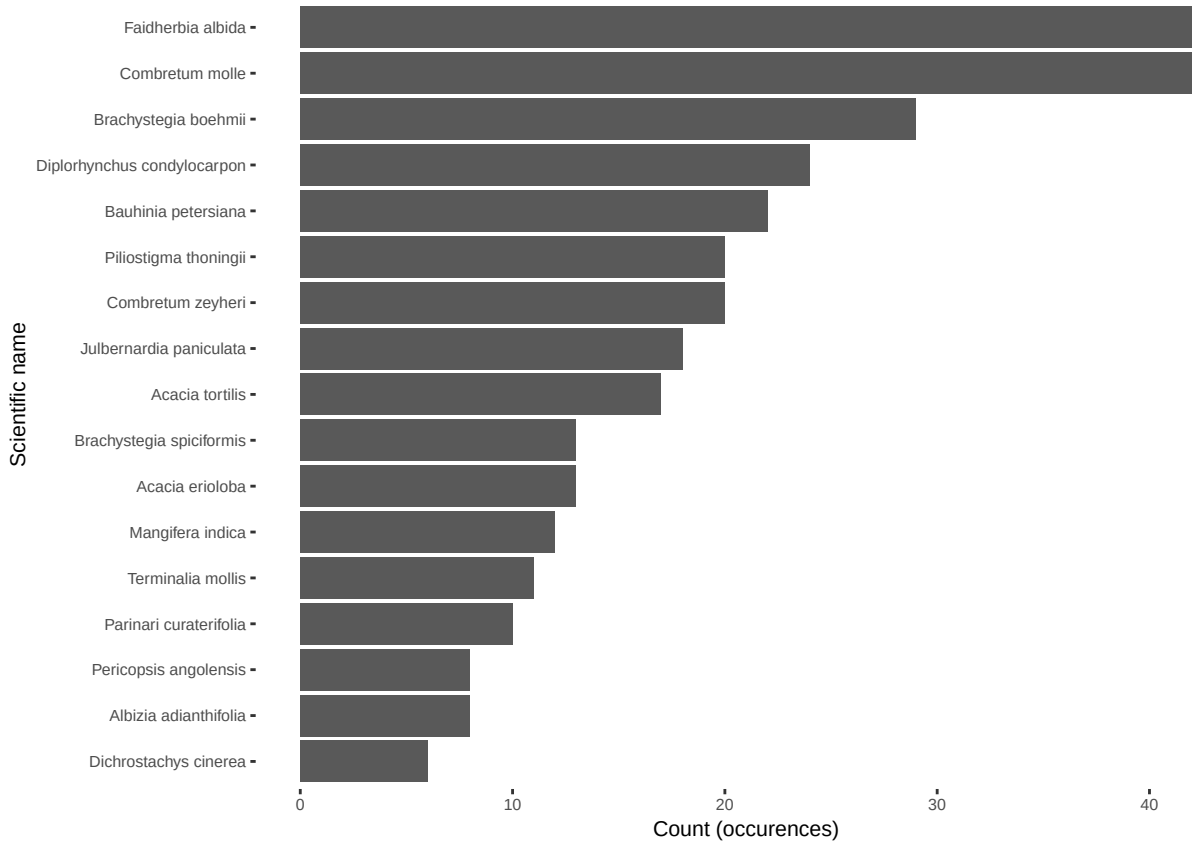

Figure 3.4: Results of tree species inventories, showing species occuring in the spatially stratified random sample of cultivated plots in south, central and eastern Zambia.

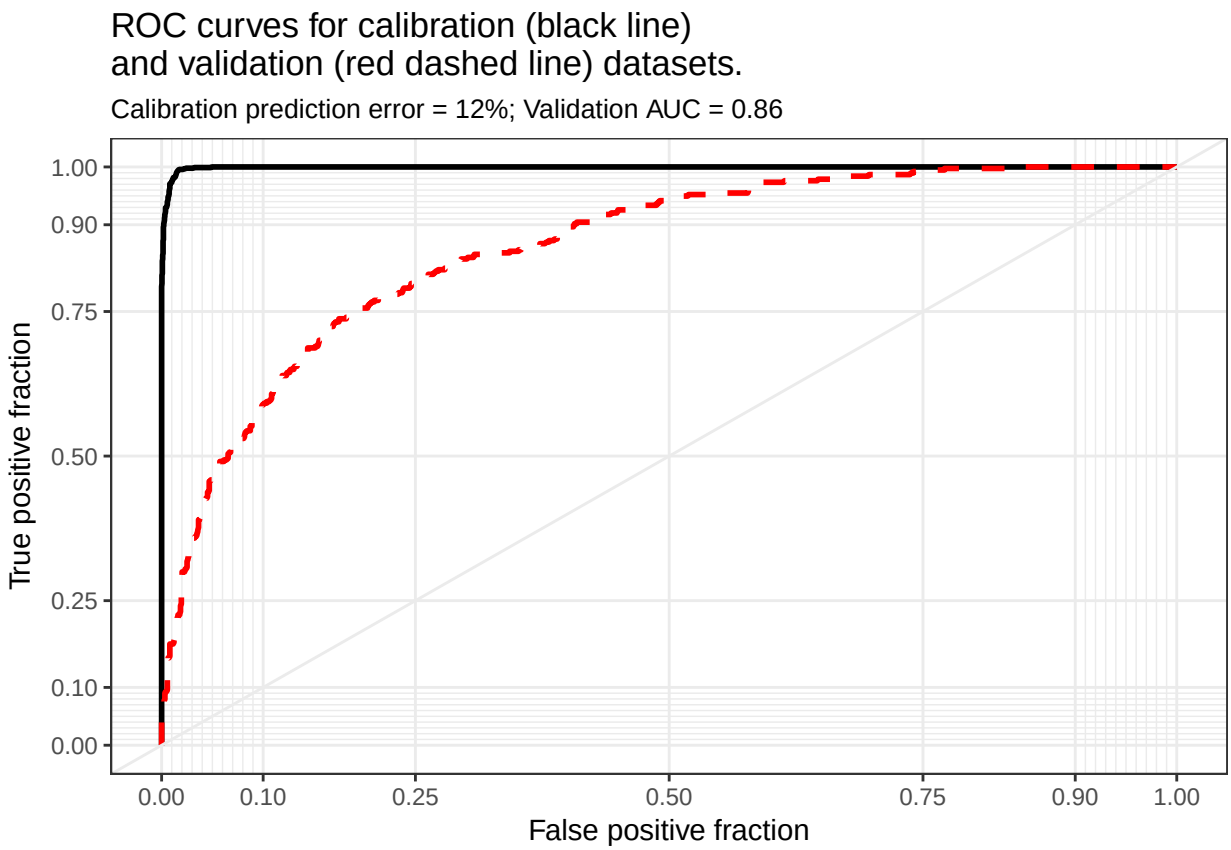

Figure 3.5: Receiver operator caracteristics (ROC) curves for both the calibration (black line) and validation (red dashed line) datasets.

