ADDIS ABABA UNIVERSITY, GRADUATE PROGRAMS

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES

DEPARTMENT OF PLANT BIOLOGY AND BIODIVERSITY MANAGEMENT

Invasion of *Prosopis juliflora* (Sw.) DC. and its ecological impacts in Afar National Regional State, Northeast Ethiopia

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July 2020

Invasion of *Prosopis juliflora* (Sw.) DC. and its ecological impacts in Afar National Regional State, Northeast Ethiopia

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A Thesis Presented to the Graduate Programs of the Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Plant Biology and Biodiversity Management

Addis Ababa University

Addis Ababa, Ethiopia

July 2020

ADDIS ABABA UNIVERSITY

GRADUATE PROGRAMMES

This is to certify that the thesis prepared by Wakshum Shiferaw Gemeda, entitled: Invasion of *Prosopis juliflora* (Sw.) DC. and its ecological impacts in Afar National Regional State, Northeast Ethiopia submitted in Partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Plant Biology and Biodiversity Management complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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Addis Ababa University, 2019

Addis Ababa, Ethiopia

Dedicated

To

Afar Region Pastoral community

Invasion of *Prosopis juliflora* (Sw.) DC. and its ecological impacts in Afar National Regional State, Northeast Ethiopia

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PhD Disseratation

ABSTRACT

The ecological impacts of *Prosopis juliflora* (Sw.) DC. on ecosystem properties have been reported to be severe especially on grazing land and woodland. The objectives of this study were to quantify the land use/cover changes in Awash Fentale and Amibara districts, (2) investigate the effects of climate variability on the phenology of *P. juliflora*, (3) assess effects of *Prosopis juliflora* invasion on species composition and diversity, (4) investigate the effects of *P. juliflora* on soil physicochemical properties, and (5) assess effects of *Prosopis juliflora* on soil seed bank compositon and density. A combination of remote sensing data and field observations were used to analyze effects of *Prosopis juliflora* invasion on land use and land cover changes from 1986 to 2017 in Amibara and Awash Fentale districts in Afar National Regional State. Data for phenology of *Prosopis juliflora* including leafing, flowering, green, and mature pod proportions (%) per tree per month were collected for a year in 2017. For floristic analysis, data were collected under four distinct habitats, namely *Prosopis juliflora* thickets (PJT), *P. juliflora* mixed with native species (PJM), non-invaded woodlands (NIWLs), and open grazing lands (OGLs). Quadrats were laid using systematic random sampling technique. In each habitat, soil samples for soil seed bank were also collected from litter layer, 0–3 cm, 3–6 cm, and 6–9 cm. In Amibara and Awash Fentatle districts, during 1986–2017 area under farm land, water bodies, grassland, area invaded by *P. juliflora* increased, while barren and woodland areas decreased. Overall, 7886 ha of woodlands and 221 ha grazing lands were converted to *Prosopis juliflora* invaded land during 1986–2017 in the study area. During 2017 growing seasons, the lowest proportion of mature and green pods per tree of *Prosopis juliflora* were recorded in *Bega* (dry season), but the highest in *Belg* (spring) season. The highest proportion of flowering per tree was recorded in November-December, while the lowest proportion of flowering per tree was in January-February. Invasion by *Prosopis juliflora* significantly changed diversity, evenness and species richness. The mean values of Shannon diversity index and species richness under PJM (H' =2.22, R= 13.94) and NIWLs (H'=2.23, R =13.44) were significantly higher than that of PJT (H'=1.96, R=11.50) and OGLs (H'=1.84, N=9.56). Invasion by *Prosopis juliflora* also significantly reduced density of native woody species. In this study, 102 trees ha^{-1} of native woody species were recorded under *P. juliflora* thicket, but 1252 trees ha^{-1} of native species were recorded under non-invaded woodlands. In Teru and Yalo districts, the mean density of soil seed bank in non-invaded grazing lands (813 ± 375 seedlings / m^{2}) was significantly higher than the soil seed bank density of *Prosopis juliflora* invaded lands (545 ± 156 seedlings / m^{2}. Invasion of *Prosopis juliflora* had significantly affected soil pH, exchangeable Na^{+}, water soluble Ca^{2+} + Mg^{2+}, water soluble Na^{+}, and exchangeable sodium percentage in Teru and Yalo distrcits. Thus, invasion of *Prosopis juliflora* significantly increased soil pH (1.5%), but decreased exchangeable Na^{+} (24.2%), exchangeable sodium percentage (21.6%), and water soluble Ca^{2+} + Mg^{2+} (39.9%) than non-invaded open grazing lands. Based on these results it is concluded that *Prosopis juliflora* drastically alters vegetation and soil properties. If the present change continues, pastoralists grazing lands will be lost. To reverse these situations, integrated management of *Prosopis juliflora* should be implemented through participation of all stockholders and multidisciplinary research approaches.

Keywords/phrases: Floristic diversity, encroachment, invasive, phenology, seed bank, soil properties

ACKNOWLEDGMENTS

I am thankful to Arba Minch University, Addis Ababa University, and GITEC project for funding different aspects of thesis. My special thanks go to my superivisors: Prof. Sebsebe Demissew, Dr. Tamrat Bekele, and Dr. Ermias Aynekulu for their unreserved guidance, valuable comments from the proposal development to the write up of the thesis. I would like to thank also Afar National Regional State Pastoral Communities Bureau for their support in writing letters of cooperation to various different and for allowing me to collect data from the varous districts. Department of Natural Resources Management in Pastoral and Agro-pastoral districts of Amibara, Awash Fentale, Teru, and Yalo are highly acknowledged for material and human resource assistance during site selection and data collection. All members of the National Herbarium of Addis Ababa University: Mr. Wage Abebe, Ms. Shewaregaw Lema, Ms. Yirgalem H/Silassie and Mr. Melaku Wondafrash are also thanked for their facilitation of material in office and the herbarium.

