DISSERTATION

DISTRIBUTION AND ECONOMIC ANALYSIS OF *PROSOPIS JULIFLORA* IN ETHIOPIA

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ABSTRACT

DISTRIBUTION AND ECONOMIC ANALYSIS OF *PROSOPIS JULIFLORA* IN ETHIOPIA

Invasive species are one of the drivers of biological and socio-economic changes around the world. Over the past 30-40 years, the non-native *Prosopis juliflora* plant has emerged as a major invader of the arid and semi-arid regions of Ethiopia. Information on its distribution, impact, use and management is highly needed to contain and prevent the spread of this highly invasive plant. In the first study, I used a correlative modeling framework to track and map the current and potential distribution of *P. juliflora* in Afar, north-eastern Ethiopia. Specifically, I used time-series of Moderate Resolution Imaging Specrtoradiometer (MODIS) satellite imagery, 143 species-occurrence records and the Maxent modeling technique to map its current distribution. I then used topo-climatic predictors, species-occurrence records and the Maxent software to map its forecasted distribution. I found that the current extent of *P. juliflora* invasion in the Afar region is approximately 3,605 Km^2, while its predicted distribution is approximately 5,024 Km^2. My findings demonstrates that MODIS vegetation indices and species-occurrence points can be used with Maxent modeling software to map the current distribution of *P. juliflora*, while topo-climatic variables are good predictors of its potential habitat in Ethiopia.

In the second study, I used a participatory research framework to map *P. juliflora* over a fine geographic scale, and to identify the major resource related problems in the region. I learned about the introduction history, spread, impacts, uses and traditional management practices of *P. juliflora* in Afar by interviewing 108 pastoralists and agro-pastoralists. Additionally, I detected the land-cover categories most affected by *P. juliflora* invasion by superimposing community produced maps on ancillary land-cover layers, and performing overlay analysis. *Prosopis juliflora* has highly invaded grasslands and open areas in Afar. The species displaces useful native grass and forage species, which are important for

sustaining the region's wildlife and livestock resources. In addition to threats from invasive species, Afar people face conflicts from neighboring Issa ethnic groups, and land-grabs from the central government and foreign investors. The findings demonstrates that participatory mapping methods are suitable for mapping species distribution, detecting land-cover changes, and managing invasive plants.

High invasive species control costs have swayed most developing countries to adopt cost effective *P. juliflora* eradication and utilization practices. However, the effectiveness and economic viability of these new approaches have not been thoroughly tested. In the third study, I used an economic analysis framework to assess the economic feasibility of selected *P. juliflora* eradication and utilization methods that are practiced in southern Afar. The dominant *P. juliflora* eradication option was to convert infested lands into irrigated farms, while the preferred utilization options were to make animal fodder from *P. juliflora* seed pods, and to produce charcoal from *P. juliflora* wood. I interviewed 19 enterprise owners (i.e., farmers, flour producers and charcoal makers) and collected primary data on prices, yields, costs and revenues. I assessed the economic feasibility of the selected methods by performing enterprise, profitability, sensitivity and risk analyses over 10 years and an interest rate of 10% per year. Converting *P. juliflora* infested lands into irrigated agriculture is a profitable and risky *P. juliflora* eradication approach. Charcoal making is a moderately profitable and less risky utilization approach, while flour production is a risky and an un-profitable utilization approach. Introducing new changes in the production and management steps of flour production may be needed to make flour enterprises profitable. My overall economic analysis suggests that *control through utilization* may be one of the effective and economically viable *P. juliflora* management strategies currently accessible to Ethiopia. I generated reliable information on the distribution and impacts of *P. juliflora* in Afar by employing a wide variety of scientific approaches. My results can guide local level *P. juliflora* utilization and control efforts in Afar, while my methodologies can be replicated for managing invasive plants in other developing countries.

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CHAPTER 1: INTRODUCTION

Invasion of non-native species is one of the major drivers of environmental and socio-economic changes around the world. Over the past 30-50 years, non-native *Prosopis* species have emerged as a major invasive plant of the arid and semi-arid lands of eastern Africa. Burkart et al. [1] described the genus *Prosopis* to have 44 species. Pasiecznik et al. [2] identified *Prosopis glandulosa*, *P. velutina, P. pallida,* and *P. juliflora* to be highly invasive. *Prosopis juliflora* is the only reported invasive *Prosopis* species in Ethiopia. Hybridization is common among *Prosopis* species [2]; however, to date, no characterization studies have been conducted to determine if other invasive *Prosopis* species and their hybrids exist in Ethiopia.

Invasive species are often tracked and mapped using Species Distribution Modeling techniques (SDMs) [3, 4]. The number and application of SDMs is increasing. Currently, the number of SDMs and software packages available to users exceed 30 [4, 5]. SDMs work by relating geographically referenced species-occurrence data with environmental variables. First, the values of the environmental variables used in the model are extracted for the species-occurrence data. Next, other locations with similar environmental values are identified, and relative habitat suitability for species-occurrence are determined by applying mathematical relationships among the occurrence-records and the environmental variables.

Environmental variables may include climate, topography, soils, satellite images and others. The types of environmental variables used for mapping current and potential distributions have not been clearly stated in the SDM literature. Current distribution is often mapped using remote sensing predictors, while potential distribution is predicted using species presence records, and topo-climatic (topographic and climatic) predictors [6-8]. Bradly et al. [9] found that including remote sensing predictors in potential distribution models can underestimate predicted distributions. Similarly, Li and Guo [10] demonstrated that a single class of interest, such as vegetation type, can be accurately mapped using remote sensing imagery, species presence records and the Maxent correlative modeling technique. Using time-series of Landsat 8 imagery and different vegetation indices, Evangelista et al. [11] mapped the current distribution of *Tamarix* in southwestern Colorado (United States). Current distribution maps show actual species distributions and are needed by land managers for controlling existing invasions. Conversely, potential distribution maps are risk maps that show predicted distributions. Potential distribution maps are usually used as part of a risk assessment to prioritize a species or for Early Detection and Rapid Response (EDRR) efforts. Regardless, no published studies could be found that used satellite imagery, topo-climatic predictors, species-occurrence data, and correlative modeling techniques to map and predict the distributions of *P. juliflora* in Ethiopia. In chapter two[1], I aim to: a) map the current distribution of *P. juliflora* in Afar (Ethiopia) using time-series of MODIS remote sensing predictors, species presence records, and Maxent modeling software; and b) map the potential distribution of *P. juliflora* in Afar (Ethiopia) using topo-climatic predictors.

In chapter three[2], I use a participatory research framework to identify major resource related problems in Afar, and map *P. juliflora* over a fine geographic scale. Several forms of participatory research methods have been described in the literature. Rapid Rural Appraisal (RRA) and Participatory Rural Appraisal (PRA) were the dominant participatory research approaches in the 1970s [12, 13]. The RRA and PRA use simple techniques such as sketch mapping, transect walks, and time line analysis to represent and incorporate local knowledge in planning and decision making [14]. An attempt to merge simple PRA techniques with Geographic Information Systems (GIS), especially in developing countries, has led to the creation of Participatory GIS (PGIS) [15, 16]. An equivalent term used in developed countries is Public Participation GIS (PPGIS). Meanwhile, new terminologies, such as Participatory Global Positioning System (PGPS) and Participatory Remote Sensing (PRS), have been recently introduced into the participatory research vocabulary [17, 18]. As a concept and a tool both PGIS and PPGIS have not been clearly defined and their meaning and interpretation is open to research [14, 19].

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[1]Paper published in the PLOS ONE journal.
Mapping current and potential distribution of non-native *Prosopis juliflora* in the Afar region of Ethiopia. Tewodros T. Wakie, Paul H. Evangelista, Catherine Jarnevich and Melinda Laituri, 2014.
PLoS ONE 9(11): e112854. doi:10.1371/journal.pone.0112854.

[2] Manuscript accepted for publication by Applied Geography.
Assessing the distribution and impacts of *Prosopis juliflora* through participatory approaches. Tewodros T. Wakie, Melinda Laituri and Paul H. Evangelista, 2015.

Here, I describe my study using the widely recognized terminologies, participatory research and participatory mapping.

Although participatory research methods have been used in land-use planning, natural resource management, and conflict-resolution [14, 20-21], to date very limited studies applied these research techniques in an invasive species management context. My objective in the third chapter was to employ Participatory Mapping (PM), GIS, GPS and remote sensing techniques and technologies, and to: a) map *P. juliflora* using two density classes; b) assess historical land-cover changes that occurred in the study site; c) identify major resource related problems of the study site; and d) assess the introduction history, uses and impacts of the invasive *P. juliflora* plant in the study site.

In chapter four[3], I use an economic analysis framework to investigate the profitability of different *P. juliflora* eradication and management practices in southern Afar. The current *P. juliflora* extent in Afar is estimated at 300,605 hectare [22]. Therefore, eradicating *P. juliflora* from Afar region is highly expensive. However, eradication at localized sites (e.g., farm lands) is possible and has been attempted in Afar. In farmlands, *P. juliflora* is usually managed by manually harvesting trees, and digging out its roots and stumps [23, 24]. Biological and chemical control methods are expensive and largely inaccessible to Afar people. Generally, biological and chemical methods are the least preferred invasive species control options in most developing countries [25].

As in other developing countries, *P. juliflora* trees in Ethiopia are exploited for different income generating purposes. In Afar, *P. juliflora* utilization is largely advocated both as a control option and a new income generating activity [12, 26-28]. Irrigated farming has been practiced in Afar since the 1960, but charcoal and *P. juliflora* pod utilizations are recent phenomena. Although *P. juliflora* has several uses including human food [29, 30] and activated carbon [31], *P. juliflora* charcoal and flour are the two widely used products in Afar [23, 24]. Despite the existence of several income generating practices in

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[3] Manuscript accepted for publication by Environmental Management.
Is control through utilization a cost effective *Prosopis juliflora* management strategy?
Tewodros T. Wakie, Dana Hoag, Paul H. Evangelista, Matthew Luizza and Melinda Laituri, 2015.

Afar, their profitability and effectiveness as a *P. juliflora* control option have not been thoroughly investigated. My objectives in the fourth chapter were to: a) identify widely practiced *P. juliflora* eradication and utilization options; and b) assess the effectiveness and economic viability of the selected options by performing enterprise, profitability, sensitivity, and risk analyses.

In chapter five, I combine and discuss the three different approaches that I used in my dissertation research, focusing on major findings, conclusions, lessons learned, and the way forward. In the sixth and final chapter I give a word of advice to new incoming students by reflecting on my four years educational experience at Colorado State University (CSU).

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CHAPTER 2: MAPPING CURRENT AND POTENTIAL DISTRIBUTION OF NON-NATIVE PROSOPIS JULIFLORA IN THE AFAR REGION OF ETHIOPIA

Synopsis

I used correlative models with species-occurrence points, Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation indices, and topo-climatic predictors to map the current distribution and potential habitat of invasive *Prosopis juliflora* in Afar, Ethiopia. Time-series of MODIS Enhanced Vegetation Indices (EVI) and Normalized Difference Vegetation Indices (NDVI) with $250m^2$ spatial resolution were selected as remote sensing predictors for mapping distributions, while WorldClim bioclimatic products and generated topographic variables from the Shuttle Radar Topography Mission product (SRTM) were used to predict potential infestations. I ran Maxent models using non-correlated variables and the 143 species- occurrence points. Maxent generated habitat suitability surfaces were converted into binary maps using the 10-percentile logistic threshold values. Performances of models were evaluated using area under the receiver-operating characteristic (ROC) curve (AUC). My results indicate that the extent of *P. juliflora* invasion is approximately $3{,}605km^2$ in the Afar region (AUC = 0.94), while the potential habitat for future infestations is $5{,}024km^2$ (AUC = 0.95). My analyses demonstrate that time-series of MODIS vegetation indices and species-occurrence points can be used with Maxent modeling software to map the current distribution of *P. juliflora*, while topo-climatic variables are good predictors of potential habitat in Ethiopia. Our results can quantify current and future infestations, and inform management and policy decisions for containing *P. juliflora*. My methods can also be replicated for managing invasive species in other East African countries.

Keywords: remote sensing, invasive species, Maxent, MODIS, topo-climatic predictors, vegetation indices

1. Introduction

Invasive plants are naturalized plants that produce large number of offspring, have the ability for long-distance dispersal, and thus have a potential to spread over a considerable area [1]. Non-native plants, which are synonymous with alien plants and non-indigenous plants, are plant taxa that are introduced to areas beyond their native range through human activity [1, 2]. Invasion by non-native species is among the most critical threats to natural ecosystems worldwide [3-6]. *Prosopis* species, commonly known as mesquite, alagarroba, and kiawe, are some of the most highly invasive plants in the world, dominating millions of hectares of arid and semi-arid lands in Africa, Asia, Australia, and the Americas [7, 8]. Historical records show that *Prosopis* was introduced to Sudan in 1917 [9]. There is growing evidence that *Prosopis* species were introduced to Kenya, Somalia, Eritrea, and Ethiopia in the 1970s through collaborative projects involving local governments and international organizations [10, 11]. Today, *Prosopis juliflora*, *P. pallida*, and *P. chilensis* are found in Kenya and Sudan [12, 13]; only *P. juliflora* has been reported in Ethiopia. *Prosopis* hybridizes very rapidly and identification at a species level is often difficult [7, 14]. *Prosopis* species are rapidly spreading in several southern and eastern African countries. In South Africa, for example, hybrids of *Prosopis* are expanding its range at a rate of 18% per annum, doubling its extent every five years [14].

Among the 44 recognized *Prosopis* species, *P. glandulosa*, *P. velutina*, *P. juliflora*, and *P. pallida* are the most invasive [7]. In Africa, *Prosopis* species are estimated to have invaded over four million ha, threatening crop and range production, desiccating limited water resources, and displacing native flora and fauna [14, 15]. *Prosopis* species have increased the mortality of *Acacia erioloba*, one of South Africa's important species, by depleting water resources [16]. In Australia, hybrid *Prosopis* species are having dramatic ecological impacts by forming extensive dense stands, and completely excluding native herbs, grasses, and shrubs [17]. Due to its deleterious environmental and economic impacts, the non-native *P. juliflora* has been rated as a very high priority invasive species in Ethiopia [18].

Early detection and mapping of invasive species are essential to formulating effective containment strategies. However, in Ethiopia quantitative assessments of the area invaded by *P. juliflora* and its potential distribution have not been adequately conducted [19]. Conventional ground surveys and mapping activities are time consuming, and costly, especially over large areas. New integrative spatial modeling approaches that employ advanced remote sensing, Geographic Information Systems (GIS) and modeling algorithms (e.g., correlative models) are increasingly being used to map both the current [20-23] and the potential distributions of invasive species [23]. Correlative models include a wide range of machine learning and regression based approaches that attempt to identify relationships between species records (presence/ absence) and environmental characteristics [24, 25].

Vegetation mapping with remote sensing primarily involves understanding the behavior of the electromagnetic radiation and the reflectance properties of features and plants. Healthy vegetation has chlorophyll which reflects the green, and absorbs the blue and red, portion of the visible electromagnetic radiation. During different phenological stages and stress conditions, the amount of blue and red electromagnetic radiation reflected by plants changes. Likewise, healthy vegetation highly reflects the near-infrared portion of the electromagnetic spectrum. Variation in internal leaf structure among plant species creates subtle differences in reflectance values. This unique spectral value, also called spectral signature, can be detected by remote sensing sensors, and can be used to discriminate plants at a species level [26]. By manipulating reflectance values in the blue, red, and near infrared portion of the spectrum, it is possible to create different ratios and vegetation indices which permit discrimination of vegetated areas. Among the commonly used vegetation indices are the Normalized Difference Vegetation Index (NDVI) [27, 28] and the Enhanced Vegetation Index (EVI) [28, 29]. The NDVI is calculated as:

$$NDVI = \frac{pNIR - pRed}{pNIR + pRed} \qquad (1)$$

where *pNIR* and *pRed* represent the surface reflectance values of the near-infrared and the red wavelengths, respectively.

The EVI is calculated as:

$$EVI = G\frac{pNIR - pRed}{pNIR + C1 * pRed - C2 * pBlue + L} \qquad (2)$$

where *pNIR*, *pRed*, and *pBlue* represent the atmospherically or partially atmospherically corrected surface reflectance values of the near-infrared, the red, and the blue wavelengths, respectively. L represents the canopy background factor, while the coefficients C1 and C2 are used to correct aerosol scattering in the red band by using the blue band. Generally, Cl = 6, C2 = 7.5, G (gain factor) = 2.5, and L = 1 [29]. In the United States, both MODIS EVI and NDVI have been used to identify crop lands with high overall accuracy (97%) [30]. The two vegetation indices complement each other in global vegetation studies and improve upon the detection of vegetation changes and extraction of canopy biophysical parameters [29]. *Prosopis juliflora* and *P. pallida* trees have evergreen to semi-evergreen leaves, shedding leaves completely only under stressful and drought conditions [7]. Besides having evergreen leaves, *P. juliflora* forms dense thickets and dominates the canopy layer, all of which are useful traits for remote detection of tree species.

Mapping current distributions of invasive plants is generally conducted by discriminating spectral reflectance from different remote sensing sensors and derived vegetation indices [20-23]. Recent studies have provided evidence that inclusion of topographic predictors with remote sensing data can improve these mapping efforts (e.g., [31]). In contrast to mapping current distributions, predicting potential distributions attempts to relate species-occurrence to environmental conditions, such as climate or topography, and then uses these relationships to predict locations with similar environmental conditions to those where a species is found [32-35]. Neither the current nor the potential habitats of invasive *P. juliflora* trees has been quantified in Ethiopia. Here, I present correlative techniques for mapping and modeling both the current and potential distributions of *P. juliflora* trees in Afar, Ethiopia, using remote sensing and topo-climatic predictors, species-occurrence points, and Maxent species distribution modeling software [36]. Specifically, my objectives were to: 1) map the current distribution of *P. juliflora* in the Afar region of Ethiopia using a time-series of vegetation indices from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite; and 2) predict its potential distribution using climatic and topographic environmental variables.

2. Materials and Methods

2.1 Study Area

The study site is in the Afar Region of the northern part of Ethiopia (between 8° 51' and 14° 34' latitudes, and 39° 47' and 42° 24' longitudes; Figure 2.1). The area covers approximately 95,266km^2 of land and water, with elevations ranging from 125m below sea level to 2,870m above sea level. Long-term climate data (1968-2001) obtained from the Ethiopian Meteorological Agency (EMA) [37] indicates that the mean annual rainfall ranges from 580mm at Melka Werer to 215mm at Dufti. The mean maximum annual rainfall recorded for Melka Werer is 673mm, while the mean minimum annual rainfall recorded at Dufti is 92mm. The mean annual temperature for Melka Werer and Dufti is 26.6^{0}C and 30.1^{0}C, respectively. The recorded mean minimum annual temperature for Melka Werer is 19.3^{0}C, and mean maximum annual temperature for Dufti is 37.3^{0}C. The study area is located within the *kolla* (arid to semi-arid) and the *bereha* (desert) agro-ecological zones of Ethiopia.

The Afar Region is one of the nine administrative regions in Ethiopia. The population living in Afar is estimated at 1,650,000 [38]. Eighty percent of Afar people are pastoralists, while another 10% are considered agro-pastoralist [39]. *Prosopis juliflora* is threatening the livelihoods of Afar pastoralists by displacing native plants that have high livestock grazing and foraging uses. The native vegetation consists of grasses, forbs, shrubs, and woody plants that are adapted to arid and semi-arid environments. The dominant herbaceous (i.e., grasses and forbs) vegetation includes *Chrysopogon*, *Sporobolus*, *Dactyloctenium*, *Cymbopogon*, and *Cynodon* species [40, 41]. The woody vegetation is mainly composed of *Acacia senegal*, *A. nubica*, *A. nilotica*, *A. tortilis*, *A. mellifera*, *Acalypha* species, *Cadaba rotundifolia*, *Dobera glabra*, *Grewia* species, *Salvadora persica*, *Tamarix nilotica*, *Balanites aegyptiaca*, and *Ziziphus spina-christi* [41-43]. In addition to livestock, the native plants also provide grazing and foraging uses to the wildlife found in the region. The region contains two national parks (Awash and Yangudi-Rassa), three wildlife reserves (Awash West, Alledeghi, and Mille-Serdo), three controlled hunting areas (Gilen Hertalie, Chifra, and Telalak-Dewe), and one open hunting area (Gelila Dura). The parks and wildlife reserves are home to the unique wildlife species of Afar including the endangered Grevy's zebra (*Equus grevyi*) and critically endangered wild ass (*E. africanus*) [44-46].

2.2 Data Collection and Pre-analyses

A total of 143 *P. juliflora* observations with geographic coordinates (presence points) were recorded in 2011 and 2012 in Awsi, Gabi, and Hari Zones of Afar. Northern parts of Afar, Kilbet and Fantena, which border the Tigray and Amhara Region to the west and Eritrea to the north and east, were not sampled due to logistical and security concerns (Figure 2.1). I followed a targeted sampling approach based on local knowledge. Local communities and government employees, who had detailed knowledge of the local vegetation, landscape, roads, foot-trails, conflict areas, and *P. juliflora* infested sites, facilitated the targeted sampling and data collection process. I covered all known infested sites within the sampled zones. The majority of the occurrence records were 1km apart with a minimum distance of 250m between occurrence points. In addition to avoiding duplication of sample records, this approach allowed me to reduce spatial autocorrelation.

For the mapping analyses, I selected MODIS products (i.e., MOD13Q1) with 250m^2 spatial resolution. Monthly NDVI and EVI for the year 2012 were extracted. I obtained all MODIS products from the Land Processes Distributed Active Archive Center [47] and conducted all pre-processing (i.e., reprojection, mosaicking and sub-setting) using the MODIS Reprojection Tool (MRT) [48]. For predictive modeling of potential distribution of *P. juliflora*, I used the 19 bioclimatic variables derived from WorldClim monthly temperature and precipitation values [49, 50]. The spatial resolution of the bioclimatic predictors for the study site was 0.00833 degrees. Additionally, elevation and slope were obtained from the Shuttle Radar Topography Mission (SRTM) data product [51]. The SRTM products had a spatial resolution of 90m^2. All topo-climatic predictors were resampled in ArcGIS 10.0 [52] to 250m^2 spatial resolution using the nearest neighborhood algorithm to match the resolution of the remote sensing predictors.