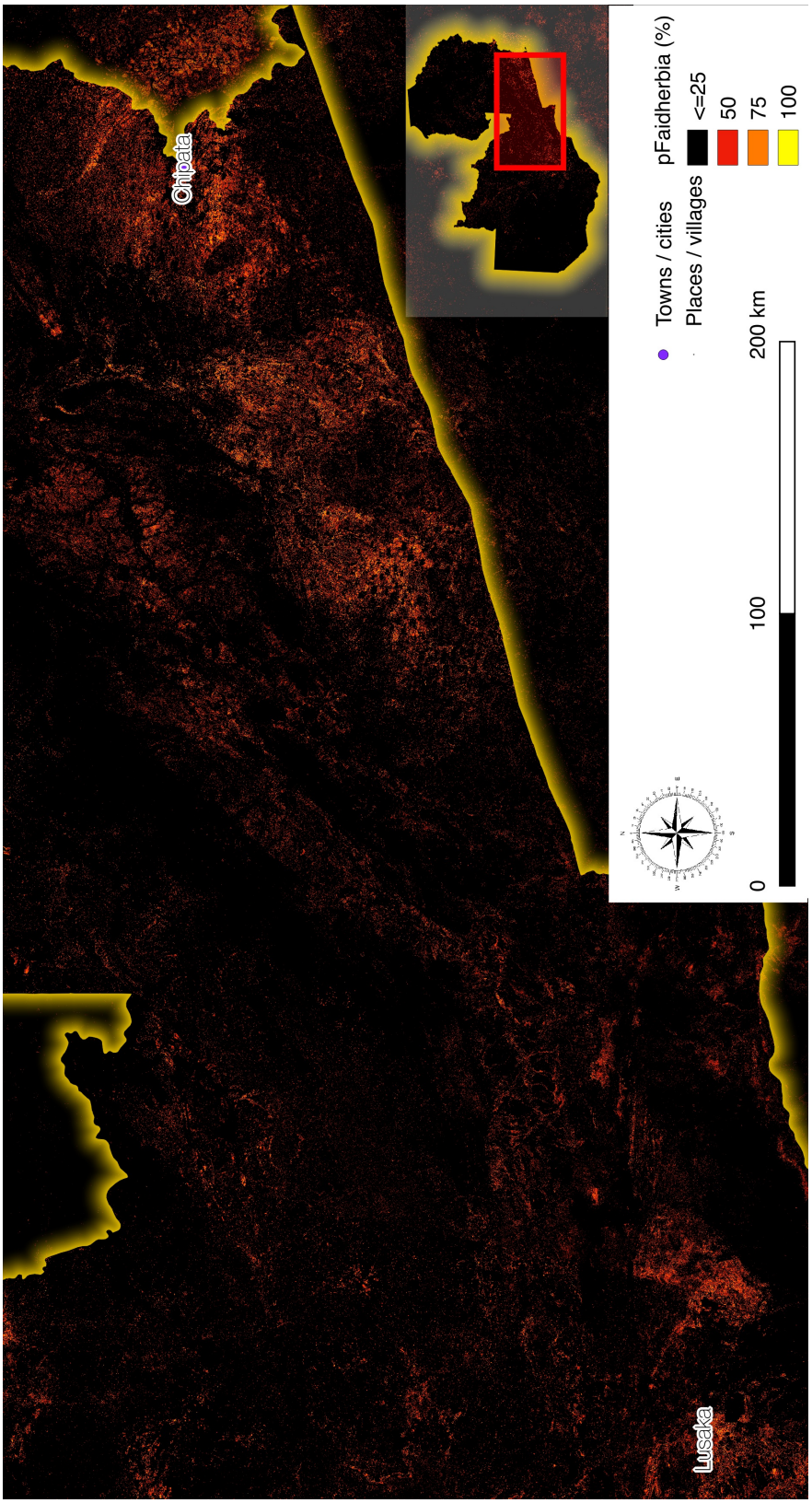

Figure 3.6: Map showing the predicted distribution of Faidherbia albida in the study area. Red and yellow areas indicate high predicted probabilities in terms of its occurence in a given pixel. The spatial resolution of the map is 30m (i.e. based on Landsat 8)

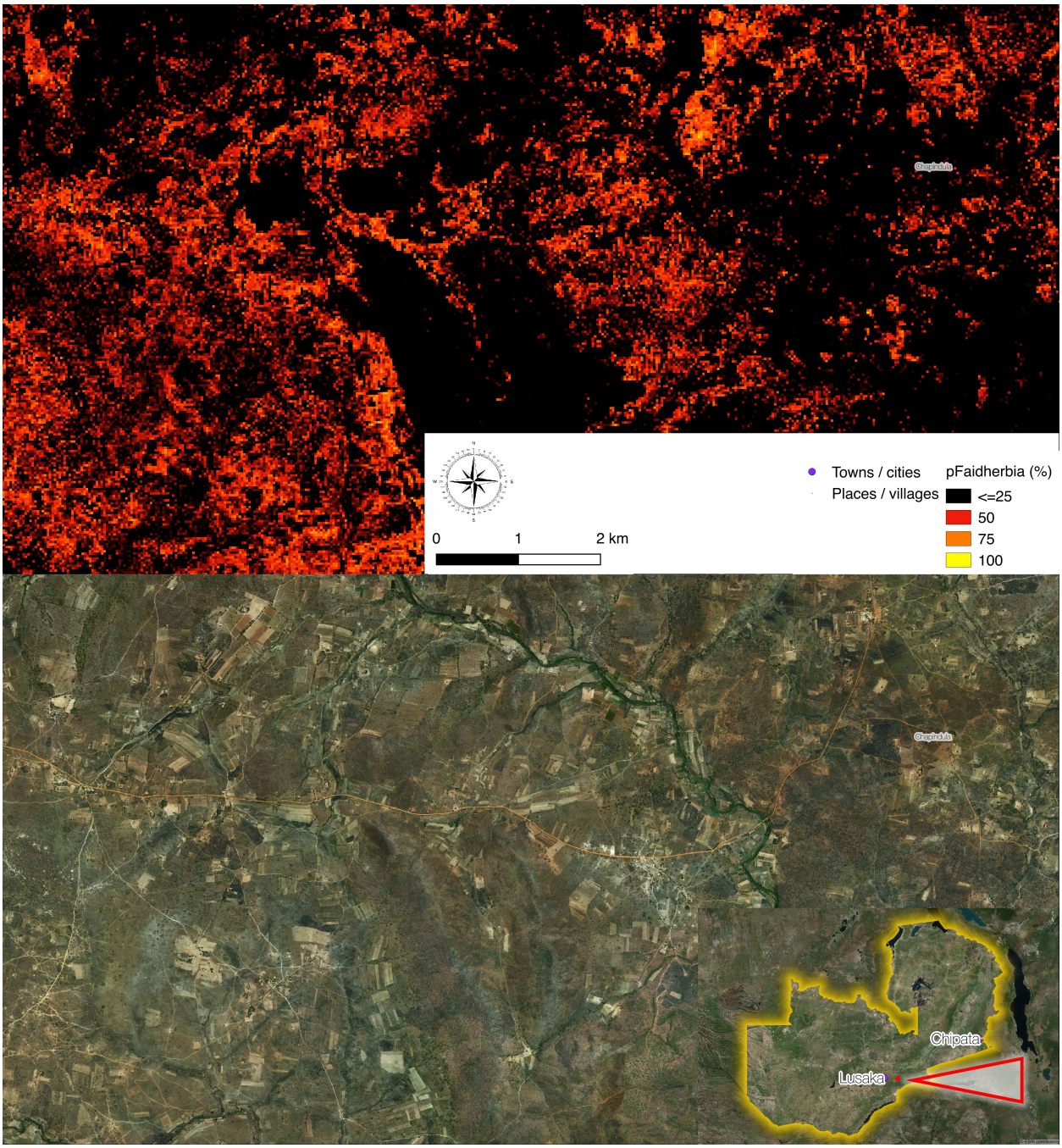

Figure 3.7: Map showing the predicted distribution of Faidherbia albida in in an area east of Lusaka (see arrow on the map inset in the lower-right corner). Red and yellow areas indicate high predicted probabilities in terms of its occurence in a given pixel. The spatial resolution of the map is 30m (i.e. based on Landsat 8). The map in the lower panel shows a high resolution satellite image for the same area.