2.3 Data Analyses and Model Evaluation

Maximum entropy modeling software (Maxent; version 3.3.3k) was selected for mapping the current and potential extent of *P. juliflora* [36]. Maxent is a widely tested correlative model that has very high predictive accuracy both in terrestrial and marine environments [24-25, 53]. Maxent is both a machine learning and statistical method that applies the maximum entropy principle. The maximum entropy principle states that probability distributions should agree with what is known (or inferred from the environmental conditions where the species has been observed), but should avoid assumptions not supported by the data [36, 54]. Maxent thus attempts to find the probability distribution of maximum entropy (i.e., most spread out or close to uniform distribution) subject to constraints imposed by the information available from the observed occurrence records and environmental conditions across the study area [36, 54-56]. Unlike other correlative based models that require presence and absence data, Maxent uses presence and background points that assess the available environment for model calibration and testing. I tested all predictors for correlation using presence and background locations in SYSTAT 11.0 software [57]. I removed highly correlated predictors (Pearson correlation coefficient values > +0.8; <-0.8) and variables with low predictive power as measured via percent contribution and variable importance during exploratory analyses.

Two preliminary Maxent models were run; the first with 24 MODIS predictors representing monthly NDVI and EVI, and a second using the 19 bioclimatic variables. I identified the best predictor variables based on the percent contribution and permutation importance values provided by Maxent outputs. The preliminary analyses allowed me to reduce the number of variables to eight non-correlated MODIS and six non-correlated Bioclim predictors for mapping distribution and predicting potential habitat, respectively. For mapping current *Prosopis* distribution, the final variables included NDVI for the months of March, April, September, and November; and EVI for the months of March, October, November, and December. For predicting potential habitat for *Prosopis*, the climate variables used were temperature annual range (Bio7), annual precipitation (Bio12), precipitation of wettest month (Bio13), precipitation of driest month (Bio14), precipitation seasonality coefficient of variation (Bio15), and precipitation of coldest quarter (Bio19). In addition, slope and elevation, which also had strong predictive contributions in the preliminary analyses, were included in both of the final models after being subjected to correlative tests (Tables 2.1 and 2.2).

The Maxent model allows the user to define or change model parameters beyond the default settings. For the final models, I set the replication type to *sub-sample*, random test percentage to 30%, the number of iterations to 5,000, and the number of replicates to 25. The regularization value in Maxent controls the complexity of the model [36, 58]. I assessed model over-fitting by testing regularization values of 0.5,1, 1.5 and 2. I selected the optimum regularization value of one, which is the default value in Maxent, after visually inspecting response curves for complexity and comparing the train and test AUC (area under the receiver-operating characteristic curve) values.

Sample selection bias is handled in Maxent by manipulating background points during model training and testing. Generating background points in the vicinity of the occurrence records allows both the background and the occurrence points to carry similar types of bias that balance out [55]. Generating background points beyond 100km distance of occurrence records may result in inflated AUC and simplified predictions [59]. In this study, I randomly generated background points within 50km distance of the occurrence records. I trained the potential distribution model using the 50km buffer and made extrapolations (projections) to the entire study site. I selected the *Do clamping* option in Maxent which applies same data ranges for model calibration and extrapolation. Clamping ensures that projection is made using data range found only within the training data set [36, 56]. Predictions into novel environments were assessed using Multivariate Environmental Similarity Surfaces (MESS), which identifies locations which are outside the range of values included in the data used to train the model (the presence and background points) for any predictor [35].

Threshold values used for converting Maxent probability outputs into binary maps can affect the extent of the predicted distribution, especially when few number of occurrence records are used and the sampling is biased [60]. Among four commonly used Maxent threshold values, the 10-percentile training presence produces reliable distributional areas [61]. The 10-percentile threshold mis-classifies 10% of the training presence locations as unsuitable. I converted the probability surfaces generated by the two Maxent models into binary maps using the 10-percentile training presence logistic threshold values and calculated their respective areas. I used large number of occurrence records (143) and I reduced the sampling bias; therefore, the threshold value selected for this study is reasonable.

Model performance was assessed using area under the receiver operating characteristics (ROC) curve (AUC) [62, 63], and maximized Kappa statistic [63, 64]. AUC values ranging from 0.5-0.7, 0.7-0.9, and >0.9 show poor, reasonable, and very good predictions, respectively [62, 65]. Kappa values <0.4, 0.4-0.75, and >0.75 indicate poor, good, and excellent agreements (predictions), respectively [63]. Both AUC and Kappa were calculated using Schröder's ROC-AUC software [66] on independent data sets obtained from the Ethiopian Wildlife Conservation Authority (EWCA; personal communication with Fanuel Kebede). I obtained 50 presence points from EWCA and collected another 50 absence points in December 2013 from the field to validate my results. The test data were evenly distributed across the study site.

3. Results

3.1 Current Distribution

The remote sensing and topographic predictors with the highest percent contribution for mapping current distributions were November EVI (43.5%), April NDVI (15.7%), elevation (12.8%), and slope (6.6%; Table 2.1). The NDVI and EVI values for *P. juliflora* showed similar trends with higher values recorded in September, and lower values recorded in March (Figure 2.2). The NDVI values were always higher than the EVI values. Visual inspection of the current *P. juliflora* distribution map shows that infestation is dominant in the Gabi, Awsi, and Hari administrative zones, respectively (Figure 2.3). According to the model, the northern most administrative area, Kilbet, is the least invaded. The banks of Awash River are heavily invaded by *P. juliflora* (Figure 2.3). Area calculations of model results show that the current predicted distribution of *P. juliflora* invasion covers 3,605km^2 of the Afar region. The remote sensing and topo-climatic predictors correlated well with the *P. juliflora* occurrence data, with both having high Kappa and AUC values. Kappa and AUC values based on the independent data for the current model were 0.85 and 0.94, respectively (Table 2.3).

3.2 Potential Distribution

The topo-climatic predictors with the highest contribution for the potential distribution model were temperature annual range (Bio7; 45.9%), and precipitation of wettest month (Bio13; 10.1%; Table 2.2). Suitable habitats for *P. juliflora* were predicted throughout the Afar region (Figure 2.3). The extrapolation assessment (MESS analysis) identified areas of extrapolation (environmental variable values outside the range of those used to train the model) in the northern tip parts of the study site, where the Maxent model did not predict suitable habitats for *P. juliflora* (Figure 2.3). I am uncertain about the models' prediction in the northern tip of Afar, and thus advise users to interpret my results with caution. Based on area calculations of model results, the potential extent of *P. juliflora* distribution in Afar is 5,024km^2. The results show that more than half of the potentially suitable habitats have been invaded. The potential distribution model had an AUC value of 0.95 and a Kappa value of 0.86 based on the independent data set (Table 2.3).

4. Discussion

I found that MODIS Vegetation Indices (VIs) are highly useful for mapping *P. juliflora* in the extensive land of the Afar. The phenological signals of *P. juliflora* were best detected by the November EVI and April NDVI MODIS predictors (Table 2.1). November represents *hagay* to Afar people, a cold and dry period early in the dry season. During this time, the foliage of most woody shrubs and trees remains green, while herbaceous flora, such as annual grasses and agricultural crops, become less green, creating phenological contrasts for better discrimination of woody vegetation. At the end of the dry season, *P. juliflora* remains green, while woody shrubs and trees lose most of their foliage or take on a yellow coloration due to water stress (personal observation). In addition, *P. juliflora* takes advantage of its deep root systems [67] and the moisture from the short rainy season (between March and April and referred by Afar people as *hugum*) to remain green (Figure 2.4). These differences were likely detected by the dry season VIs (November, October and December EVIs), and the short rainy season *hugum* VIs (April and March NDVIs, and March EVI). The trend for NDVI and EVI was similar, but EVI values were lower (Figure 2.2). EVI values are generally lower as they avoid saturation in high biomass areas

[29]. In mapping current distributions, I hypothesize that EVI was the top predictor because it was able to detect the dense *P. juliflora* thickets that often possess high biomass. Wet season NDVI and dry season EVI predictors highly contributed to the model. The observed seasonal variability among EVI and NDVI predictors in model contribution needs further investigation. My findings suggest that images taken in November and April are highly useful for remotely detecting *P. juliflora.* In general, my intensive sampling and data collection efforts, the species' distinct canopy architecture and its unique spectral signature have allowed me to detect and map *P. juliflora* trees with acceptable degree of accuracy (Table 2.3). My results support the conclusion made by Viña et al. [68] that MODIS vegetation indices can have considerable potential in mapping distributions of species.

Two climate variables appear to best predict the potential distribution of *P. juliflora*. Temperature annual range (Bio7), which is a function of maximum temperature of warmest month and minimum temperature of coldest month, was the most important variable, followed by precipitation of wettest month (Bio13). My results suggest that temperature and rainfall are important in the distribution of *P. juliflora*. Although slope and elevation did not contribute much in the prediction of potential habitat, they were the third and fourth contributors in mapping current distributions, suggesting incidence of topographic preferences in the distribution of *P. juliflora*. The potential distribution did not cover 100% of the current distribution. This is to be expected when sampling is conducted only in the invaded range, where the invasive species is still expanding and may not be in equilibrium with its environment [54].

The models' high AUC values give me confidence in the overall accuracies of the current and potential distribution maps. However, I believe the model results might be improved if I had the opportunity to sample a wider area within the Afar. I also tested a single correlative modeling approach, Maxent, where other modeling techniques might have produced different results (e.g., Boosted Regression Trees) [69]. Future modeling efforts may consider using samples from the native range for the potential distribution model and using models that can handle both presence and absence data for the current distribution model. Finally, we must recognize the limitations in using coarse-resolution satellite imagery such as MODIS. Detailed modeling using moderate-resolution remote sensing (e.g., Landsat 8, SPOT) and topo-climatic variables may provide more accurate results for smaller geographic areas of interest. For a different perspective on current distribution vs potential distribution (with wildlife examples), and realized-potential niche gradient concept, I advise the reader to refer to Jiménez-Valerde et al. [70], Lobo [71], and Gormley et al. [72].

5. Conclusions

I identified suitable habitats for the invasive *P. juliflora* plant throughout the Afar region. Since *P. juliflora* seeds are easily dispersed by domestic and wild animals, streams, and overland water flow [7, 8, 73], I anticipate further expansion of *P. juliflora* invasion into most parts of Afar, Ethiopia. I quantified, for the first time, the current and potential extent of *P. juliflora* invasion in Afar. I found that MODIS vegetation indices and topo-climatic variables can be used with species-occurrence data and correlative models to map both the current and potential distribution of *P. juliflora*. The methods described here can be easily applied in other countries that need to monitor invasive species in arid and semi-arid ecosystems. I anticipate that the *P. juliflora* distribution maps that I created will be used as baseline for future monitoring activities, and may inform land managers and policy makers in formulating preventive, control and or eradication measures. My estimates can also be used to parameterize economic models that may be conducted in the region. Future research should incorporate species presence points from northern parts of Afar and from the species native range. Including soil and hydrologic related predictors in the analyses, using high-resolution time series images and additional species distribution models may also give new insights on the current and potential distribution of *P. juliflora* in Ethiopia.

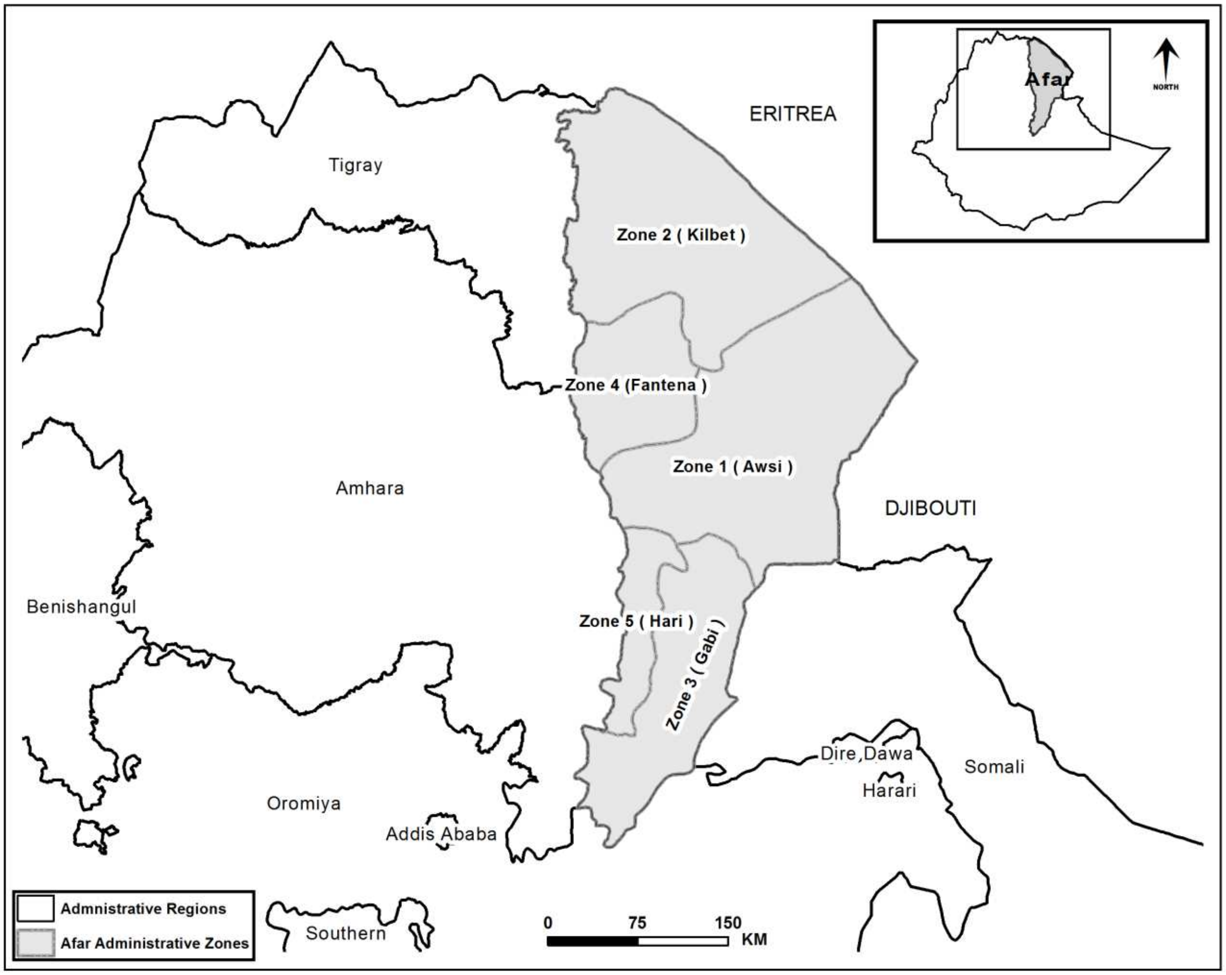

Figure 2.1. **Study Site.** Zones are administrative units that are found within *Killils* (regions or states) and can have several *Woredas* (counties). The five zones are referred as Awsi Rasu (Zone 1), Kilbet Rasu (Zone 2), Gabi Rasu (Zone 3), Fantena Rasu (Zone 4) and Hari Rasu (Zone 5).

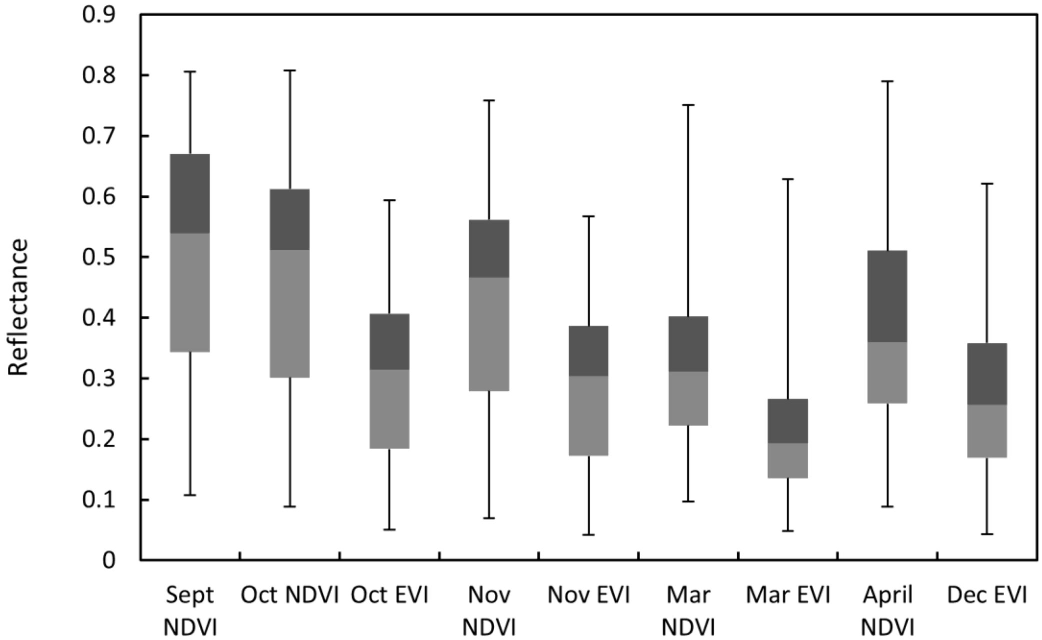

Figure 2.2. ***Prosopis juliflora* reflectance**. Box plots of *P. juliflora* EVI and NDVI reflectance values. Note that NDVI and EVI values for the other months were dropped from the final model due to cross-correlations.

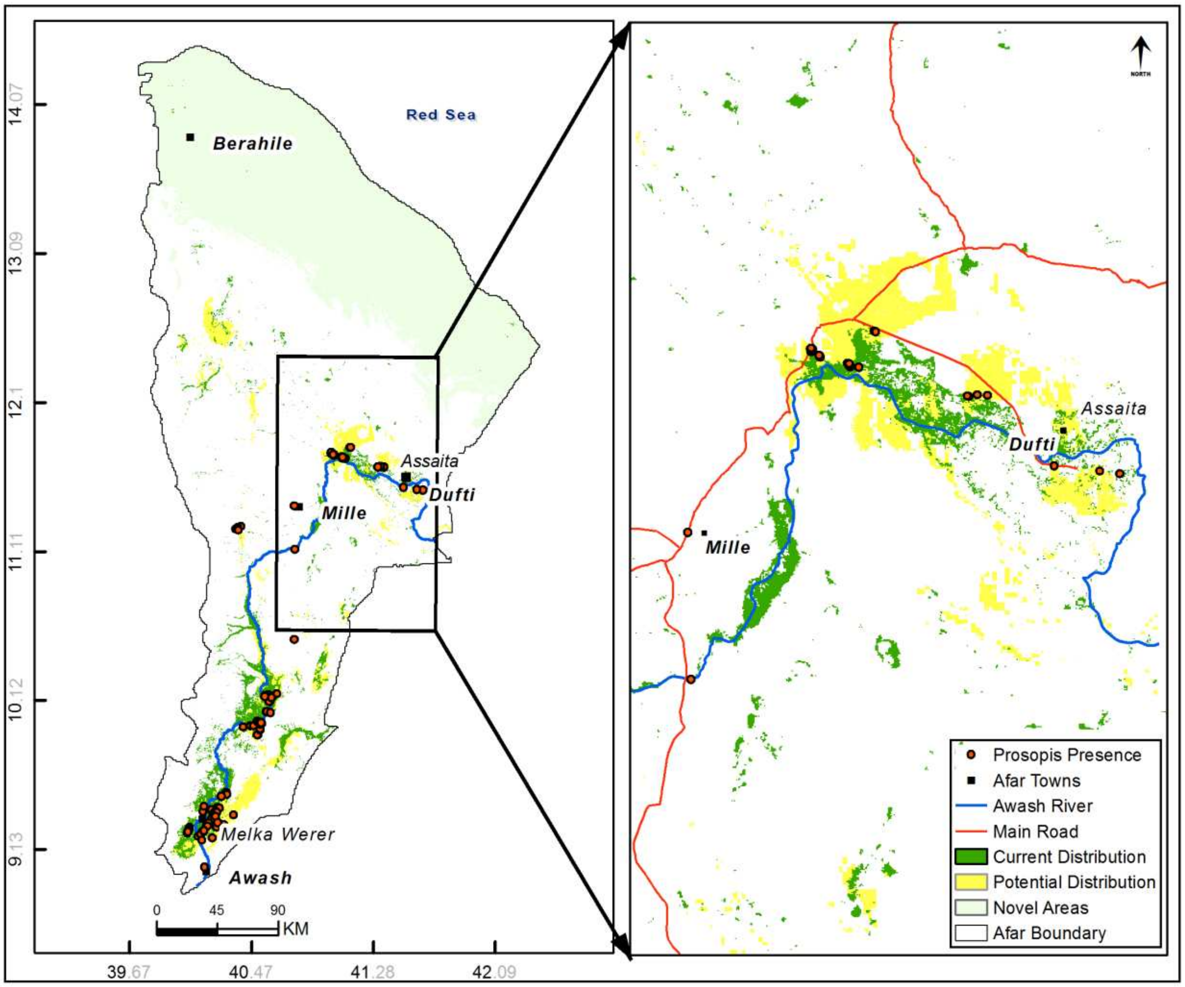

Figure 2.3. **Distribution of *P. juliflora***. The current distribution (shown in green) is superimposed on the potential distribution (shown in yellow). The 143 *P. juliflora* occurrence records used in the model are shown in red. The Multivariate Environmental Similarity Surfaces (MESS) results highlighting areas that are environmentally dissimilar to the training data are shown in light green color.

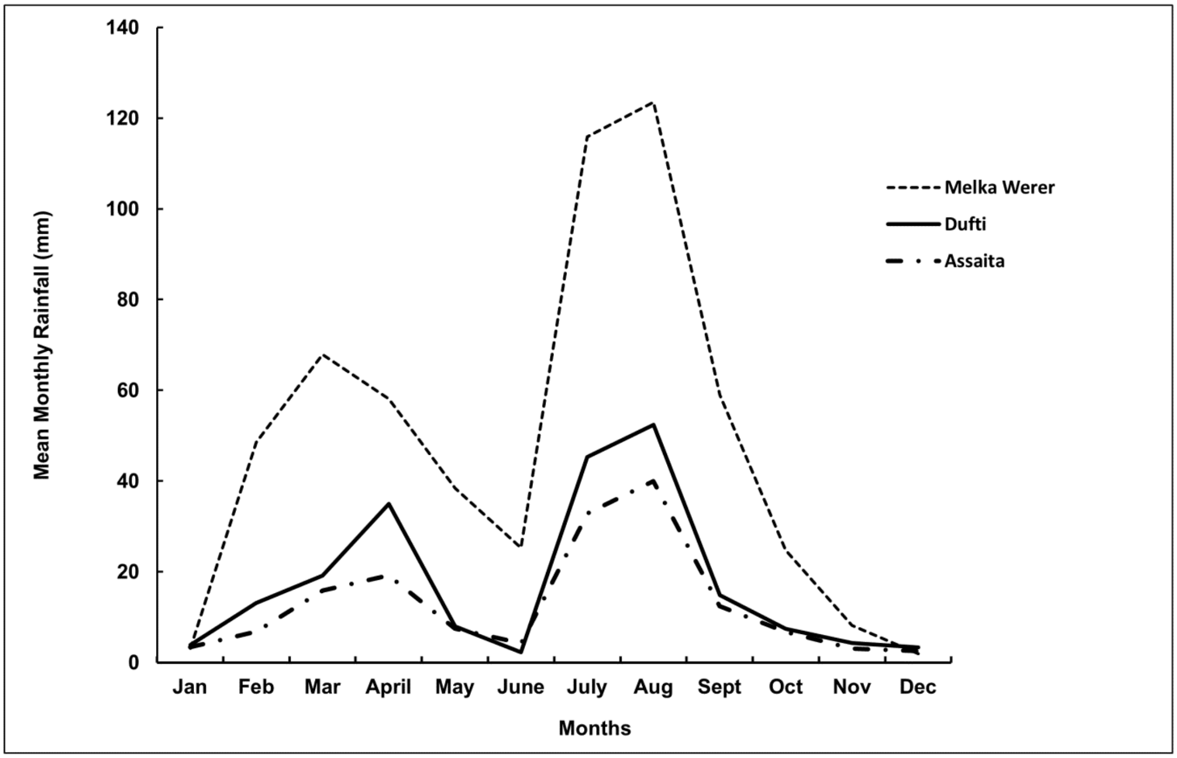

Figure 2.4. **Long term rainfall pattern in Afar**. Average mean monthly precipitation for Melka Werer, Dufti, and Assaita stations (1968-2001). The graph shows a distinct S-N aridity gradient between Melka Werer and Assaita.