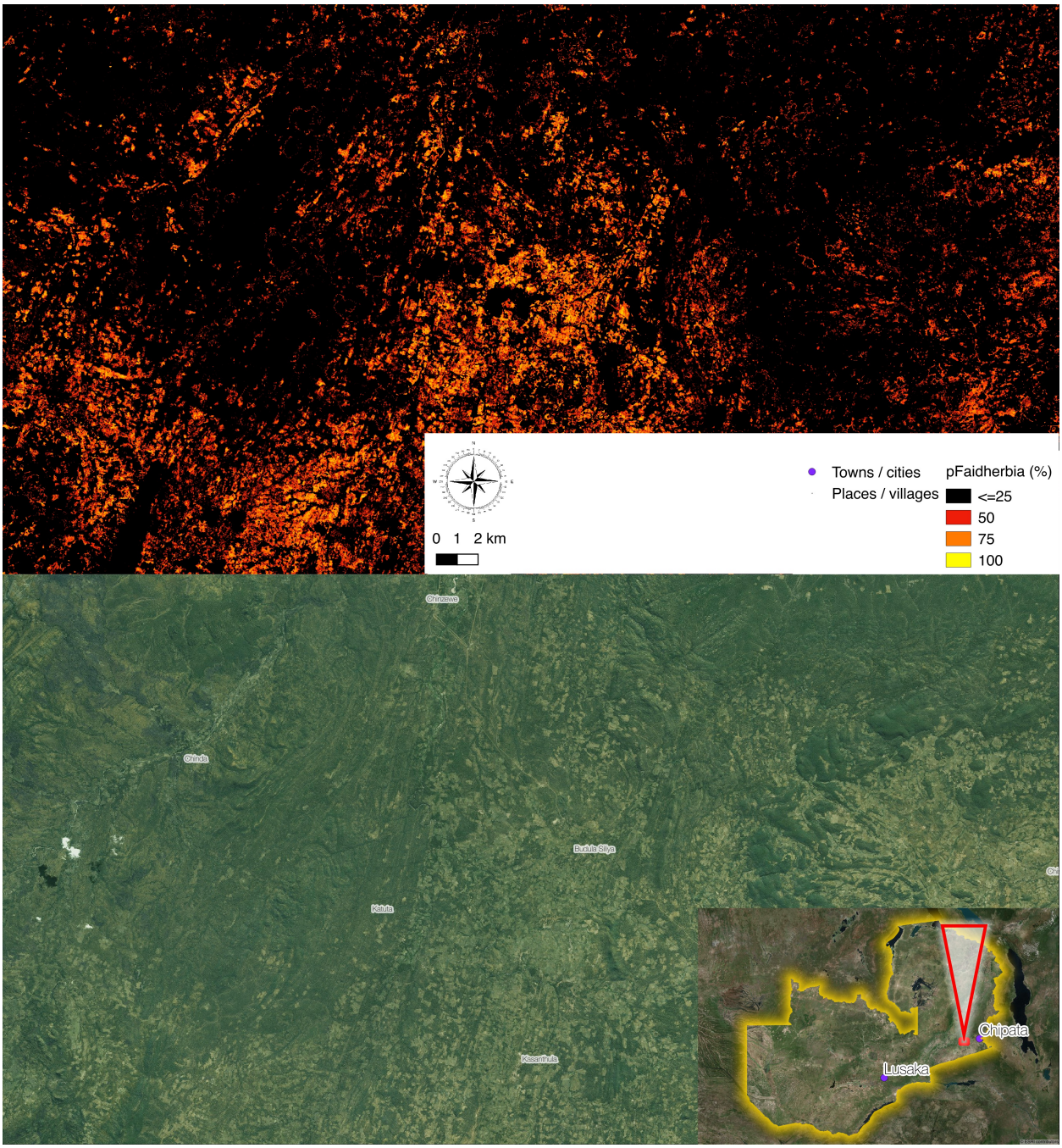

Figure 3.8: Map showing the predicted distribution of Faidherbia albida in in an area west of Chipata (see arrow on the map inset in the lower-right corner). Red and yellow areas indicate high predicted probabilities in terms of its occurence in a given pixel. The spatial resolution of the map is 30m (i.e. based on Landsat 8). The map in the lower panel shows a high resolution satellite image for the same area.

Table 3.2: Percentage of households growing fertilizer trees (by province), based on RALS survey data from 2015.

Province	Farm HHs	Fertilizer tree	Faidherbia albida	Gliricidia sepium	Sesbania sesban	Cajanua	Leucaena
Central	8.19	25.35	25.35	0.00	0.00	0.00	0.00
Copperbelt	6.92	3.13	2.08	0.00	1.04	0.00	0.00
Eastern	8.72	25.97	21.89	2.95	0.81	0.92	0.20
Luapula	9.97	21.43	0.00	0.00	7.14	14.29	0.00
Lusaka	6.50	21.26	21.26	0.00	0.00	0.57	0.00
Muchinga	11.26	59.38	59.38	0.00	0.00	0.00	0.00
Northern	7.78	3.28	0.55	0.00	1.64	1.09	0.00
Northwestern	26.00	4.80	0.00	0.00	4.00	0.80	0.00
Southern	9.04	22.95	22.55	0.20	0.00	0.20	0.00
Western	5.62	20.00	20.00	0.00	0.00	0.00	0.00
Total	100.00	21.76	19.19	1.35	0.81	0.72	0.09

3.4 Adoption (uptake) of fertilizer trees in Zambia

3.4.1 Summary of findings from the Rural Agricultural Livelihoods Survey

The RALS survey report[12] summarises findings on households practicing agroforestry in Zambia, with almost 15% of households reporting that they practice agroforestry. The spatial distribution of households practicing agroforestry in general largely followed that of *Faidherbia albida* shown in Figure 2.1. Of the 2,215 farmers reporting that they practiced agroforestry, *Faidherbia albida* was most common (19.1% of farmers), followed by Gliricidia (1.4%), Sesbania (0.8%) Cajanus (0.7%) and Leucaena (0.1%) (Table 3.2).