Table 2.1. Percent contribution and permutation importance of remote sensing predictors. Maxent model was set to 30% random test percentage and *sub-sample* replication type.

Variable name	Percent contribution	Permutation importance
November EVI	43.5	50.0
April NDVI	15.7	10.8
Elevation	12.8	18.7
Slope	6.6	7.3
October EVI	8.2	1.2
March EVI	4.6	1.8
December EVI	2.6	0.8
September NDVI	2.1	1.9
March NDVI	2.0	3.0
November NDVI	1.8	4.4

Table 2.2. Percent contribution and permutation importance of topo-climatic predictors. Maxent model was set to 30% random test percentage and *sub-sample* replication type.

Variable name	Percent contribution	Permutation importance
Temperature annual range (bio7)	45.9	73.9
Precipitation of wettest month (bio13)	10.1	16.6
Precipitation of coldest quarter (bio19)	12.4	2.0
Slope	9.5	1.7
Precipitation seasonality (bio15)	8.3	2.7
Precipitation of driest month (bio14)	7.5	1.5
Annual precipitation (bio12)	3.8	1.0
Elevation	2.5	0.6

Table 2.3. AUC and Maximized Kappa Statistic values calculated for an independent data set for both the current and the potential distribution models.

Model Type	AUC	Maximized Kappa Statistic
Current Distribution	0.94	0.85
Potential Distribution	0.95	0.86

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CHAPTER 3: ASSESSING THE DISTRIBUTION AND IMPACTS OF *PROSOPIS JULIFLORA* THROUGH PARTICIPATORY APPROACHES

Synopsis

I assessed the introduction history, impacts, uses, and control strategies of invasive *Prosopis juliflora* plant in the Afar, Ethiopia, by interviewing 108 pastoralists and agro-pastoralists. In addition, I used Participatory Mapping (PM), Geographic Information Systems (GIS), Global Positioning System (GPS), and remote sensing technologies and approaches to map sites invaded by *P. juliflora*. Sketch maps were produced by men, women, pastoralist and agro-pastoralist groups. I aggregated, scaled and reproduced the sketch maps with support from the Afar communities and experts. I provided GPS and GIS trainings to selected community members who assisted me in collecting the GPS locations of more than 70 key features and landmarks. The sketch maps were digitized and geo-referenced by experts using the 70 GPS records as control points. Geo-referenced community maps were superimposed on pan-sharpened Landsat 8 satellite images and presented to the communities for verification. I overlaid the validated community maps on ancillary land cover layers, and detected the land-cover classes that were most affected by *P. juliflora* invasion. Despite its uses as source of fire wood, charcoal, and animal fodder, the species has adverse impacts on native species and livestock resources. Afar communities mapped *P. juliflora* infestations, particularly those that occurred near their villages, using high and moderate density classes. The two highly invaded land-cover categories were dense grassland, and exposed sand and soil. Participants collaborated in creating the produced maps, suggesting that participatory research approaches are another tool for early detection of invasive species and guiding fine-scale management strategies.

Key words: Community maps, invasive species, participatory mapping, *Prosopis juliflora*, sketch maps

1. Introduction

Incorporating the spatial and cognitive knowledge of local communities is essential in designing and implementing successful conservation and development projects. Projects that lack community involvement and support are often unsustainable. Participatory research approaches are increasingly being used to map resources [1, 2], identify and prioritize social and economic problems of rural communities [3, 4], and find sustainable solutions to agriculture and natural resource management related problems [5-8].

The origin of participatory research methods can be traced back to Participatory Rural Appraisal (PRA) techniques of the 1970's, which are a suite of approaches and methods that are designed to enable rural people to share, enhance and analyze their knowledge of life and experience, and to assist them in planning and decision making [9]. Participatory research techniques can include interviews (e.g., focus groups, key informants), transect walks, timeline analyses, and other participatory mapping approaches. Participatory Mapping (PM) recognizes the cognitive spatial and environmental knowledge of local people and transforms this into more conventional forms that can be shared within a community as well as with governmental agencies [1].

Participatory maps, also referred to as community maps or indigenous maps, are creatively produced by participants through locally available materials [10]. Participation is a key component of the process whereby community members fully participate in the planning, mapping, and implementation phases. In a true participatory mapping process, the researcher's or outsider's task is to facilitate the participatory mapping and research process rather than to extract data. Participatory mapping methods can range from those that are simple and ephemeral such as drawing maps on sand, to advanced Global Positioning System (GPS) and web-based mapping methods. Currently used PM methods include ground mapping, stone mapping, sketch mapping, scaled 2D mapping, web-based and interoperable Geographic Information Systems (GIS) mapping, GPS mapping, and 3D mapping [11]. Other commonly used techniques include placing transparent papers on top of aerial photographs and satellite images, participatory 3D modeling (P3DM), and multimedia mapping [12]. Laituri [13] points out that the relationship between the outside researcher and local informants is a critical aspect of indigenous mapping projects, especially when local expertise for creating final map products is limited. In order to gather information, the outside researcher first needs to have the communities' trust. Trust develops through clarification of objectives, community coordination, and long-term relationships. Participatory mapping practitioners should avoid sharing sensitive information with outsiders to protect the indigenous communities from exploitation and abuse. For instance, if showing particular spatial information on a map leads to the forced displacement of the indigenous people, then the facilitator/practitioner should refrain from displaying the feature on the community map [14].

Community maps generally have two broad uses; the first is to act as counter-maps that challenge existing spatial documents, while the second is to supplement formal planning through incorporation of local knowledge [15]. Currently, participatory research approaches are used across different disciplines to address a range of issues including ethnobiology [16], disaster risk reduction [11], management of natural resources [10, 17-18], resolving land and natural resource related conflicts [1, 19], empowering local communities [20], development of land use plans [19], and mapping of illegal settlements [21].

Although participatory research approaches are widely used in land-use planning and conflict resolution, the techniques have not been sufficiently tested in invasive species research and management applications. Through communication with all stakeholders, map products can be used to create awareness about invasive species, to inform local level land-use planning, and to aid invasive species utilization and control efforts. In this research paper, I present the results of a three-year participatory research endeavor conducted in Afar, Ethiopia between December 2011 and 2014. Collaboratively working with Afar indigenous communities, experts [4], governmental and non-governmental organizations (GOs and NGOs), I used participatory research techniques to understand the introduction history, spread, density, impact, use, and controlling strategies of the invasive *Prosopis juliflora* plant in Amibara *woreda* (county) of Afar, northeast Ethiopia. My specific objectives were to: a) map the current distribution and

[4] Throughout this article, the term expert is used to refer to the GIS and natural resource management professionals who came from GOs and NGOs in Ethiopia and from Colorado State University.

density of invasive *P. juliflora*; b) investigate its introduction history, spread, use and control strategies; and c) assess its impacts on the regions' land cover, native vegetation, wildlife, and livestock resources.

2. Methods

2.1 Study Site

Based on my prior knowledge of the area [22], and with the assistance of GOs and NGOs that actively work in the region, I selected seven representative villages from Amibara *woreda* (Ethiopia) to conduct the participatory research. The seven villages selected for the study were: Serkamo, Udleisi (Alledeghi), Melka Sedi, Bedulale, Buri, Sheleko, and Eeble (Figure 3.1). The main sources of livelihoods in the study site are pastoralism, agro-pastoralism and farming. Eeble, Sheleko and Melka Sedi villages are located near the Awash River, one of the most utilized major rivers in Ethiopia. Some of the largest state and privately owned farms are present near these three villages. The people in Udleisi village are primarily pastoralists, while the people in Buri, Bedulale, and Serkamo villages are mostly agro-pastoralists. Elevation in Afar ranges from 125m below sea level to 2,870m above sea level. Afar has three agro-climatic zones which include semi-arid, arid, and desert. Afar has a distinct south-north aridity gradient having relatively lower temperature and higher rainfall in the south, and higher temperature and lower rainfall in the north. The region is home to 81 mammal species, and over 640 bird species of which six are endemic [23].

Afar has the largest *P. juliflora* infestation in Ethiopia which has considerable effects on traditional livelihoods. Further impacts driving the landscape's rapid environmental change are recurring drought, ethnic conflict, and land-grabs by large-scale commercial agriculture [24, 25]. Afar is one of the top four regions in Ethiopia affected by land-grabs, a phenomenon where foreign companies acquire huge tracts of land from developing countries for long durations at very cheap prices [25, 26]. Afar people also face ethnic conflicts from the neighboring rival Issa (Somali) ethnic groups. Recently, the Issa have managed to annex large amounts of pastoral lands from the eastern parts of Afar.

2.2 Interviews

In December 2012, I interviewed 108 people (62 pastoralists and 46 agro-pastoralists) from the seven villages. Seventy-three of the interviewed people were men (43 pastoralists and 30 agro-pastoralists), while 35 were women (19 pastoralists and 16 agro-pastoralists). After arriving at each village, I contacted village leaders and asked them to invite interviewees from nearby Afar communities to represent men and women of all ages. Once the interviewees arrived, I briefed them about my objectives, asked their willingness to share their knowledge with me, and interviewed them individually. On average, I interviewed 15 individuals from each village. I am originally from Ethiopia, and understand the culture and the main language spoken in the region. In addition to leading the interview, I trained four multilingual Ethiopian professionals (two men and two women) to assist me with the interviews. Before conducting the actual interview, I translated the questions to local languages and tested them on a few individuals. I removed redundant questions and kept 11 questions for the final interview (see Appendix A). Most of the questions were open ended type that needed qualitative responses. All women were interviewed by the two trained women experts. I translated the interview responses to English and entered them in a spreadsheet. Interview questions were organized, auto-coded and analyzed in NVIVO qualitative data analysis software version 10.0 [27]. I auto-coded the responses from all respondents by the 11 interview questions, and queried the top 90 repetitive words and concepts using NVIVO word frequency analyzer. The word frequency analysis lets users identify repeatedly used words, count the number of times that words are used, and visualize the words in unique ways. I selected the word cloud option in NVIVO to visualize the top 90 frequent words and concepts, and used a table to summarize the top 10 repeated words and concepts.

2.3 Participatory Mapping (PM)

In January and June 2013, I provided GPS and Participatory GIS (PGIS) trainings to 46 individuals who represented rural communities, higher learning institutes, agricultural research centers, GOs and NGOs in Afar. The trainings were conducted through collaborative efforts of various stakeholders that included U.S. Agency for International Development (USAID), U.S. Forest Service

International Program (USFS), and the Afar Pastoral, Agriculture and Rural Development Offices (APARDO). At the end of the training, seven hand-held GPS units were transferred to the Ethiopian organizations. I conducted the trainings and transferred the instruments to raise the participants GPS and GIS skills, and build their capacity.

In June 2013, leaders from the seven villages invited representative participants (i.e., youth, adult, men and women) to participate in the PM activities. I divided the participants into men and women mapping groups who separately partook in the PM activities. At least ten men and eight women participated in each mapping activity. The PM activities were conducted independent of the interviews (section 2.2 above). Furthermore, taking the GPS and PGIS training, and participating in the interviews were not set as preconditions to participate in the PM activities; therefore, only a few people participated in all three activities (i.e., training, interview and PM). Prior to mapping, I briefed the participants about the objectives and showed them previously produced sketch maps as examples. I provided sheets of paper and markers, and asked them to: a) map their resources; b) identify major resource related problems; c) draw key features and landmarks; and d) map *P. juliflora* using high and moderate density classes using their own symbols. After the mapping exercise, we walked along transects and collected 70 GPS coordinates of key features and land marks that were shown on the sketch maps. Transects were placed along foot trails and their length ranged from 0.2km-5km. I and the local people together determined the directions and lengths of transects. Both men and women mappers participated in short transect walks, but only fit men participated in long transect walks. With the help of participants, trainees and experts, we aggregated and scaled the sketch maps (produced by different men and women groups), and produced community maps for the study site. The scaled maps were digitized and geo-referenced by experts using ArcGIS software version 10.0 [28]. The 70 GPS coordinates were used as control points during the geo-referencing process. All steps used in the participatory mapping process are presented in Figure 3.2.

In April 2014, I presented all community maps (i.e., sketch maps, aggregated and geo-referenced community maps) to the same communities for verification and approval. I downloaded four cloud-free Landsat 8 scenes (path 167 row 53; path 167 row 54; path 168 row 53; and path 168 row 54) using the

USGS global visualization viewer (GLOVIS) [29]. The satellite images were taken in December 2013. I pan-sharpened the 30m spatial resolution multispectral bands by using the 15m resolution panchromatic band, and mosaicked the scenes in ENVI software version 5.1[30]. I superimposed the geo-referenced community maps on the pan-sharpened images at 15m spatial resolution, printed them in natural color on poster sized papers, and presented them to each community with the other community maps for verification. I added key geographic features such as villages and roads as layers, labeled the features, and placed the villages at the center of the maps to simplify the verification process. I placed transparent mylar on top of all presented maps and asked participants to use markers to delete or add new features as needed. Participants concurred that the presented maps were accurate; but, they added additional villages and new *P. juliflora* infested areas on the mylar. In two villages, participants identified areas on the images that were recently flooded and deforested with bulldozers and heavy equipment. I updated the community maps by incorporating all changes made during the verification stage.

I assessed the land cover change brought by *P. juliflora* invasion in the study site by comparing the verified community map with an ancillary land-cover map. The ancillary land-cover map, which was produced in the 1990's by the Woody Biomass Inventory and Strategic Planning Project [31], identified six land-cover categories in the study site. These include dense grassland, exposed sand & soil, dense shrub-land, dense woodland, state farm, and riparian woodland. Along with other experts, I drew polygons around the verified *P. juliflora* map and performed an overlay analysis by superimposing and intersecting the *P. juliflora* map with the ancillary land cover layer. Through the overlay analysis, I identified all infested land-cover classes and calculated their proportions.

3. Results and Discussion

3.1 Introduction History and Spread

Though *P. juliflora* was introduced to Afar in the 1970's, people began noticing its invasive characteristics on the landscape in the early 1990's. Introduced non-native plants must overcome a variety of environmental, reproduction and dispersal barriers to become invasive [32]. My findings suggest that it took only 20 years for *P. juliflora* to overcome all barriers and become an independent and prolific invader. Eighty-eight percent of the respondents (56 men and 28 women) replied that foreigners working on the Awash Irrigation Project and government employees planted *P. juliflora* in the 1970's in Gewane and Amibara *woredas* with the aim of stopping desertification, greening up the region, and preventing drought (interview questions one and two; Appendix A). In 2012, I visited some of the oldest *P. juliflora* trees that were found in Gebeya-Bora village, Gewane *woreda*. Among studied villages, Udleisi (Alledeghi) was the most recently invaded site where *P. juliflora* was reported to have first established 10-12 years ago. In the rest of the villages, *P. juliflora* was reported present for the past 20-40 years.

Forty percent of the respondents (27 men and 16 women) mentioned that *P. juliflora* came to Afar with the *weyane* rebel group known as the Tigrayan People's Liberation Front (TPLF). The TPLF was instrumental in overthrowing the socialist *derg* regime in 1991 and creating the Ethiopian People's Revolutionary Democratic Front (EPRDF), which is the current ruling political party of the Ethiopian government. *Weyane* (also spelled *woyane*) refers to the 1943 unsuccessful revolt of Tigrayan peasants against Emperor Haile Selassie rule [33], and the more recent TPLF armed struggle against the *derg*. While the term *weyane* is rarely used today by government officials and supporters, it has become a popular term among opposition parties which construe it as separationist. In Afar, *P. juliflora* is known by the names *weyane*, *weyane hara* and *dergi hara*. In the local Afar language, *hara* means tree while, *derg* refers to the communist government preceding the current Ethiopian Democratic Republic. Interviewees reported that government officials advise them to use the word *dergi hara* in place of *weyane hara*. My findings suggest that the coincidence of *P. juliflora* invasion and the arrival of the "*weyane*" government in Ethiopia might have motivated the controversial name *weyane*. However, Rettberg [24] points out that Afar people perceive the term *weyanes*, *P. juliflora* and the state, as invaders and thus recognize both of them by the same name.

There is a strong awareness among Afar communities of how *P. juliflora* spreads. Both men and women groups described the main seed dispersal agents as cattle, camels, goats, sheep, warthogs (*Phacochoerus africanus*), hamadryas baboons (*Papio hamadryas*), grivet monkeys (*Chlorocebus aethiops*), flood, and humans. Most respondents described the dispersal agents allowing me to capture the list through the word frequency analysis (Figure 3.3). In drought conditions, livestock feed on *P. juliflora* pods. Shiferaw et al. [34] counted up to 760, 1642, 2344 and 2833 seeds from 1kg droppings of goats, camels, warthogs, and cattle, respectively. Respondents in Afar also mentioned humans as main dispersal agents. One male respondent said that "we are pastoralists and travel to different locations in search of grass there by disseminating *P. juliflora* to everyplace we go. It is unfortunate, but we are the major cause of *weyane* spread in Afar". Another male respondent said "wherever there is livestock, there is *weyane*". Afar communities also pointed out that hotspots of *P. juliflora* thickets are found near roads, trails, rivers, villages (settlement areas) and near wild animal resting or sleeping areas. Ninety-nine percent of the interviewed people confirmed that *P. juliflora* is spreading and expanding its range throughout the Afar (interview question seven; Appendix A). One female respondent stated that "*weyane* grows everywhere except on rocks".

3.2 Impact of P. Juliflora on Livestock

According to both male and female respondents, over the past four decades the number of livestock owned per households in the seven studied villages has declined by more than 50% (interview questions eight and nine; Appendix A). The main reasons reported for the decline include drought, disease, annexation of Afar lands by rival Issa ethnic groups, land-grabs by foreign companies and the central government for large-scale agribusiness, and invasion by *P. juliflora*. They reported that the most negatively affected domesticated animals (ordered by level of impact) were cattle, camels, sheep, and goats, respectively. Interview respondents mentioned these animals, which also disseminate *P. juliflora* seeds, repeatedly allowing me to capture the list through the word frequency analysis (Figure 3.3 and Table 3.1). According to the interviewees, donkeys are the least affected. The only *P. juliflora* related impact reported on donkeys in the current study is injury from the species' thorns. However, Mosweu et al. [35] has reported deaths of donkeys and horses in Botswana after feeding on *P. juliflora*. *Prosopis juliflora* invades grasslands, displaces the native vegetation, and creates shortage of grass and forage. In a study by Tabosa et al. [36], it was found that when livestock consume large amounts of *P. juliflora* seed pods (more than 20% of diet), they become susceptible to a nervous disease called denervation atrophy. In Afar, this fatal disease is known as *armeku* and has affected large numbers of livestock [37, 38]. In addition to mortality and decreased health of livestock, *P. juliflora* invasion was reported to reduce the production and quality of milk and dairy products. One female respondent stated that "milk was plenty and we used to give it for free; now, there is a serious shortage of milk and it is no more a freely available product". The long thorn of *P. juliflora,* which is known to pierce tractor tires, can cause serious injury to livestock. Camels, in particular, have been reported to have thorns puncture their flat hooves. *Weyane* can form very dense thickets, and block roads and trails; thus, it can highly increase the risk of livestock injury (personal observation).

3.3 Impact of P. Juliflora on Native Species

Prosopis juliflora negatively affects the native flora by invading grasslands, shrub lands, and woodlands (Figure 3.4). The most affected useful native grass and herb species include *durfu*, *denikto*, *delaita*, *serdoita*, *isisu*, *rareita*, and *melif*[5], while the most affected useful native tree species include *Acacia tortilis* (*ehebto*), *Acacia nilotica* (*keselto*), *Combretum aculeatum* (*kilito*), and *Acacia senegal* (*adado*; Figure 3.3). Afar people rely on the native flora for livestock forage, construction materials, tool handles, furniture, fire wood, food, and medicinal purposes (both for treating livestock and humans). For instance, the native fruit tree, *Dobera glabra* (*gerssa)*, provides significant food and cultural services to the Afar people [39]. There are more than 137 native plant species in Afar that are used for livestock feed, fuel wood, construction and/ or medicine [40, 41]. Thus, losing native plants can damage the livelihoods, well-being and cultural knowledge of Afar people.

Prosopis juliflora grows fast, closes the available space rapidly, forms dense thickets, and prevents nearby native plants from growing. Several respondents replied that "no native plants are present in a dense *weyane* thicket", an observation that was confirmed during my field visits. Kumar and Mathur [42] reported that *P. juliflora* have caused adverse impacts on Indian native plant communities. The

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[5] Identifying the native grass and herb species was challenging; therefore, the names of native grass and herb species are shown only in Afar language.

species outcompetes native plants by depleting water resources [43, 44], blocking sun light [45], and producing bio-chemicals that reduce the growth and survival of native plants [45, 46].