In Figure 3.9, we have summarised the findings of the RALS surveys in terms of sources of seedlings for *Faidherbia albida* by district in the country. Based on these data, the main source of seedlings is from projects and/or NGOs, followed by neighbours and relatives. Relatively few districts have private nurseries as a source. In districts such as Chipata, Chongwe and Mambwe there are multiple sources of seedlings, while for example Kabwe and Kafue appear to only source seedlings from projects and/or NGOs. In some parts of the country, such as Kalomo, Chibombo and Kitwe the main mechanisms for uptake of agroforestry seem to be through local diffusion (Figure 3.9).

Faidherbia albida seedlings appear to be sourced mainly from projects and/or NGOs according to the results of the RALS surveys (Figure 3.10), although there is a wide range of sources. If we look at *Gliricidia sepium*, which is an important fodder species in many countries in East and southern Africa, it is not widely utilized in Zambia and is found mainly in the Eastern Province (Figure 3.11).

[12] IAPRI, 2016. Rural Agricultural Livelihoods Survey: 2015 Survey Report. Lusaka, Zambia.

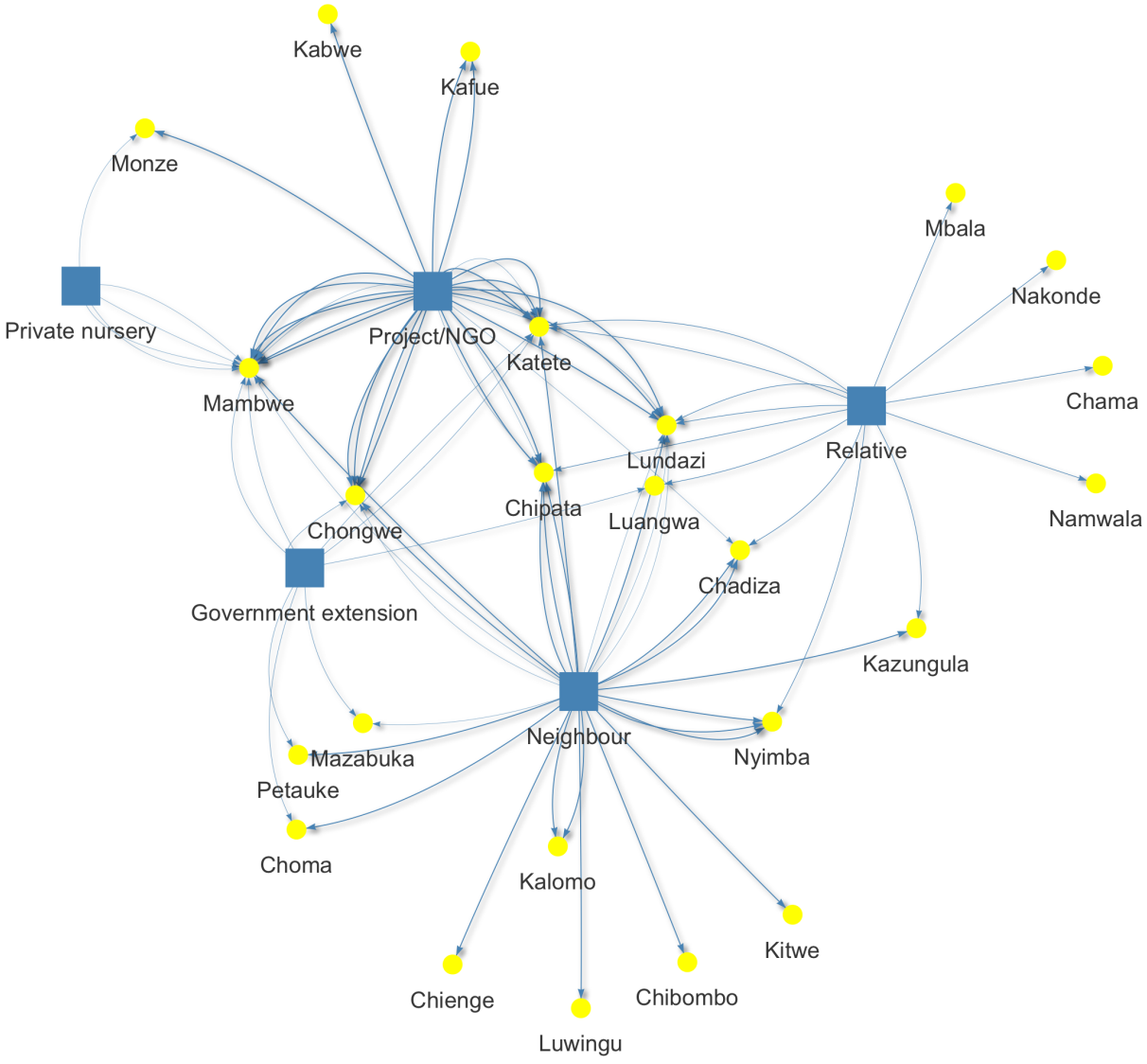

Figure 3.9: Network graphic showing sources of seedlings (blue squares) and destination districts (yellow circles) for agroforestry species surveyed as part of RALS in 2015. This analysis does not capture whether the source is from within a particular district or not.

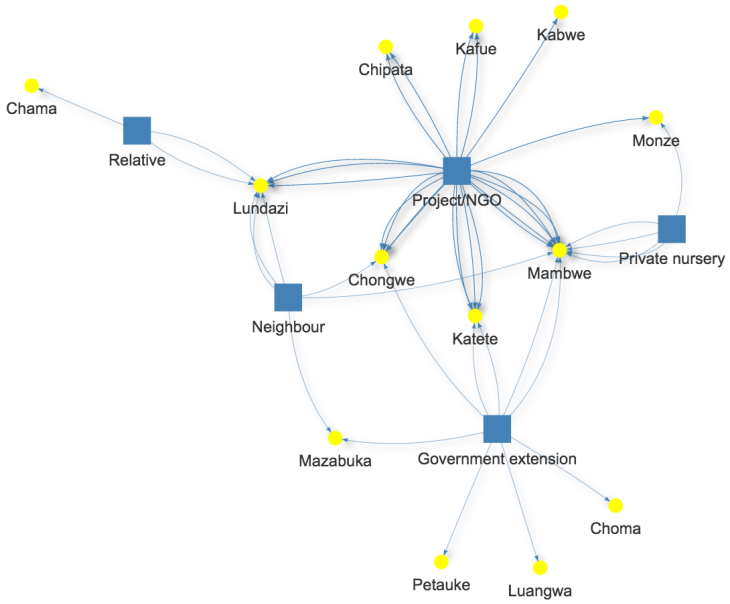

Figure 3.10: Network graphic showing sources of Faidherbia albida seedlings (blue squares) and destination districts (yellow circles). Source: RALS (2016)

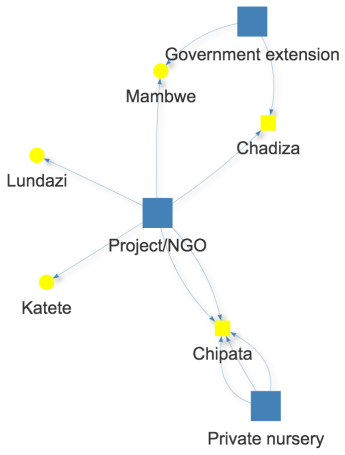

Figure 3.11: Network graphic showing sources of Glricidia sepium seedlings (blue squares) and destination districts (yellow circles). Source: RALS (2016)

3.4.2 On-farm surveys to assess uptake of *Faidherbia albida*

3.4.2.1 Household characteristics of sampled farmers by province

The on-farm surveys collected information from a total of 550 households, of which 288 were sampled from Eastern province and the remaining 262 from Lusaka province. Table 3.3 shows descriptive statistics of sampled farmers disaggregated at the provincial level.