According to interviewees, the toll that occurred on the wildlife population as a result of the *P. juliflora* invasion is similar to that of livestock. Eighty-seven percent of the respondents (69 men and 25 women) stated that the wild animals, particularly the herbivores, migrated to other sites and their number declined because the native grass and forage species have been replaced by *weyane* (interview question six; Appendix A). The number of soemmerring's gazelle (*Nanger soemmerringii*; *waydedo*[6]), beisa oryx (*Oryx beisa*; *beida*), lesser kudu (*Tragelaphus imberbis*; *ambarile*), swayane's heartbeast (*Alcelaphus buselaphus* ssp. *swaynei*; *korke*), defassa waterbuck (*Kobus ellipsiprymnus*; *gurdi*), and Grevy's zebra (*Equus grevyi*; *daama*) were reported to have declined near all the studied villages. All respondents replied that it has been awhile since they spotted the critically endangered wild ass (*Equus africanus*; *dibekul*) suggesting that the species might have been locally extinct in the studied villages. The population of common warthogs (*Phacochoerus africanus*), which are considered crop pests by Afar agro-pastoralists, has increased. Warthogs hide in the dense *P. juliflora* thickets and damage agricultural crops. Dense *P. juliflora* thickets also shelter lions (*Panthera leo*) and bat-eared foxes (*Otocyon megalotis*). Lion attacks on sheep, goats, camels, and livestock have increased in all the studied villages (interview question six; Appendix A).

3.4 Impact of P. Juliflora on Culture

Thirty percent of the interviewees (22 men and 10 women) agreed that *P. juliflora* has changed the culture of Afar people (interview questions 10 and 11; Appendix A). Afar culture discourages the felling of native trees. Charcoal making was considered a bad practice, and those who made charcoal, or gave permission to others to make charcoal, were punished by traditional laws. However, due to its negative impacts, felling *P. juliflora* trees is tolerated by a large majority of the Afar people. Afar regional policies also encourage clearing *P. juliflora* trees, and producing *P. juliflora* charcoal. Many people in

[6] Common wild animal names are used first, followed by their respective scientific and local names.

Afar made money by producing and selling *P. juliflora* charcoal [37]. Motivated by this new source of income, some Afar people started harvesting native plants such as *Acacia nilotica* and *Combretum aculatum* for charcoal making purposes, often using *P. juliflora* as a pretext. During one of the transect walks, I observed one hectare of *Combretum* woodland that was cleared for charcoal making purpose. Interviewees pointed out that the culture of protecting native trees in Afar has been eroded and the harvesting of native trees for charcoal making now is tolerated.

Prosopis juliflora is commonly found in most of the Afar landscape. Open areas which were used as venues for playing Afar traditional sports are now invaded by *P. juliflora*. *Prosopis juliflora* has also blocked roads, reduced peoples' visibility, and thus made night walks dangerous. Young Afar boys and girls who once traveled long distances at night to sing traditional songs and participate in traditional dances now stay at home to avoid injury from *P. juliflora* thorns. Afar youth also take precautions to evade attacks from wild animals and enemies that may be hiding in the dense *P. juliflora* thickets. The problem is more serious in the rural villages of Afar where there is no electricity. According to interviewees, *P. juliflora* has directly or indirectly suppressed traditional Afar sport and dance activities in all of the studied villages.

3.5 Prosopis Juliflora Utilization and Control

Prosopis juliflora was reported to be widely used for firewood, charcoal and construction purposes. Eighty-two percent of the interviewed people admitted that they use *P. juliflora* products in their household. We found that women use *P. juliflora* products more than men, and agro-pastoralist groups use *P. juliflora* more than pastoralist groups. One-hundred percent of women agro-pastoralists use *P. juliflora* products. Two women pastoralists, 15 men pastoralists, and three men agro-pastoralists, i.e., eighteen percent of the interviewees, reported that they do not use *weyane* (Table 3.2). In Afar, women do most of the household work including preparation of food, firewood collection and traditional house construction. Therefore, the high rate of *P. juliflora* use by women groups was not unexpected. Because of the migratory way of life, pastoralists cover large areas of land and have easy access to the native plants. Alternatively, agro-pastoralists stay in one location and depend more on the easily available *P.*

juliflora plant. Thus, the observed difference in *P. juliflora* use between pastoralist and agro-pastoralist groups appears to be driven by the availability of native plants. Our findings suggest that women and agro-pastoralist groups who already use *P. juliflora* products in their household will likely adopt recently introduced *P. juliflora* utilization and control methods such as "control through utilization".

Thirty-nine percent of the interviewed people were involved in charcoal production and trade. More men are involved in the charcoal business (i.e., producing charcoal and selling it) than women (Table 3.2). Most people stated that they earn a good profit from the production and sale of charcoal. Several people who were not involved in the charcoal business mentioned that they look after their livestock and do not have time to take part in extra activities, while others said that they lack the materials, tools, knowledge, finance and the resources to engage in charcoal business. Despite its potential economic value, a huge majority of the interviewees (99 percent of both men and women) stated that *P. juliflora* needs to be controlled and managed as its overall negative impacts exceed its positive impacts (Table 3.2).

Because *P. juliflora* seeds can persist for long periods in the seed bank [47] and coppices vigorously after harvest, charcoal making per se does not contribute to its control unless there is a follow up management intervention to suppress the regeneration. The most effective and widely practiced control methods include cutting trees, uprooting stumps, burning, and converting cleared lands into crop lands or managed grasslands (Figure 3.3). Mechanical clearing of *P. juliflora* monocultures using bulldozers along the Awash River has also had promising results (personal observation). Most interviewed people called for large-scale interventions from the government, including chemical treatments.

3.6 Community Maps

Afar communities identified *P. juliflora* infested sites and important resources such as rivers, grazing areas, roads, trails, mountains and ridges. *Prosopis juliflora* was present in all the studied villages. Dense populations of *P. juliflora* trees were identified around Bedulale, Serkamo, Melka Sedi, Udleisi and Buri villages, and near Awash River, whereas moderate densities of *P. juliflora* infestations were identified adjacent to densely invaded sites, and between Awash Arba town and Udleisi village

(Figure 3.5). At the sketch mapping stage, men and women participants were inclined to map dense stands more than they did sparsely infested sites. The communities also mapped *P. juliflora* infestations in greater detail and frequency that were near settlement areas as opposed to distant sites, suggesting that sketch mapping may be more suited to fine-scale mapping than coarse-scale mapping.

The overlay analysis indicated that *P. juliflora* has predominantly invaded two land cover categories i.e., Dense Grasslands (48%) and Exposed Sand and Soil (39%; Figure 3.4). The species has also invaded Dense Shrub Land (5%), Dense Woodland (4%), Riparian Woodland (2%) and State Farms (2%; Figure 3.4). The high level of *P. juliflora* occurrence in the grasslands, and exposed sand and soil land cover categories, and the relatively low level of its occurrence in the dense vegetation classes (shrub and woodlands) suggest that the species prefers open lands to densely vegetated areas. This view is further supported by its expansion into state farms which were abandoned and left open (personal observation). The expansion of *P. juliflora* into the exposed sand and soil land cover class also demonstrates the species' suitability for reducing desertification, one of the motives which led to its introduction to east African countries [38, 48]. The ancillary data used in the overlay analysis did not have categories of wetlands and residential areas; thus, we could not compare *P. juliflora* invasion trends on wetlands and settlement areas.

In the study site, farming is done through irrigation, and new farmlands are usually established by removing the native vegetation. Afar communities mapped the large-scale farmlands found near Sheleko and Eeble villages, east of the Awash River (Figure 3.5). Similarly, the sketch mappers from Udleisi village mentioned a large sugarcane plantation that was to be established on their communal grazing area and the Alledeghi Wildlife Reserve. During the transect walks, I observed more than 10 deep water wells that were dug to secure irrigation water for the new sugarcane plantation. However, the boundaries of this new plantation were not known to the communities, and we were not able to show it on the community maps. Removing the native vegetation, especially over a larger-scale, creates open areas which are highly suited for *P. juliflora* spread. Thus, the establishment of new large-scale farmlands in Afar is likely to escalate the spread of *P. juliflora* in the region.

Besides mapping, the PM activities also involved identifying the major resource related problems of Afar communities (see section 2.3). Both men and women mapping groups, in all the studied villages, identified *P. juliflora* as a major problem and comprehensively described its adverse impacts on the region's land cover, useful native species, and livestock resources. They also identified additional problems that include overtaking of their land by the government for new large-scale agribusinesses, flooding from Awash and Gelealo Rivers, drought, shortage of drinking and irrigation water, shortage of electric power, and conflict with neighboring pastoralist communities. Women mapping groups stressed water related problems, while men mapping groups stressed the on-going conflict with the rival Issa pastoralist communities. Fetching water is one of the traditional responsibilities of Afar women, while protecting people and livestock is one of the traditional responsibilities of Afar men. Both men and women mapping groups drew conflict areas and boarder villages on the community maps. The community maps should be interpreted with caution as my main objective centered on the invasive *P. juliflora* plant, not on conflict resolution. Rettberge (2010) provides detailed analyses of conflicts in the region and their impacts on the Afar people.

4. Conclusions

I generated new information on the invasive *P. juliflora* plant by interviewing 108 pastoralists and agro-pastoralists in the Afar region of Ethiopia, and applying PM approaches. Interview results revealed valuable information about the introduction history, spread, impacts, uses, and control mechanisms of *P. juliflora* in Afar. Introduced in the 1970s for its alleged multiple benefits, the species has caused adverse impacts on Afars' native plants, wildlife, and livestock resources. *Prosopis juliflora* seeds are dispersed by cattle, goats, sheep, camels, warthogs, humans and flood. In Amibara *woreda*, southern Afar, *P. juliflora* is used to produce fire wood, charcoal, and animal fodder. The effective *P. juliflora* control methods currently practiced in Afar include cutting trees, digging out stumps, and burning.

By applying PM techniques, I mapped *P. juliflora* infested areas and other important features and resources. Comparison of current *P. juliflora* maps with ancillary land cover data showed that *P. juliflora* is altering the regions' land cover by invading grasslands and open areas. The PM methods also allowed me to understand the communities' major resource related problems. In addition to the threats posed by invasive species like *P. juliflora*, Afar people face conflicts from the rival pastoralist communities, and land grabs from the central government. Afar communities fully participated in the PM process and highly accepted the final map products. By integrating interview, PM, GIS, GPS, and remote sensing technologies and approaches, I collected geo-spatial information that is crucial for the management of the invasive *P. juliflora* plant. My methods are suitable for mapping, detecting, and managing invasive species, especially at a fine geographic scale. The social, economic, and environmental costs and benefits of *P. juliflora* invasion in Ethiopia require further investigation. Additional research works are also needed on land-grabs, conflicts, and land-cover change dynamics, particularly over a larger geographic extent

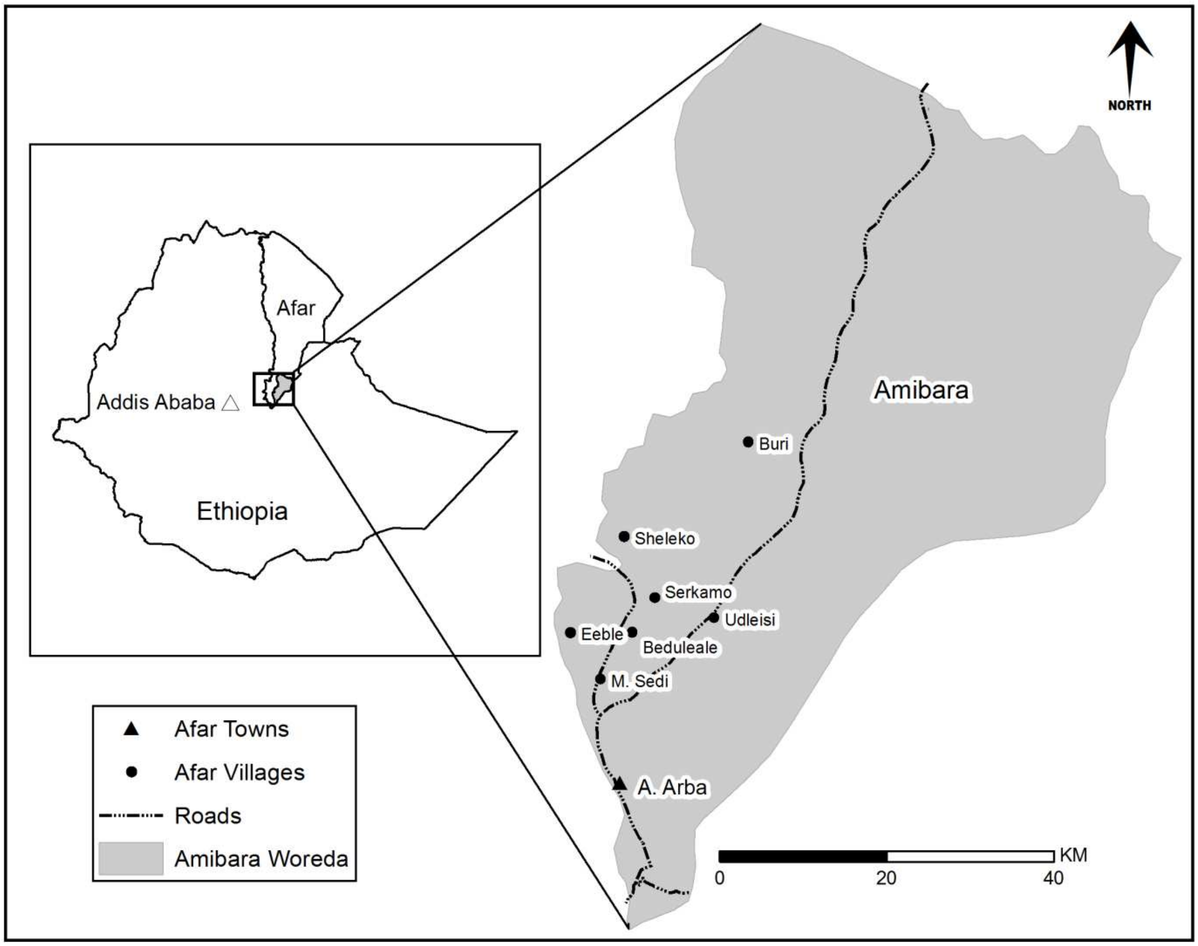

Figure 3.1. **Study Site**. Map of the study site.

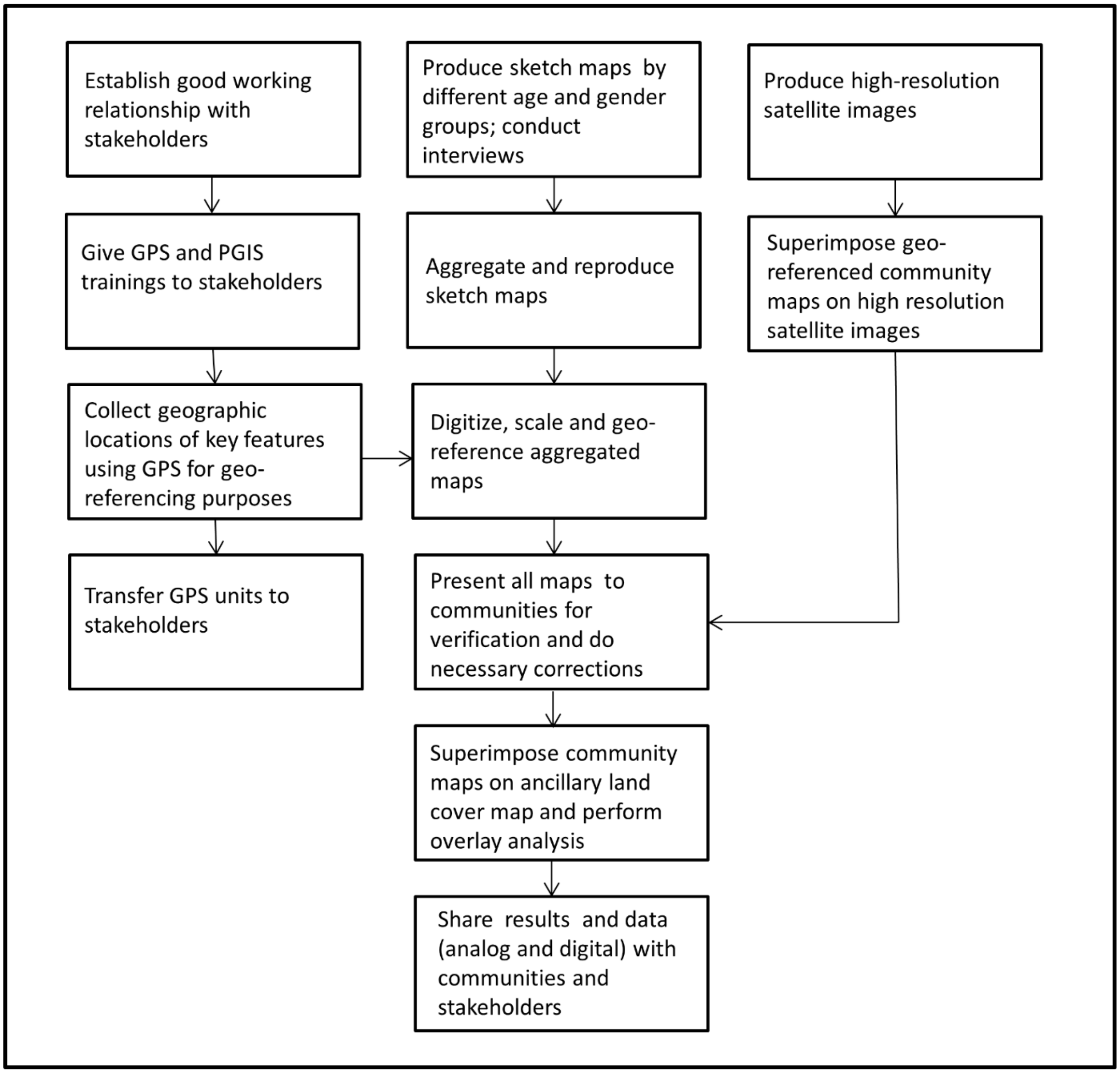

Figure 3.2. **Flow Chart**. The flow chart illustrates the participatory research steps used to map *P. juliflora* in the Amibara *woreda* of Ethiopia. GPS stands for Global Positioning System; PGIS stands for Participatory Geographic Information Systems.

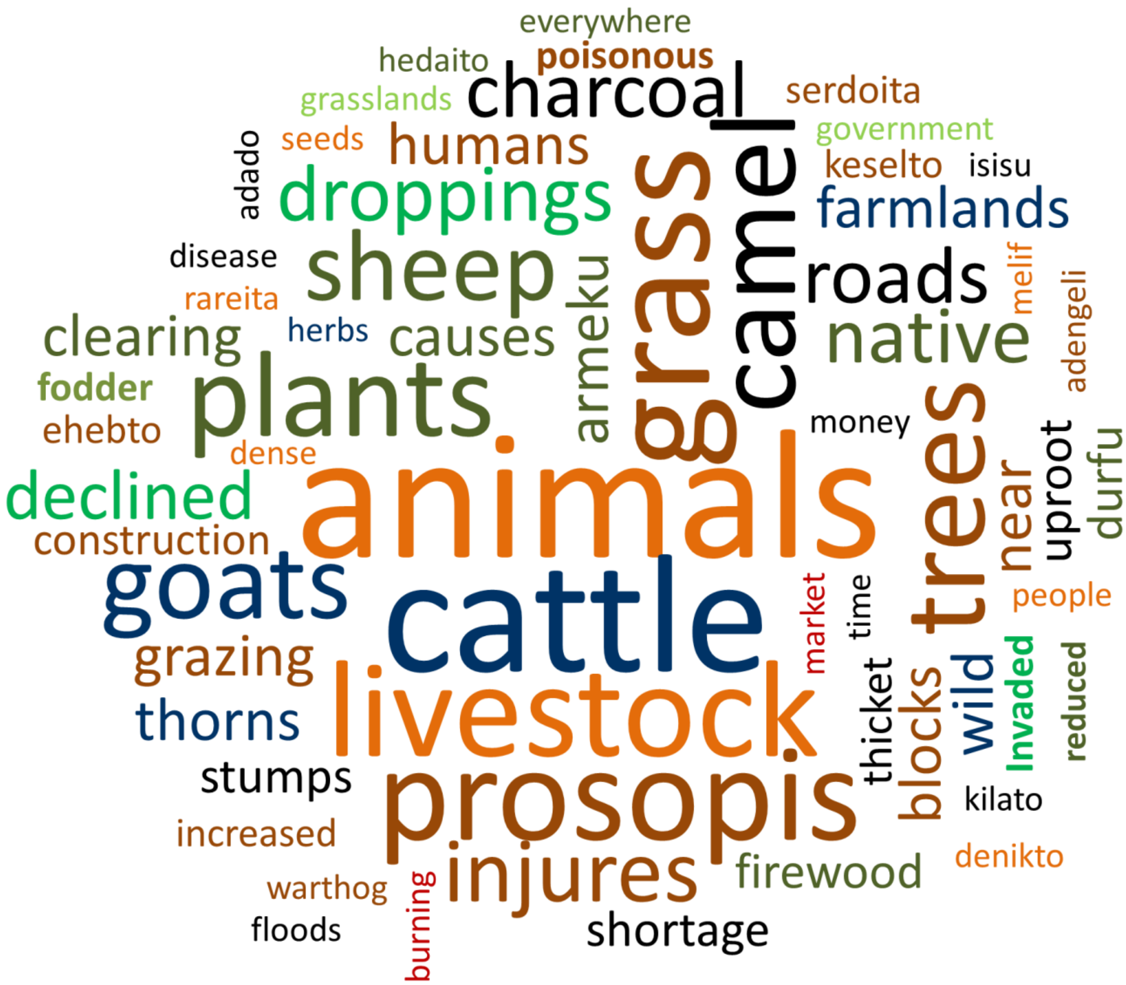

Figure 3.3. **Word cloud showing the top 90 frequently used words and concepts during the interviews**. Font size reflects frequency, with larger being more frequent. Words such as "grassland", "roads", "near" and "everywhere" represent *P. juliflora* infested sites; "charcoal", "fodder", "construction" and "firewood" indicate *P. juliflora* uses; "poisonous", "injures", "disease", "declined" and "blocks" indicate the species' negative impacts; "clearing", "burning", "uproot" and "stumps" indicate commonly used *P. juliflora* controlling methods, while words such as "grass", "trees", "herbs", "serdoita", "keselto" and "isisu" represent the native plants that are negatively affected by *P. juliflora*.

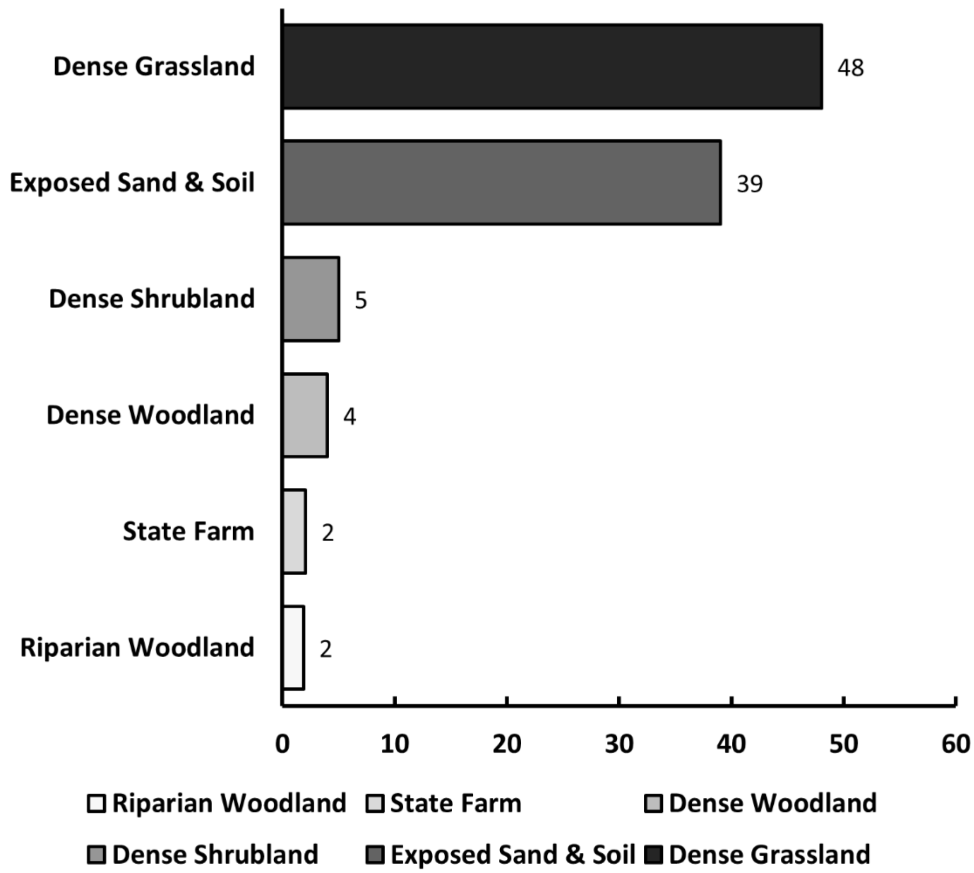

Figure 3.4. **Land cover types affected by *P. juliflora* infestation**. Forty-eight percent, 39%, 5%, 4%, and 2% of the *P. juliflora* infestations occurred in what was previously classified as Dense Grassland, Exposed Sand & Soil, Dense Shrub Land, Dense Woodland, State Farm, and Riparian Woodland, respectively.

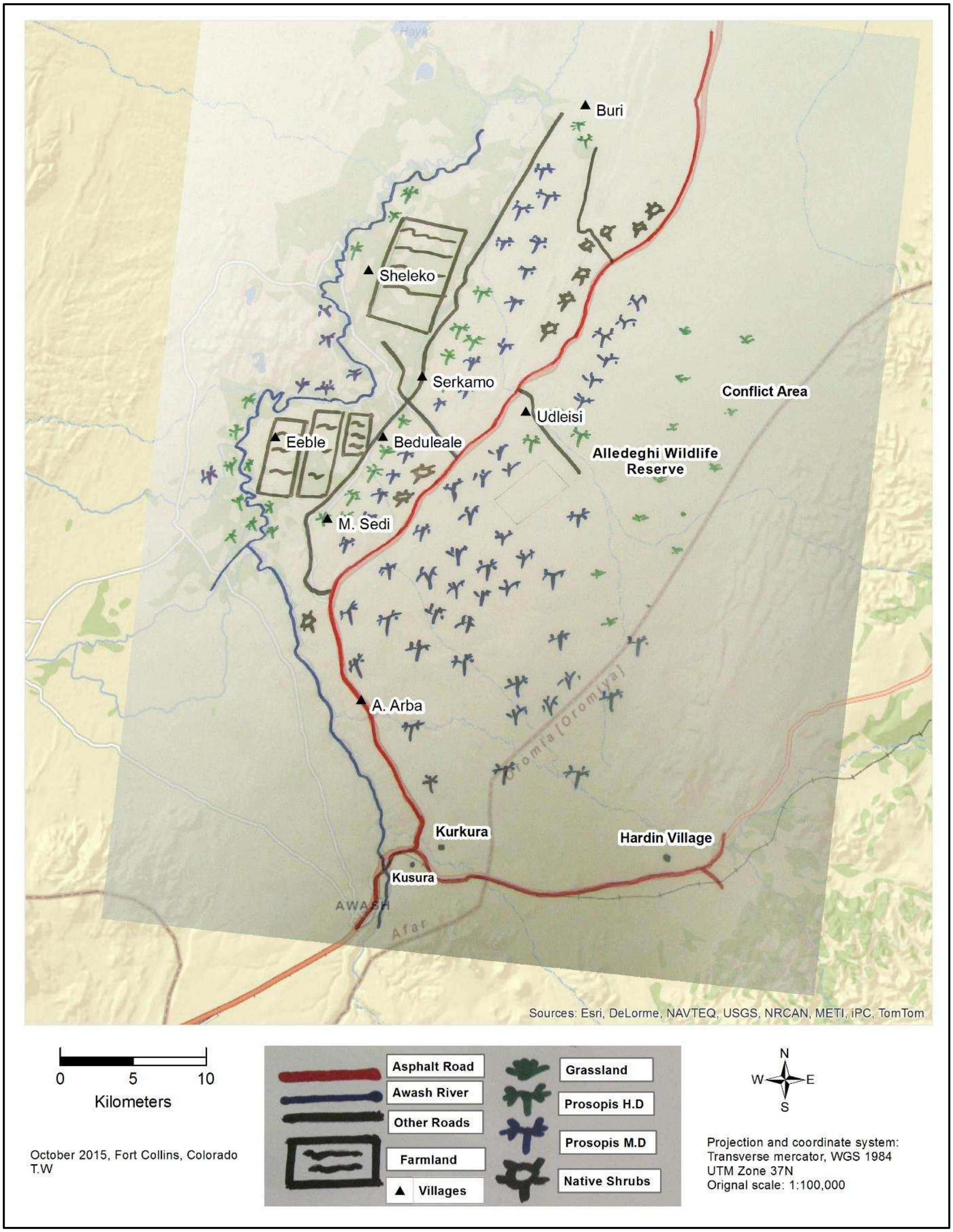

Figure 3.5. **Community map**. Community map showing *P. juliflora* distribution and density in Amibara *woreda*. H.D stands for High Density and M. D stands for Moderate Density *P. juliflora* invasion. Source of background image: ESRI.

Table 3.1. **The top 10 most frequently used words and concepts, and their counts**. The responses from all respondents were auto-coded by the 11 interview questions, and the word frequency analysis was performed using NVIVO qualitative data analysis software (version 10.0). The most repeated words and concepts are highly related to animals and their declining resources.

Words and Concepts	Count
Animals	766
Grass	682
Cattle	670
Plants	646
Livestock	578
Prosopis	544
Camel	512
Trees	502
Sheep	476
Goats	462

Table 3.2. ***Prosopis juliflora* utilization in Afar**. One-hundred percent of women agro-pastoralists use *P. juliflora* products suggesting that targeting these groups may increase the adoption rate of new *P. juliflora* control strategies such as "control through utilization". The table was prepared using interview questions three, four and ten (Appendix A).

Description	Pastoralists			Agro-pastoralists			Pastoralists & Agro-pastoralists		
	Men	Women	Total	Men	Women	Total	Men	Women	Total
Number of interviewees	43	19	62	30	16	46	73	35	108
Number of people who use *Prosopis*	28	17	45	27	16	43	55	33	88
Percent of people who use *Prosopis*	65	89	73	90	100	93	75	94	81
Number of people who produce and sell *Prosopis* charcoal	11	2	13	24	6	30	35	8	43
Percent of people who produce and sell *Prosopis* charcoal	26	11	21	80	38	65	48	23	40
Number of people who agree that *Prosopis* needs to be controlled or managed	43	19	62	29	16	45	72	35	107
Percent of people who agree that *Prosopis* needs to be controlled or managed	100	100	100	97	100	98	99	100	99

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CHAPTER 4: IS CONTROL THRROUGH UTILIZATION A COST EFFECTIVE *PROSOPIS JULIFLORA* MANAGEMENT STRATEGY?

Synopsis

The invasive *Prosopis juliflora* causes environmental and economic damages on invaded ranges. High invasive species eradication costs have swayed developing countries to follow a new and less expensive control approach known as *control through utilization*. However, the net benefits of this new approach have not been thoroughly tested. My objective was to identify *P. juliflora* eradication and utilization methods practiced in Afar (Ethiopia), and assess their economic feasibility. I identified one major *P. juliflora* eradication method, converting infested lands into irrigated farms (conversion), and two utilization practices, charcoal and flour production. I interviewed 19 enterprise owners, recorded the production and management steps of all enterprises, and estimated their costs and revenues. I assessed the economic feasibility of the enterprises by performing enterprise, break-even, investment, sensitivity, and risk analyses. The results show that conversion is economically profitable, with Net Present Value (NPV) of 5,234 US$/ ha over 10 years and an interest rate of 10% per year. Conversion highly reduces the spread of *P. juliflora* in farmlands. Managing *P. juliflora* infested lands for charcoal production with a four-year harvest cycle is profitable, with NPV of 805 US$/ ha. However, the production process needs vigilant regulation to protect native plants from illegal exploitation. Caution should also be taken to prevent charcoal production sites from becoming potential seed sources. Producing *P. juliflora* flour for animal feed purposes was unprofitable. Flour production can reduce new invasions by destroying viable *P. juliflora* seeds. Conversion and charcoal production can be undertaken with small investment costs, while flour production requires high investment costs. Introducing new changes in the production and management steps of *P. juliflora* flour might be considered to make the enterprise profitable. My study shows that conversion can be a profitable management option in the right environmental setting.

Key words: animal feed, charcoal, control through utilization, irrigated farming, *P. juliflora*, profitability

1. Introduction

Prosopis juliflora is a fast growing plant that is native to Argentina, Peru, Venezuela, Mexico and Caribbean [1, 2]. In the 1970's it was introduced to East African countries through collaborative efforts of governments and international development organizations [3]. It was primarily introduced to rehabilitate degraded soils, to supply firewood and fodder, and to combat desertification [4, 5]. However, the species rapidly naturalized and expanded into new locations, where it was neither anticipated nor desired. *Prosopis* taxa, which comprise 44 species [1], are known to occur in 40 African and 129 world countries [5]. The invasive *P. juliflora* plant widely occurs in Ethiopia's Afar region where it currently occupies an estimated 360,500 ha of arid and semi-arid lands [6].

The purpose of this study was to compare management strategies that aim to eradicate the species with those that try to utilize it. *Prosopis juliflora* is one of the controversial plants globally because it has both beneficial and harmful impacts. For instance, Kenyan women benefited from the easily available *P. juliflora* firewood, while, Kenyan farmers and herders were harmed because of *P. juliflora* related control costs and livestock deaths [7].The species has several documented uses, both in its native and introduced ranges. In its native range, the species is exploited for human food, animal feed, medicine, timber, honey, and energy products [8, 9]. In India, the species is grown for firewood, charcoal, and generating electric power [10, 11]. The species has potential as an agroforestry plant [12] and biotic carbon pool [13]. In Ethiopia, *P. juliflora* is widely used for animal feed, firewood and charcoal production purposes [14], but it is unexploited for human food, honey, timber, and electric power production purposes.

Despite its beneficial uses, the species pose a threat to native ecosystems, pastoralism and dry-land farming. The negative impacts of *P. juliflora* include loss of biodiversity [15], reduction of water resources [16], degradation and loss of rangelands and farmlands [17], decreased health and mortality of livestock [18, 14], and high clearing costs on farmlands and rangelands [19]. Efforts to control *Prosopis* species around the world, particularly by mechanical and chemical means, have been expensive and ineffective [11, 19-20]. As a result strategies that aim to minimize costs and maximize economic benefits are being sought in several developing countries. For instance, a strategies of *managed utilization*, *controlling through utilization* and *eradication by utilization* have been advocated in Ethiopia, Nigeria, and Kenya [21-23]. These utilization schemes are promoted in developing countries because they create new incomes for the affected communities, while positively contributing to the control and management of the invasive species. Biological and mechanical controlling approaches, which incur higher costs, are the least preferred options in most developing countries [5].

While much of the management energy concerning invasive species might be oriented toward eradication, people in developing countries have generated new incomes by exploiting the invasive *P. juliflora* trees. Rural households in developing countries have increased their average income by growing and managing *P. juliflora* trees (e.g., [11]). Common *P. juliflora* control and management practices include burning, digging out stumps, thinning, pruning, and harvesting [8, 24]. The decision to eradicate *P. juliflora* or to manage it for different income generating purposes may depend on its location. For instance, near water sources where irrigation is possible, farmers choose growing agricultural crops over *P. juliflora*. However, in marginal lands where water-intensive agriculture is not possible, farmers choose growing *P. juliflora* over agricultural crops [11].

Agro-pastoralists in eastern Ethiopia use *P. juliflora* firewood in their households [25]. Managing *P. juliflora* trees for firewood production can be profitable. For instance, in India a *P. juliflora* fuel-wood plantation managed with a six-year harvest cycle, was found to be profitable; Net Present Value (NPV) = $4,040 [10]. In Afar, transporting charcoal is cheaper than transporting fuel-wood logs. Thus, more people in Afar are involved in *P. juliflora* charcoal business than *P. juliflora* firewood business.

Existing *P. juliflora* eradication and utilization practices in Ethiopia include conversion of *P. juliflora* invaded lands into irrigated agriculture, charcoal production, and flour production [14, 23]. Non-governmental organizations (NGOs) working in Afar have in the past formed cooperatives that produced and sold *P. juliflora* charcoal and flour [14]. *Prosopis juliflora* charcoal, grown and produced in Afar, is currently distributed and sold in major Ethiopian cities including Addis Ababa and Mekelle [26]. Flour, which is used as animal feed, is produced by crushing and milling *P. juliflora* pods. In its native range, growing *Prosopis* for timber production with a thirty-year harvest cycle was found to be profitable (net profit = 9,777 US$/ ha; [27]); however, the practice of harvesting trees at a younger age has restricted *P. juliflora* timber production in Ethiopia.

Though several *P. juliflora* utilization and eradication methods are practiced in Ethiopia, I could not find any published studies that analyzed and compared their economic profitability. Identifying and implementing economically feasible *P. juliflora* management strategies is essential for developing countries like Ethiopia, as biological and mechanical approaches for controlling its spread are expensive and largely inaccessible. My objectives were to: a) identify *P. juliflora* eradication and utilization approaches, b) describe the production and management steps of the identified practices and estimate all costs and revenues; and c) assess the economic viability of selected *P. juliflora* eradication and utilization approaches.

2. Methods

2.1 Study Site

The study was conducted in Amibara and Gewane *woredas* (counties) of southern Afar, northeastern Ethiopia (Figure 4.1). The majority of the Afar people are pastoralists and their main livelihood is founded on rearing livestock. The region's climate is semi-arid in the south, arid in the center, and desert in the north and northeast. Elevation in Afar ranges from 125m below sea level to 2,870m above sea level. The mean annual precipitation of the study site is 580mm, while the mean annual temperature is 26.6^{o}C. Afar faces recurrent natural drought and intermittent flooding from the Awash River. Recent policies (e.g., the agriculture led industrialization, growth and transformation) of the central government encourages the Afar people to minimize their mobility and practice farming. Several government and privately owned large-scale farms are present in the study site. Farming is mostly conducted by irrigating the fields using water from the Awash River. Rain-fed farming is not practiced in the study site due to the lack of precipitation and high rate of evapotranspiration. The region contains the largest *P. juliflora* infestation in Ethiopia. In Afar, *P. juliflora* has extensively invaded the flat lands along the Awash River and the Alledeghie Plain. The Alledeghie Plain is an extensive grassland area that starts in Amibara *woreda*, and extends into northern Afar and the Somali region.

2.2 Data Collection

Based on previous *P. juliflora* research findings, I identified one eradication and three utilization strategies practiced in the study site [23, 28]. The primary eradication practice identified was converting *P. juliflora* infested lands into irrigated farms (farm enterprise), while the three utilization practices identified were charcoal production (charcoal enterprise), *P. juliflora* flour production (flour enterprise), and firewood production. Afar communities regularly use *P. juliflora* in their households for firewood, but I found very few people who sell it for profit making purposes. Since *P. juliflora* firewood production did not exist as an enterprise in the study site, I did not include it in the economic analysis. My study included one cooperative owned flour enterprise, eight farm enterprises, and 10 charcoal enterprises (a total of 19 enterprises). Cotton and sugarcane are the two top agricultural crops grown in the study site. I collected data only on small-scale cotton farm enterprises (<10 ha of farmland). Most small-scale farmers in Afar clear *P. juliflora* infested lands using manual labor and grow agricultural crops on cleared lands. However, the large-scale farmers, who have big financial capital, indiscriminately clear both the native vegetation and invasive *P. juliflora* trees using heavy machinery. For this reason, my study focused on the small-scale farmers because they see *P. juliflora* both as a challenge and as an opportunity.

I collected data through interviews in April and May 2014 by obtaining the names and addresses of the 19 enterprise owners from the *kebele* representatives. According to the regions' government structure, *kebele* constitutes the lowest legal administrative body. I collected data on the production and management steps required to produce three products, i.e., cotton, *Prosopis* charcoal, and *Prosopis* flour by interviewing the 19 enterprise owners (see Appendix B for interview questions). Additionally, I collected data on costs (i.e., investment, production, and labor), yields, prices and revenues for all three products from the 19 interviewees. I administered the interviews with the assistance of a graduate student and a multi-lingual Ethiopian professional. The study design was pre-approved by the Social, Behavioral, and Education Research Institutional Review Board at Colorado State University (Protocol # 14-5049H).

2.3 Data Analysis

Based on the collected information, I estimated all costs and revenues for the three enterprise types, prepared enterprise budgets, and performed enterprise, investment, break-even, sensitivity, and risk analyses. Large initial costs occurring at the establishment of an enterprise were amortized [29]. For estimating costs of farm and charcoal enterprises, I assumed the lifetime of machineries and equipment to be 10 years, and their terminal values to be 10% of their purchase prices. For the expensive flour enterprise, I changed the lifetime of machineries to 20 years, and kept terminal values at 10% of purchase prices. I calculated machinery and equipment depreciation for all enterprises using the straight line method. I used 10% interest rates in all of our calculations as this rate was used by Ethiopian banks in most long-term loans. Annual investment cost was obtained by adding annual depreciation and annual interest cost. The annual interest cost (I) was calculated using the equation:

$$I = [(Purchase\ price + Salvage\ value)/2]*i; \quad \text{where i=10\%}$$

I calculated gross margins by subtracting operating costs from revenues. Break-even prices were obtained by dividing total costs with expected yields, while break-even yields were obtained by dividing total costs with output prices [30]. I assessed the profitability of enterprises by projecting cash flows for 10 years, and computing Net Present Values (NPV) [31-33]. In NPV analysis, all future costs and benefits are discounted to the present value, permitting easy comparisons of policy or management alternatives [34]. The NPV decision rule specifies that projects with positive NPVs are profitable, while projects with negative NPVs are un-profitable. A NPV of zero indicates no change in the value of the investment. For a given discount rate (r), time (t), project life in years (n), total revenue (Rt) and total expenses per year (Et), the total Net Present Value (Birr/ ha) over the life of an investment (T) is calculated using the following equation:

$$NPV_T = \sum_{t=0}^{n} (Rt - Et) \,.\, (1+r)^{-t}$$

I performed sensitivity tests for all enterprise types by making ± 20% changes in investment costs, gross revenues (prices and yields), and interest rates. The sensitivity tests were conducted to investigate the relative contribution of each economic variable to the NPV (profit) and to the vulnerability of each enterprise to changes in input costs. Sensitivity tests show how the profit changes ceteris paribus of the variables' changes. I used tornado diagrams (tornado charts) to visualize sensitivity test results. Long bars in tornado charts indicate high sensitivity, while short bars depict low sensitivity.

I analyzed and ranked the risk of the three enterprise types using Simetar© software [35]. I selected prices, yields, fixed costs, and operating costs as stochastic variables. I estimated the means and standard deviations of the selected variables using my data and secondary sources (Table 4.1). I calculated gross margin values for all enterprise types by simulating the stochastic variables one-hundred times (normal distributions with means and standard deviations). I generated cumulative distribution functions (CDFs) of the gross margin values, and subjected the CDFs to first- and second-order Stochastic Dominance tests, which are concepts used for ranking risky alternatives [36]. The decision rule specifies that, for non-crossing CDFs, one distribution dominates another for any risk preference by a decision maker, whether they are risk averse, risk neutral or risk loving. If CDFs intersect, then second-order stochastic dominance can be used to rank distributions, with the assumption that the decision maker is risk averse [36, 37]. Distributions cannot always be ranked, but when they can, Stochastic Dominance is a valuable tool because it ranks different options for risk and returns without the need to measure individual risk preferences of the decision makers that will be considering these production alternatives. When distributions cannot be ranked with Stochastic Dominance, they can be ranked with other methods that require more information about the unique risk preferences of the decision makers.

3. Results

3.1 Conversion

Conversion is usually practiced on flat lands near the Awash River where the land is suitable for irrigated farming. *Prosopis juliflora* infested lands are converted into irrigated cotton, onion, and corn farms. The production and management steps undertaken for the widely grown cotton crop include clearing invaded lands, digging out stumps and roots, burning (charcoal making is optional), land preparation (ploughing, grading, leveling and ridging), seed sowing, weeding, watering, applying pesticides, guarding, picking cotton, packaging, storing, and transporting the product to Awash market (interview questions 1- 4 & 6-11, Appendix B). New *P. juliflora* seedlings that regenerate on cleared lands are regarded as normal weeds and controlled by regular land preparation and weeding practices. Cotton is grown once per year and the whole process can be completed within 10 months. After cotton is harvested the remaining stalk is left for the Afar livestock to freely browse. Small-scale farmers get the land preparation work done through contractual agreements with large-scale farmers in the study site. The average yield of cotton in the study site was 36 quintal/ ha, and one quintal of raw cotton was sold for 61.86 US$ (1,200 Birr[7]) at Awash market (interview question 11; Appendix B). Farmers reported that growing cotton on *P. juliflora* cleared lands can increase cotton yield by 27% (10 quintal/ ha/ year) in the first five years (interview question 3; Appendix B).