In terms of household characteristics, there are only two variables that show significant differences between sampled households from the two provinces. In the Eastern province, there are more households that are headed by males, with a lower domestic asset index compared to households in Lusaka. The household domestic asset indicator is a weighted index of all domestic, productive and transport assets owned by the household and adjusted for their age. All other indicators in this category such as labor capacity, tropical livestock units (TLU), proportion of land controlled by males or females show no significant differences between the two provinces.

When it comes to farm characteristics, there are a number of differences that can be observed between households in the two provinces. Farms in Lusaka province are larger in size, with more cultivated land and plots, and on average lie on a higher altitude compared to farms in the Eastern province. There are also more on-farm trees in terms of numbers and diversity in farm households in Lusaka. Considering the adoption or uptake of other natural resource management (NRM) such as crop rotation, mixed cropping and zero tillage as a binary it is evident that that uptake is higher in Lusaka, but when a continuous measure of adoption, such as proportion of land under NRM or number of *Faihderbia albida* per ha, then extent of uptake is significantly higher in the Eastern province. Comparing farm characteristics, farmers who maintain more *Faihderbia albida* trees in their fields maintain more trees in general and have higher tree diversity than non-adopters in both districts. We also found that uptake of other natural resource management (NRM) practices was higher for adopters than non-adopters in Lusaka, in terms of number of NRM practices applied, but that non-adopters committed more land for NRM practices than adopters.

We compared the study regions by applying the Progress out of Poverty Index (PPI)[13], which is a poverty measure of the likelihood that a household falls below a certain threshold (in this case 1.25 USD per day) developed by the Grameen Foundation. From the results, households in Lusaka province have a lower likelihood of falling below the 1.25 USD poverty threshold (70% of households) compared to households in Eastern province, which have a likelihood of 77% of falling below this threshold. As shown in the last row in Table 3.3, adopters in Lusaka province have a lower likelihood (66%) of falling below the 1.25 USD poverty threshold compared to non-adopting households (74%).

Of the 550 farmers surveyed, just over 10% (57 farmers) had heard of ICRAF while about 68% (373 farmers) reported gaving received agroforestry training. Furthermore, of the 373 farmers in the survey who had agroforestry training, 50% received it from CFU, followed by extension officers (12%), the FAO CASU project (10%) and Kasisi (8%), as shown in Table 3.4. As the table also shows, only about ten organizations were listed as providing trainings, of which over 90% were projects related to Conservation Agriculture activities.

In all the three surveyed districts, the most important sources of *Faidherbia albida* seedlings for farmers were from government extension, projects/NGO such as CFU, CASU and World Vision. Private nurseries alongside friends and neighbors are also other important sources (Figure 3.12). These findings are similar to those reported from the RALS surveys shown earlier (Figure **??**)

[13] http://www.progressoutofpoverty.org/country/kenya

Table 3.3: General differences between adopters and non-adopters of Faidherbia albida. Notes: Mean values are shown with standard deviations in parenthesis.

	Eastern (n=288)		Lusaka (n=262)	
	Non-adopters	Adopters	Non-adopters	Adopters
Household characteristics				
Male household head (dummy)	0.74	0.86**	0.74	0.76
	-0.44	-0.35	-0.44	-0.43
Household size	4.1	4.76**	4.44	4.81
	-2.27	-2.61	-2.25	-2.1
Household labor capacity	3.14	3.78***	3.34	3.79**
	-1.75	-1.96	-1.75	-1.62
Household domestic asset index	72.09	66.87	73.67	91.19
	-77.61	-93.59	-106.32	-90.81
Agroforestry training (dummy)	0.56	0.65	0.47	0.65***
	-0.5	-0.48	-0.5	-0.48
Proportion of male-controlled land	0.55	0.63	0.55	0.65
	-0.5	-0.48	-0.5	-0.48
Proportion of female controlled land	0.17	0.05***	0.14	0.08
	-0.37	-0.21	-0.35	-0.28
Tropical livestock unit (TLU)	4.36	3.43	3.55	4.4
	-5.95	-5.66	-9.08	-6.79
Farm characteristics				
Total farm size (ha)	4.33	2.95	5.2	4.21
	-12.57	-2.99	-10.64	-4.82
Cultivated land (ha)	2.65	2.47	4.19	3.55
	-3.45	-2.3	-10.52	-4.61
Number of plots cultivated	1.08	1.04	1.1	1.1
	-0.31	-0.19	-0.33	-0.35
Altitude (m)	289.31	333.46***	172.31	171.86
	-125.33	-131.45	-143.08	-104.83
Total number of trees	22.05	35.07**	48.96	34.01*
	-38.46	-43.88	-85.73	-41.74
Tree diversity (number)	1.26	0.98*	1.83	1.78
	-1.21	-1.13	-1.32	-1.11
Number of trees per ha	11.65	18.62***	19.06	13.44*
	-18.19	-21.73	-35.98	-16.25
Adoption of NRM practices				
Adoption of NRM paractices (dummy)	0.86	0.88	0.89	0.95*
	-0.34	-0.33	-0.31	-0.22
Number NRM practices adopted	2.88	2.93	2.59	2.73
	-1.8	-1.72	-1.73	-1.57
Area under NRM practices (%)	77.26	78.07	75	65.43**
	-21.13	-22.14	-24.48	-32.84
Welfare indicator				
Likelihood of living below USD1.25 2005 PPP	73.79	78.58	74.34	66.32**
	-26.93	-22.87	-26.13	-27.99
No. of cases	96	192	109	153

Table 3.4: Farmer responses on who had given them training on agroforestry (N=373).

Who did training	N	Percent
Conservation Farming Unit (CFU)	185	50%
Agriculture/Block/Camp Extension Officer	43	12%
Conservation Agriculture Scaling Up (CASU)	36	10%
Kasisi Ag Training Centre	28	8%
Lead Farmer	24	6%
World Vision International	15	4%
Ministry of Agriculture	11	3%
CLUSA Farmer to Farmer Program	10	3%
COMACO	7	2%
Friends and Family	2	1%
Zambia National Farmers Union (ZNFU)	2	1%
Other	10	3%

3.4.2.2 Comparing remote sensing based predictions of *Faidherbia albida* and on-farm survey results

As shown in Figure 3.13, our predictions of *Faidherbia albida* presence correspond well with those observed in the on-farm surveys for the two provinces and three districts included in the study, with the remote sensing models being able to separate farmer fields with/without *Faidherbia albida* well. This means that maps of the occurence of fertilizer trees using the models developed as part of this study are likely to be able to distinguish between farmers' field with and without *Faidherbia albida* with a resaonable level of accuracy. However, detection rates for *Faidherbia albida* are likely to improve with larger sample sizes and future work should also focus on sensors such as Sentinel-2A from the European Space Agency (ESA), which has a higher spatial resolution and better radiometric characteristics than Landsat 8. Nonetheless, these results are highly promising and show the potential for the application of remote sensing and geospatial methods for the assessment of uptake of agroforestry practices such as the use of fertilizer trees.