Investment costs needed to grow cotton on one hectare of *P. juliflora* cleared land is 53 US$ (Figure 4.2). Growing cotton with own machinery and at a larger scale (100 ha of land on average) requires a large initial investment worth 136,521 US $ (Figure 4.2). Detailed economic analysis is done only for small-scale farms, which were the focus of this study. The gross margin for converting *P. juliflora* infested land into irrigated cotton farm in southern Afar was found to be 508 US$ (Figure 4.3). Enterprise budgets and investment costs for all the studied *P. juliflora* eradication and utilization options are shown in Appendix C. The investment analysis, conducted based on 10 years of projected returns and

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[7] Birr is the unit of currency used in Ethiopia. In April and May 2014, 1US$ was equivalent to 19.4 Ethiopian Birr.

expenses, showed that the investment can be profitable with Net Present Value (NPV) of 5,234 USS/ ha (Figure 4.4). The NP values for conversion remained above zero throughout the ten projected years (Figure 4.5). The break-even price was 48 US$/ quintal, while the break-even yield was 28 quintal/ ha. Sensitivity tests using a tornado diagram showed that conversion is sensitive to gross revenue, slightly sensitive to interest rate, and less sensitive to initial investment (Figure 4.6). The risk analysis shows that conversion has first-order stochastic dominance (preferred by all risk averse decision makers) over flour, while charcoal has second-order stochastic dominance over conversion (Figure 4.7).

3.2 Prosopis Charcoal

Prosopis juliflora infested lands that are currently unsuitable for conversion (e.g., due to inaccessibility to irrigated water or due to high flood risks) are exploited for charcoal. In the study site, most of the charcoal is also produced from *P. juliflora* trees growing in communal lands. Charcoal is produced near tree harvesting sites using the earth-mound-kiln method. Charcoal producers (usually Afar men or women with traditional land use right) produce charcoal by hiring immigrant labor[8]. The charcoal production and management steps include felling trees, debranching, cutting wood into smaller pieces (the remaining leaves and branches are usually burned), drying wood, gathering dried wood in one location and pilling it, covering pilled wood with soil and tree leaves, lighting the pilled wood and closely monitoring the carbonization process (interview questions 1, 2 & 4; Appendix B). When carbonization is complete, the produced charcoal is cooled, packed using polypropylene bags, and temporarily stored at the production site (interview question 4; Appendix B). The average charcoal yield obtained in one production cycle is 150 bags. On average, one bag of *P. juliflora* charcoal weighs 25kg. All charcoal making steps, i.e., from harvesting to packaging, are completed within one month. Charcoal distributers, who also absorb the loading and unloading fees, drive to the production site and buy charcoal at an average price of 2.58 US$/ bag. Charcoal producers reported that, on average, one hectare of *P. juliflora* infested land can yield 450 bags of charcoal every four years (interview question 4; Appendix B). I

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[8] Ethiopians from the densely populated Southern Nations, Nationalities, and Peoples' region (SNNP), migrate to sparsely populated areas like Afar to get temporary employment.

performed the economic analysis using this average yield (i.e., 450 bags of charcoal/ ha), and assessed the sensitivity of the business to ± 20% changes in charcoal gross revenue (yield and price), investment cost, and interest rate (see section 2.3).

The investment cost needed for a charcoal enterprise in southern Afar was 127 US$ (Figure 4.2). Harvesting occurs on mature *P. juliflora* trees that are freely available. Therefore, I assumed the tree tending costs that occur prior to harvesting trees are zero. Replanting is also not needed as *P. juliflora* trees coppice soon after harvest. However, the coppice stand has to be thinned and pruned to produce sustainable yield. The gross margin of a *P. juliflora* stand that is managed for charcoal production with a four-year harvest cycle was 571US$ (Figure 4.3). The investment analysis showed that a *P. juliflora* charcoal enterprise in southern Afar is profitable with NPV of 805 US$/ ha (n=10; Figure 4.4). The NP values in non-harvest years remained below zero (Figure 4.5). The break-even price was 1.34 US$/ bag of charcoal, while the break-even yield was 236 bags of charcoal/ ha. The sensitivity tests showed that charcoal enterprise is sensitive to gross revenue, slightly sensitive to interest rate, and less sensitive to initial investment (Figure 4.8). Charcoal enterprise emerged as the most preferred alternative when risk is considered, with first-order stochastic dominance over flour, and second-order stochastic dominance over conversion (Figure 4.7).

3.3 Prosopis Flour

Flour made from *P. juliflora* pods is used to feed cattle (both beef and dairy), poultry, sheep, goats, and camels. In the study region, *P. juliflora* produces pods twice a year. The main pod production and harvesting season (locally referred as *hagai*) occurs in May and June, while the second harvesting season (locally referred as *gilal*) occurs in October. The production and management steps involved in *P. juliflora* flour production include purchasing pods, drying pods, crushing pods (using mortar and pestles), and milling crushed pods using electric mills (interview question 4; Appendix B). The produced flour is packed using polypropylene bags and sold in the local market at a price of 0.1 US$/ Kg (interview question 4, Appendix B). The investment costs needed to start a *P. juliflora* pod milling plant is 12,247 US$. Although the pods are purchased at lower prices, pod drying and crushing costs drive up the total flour production costs. I found that less than 50% of milling time is allocated for flouring *P. juliflora* pods. The mills do not process *P. juliflora* pods at full capacity because there is less demand for the product and pods are available only in certain seasons (*hagai* and *gilal*). The gross margin of the *P. juliflora* flour producing enterprise in southern Afar was -1,351US$ (Figure 4.3). The investment is not profitable with NPV of –17,905 US$ (n=10; Figure 4.4). The break-even price was 0.47 US$/ Kg of *P. juliflora* flour, while the break-even yield was 31,988 Kg of *P. juliflora* flour/ year. Increasing the production level alone did not make the enterprise profitable unless pod processing costs were highly reduced. Unlike conversion and charcoal, *P. juliflora* flour enterprise is sensitive to initial investment, slightly sensitive to gross revenue, and less sensitive to interest rate (Figure 4.9). Both charcoal and conversion have first-order stochastic dominance over flour, making it the most risky alternative (Figure 4.7).

4. Discussion

I compared the best *P. juliflora* eradication approach, conversion, with two utilization approaches, charcoal and flour. Converting *P. juliflora* infested sites into irrigated farms (conversion) resulted in the highest NPV. However, conversion can take place only on sites that are close to water sources, and sites that are edaphically and topographically suitable for irrigated farming. Government owned irrigation projects in Awash regularly maintain irrigation channels and dykes in the study site. However, broken and unmaintained dykes may put some farm enterprises under high flood risk. Furthermore, conversion was inferior to utilization for charcoal when risk is considered.

Prosopis juliflora is a nitrogen fixing plant that improves soil nutrient conditions [38-40], and is known to rehabilitate saline soils [41]. Thus, the 27% additional yield reported by farmers, who grow cotton on *P. juliflora* cleared lands (see section 3.1), is probably caused by the soil ameliorating effects of the invasive *P. juliflora* plant. This new income (not used in the economic analysis) amounts to 139 US$/ ha in a single year, and 695 US$/ ha in five years (interest not included). Thus, farmers who participate in conversion business can get additional revenue and competitive advantage over non-participating farmers. I do not advocate for large-scale removal of forests and expansion of irrigated farms in the study site as this creates disturbance and facilitates the expansion of invasive plants [28]. However, my results show that converting infested sites into irrigated farms is an effective *P. juliflora* eradication option that is economically viable.

My findings also show that managing *P. juliflora* infested sites for charcoal production purposes is economically feasible. Studies conducted in India also suggest that making charcoal from *P. juliflora* wood is profitable [10, 33]. Charcoal yield can be considerably increased by introducing new carbonization techniques such as the adam-retort [42]. Improving charcoal yield can increase the gross margin of charcoal enterprises in Afar and make charcoal business even more profitable. However, I do not suggest planting new *P. juliflora* seedlings for charcoal making purposes as this may hasten the spread of *P. juliflora* in Afar. One of the challenges facing the charcoal enterprise is ensuring that charcoal is produced only from *P. juliflora* trees, not from the native plants. Caution should also be taken to prevent charcoal forests from becoming potential seed sources for *P. juliflora* spread. Charcoal policies (e.g., production, transportation) which seem to be lacking in the country [26] also need to be dealt with for the sustainable growth of the charcoal business in the region.

Making flour from *P. juliflora* pods can prevent new invasions by destroying viable seeds. However, the business was not economically viable under the current management practices implemented in southern Afar. The reasons include high initial investment costs, high pod processing costs (e.g., drying, crushing), and poor marketing practices. As a result, the major flour producing cooperative in southern Afar has shifted to milling food grains in place of *P. juliflora* pods. New ideas and practices should be introduced to make flour enterprises profitable. Reducing the initial investment cost, which was the sensitive economic variable, may make the enterprise profitable. Investment costs can be reduced through owning and using flour mills in groups rather than individually. Other needed steps may include adoption of new marketing strategies (e.g. selling products at Awash and Addis Ababa markets), reducing pod drying and crushing costs, and changing the product type. In Kenya, for instance, the value of *P. juliflora* flour was highly improved by supplementing it with antiemetic medicines, converting it into feed blocks, and marketing the product as best animal feed that controls worms and increases livestock productivity [43]. Flour enterprises in Ethiopia need support from research organizations, especially on nutritional values, chemical compositions, and toxicity levels of *P. juliflora* pods. Subsidizing flour producers should also be considered as destroying *P. juliflora* seeds highly contributes to the control and eradication of this highly invasive plant.

The profitability analyses clearly identified conversion as the best management alternative that gives high NPV. However, the risk analyses ranked charcoal production as the least risky alternative. An individual who chooses conversion will likely make a profit in most production seasons, but may occasionally loose or record a very high profit (Figure 4.7). Conversion is the suitable option for risk-taking individuals. Conversely, an individual who engages in charcoal production makes less profit than a cotton farmer. However, it is very unlikely for the charcoal producer to register a loss. Charcoal production is the suitable alternative for risk-averse individuals. Both the NPV and risk analyses results ranked flour production as the least preferred alternative. However, appropriate policy and management interventions can reverse the trend and make flour production profitable. My overall economic analysis demonstrates that *control through utilization* is one of the effective and economically feasible invasive species management approaches currently accessible to Ethiopia.

5. Conclusion

The main *P. juliflora* eradication and utilization approaches practiced in Afar include converting infested lands into irrigated farms, charcoal making, and production of flour from *P. juliflora* pods. I found converting infested lands into irrigated farms (conversion) to be the most profitable *P. juliflora* eradication technique practiced in Afar. In addition to providing economic benefits to farmers, conversion ensures total removal of *P. juliflora* from agricultural lands. However, lands allotted for conversion need to be accessible and suitable for irrigated farming. Conversion has also high economic risk compared to charcoal production. Managing *P. juliflora* infested lands for charcoal production with a four-year harvest cycle is an economically viable utilization technique. However, caution must be taken to stop the production sites from becoming potential *P. juliflora* seed sources, and to prevent native plants from illegal exploitation. Regional policies, particularly those that favor *P. juliflora* charcoal production and transport, should be upheld for the charcoal enterprise to grow. Producing *P. juliflora* flour prevents the expansion of new invasions by destroying viable seeds. However, *P. juliflora* flour producing enterprises are not economically profitable under the currently implemented management practices. Subsidies, enhanced products, and new marketing strategies may be considered to make flour enterprises profitable.

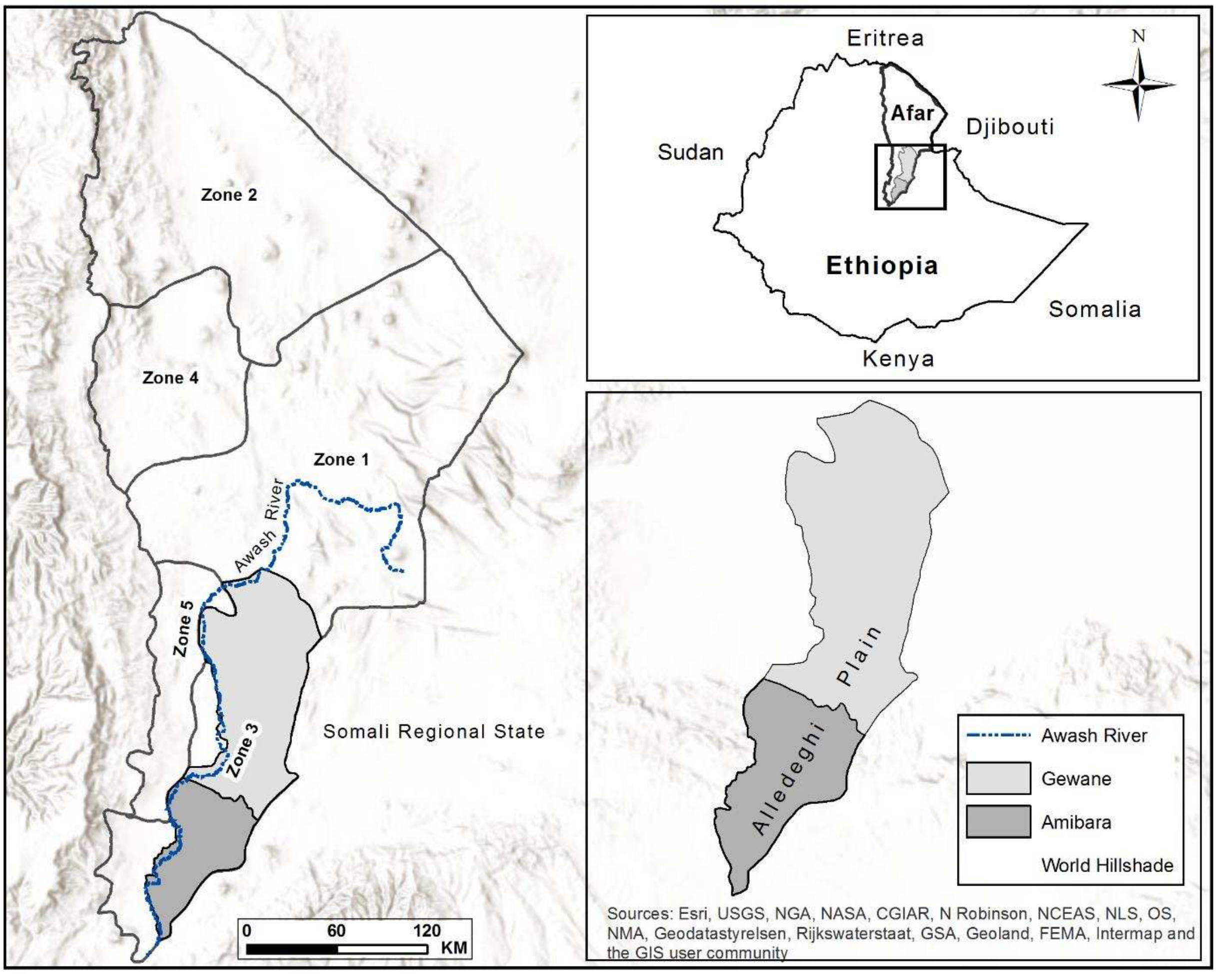

Figure 4.1. **Map of the study site**.

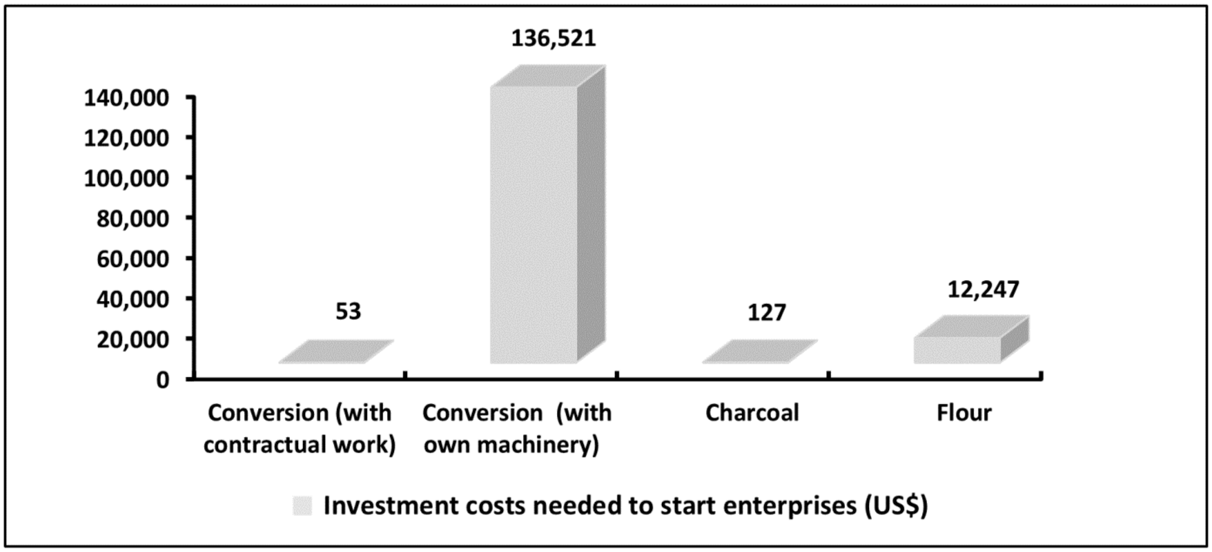

Figure 4.2. **Initial investment costs.** Conversion with own machinery and flour production require high initial investment, while conversion with contractual work and charcoal production require low initial investment.

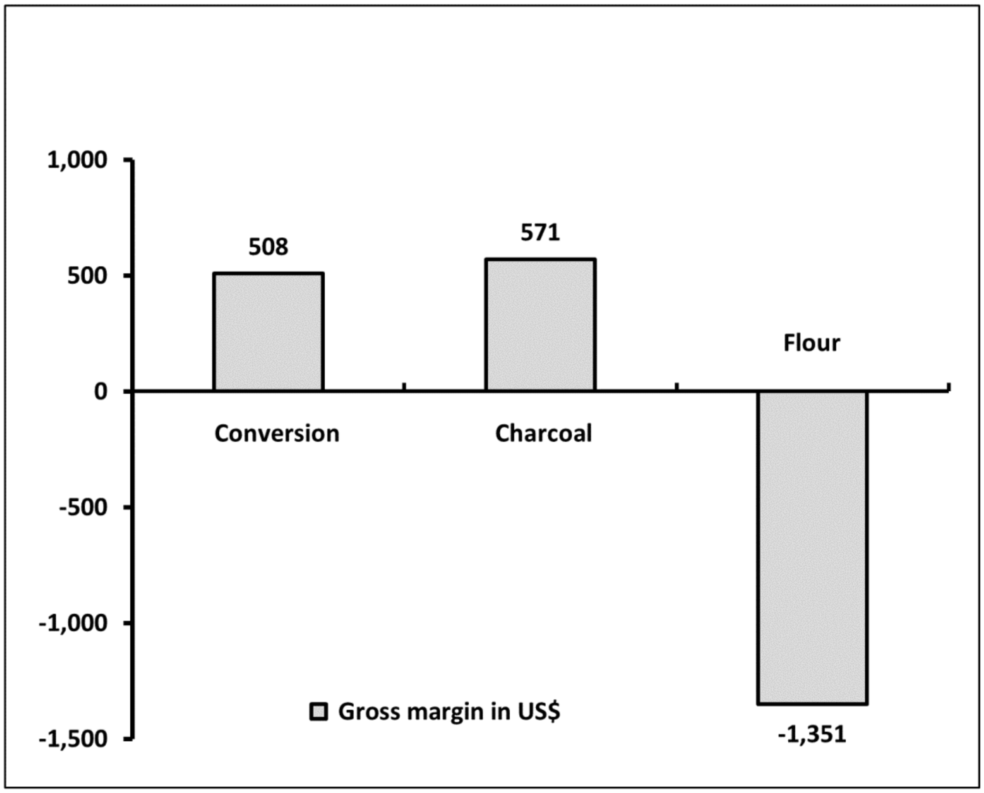

Figure 4.3. **Gross margins.** Gross margins for conversion, charcoal making, and flour production (US$).

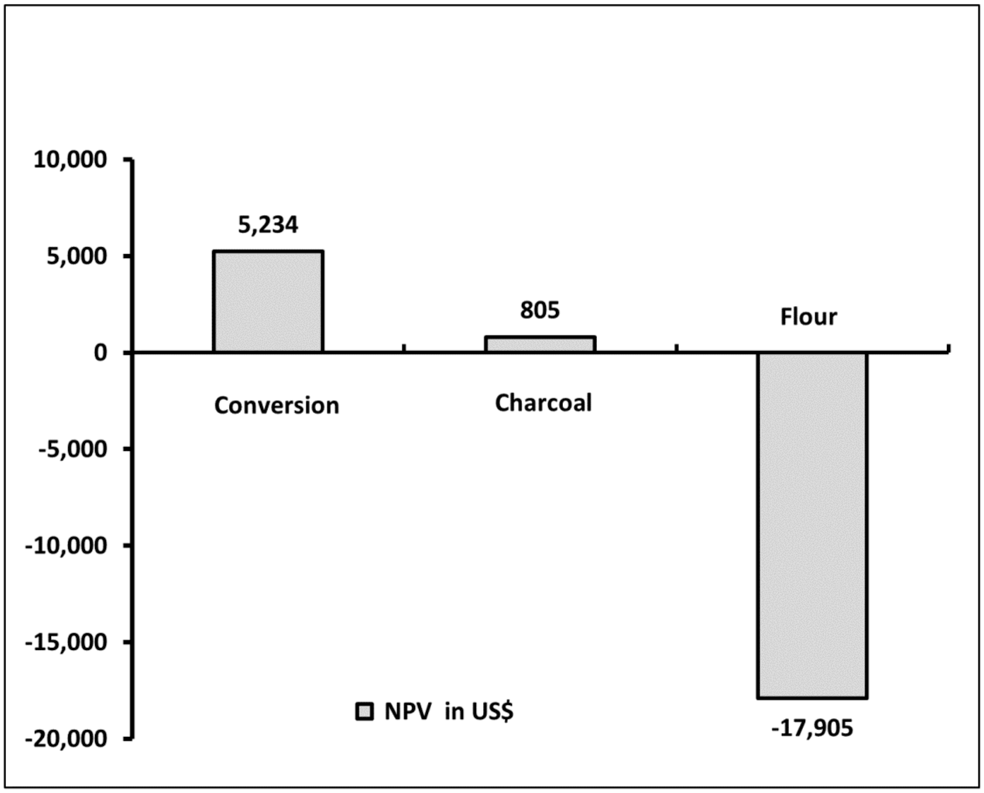

Figure 4.4. **Net Present Values for conversion, charcoal making, and flour production (US$).** The profitability analysis ranked conversion to be the most profitable, followed by charcoal and flour, respectively.