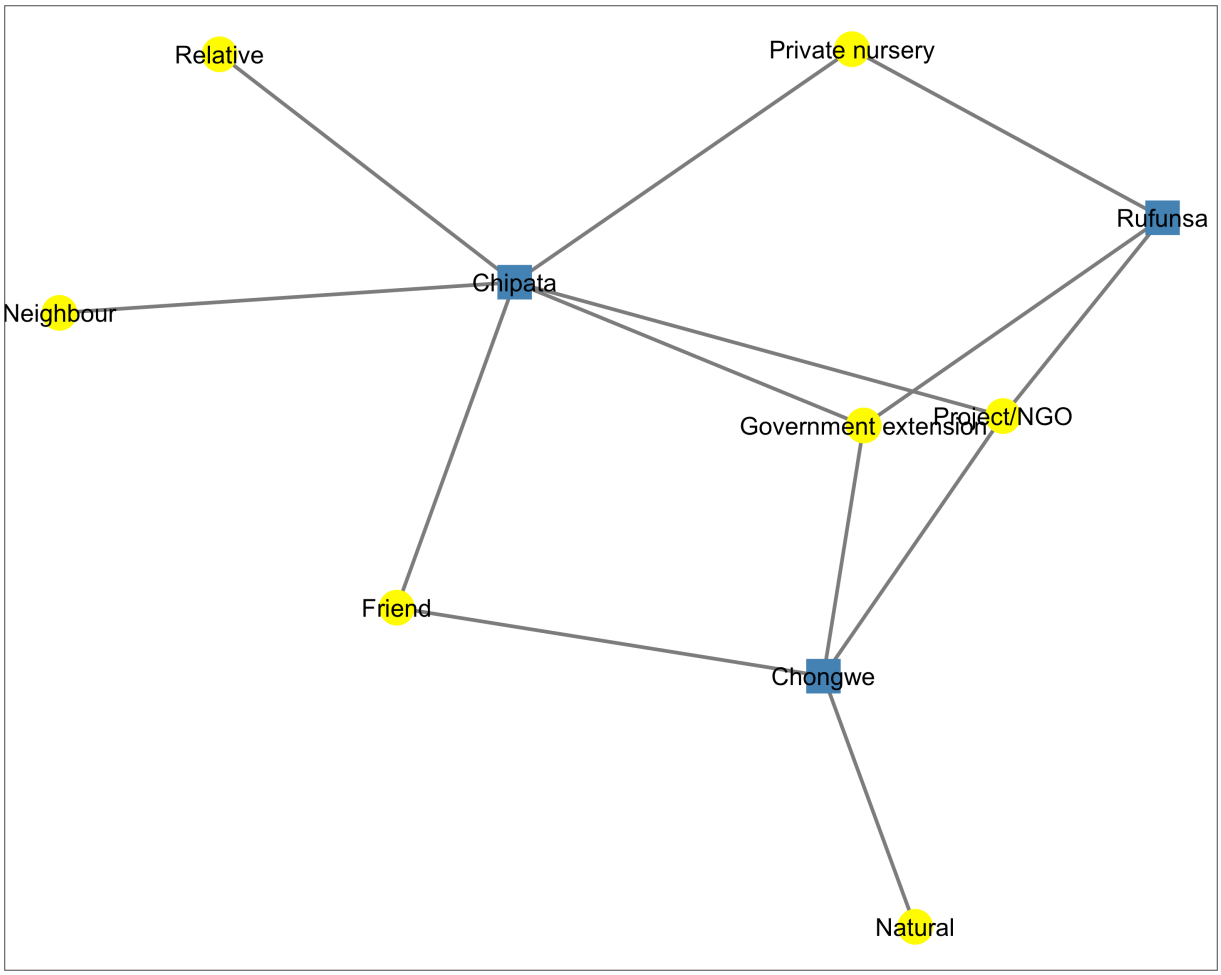

Figure 3.12: Network graphic showing sources of Faidherbia albida (yellow circles) and destination districts (steel-blue boxes/squares)

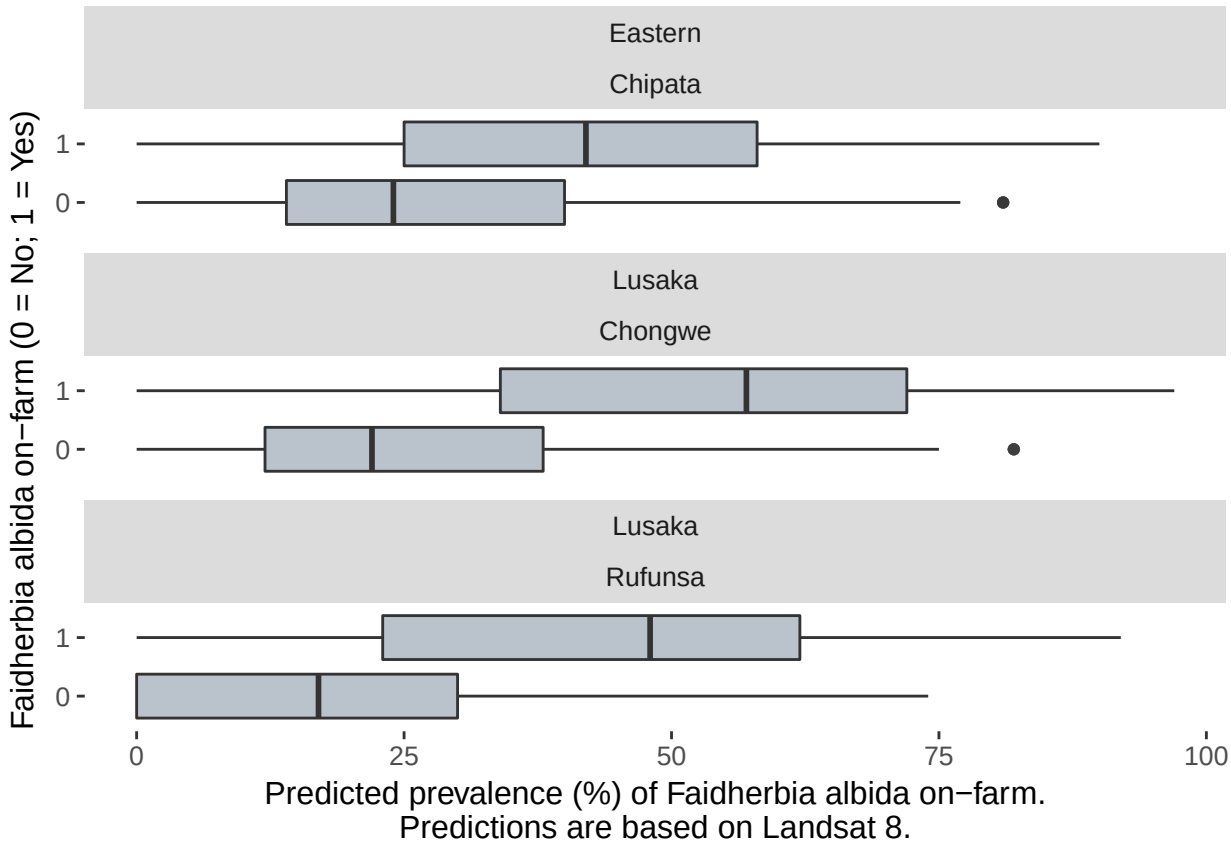

Figure 3.13: Predicted versus observed occurence of Faidherbia albida on-farm for the two provinces and three districts surveyed, based on surveys of 547 individual HHs. Where farmers reporting having Faidherbia albida trees on their farm, three trees were georeferenced per plot and the plot coordinates were also taken.