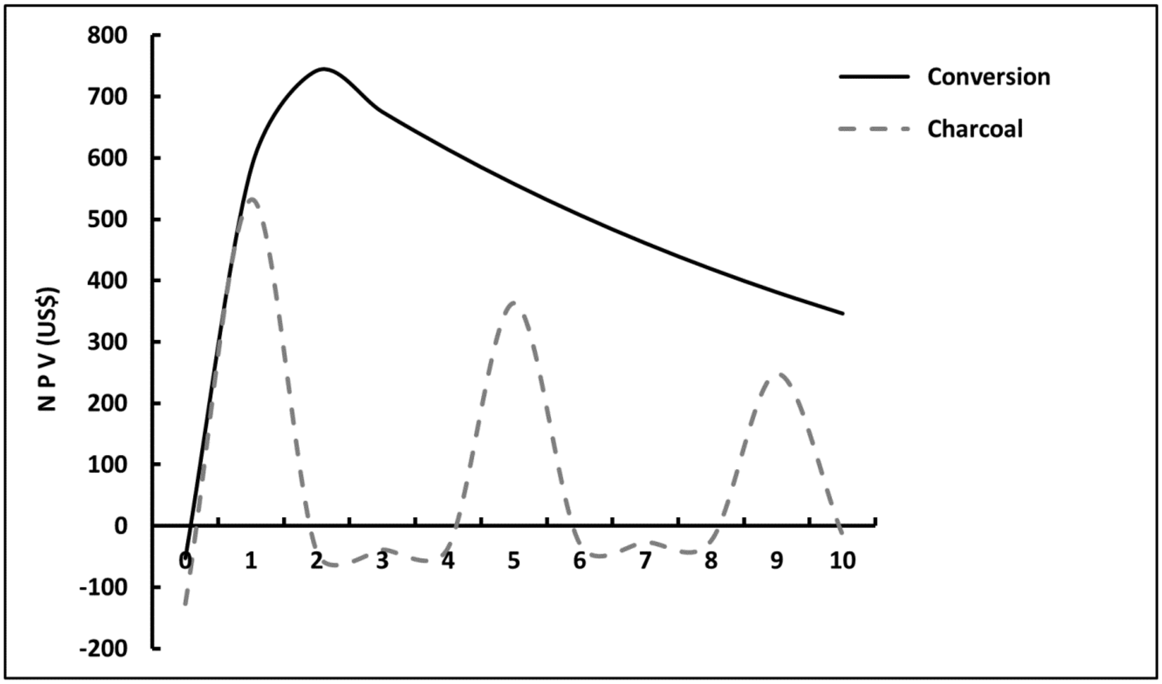

Figure 4.5. **NPV trends of farm and charcoal enterprises over 10 years (US$).** NPVs for conversion were positive throughout the 10 years, while NPVs for charcoal showed positive values only in harvest years.

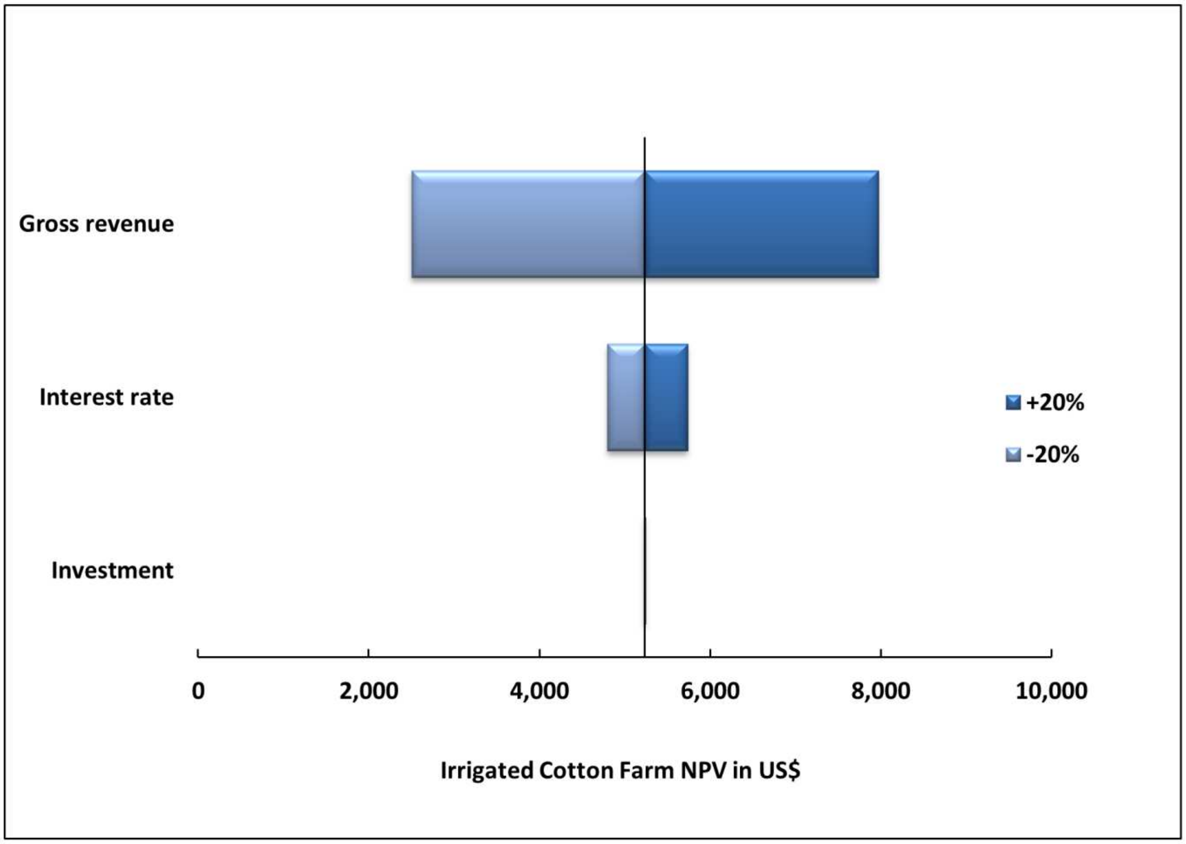

Figure 4.6. **Sensitivity of farm enterprises.** Sensitivity of farm enterprises to a ± 20% changes in gross income, interest rate, and initial investment costs.

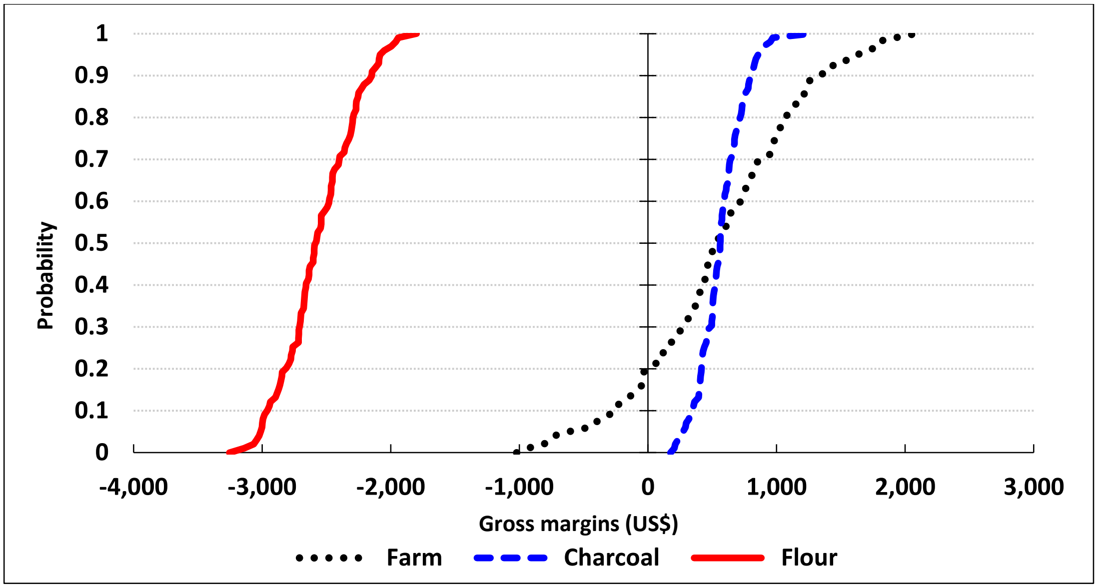

Figure 4.7. **Cumulative distribution functions (CDFs).** CDFs of profits for conversion and utilization methods for controlling *Prosopis juliflora* (US$).

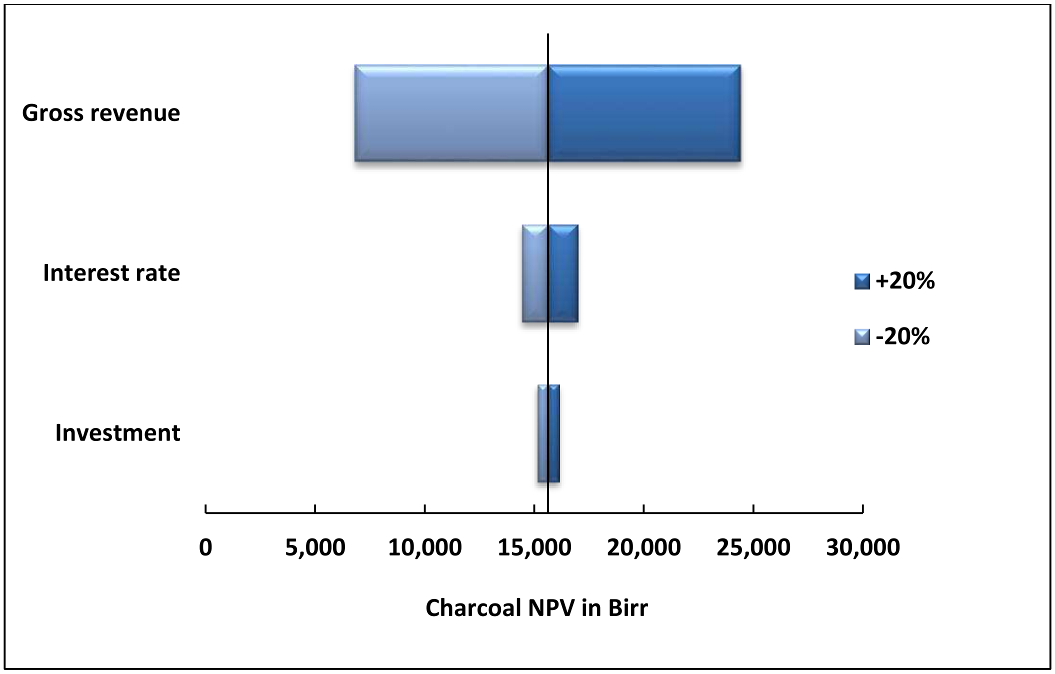

Figure 4.8. **Sensitivity of charcoal enterprises.** Sensitivity analysis of charcoal enterprises to a ± 20% changes in gross income, interest rate, and initial investment costs.

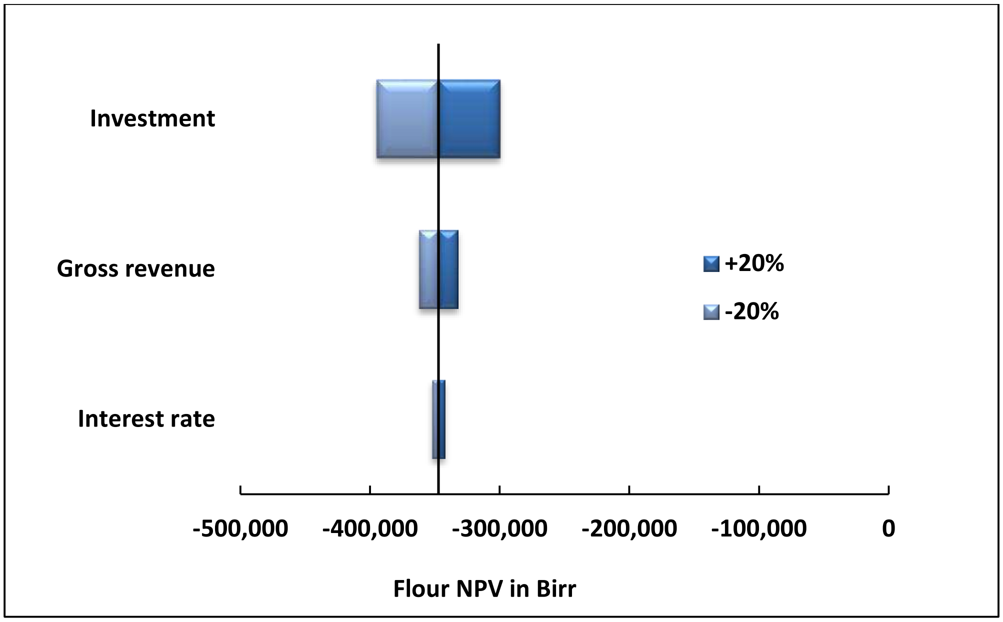

Figure 4.9. **Sensitivity analysis of a flour enterprise**. Sensitivity analysis of flour enterprises to a ± 20% changes in gross income, interest rate, and initial investment costs.

Table 4.1. **Means and Standard Deviations (SDs)**. Means and SDs of prices, yields, operating costs, and fixed costs; we estimated the values using our data and secondary sources.

Stochastic Variables (Means, SDs)		**Enterprise Types**		
		Farm	**Charcoal**	**Flour**
Price (US$)	Mean	61.86	2.58	0.10
	SD	2.58	0.26	0.03
Yield (Quintal)	Mean	36.00	450.00	7,000.00
	SD	10.00	50.00	2,000.00
Operating Costs (US$)	Mean	1,460.82	589.12	2,072.94
	SD	154.64	51.55	77.32
Fixed Costs (US$)	Mean	7.63	18.40	1,224.74
	SD	2.06	2.32	51.55

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CHAPTER 5: DISCUSSION AND CONCLUSIONS

In chapter two, I demonstrated that species presence records and vegetation indices derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery can be used with Maxent correlative modeling technique to map existing distribution of *P. juliflora*. Although similar techniques have been used with Landsat imagery to map the current distribution of invasive plants [1, 2], MODIS imagery has not been used with correlative modeling techniques for mapping current distributions. My study demonstrates that correlative modeling techniques such as Maxent, can be used as an analytical tools to process MODIS imagery to map current or actual distributions.

Modeling the potential distribution of invasive species generally relies on species-occurrence data and environmental variables such as climate and topography to identify the species' suitable habitats [3-6]. Caution should be taken when modeling the potential distributions of invasive plants using remote sensing predictors, as this may underestimate predicted distributions [7][9]. A recent study by Rocchini et al. [8], published after my study was completed, corroborates my claim that remote sensing predictors are only appropriate for mapping the current distributions of plants. Predictor selection pathway for mapping current and potential distribution of invasive plants such as *P. juliflora* is shown in Figure 5.1.

Validation tests conducted on independent datasets showed that both of my current and potential distribution models had high accuracy; area under the receiver-operating characteristic curve (AUC) = 0.98 for current model and AUC = 0.97 for potential model (see table 2.3 for additional model evaluation approaches). The high AUC values show that the results were reasonable. However, I believe that the results could be improved by using Landsat imagery, which has a better spatial resolution, and by applying robust modeling algorithms that use both species presence and absence data (e.g., boosted regression trees) [9]. I found that the threshold values used in converting Maxent outputs into binary maps

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[9] Remote sensing layers capture the electromagnetic radiation that is reflected by the different features and plants. Although we know that exposed sand and soil land-cover category is highly suitable for *P. juliflora* invasion, we cannot detect these sites by using the reflectance properties of *P. juliflora* (often represented by the species-occurrence records). However, rainfall and other climatic patterns can stay the same for different locations (whether they are invaded by *P. juliflora* or not); thus, climatic predictors can detect both currently infested sites and suitable sites that are not currently invaded.

can influence the predicted area. I conclude that better results are only achieved through repeated sampling, modeling, and validation process, not just by a one-time mapping effort.

In chapter three, I used Geographic Information Systems (GIS), Global Positioning System (GPS), remote sensing, and participatory mapping (PM) techniques and technologies to map *P. juliflora* over a small geographic area. In collaboration with Afar communities and experts, I mapped *P. juliflora* using high and moderate density classes. I demonstrated that PM methods are highly useful for mapping invasive plants. The map products were accepted by Afar communities, suggesting that PM methods are another tool for managing invasive species in Ethiopia.

I identified the most affected land-cover categories by comparing the community crated maps with an ancillary land-cover layer. I found that the most affected land-cover categories were dense grass land, and exposed sand and soil. Ayanu et al. [10] found wetlands to be the highly invaded land-cover category in Badu (Gewane *woreda*, north of the current study site). The two studies produced slightly different results because the studies were conducted at two separate locations, spanning two separate time periods (two decades for my study and one decade for the Gewane-Badu study). However, the *P. juliflora* infested wetlands in Gewane-Badu were described by Ayanu et al. [10] as seasonally flooded areas that are used by Afar pastoralists for dry season grazing; therefore, it can be deduced that, even in Badu, grassland was the most invaded land-use category. Land-cover change studies that consider larger areas (e.g. the whole Afar regional state) may provide new insights on the land-cover dynamics of the region.

From my four years of research in Afar, I learned that PM has a huge potential in mapping invasive species and identifying resource related problems of rural communities. I identified major resource related problems in Afar, and generated new information on the introduction history, uses and impacts of the invasive *P. juliflora* plant. The major problems of Afar people include conflicts from neighboring Issa tribes, land-grabs from the central government and foreign nationals, shortage of water and electricity, flooding, and invasion by non-native plants. I found that the PM method depends on the cognitive spatial memory of participants, and is more accurate when used at a fine geographic scale. People are more familiar with their surrounding environment than distant sites. Therefore, applying PM techniques over a coarse geographic scale may result in imprecise map results. I conducted the PM research after completing my correlative modeling study. This allowed me to validate the Maxent derived map products using the community maps. I found the potential distribution map produced from the correlative modeling study to have high accuracy. Assigning probability of occurrence using different threshold values, validating and readjusting model outputs in the field may result in more accurate current *P. juliflora* distribution maps. I conclude that participatory mapping techniques are more appropriate for fine scale studies, while correlative modeling techniques with MODIS and topo-climatic predictors are more appropriate for coarse scale studies (Figure 5.2).

In chapter four, I used economic analyses techniques and compared the economic feasibility of one *P. juliflora* eradication approach (converting *P. juliflora* infested lands into irrigated agriculture) against two *P. juliflora* utilization approaches (charcoal and flour production). I prepared budgets for all the three studied management approaches by interviewing 19 enterprise owners. I analyzed the profitability, sensitivity, and risk of all three enterprise types. I found converting *P. juliflora* infested lands into irrigated agriculture (conversion) to be highly profitable with Net Present Value (NPV) of 5,234 US$/ ha. Flour production was un-profitable with NPV of -17,905 US$. Charcoal making was moderately profitable with NPV of 805 US$/ ha. I ranked flour production as the highly risky, conversion as the risky, and charcoal production as the non-risky alternatives.

Conversion was the profitable and the effective *P. juliflora* eradication method on farmlands. However, it carries some risk and can only be practiced on flat lands where irrigation is possible. Thus, conversion is not always the preferred approach for controlling *P. juliflora*. Compared to conversion, charcoal production is less profitable; however, it has no risk and the product can be produced from *P. juliflora* trees growing in all locations. Poor marketing practices, higher initial investment costs, and wasteful pod drying and processing practices appear to have inflated the flour production costs. If appropriate policy and management actions are effected, the risky flour business can become one of the economically viable and effective *P. juliflora* utilization approaches in Afar. Enhanced products in the form of animal silage [11], and feed blocks [12] can be produced from *P. juliflora* pods and sold at relatively higher prices. Based on my studies, I conclude that *utilization through control* is one of the effective and economically viable *P. juliflora* management approaches currently accessible to Ethiopia. Clearing the existing 360,500 hectare of *P. juliflora* thicket in Afar would cost an estimated 92.9 million US$ (see chapter two for current *P. juliflora* extent and Appendix C for average *P. juliflora* removal cost per one hectare).

Researchers from University of Bayreuth, Germany (e.g., [13]), and Colorado State University, USA, [14, 15] have documented some of the social, economic and ecological changes that are rapidly occurring in Afar. New invasive species such as the rubber vine (*Cryptostegia grandiflora*) are spreading in Afar [13]. Land-grabs by central government and foreign investors continue to affect Afar pastoralists by reducing communal lands and grazing areas [15]. The expansion of Issa pastoralists into Afar regional territories further restricts Afar pastoralists and their herds from accessing critical resources. The impacts of these rapid changes on Afar communities and the region's wildlife resources needs further investigation.

I used a wide variety of approaches to investigate the ecological and socio-economic conditions in Afar (in relation to *P. juliflora* invasion). My methodologies can be replicated for managing invasive species elsewhere (in most of the 129 world and 50 African countries where the species occurs now). However, there remains several questions that need to be answered in the future. Unanswered questions include: What are the genetic characteristics of *Prosopis* species occurring in Ethiopia? How would *P. juliflora* respond to climate change? What are the impacts of *Prosopis* on hydrology, ecosystem service and native biodiversity? What governance related issues should be addressed to prevent new invasions and manage existing ones? Invasive species and bio-security related policies are lacking in Ethiopia. It is likely that some outside organizations may introduce bio-control agents in Afar (without the consent of the Afar people). Introduced bio-control agents may adapt to the new environment (or evolve to a different species) and may cause series damages on native species. Additionally, bio-control agents may damage the *Prosopis* charcoal and flour enterprises that are currently supporting a number of Afar communities. Comprehensive cost benefit analyses are needed before introducing bio-control agents in

Afar. Mechanisms should be created to ensure that species introduction efforts are transparent, and involved parties are accountable.