3.4.3 Attribution to ICRAF/CGIAR

3.4.3.1 ICRAF Operations in Zambia: 1986-2006

ICRAF carried out **Diagnosis and Design** from 1985-87. In 1987, in collaboration with Zambia Agricultural Research Institute (ZARI), they began improved fallow trials at Msekera Research Station (Chipata). ICRAF also supported research at Chalimbana Research Station (Lusaka), but to a much lesser extent. From 1987 to 1996, the focus was research station trials on species selection, production, coppicing, and incorporation of biomass into the soil. By the early 1990s, ICRAF had begun coordinating on-farm trials to test different systems and species. Issues addressed included pest management, site selection, seed sourcing and nursery systems, and adoption issues.

Starting in 1997, scaling up efforts for improved fallows were heavily promoted through the Swedish International Development Agency (SIDA) Zambia Agroforestry Project, the Canadian International Development Agency (CIDA) Zambezi Basin Agroforestry Project, the USAID Target Project, and the SIDA Soil Conservation and Agroforestry Extension (SCAFE) Project. With partners, ICRAF established a scaling team to promote adoption of improved fallows, not only in Zambia but across southern Africa. An informal Adaptive Research and Development Network (ARDN) with many different stakeholders was facilitated by ICRAF. Examples of promoting organizations during this period were World Vision, the District Women Development Association (DWDA), the Eastern Province Development Women Association, PLAN International, and KEPA (a Finnish development organization).

Dissemination was multipronged and included 1) extension officer trainings, 2) lead farmers trainings, 3) NGO trainings, and 4) exchange visits to research and on-farm trials. ICRAF developed trainings materials, pamphlets, leaflets, and policy briefs. It also used schools and radio across the Eastern Province. Direct training and seed were given to lead farmers to help spread the technology. Other efforts that ICRAF was involved in during that period included a National Steering Committee (NASCO) for agroforestry facilitation and the African Network for Agroforestry Education (ANAFE). By the 2000 - 2001 cropping season, over 20,000 farmers were planting improved fallows (about 21% of farmers) in the districts around Chipata. By the time ICRAF exited Zambia in 2006, over 61,000 farmers had been "reached" with these technologies. Interviewees did say that adoption, albeit good in some areas around Chipata, was overall low.

ICRAF only carried out a few trials of intercropping systems at the research stations. Most of the work on alley cropping, intercropping, and Faidherbia was carried out in Malawi. Mixed intercropping, especially relay intercropping, had its benefits on smaller plots and where land was scarce. Today one sees very little of this practice promoted except by NGOs and companies who provide incentives, such as free seed or other inputs, and/or require planting of trees as part of their purchasing contract. Otherwise, some interviewees suggested only resource-rich and larger farmers are practicing any agroforestry system. In addition to fertilizer trees, whilst ICRAF was in Zambia, they also actively worked on fruit tree domestication and fodder banks. Some of the fodder banks included fertilizer trees, in a system known as "cut and carry".

3.4.3.2 Post ICRAF Period: 2007-present

ICRAF left operations at Msekera Research Station in the hands of the ZARI, with a little support by partially funding a ZARI position for continuing and maintaining the research trials. Funding and consolidation of ICRAF operations was the main reason for the closure of their operations in Zambia. The terms used most by interviewees was that ICRAF left a "vacuum" and "gap" in agroforestry in Zambia. The intention was for ZARI to continue research activities whilst the government extension services would continue promotion. ICRAF as a lead research institution was hosted by

the Government of Zambia and had government employee researchers to work alongside them as a commitment to continuity of the technology beyond the project cycle. However, this continuity did not occur. Also, there were expectations that donors and NGOs would continue to fund activities.

Opportunities to continue promoting agroforestry in the Eastern Province and expand to new areas were not pursued. In active areas of adoption, extension officers began to focus on other agricultural technologies leading to the decline of fertilizer tree activity. What ICRAF had built up over the years basically died out, including NASCO and ANAFE. In fact, some interviewees noted that ZARI stopped funding research in agroforestry. However, ZARI is maintaining the research trials and a gene bank (started by ICRAF) in Msekera. Copperbelt University continued to offer a degree in agroforestry, and some agroforestry research continued by scientists at University of Zambia (UNZA). What was left were a few NGOs and donor efforts to promote fertilizer trees as part of other projects. Some NGOs interviewed mentioned they want to do more fertilizer tree promotion but need ZARI to step up and help facilitate these efforts. There was a sense that ICRAF "owned" agroforestry technologies in Zambia, and those with agroforestry plots still referred to them as "belonging to ICRAF". In other words, after all the years of agroforestry research and promotion, there appears to be a lack of "sense of ownership" by the government, the farmers, or other entities to agroforestry.

The absence of fertilizer tree activity over the last decade to a large degree was in part due to heavy promotion of Conservation Agriculture by many of the same institutions that were and would be interested in agroforestry. In some institutions, fertilizer trees are promoted as add-ons to the conservation farming technologies, i.e., CA plus trees. However, fertilizer trees, for the most part, are seen as minor and not widely adopted in the CA projects, even in the widely recognized Conservation Farming Unit (CFU). The CFU focus and most CA activities are with Faidherbia only. There is much less research on Faidherbia compared to the species ICRAF worked on[14]. There has been some applied research on Faidherbia by Kasisi and Golden Valley Research Trust (GART) but very little at present due to funding constraints.

The other main way fertilizer trees are currently promoted is through tobacco, cotton, or groundnut processing companies who encourage their farmers to plant fertilizer trees. These companies see it as part of their corporate social responsibility to reforest and, in some cases, as part of the contract, provide direct incentives and/or require their farmers to plant trees. COMACO is a good example of an active Gliricidia intercropping campaign. Under the rubric of climate smart agriculture, fertilizer trees and agroforestry are also being discussed as providing important ecosystem benefits. This is an important part of Evergreen Agriculture led by ICRAF. Papers have been prepared indicating their need for payments for environmental services to farmers for growing these trees[15]. ICRAF returned to Zambia in 2014 and has three scientists based in Lusaka. Currently, the focus is on agroforestry practices such as fruit trees, markets, and value chains. ICRAF is also involved in policy discussions and perhaps rewriting the 2013 Zambia Agroforestry Strategy[16]. Other evidence of CGIAR attribution related to fertilizer trees in Zambia is CIMMYT work with Total Land Care and COMACO on Gliricidia and Cajanus intercropping systems with maize. *Cajanus cajan* is a product of CIAT-ICRAF's program in Malawi.

[14] One exception is Shitumbanuma, V. 2012. Analyses of crop trials under Faidherbia albida: Results of crop yields for the 2010/2011 agricultural season and overall summary of yields and yield trends from 2008 to 2011, Conservation farming unit. Lusaka Zambia. Also, as mentioned, GART and Kasisi have some Faidherbia trials.

[15] See Ajayi et al. 2008. Payment for Environmental Services (PES): A Mechanism for Promoting Sustainable Agroforestry Land Use Practices among Smallholder Farmers in Southern Africa. Presented at Tropentag 2008 Conference on International Research on Food Security, Natural Resource Management, and Rural Development, and Garrity D. et al. 2010. Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Security. 2:197-214.

[16] Republic of Zambia. 2013. National Agroforestry Strategy 2013-2020. Ministry of Agriculture and Livestock and World Agroforestry Centre. Lusaka, Zambia.

Appendix A: Adoption Issues (including comments from interviews)

Time constraints:

- Scientifically, the fertilizer trees work and provide soil benefits but farmers want something in return for the cost of waiting for trees to mature.
- Understandable lack of patience by farmers during transition period to sustainable agriculture practices. Even three years is a long time to wait for improved fallows to show benefits.
- Farmers don't see long-term soil fertility benefits of trees – want immediate returns.
- Those who have trees usually use them less for soil benefits on land itself but for other purposes such as "cut and carry" to amend vegetable gardens. Aka, biomass transfer.
- ICRAF focus over time shifted toward Tephrosia and Cajanus promotion because they grew faster than Gliricidia and Sesbania and provided income.
- Farmers do tend to allow naturally regenerated Faidherbia on-farm but are more wary of the opportunity costs associated with planting alleys of Faidherbia.

- Farmers are always intercropping other crops such as beans in maize; it's a traditional system so introducing new species is a novelty that needs time and effort to adopt.

Labor constraints:

- Pruning and related activities interfere during the time farmers are getting ready to plant food crops.
- Labor intensity – planting, tending, and pruning takes too much time and effort. A counter-argument from some interviewees argued that farm work is only four months – what do they do with the other (idle?) time?
- Cow peas and other annual leguminous food crops provide food within a few months, unlike fertilizer trees, except Pigeon Pea.

Tenure and land use:

- Improved fallows could be appealing if land is scarce. As land becomes scarcer, perhaps more farmers will pick it up. Therefore, more uptake is seen in Malawi because of land pressures.
- Those with "customary" ownership rights tenure may feel tenure is insecure and as such be less likely to grow trees. That is why relay intercropping with easy-to-remove perennial trees (e.g., Cajanus and Tephrosia) is more appealing.
- Land opportunity cost – trees utilize food crop space.

Fertilizer subsidies:

- Government subsidizes inorganic mineral fertilizers which is the "easyroute" for farmers.
- Reintroduction of fertilizer subsidy program was during the height of ICRAF's improved fallow promotion.
- As fertilizer subsidies goes up, likely more fertilizer trees will be adopted.

Institutions:

- Agroforestry in Zambia has focused on projects and not on institution and capacity building.
- Projects are usually of 3-5 years' duration, but trees and many of these systems take longer periods to show benefits.
- Donors and projects do not include local organizations enough to ensure ownership and continuity of project activities.

- Funders are too project-focused with without institutionalizing it in the mainstream.
- Lack of donors, industry, NGOs, or government entities to continue promoting fertilizer trees, other than as add-ons to other foci, e.g., Conservation Agriculture.
- NGOs and donors that do promote fertilizer trees do not follow up after the project ends, so one finds scattered plots with trees.
- Some adoption is "pseudo-adoption" – only involved to the extent of payments to farmers. For example, the project buys seed from trees planted. Or, only one or two trees are planted, which does not have the intended impact on farming system. National Policies
- Lack of effort (push) and funds by government research entities to continue research on trees after ICRAF left.
- National Agricultural Policy only mentions agroforestry briefly.
- Government policy focuses on commercial industry agriculture.
- Agroforestry is just a sentence in Ministry of Agriculture policy.
- Small allocation for agriculture in general budget.
- Trees for climate change now focus on reforestation and not integrating with farming systems.
- Political climate has created a type of dependency – smallholder farmers see projects as a "free lunch."
- Perhaps colonial conservation practices, such as forced contouring and grass strips, has led to opposition to tree planting.

Extension:

- Extension workers are involved with promoting many other agricultural technologies, some of which have better financial support.
- Extension workers in some cases have inadequate or outdated training in agroforestry.
- Extension system failure; no good transmission from research to farmer.
- Research scientists (e.g., Ph.D. level) don't link well at field level which affected scaling up efforts.
- There is no longer the respect there once was for government positions, especially extension officers.
- Extension workers themselves can be skeptical about agroforestry. As such, when ICRAF left, extension officers did not pick up on agroforestry.

Other:

- More is needed on products and marketing for fertilizer trees, e.g., fuelwood or seed.
- Farmers don't like dealing with thorns on trees.
- Seed unavailability is why farmers are only planting a few trees (a small area).
- Farmers may be called adopters even if they are only doing a corner of their field.
- Farmers cannot afford to buy and plant trees because of other inputs costs.
- Animals browse on trees. Faidherbia is known to be less preferred than others.
- It is traditional to burn fields before cropping season; perception is that it is clean and fresh – new foliage, but can destroy trees in process.
- Wildfires by burning thickets to trap rabbits and mice – fire spreads onto farms and kills trees.
- Agroforestry adoption has always been low.

Appendix B: Institutions and Individuals Contacted

Name	Type
Zambia Agricultural Research Institute (ZARI) http://www.agriculture.gov.zm/	Government
Golden Valley Agricultural Research Trust (GART)	Public private partnership (trust)
Catholic Relief Services (CRS) https://www.crs.org/our-work-overseas/where-we-work/zambia	NGO
Conservation Farming Unit (CFU) http://conservationagriculture.org	NGO (but started through government)
Copperbelt University (CBU)	Academic
Programme Against Malnutrition (PAM)	NGO
Kasisi Agricultural Training Centre (KATC) http://www.katczm.org/	NGO
World Wide Fund for Nature (WWF)	International NGO
SNV	International NGO
University of Zambia (UNZA)	Academic
World Vision International http://www.wvi.org/zambia	International NGO
Green Living Movement	NGO
Zambia National Farmers Union (ZNFU) http://www.znfu.org.zm/	National membership-based organization
National Union for Small Scale Farmers in Zambia (Nusfaz)	National membership-based organization
COMACO	Private company
Total Land care	NGO
Grassroots trust	NGO
Centre for Environment Research Education and Development - Patrick Matakala (previous ICRAF employee)	NGO/Consulting
World Fish	Research institute
FAO	UN organization
CIFOR	Research institute
Biocarbon partners	International NGO
Musika	NGO
Vitalite	NGO
Indaba Agricultural Policy Research Institute (IAPRI)	NGO
OXFAM	International NGO