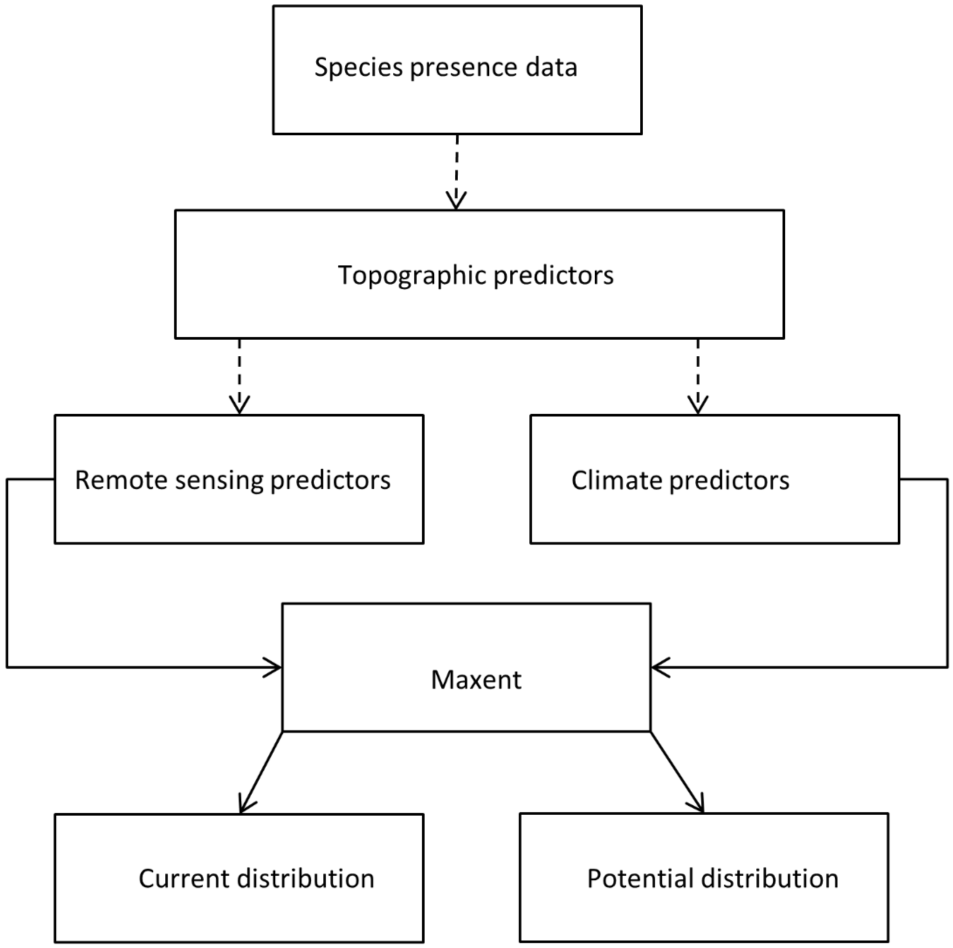

Figure 5.1: **Predictor selection pathway for mapping current and potential distribution of *P. juliflora***. The decision to include topographic predictors in the model depends on species and location. Therefore, topographic predictors are connected using dashed lines, not solid lines.

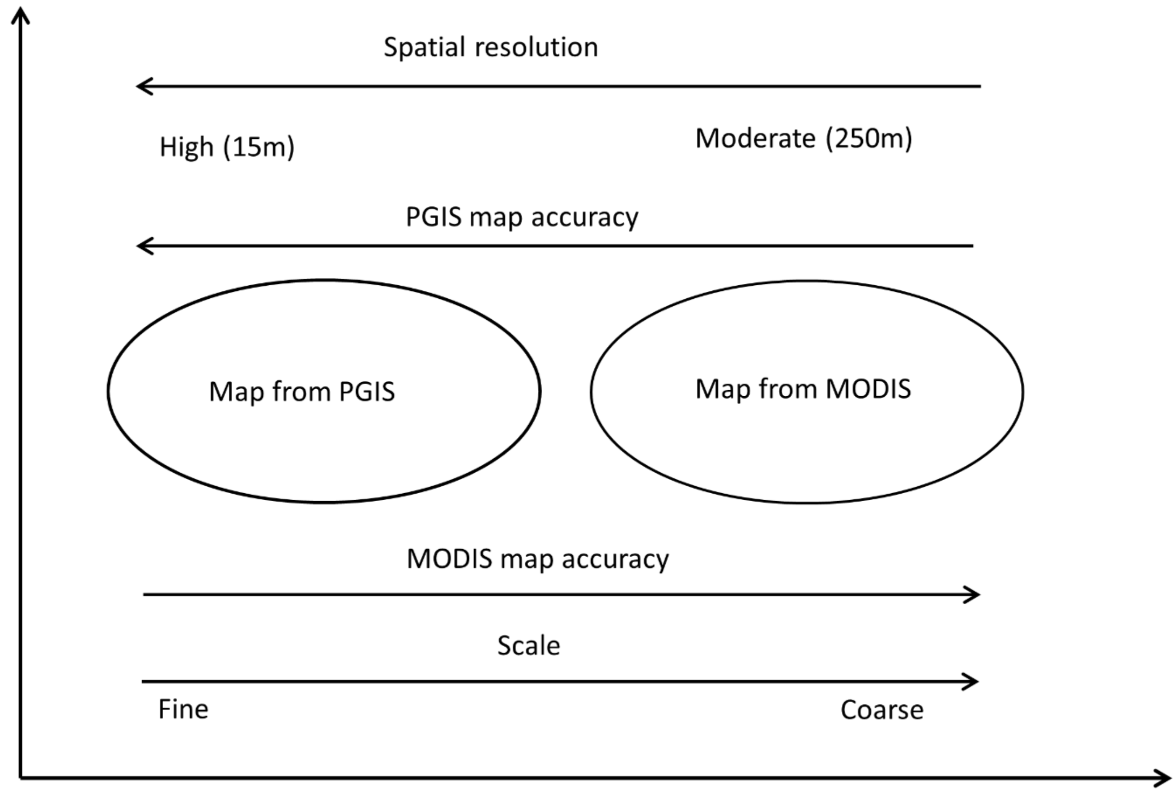

Figure 5.2. **Comparison of MODIS derived versus PGIS derived maps**. Relatively, as the spatial resolution changes from high (15m) to moderate (250m), MODIS map accuracy improves, but PGIS map accuracy gets low. Similarly, as the scale changes from fine to coarse, MODIS map accuracy improves, but PGIS map accuracy gets low.

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CHAPTER 6: REFLECTIONS

This final chapter focuses on my four years of educational experience at Colorado State University (CSU). The objective is to share my educational and life experience with other CSU students. My educational background (from Ethiopia) was in Forestry, though, I latter received additional training in GIS from San Diego Mesa College (California). Before coming to United States, I worked as a researcher in the Ethiopian Forestry Research Center (FRC), Addis Ababa city. My job at FRC allowed me to travel to several African countries and witness the threats posed by invasive plants. I was aware of the growing problems posed by the invasive *Prosopis juliflora* in Ethiopia. In 2011, I joined CSU as a PhD student to receive additional training in biology, ecology, spatial and economic analysis. One of the courses that attracted me to CSU was titled “Invasive plants/weeds: Ecosystems to molecules”. By joining CSU, I wanted to learn everything about invasive plants (i.e., from ecosystems to molecules).

At CSU, I learned about invasive species formally by taking graduate level courses, and informally from mentors and co-workers who were mostly based at the Natural Resource Ecology Laboratory (NREL), CSU. The collaboration between NREL and the U.S Forest Service International program (USFS), which aimed at assisting pastoralists in Ethiopia, crated a special opportunity for me to travel to the Afar region, one of the world’s driest and remote locations. The region harbors the largest *P. juliflora* invasion within Ethiopia. Going to Afar was daunting at first (due to its harsh weather and security concerns), but my close interactions with the Afar people soon revealed that there is nothing to be scared of. I found that the Afar people are open and welcoming. Without the support of the Afar communities my work (all previous chapters and reports) would not have been completed. I have learned from the Afar people as much as I did from CSU and NREL.

My dissertation research was organized under three separate research frameworks and approaches (i.e., ecological modeling, participatory research, and economic analysis). These demanded learning different skills and closely working with more than a few mentors. I have found the mentoring arrangement at CSU to be unique and effective. Mentoring programs are rare in most Ethiopian higher learning institutes and research centers. I am a good listener and my listening skills have helped me to pay attention to the ideas raised by my advisors, and relate those ideas to my dissertation research. Selecting the three important subjects (chapters) of my dissertation research required several fruitful discussions with all of my advisors.

As an "International Student[10]", I have had several challenges. The major challenge has to do with the English language. Writing is difficult by itself, but writing manuscripts for a journal is even more challenging. The rules (e.g., capitalization, abbreviation, punctuation) vary from journal to journal and from one editor to the other. I spend more time writing and editing paragraphs than an average native English language speaker. It is better to deal with the writing issue as early as possible since it is a highly needed skill in research and teaching. Deficiencies in writing skills may lead to plagiarism. In 2014, one of my class mates attempted to do his/her homework by posting the questions on a professional list-serve. The professor learned about the post and identified the involved student. It must have been embarrassing for the involved student. Recently, "researchers" from Ethiopia copied a lot of text from my reports and published it on an open access journal. Fortunately, I was able to see it on time and report the incident to the journal editor. The editor investigated my complaint and immediately removed the fake paper from the journal's volume. Plagiarism is a serious issue in the academics world and students must be aware of it at all times.

The second challenge (in my case) has to do with financing my education. My funding ran out before I completed my dissertation research. I attempted to resolve the issue by writing research proposals. However, I underestimated the grant review process and applied only to one funding organization. Students should not "put all their eggs in one basket", but seek funding from several organizations and funding agencies. I ended up taking financial aid and private loans, which is definitely not the best decision. Financial aid (from fafsa.ed.gov) may be a good option to students who are enrolled

[10] I put this word in quotation because it may have different meanings depending on the context used. Usually it refers to non-U.S students who study at CSU. As a student who has an Ethiopian background, I identify with the term - international student. However, tuition charges, work rights and health care fees of a U.S. student are sometimes different from an international student (i.e., fees are usually higher and some rights are limited to an international student). Thus, as a naturalized U.S citizen, I also identify with U.S. students, not international students.

at least for 6 credit hours (half time). But, it is not available to students who take dissertation credits or follow the “continuous registration” option. In short, it is good to have a well thought financial plan before going to graduate school.

At CSU I was able to learn about professional organizations and their activities. I am now an active member of four professional societies (three American and one Ethiopian). The societies organize annual meetings where researchers present and discuss their findings. I was able to participate in six different professional meetings. These gave me the opportunity to communicate research findings and improve my presentation and public speaking skills. Additionally, it increased my access to information (e.g., training and job opportunities, funding organizations, list-serves) and my professional networks.

Post-graduate education is not only about taking courses and doing research, but it is also about teaching and sharing what you have learned. At the beginning, I was a little bit scared of teaching and never bothered to apply for a teaching job. But, fortunately a Graduate Teaching Assistant (GTA) opportunity opened up in one of my favorite subjects, Geographic Information Systems (GIS). I applied for the job and got accepted. I teach the laboratory cessions, but I also sit in the class and attend lectures. Sitting in a class as a GTA is a unique experience because, the GTA learns both about GIS and how to teach GIS.

Four years ago, I came to CSU with the expectations of studying invasive plants. I believe that I have learned more than my expectations. I have learned about aquatic weeds, invasive fishes, insects and animals. I have acquired useful skills in spatial analysis, economic analysis and software use. Additionally, I have improved my writing (both grant writing and writing for publication), teaching, and communication skills. I have learned about invasive species detection, prevention and management. I have successfully transitioned in to an ecologist. This was apparent to me when I attended the Ethiopia Foresters Association meeting in Bahir Dar in December 2014. It seemed like all my former colleagues were talking about planting, protecting and harvesting trees. My education at CSU has created a strong appetite for learning. Even after completing my required courses, I find myself sitting in a “Landscape ecology” class. I believe that my PhD degree is not the end of my education, but a new beginning. Despite several difficulties, I am confident that I will continue to learn and share what I have learned. I envisage a great future in research and teaching.

APPENDIX A: CHAPTER THREE INTERVIEW QUESTIONS

Date: ________________ Location: ____

Job/livelihood: ______________ pastoralist agro-pastoralist farmer

Gender: Male Female

Education level: ___________________

Age: 10-20 20-30 30-40 40-50 50+

1. How long do you remember *Prosopis* growing in this area? How did it get here?

(Provide details) ____

2. Where is *Prosopis* found?

(Provide details) ____

3. Do you use *Prosopis*?

a. Yes (Go to questions #3a.1 and 3a.2)

b. No (Go to questions #3b.1 and 3b.2)

3a.1 What do you use *Prosopis* for? (Only ask if the answer to #3 was "'yes")

(Provide details) ____

3a.2 Are there any negative consequences to *Prosopis*? (Only ask if the answer to #3 was "'yes")

a. Yes

b. No

(Provide details) ____

3b.1 Why not? (Only ask if the answer to #3 was "No")

(Provide details) ____

3b.2 Are there any benefits to *Prosopis*? (Only ask if the answer to #3 was "No")

a. Yes

b. No

(Provide details) ____

4. Does *Prosopis* need to be controlled or managed?

a. Yes (Go to questions #4a.1 and 4a.2)

b. No (Go to questions #5)

4a.1 Why should *Prosopis* be controlled or managed? (Only ask if the answer to #4 was "'yes")

(Provide details) ____

4a.2 How should *Prosopis* be controlled or managed? (Only ask if the answer to #4was "Yes")

(Provide details) ____

5. Has *Prosopis* changed the vegetation or plant composition?

a. Yes (Go to questions #5a.1)

b. No (Go to questions #6)

5a.1 How has *Prosopis* changed the vegetation? (Only ask if the answer to #5 was "'yes")

(Provide details)____

6. Has *Prosopis* changed wildlife abundance?

a. Yes (Go to questions #6a.1)

b. No (Go to questions #7)

6a.1 How has *Prosopis* affected wildlife abundance? (Only ask if the answer to #6 was "'yes")

(Provide details)____

7. Is *Prosopis* spreading in the area?

a.Yes (Go to question #7a.1.)

b. No (Go to question #8)

7a.1 How is *Prosopis* spreading

(Provide details) ____

8. Do you own livestock?

Yes. (Go to question #8a.1)

No (Go to question #10)

8a.1 What kind and how many livestock do you own?

(Provide details) ____

9. Has *Prosopis* affected your livestock?

a. Yes. (Go to question #9a.1 and 9a.2)

b. No. (Go to question #10)

9a.1 Which livestock are affected?

(Provide details) ____

9a.2 How are the livestock affected by *Prosopis*?

(Provide details) ____

10. Do you sell *Prosopis* products?

a. Yes. (Go to question #10a.1 and 10a.2)

b. No. (Go to question #11)

10a.1 What products do you sell?

(Provide details) ____

10a.2 Where do you sell the products? For how much?

(Provide details) ____

11. Has *Prosopis* changed the culture of Afar people?

a. Yes. (Go to question #11a.1)

b. No. (End)

11a.1 How has *Prosopis* changed the culture of Afar people?

(Provide details) ____

APPENDIX B: CHAPTER FOUR INTERVIEW QUESTIONS

Location: ____________________________**Date**:_____________________________

Primary Occupation: (Pastoralist, Agro-pastoralist, Farmer, Enterprise Owner)

Gender: (Male / Female)

1. What are the production and management steps required to clear *Prosopis*, and what time of year do they occur?

   ____

   ____

2. What is the cost of each of these steps? (Define quantity of labor or other inputs used and prices of inputs).

No.	Production & Management step	Time of year	Units	Quantity	Unit Cost	Cost
2.1						
2.2						
2.3						
2.4						
2.5						

3. After removing *Prosopis* would your crop yield go up? (Yes/ No). If yes, indicate the quantity? Answer for all Prosopis control types and competing crops.

____

____

4. Do you generate income from *Prosopis* products? (Yes / No)

If yes, please answer 4.1 - 4.4; if no, proceed to 5. Answer yes if you harvest for your own use but do not sell any product.

4.1 What are the income generating *Prosopis* products that you produce? Give details about yields.

____

____

____

4.2 How much income do you get from each product (Birr/ha/yr)? Where is your market? What are the prices? Give details (If used at home, then specify what you could have sold the product for if you had not used it for home use)

____

____

____

4.3 What are the production and management steps required to harvest Prosopis?

No.	Production & Management step	Time of year	Units	Quantity	Unit Cost	Cost
4.31						
4.32						
4.33						
4.34						
4.35						
4.36						
4.37						
4.38						

4.4 How do you store or process these products? (Answer for each product sold).

No.	Steps	Time of year	Units	Quantity	Unit Cost	Cost
4.41						
4.42						
4.43						
4.44						
4.45						
4.46						
4.47						
4.48						
4.49						

5 Is there any other use of *Prosopis* that you know about?

____

____

6 Would you be willing to convert the *Prosopis* infested land into other land use types? (Yes/ No) Please give details.

____

____

____

7 What are the pros and cons of converting *Prosopis* into other land use types?

____

____

____

8 What are the pros and cons of leaving *Prosopis* instead of clearing it?

____

____

9 What kind of enterprise do you own where the *Prosopis* is located?

____

____

10 What are the costs related to this enterprise? Use the following table to estimate costs.

No.	Steps	Time of year	Units	Quantity	Unit Cost	Cost
10.1						
10.2						
10.3						
10.4						
10.5						
10.6						
10.7						
10.8						

11 What are the incomes from this enterprise? Indicate product type, price and market location.

____

____

12 What are the main problems associated with this enterprise?

____

____

____

13 How much do you feel *Prosopis* reduces the profit of this enterprise (birr/hectare)? Please explain.

____

____

____

14 What solutions do you suggest, with respect to *Prosopis*, to make your enterprise more profitable?

____

____

____

15 Is there anything that we didn't ask regarding *Prosopis* that you would like to share?

____

____

____

APPENDIX C: ENTERPRISE BUDGETS

Irrigated cotton enterprise investment cost for southern Afar (Ethiopia)

Interest rate: 10%

Hectare: 1

Farm tools	Unit price (Birr)	Quantity	Total purchase price (Birr)	Salvage value	Useful life (Years)	Depreciation	Interest	Annual cost (Birr)
Hand saw	400	1	400	40	10	36	22	58
Axe	200	1	200	20	10	18	11	29
Spade	90	1	90	9	10	8	5	13
Rake	90	1	90	9	10	8	5	13
Machete	90	1	90	9	10	8	5	13
File	60	1	60	6	10	5	3	9
Hoe	90	1	90	9	10	8	5	13
Total equipment investment	1020			102		92	56	148

Irrigated cotton farm investment cost for southern Afar (Ethiopia)

Interest rate: 10%

Hectare: 100ha

Machine	Purchase price (Birr)	Salvage value (Birr)	Useful life (Years)	Depreciation cost/ ha (Birr)	Interest cost/ ha (Birr)	Annual cost/ ha (Birr)	Annual cost/ 100ha (Birr)
Tractor	1800000	180000	10	162000	99000	261000	2610
Plougher	188000	18800	10	16920	10340	27260	273
Grader	150000	15000	10	13500	8250	21750	218
Ridger	60000	6000	10	5400	3300	8700	87
Leveler	188000	18800	10	16920	10340	27260	273
Planter	150000	15000	10	13500	8250	21750	218
Lillstone	80000	8000	10	7200	4400	11600	116
Pesticide sprayer (manual)	1500	150	10	135	83	218	2
Pesticide sprayer (motorized)	30000	3000	10	2700	1650	4350	44
Ulva sprayer	1000	100	10	90	55	145	1
Total machinery investment	2648500	264850		238365	145668	384033	3840

Charcoal enterprise investment cost for southern Afar (Ethiopia)

Interest rate 10%

Equipment	Unit price (Birr)	Quantity	Total purchase price (Birr)	Salvage value	Useful life (Years)	Depreciation (Birr)	Interest (Birr)	Annual cost (Birr)
Hand saw	400	2	800	80	10	72	44	116
Axe	200	2	400	40	10	36	22	58
Spade	90	2	180	18	10	16	10	26
Rake	90	2	180	18	10	16	10	26
Machete	90	2	180	18	10	16	10	26
Shears	300	2	600	60	10	54	33	87
File	60	2	120	12	10	11	7	17
	Total equipment investment					221	135	357

Prosopis flour producing plant investment cost for southern Afar (Ethiopia)

Interest rate 10%

Machine	Unit price (Birr)	Quantity	Total purchase price (Birr)	Salvage value	Useful life	Depreciation (Birr)	Interest (Birr)	Annual cost (Birr)
Mill (30 watt dynamo)	40000	1	40000	4000	20	1800	2200	4000
Transformer	100000	1	100000	10000	20	4500	5500	10000
Scale	15000	1	15000	1500	20	675	825	1500
Store (for drying pods and housing the mill)	80000	1	80000	8000	20	3600	4400	8000
Mortar	1000	2	2000	200	20	90	110	200
Pestle	300	2	600	60	20	27	33	60
	Total machinery investment					10692	13068	23760

Irrigated cotton farm enterprise budget

Interest rate: 10%

Hectare: 1

Item	Units	Unit cost (Birr)	Quantity	Cost/ ha (Birr)
Operating costs				
Land preparation (contract)	ha	4400	1	4400
Seed	Kg	18	30	540
Cultivation	ha	800	3	2400
Water fees	ha	171	7	1197
Insecticide	ha	370	9	3330
Cotton bags (picking & compacting)	ha	82	21	1740
Storage	ha	504	1	504
Loading & unloading	Quintal	10	36	360
Transportation	Quintal	31	36	1116
Marketing costs	ha	300	1	300
Labor costs				
Land clearing (vegetation removal)	ha	5000	1	5000
Seed sowing	ha	800	1	800
Weeding	ha	250	6	1500
Watering	ha	240	7	1680
Insecticide application	ha	190	9	1700
Guarding	ha	500	1	500
Cotton picking and compacting	ha	3708	1	3708
Sub total				30775
Interest expense (10 months)				2565
Total operating costs				33340

Fixed costs				
Farm tools depreciation				92
Interest				56
Total fixed costs				148
Total costs				33487
Income				
Cotton (unprocessed)	Quintal	36	1200	43200
Total income				43200
Gross margin				9860
Profit (return to land and management)				9713

Charcoal enterprise budget (450 bags/ha)

Interest rate: 10%

Yield: 11.25 ton (450 bags each weighing 25kg) of charcoal with four years rotation

Item	Units	Unit cost (Birr)	Quantity	Cost per hectare (Birr)
Operating costs				
Labor costs				
Harvesting trees	ha	4000	1	4000
Cutting wood into smaller pieces	ha	2000	1	2000
Drying and pilling wood	ha	900	1	900
Carbonization	ha	800	1	800
Cooling and packaging	ha	300	1	300
Packaging material	No.	7	450	3150
sub total				11150
Interest expense (3 months)				279
Total operating costs				11429
Fixed costs				
Equipment depreciation				221
Interest				135
Total fixed costs				357
Total costs				11785
Income				
Yield (bags of charcoal/ha)	No.	50	450	22500
Total Income				22500
Gross margin				11071
Profit (return to land and management)				10715

Prosopis flour enterprise budget for southern Afar (Ethiopia); Interest rate : 10%

Item	Units	Unit cost (Birr)	Quantity	Cost (Birr)
Operating costs				
Purchasing pods (fresh weight)	Kg	0.5	20000	10000
Electric cost	month	700	6	4200
Packaging material	Kg	0.4	7000	2800
Marketing costs	Kg	0.05	7000	350
Machinery maintenance	No.	400	2	800
Labor costs	Kg			
Pod drying	Kg	0.3	20000	6000
Pod crushing	Kg	0.8	12000	9600
Packaging costs	Kg	0.05	7000	350
Mill operator	month	700	6	4200
Sub total				38300
Interest expense (6 months)				1915
Total operating costs				40215
Fixed costs				
Machinery depreciation				10692
Interest				13068
Total fixed costs				23760
Total costs				63975
Income				
Prosopis flour	Kg	2	7000	14000
Total income				14000
Gross margin				-26215
Profit (return to management)				-49975