Mr. Ali Ahimed Ibrahim and Yesuf Baba are also acknowledged for their help during data collection. I also extend my gratitude to Central Ethiopian Environmental, Forestry and Climate Change Research Center, Addis Ababa for their permission to use greenhouse for soil seed separation. I like to extend my gratitude for Mr. Habtamu Degefa of Wondo Genet College of Forestry and Natural Resources Management for his assistance in facilitating access to field equipment and encouragement during data collection. Last but not least, I extend my sincere gratitude to my family for their patience and encouragement in the course of my study.

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LIST OF ACRONYMS

C	Carbon
Ca	Calcium
CAPRi	Collective Action and Property Rights =
CEC	Cation Exchange Capacity
CSA	Central Statistical Agency
DBH	Diamter at Breast Height
DSH	Diameter at Stump height
EBI	Ethiopian Biodiversity Institute
EC	Electric Conductivity
EP	Environmental Policy
ESP	Exchangeable Sodium Percentage
EWDCA	Ethiopian Wildlife Development and Conservation Authority
IAP	Invasive Alien Plants
IAS	Invasive alien species
ICARDA	International Center for Agricultural Research in the Dry Areas
ISRIC	International Soil Reference and Information Centre
K	Potassium
LULC	Land Use and Land Cover
Mg	Magnesium
N	Nitrogen
Na	Sodium
NBSAP	National Biodiversity Strategy and Action Plan
NDVI	Normalized Difference Vegetation Index

NIWLs	Non-invaded woodlands
NRC	Natural Resources Canada
OGLs	Non- invaded open grazing lands
P	Phosphorus
PENHA	Pastoral and Environmental Network in the Horn of Africa
PJM	*Prosopis juliflora* mixed with other native species
PJT	*Prosopis juliflora* thicket
S	Sulfur
SAR	Sodium Adsorption Ratio
SOC	Soil organic carbon
SOM	Soil Organic Matter
SSB	Soil seed bank
UNEP	United Nations Environment Programme

CHAPTER 1

1. INTRODUCTION

1.1. Background and justification

In recent decades, biological invasions are increasing globaly (Pysek and Richardson, 2010; Thapa *et al*., 2018), and threaten ecosystems, biodiversity and food security (Sileshi Gudeta *et al*., 2019; Turbelin *et al*., 2017). Those invasive species are exotic plants, animals, and microorganisms which can heavily colonize a particular habitat (Ng'weno *et al*., 2009). Alien species are defined as exotic organisms that occur outside their geographic ranges (McNeely *et al*., 2001; Shine *et al*., 2009; Surendra *et al*., 2013; EBI, 2014).

Prosopis juliflora is a shrub or tree native to Mexico, Central and Northern America. From its native ranges, *P. juliflora* spread to Africa, Asia and Austria (Pasiecznik *et al.*, 2001) mostly through human activities. In Africa, *Prosopis juliflora* was first introduced to Senegal in 1822 and continued to establish in other countries at different times (Jama and Zeila, 2005). In Ethiopia, information is not available regarding when, where, how it was first introduced (Zeraye Mehari, 2015) although it was said to have been introduced in the 1970's for reclamation of degraded areas in low lands (Yibekal Abebe, 2012). Recent report by Hailu Shiferaw *et al*. (2019a) revealed that 1.2 million ha of *P. juliflora* invaded land cover expanding at the rate of 31,127 ha annually and constituted 12.3% of the land surface in Afar region. In addition, Pittroff (2019) reported that *Prosopis juliflora* invaded over 1.8 million ha in Afar region.

In the introduced areas, *Prosopis juliflora* expansion was increased. For instance, PENHA (2014) reported that cover of *P. juliflora* as a whole was 50 million hectares at global level. Furthermore, *P. juliflora* covered about 5 million hectares forming dense thicket in Africa. It has become an invasive or noxious weed in several African countries including Kenya, Ethiopia, Sudan, Senegal, and South Africa (Pasiecznik *et al.*, 2001; Shackleton *et al*., 2014).

In the Afar region, *Prosopis juliflora* is now posing a serious threat to the pastiral areas where its invasion exists in four of the five zones and 11 of 32 districts of Afar region. Afar region have five Administrative Zones namely Zone 1, Zone 2, Zone 3, Zone 4, and Zone 5. Among these, Amibara district of Zone 3 is thought to be recognized as the starting point for the introduction and spread of *Prosopis juliflora*. This district represents a degraded semi-arid ecosystem (Ilukor *et al*., 2016; Mohammed Mussa, 2017). Recently, Zone 1 and 3 are the two zones which are severely invaded by *P. juliflora* and it has expanded to the remaining zones in the region (Wakshum Shiferaw *et al.*, 2019). Dubti, Asayita in Zone 1 and Mile, Gewane, Amibara, Buremoditu/Gelealu, and Awash Fentale in Zone 3 are the most severely invaded districts in the region. There are also other partly invaded districts in Zone 4 and Zone 5 (Dubale Admasu, 2008).

Prosopis juliflora is threatening vegetation types including *Acacia-Commiphora* woodland, desert and semi-desert scrubland in the Afar Floristic Region (EBI, 2014). Within these vegetation types, the local habitats which have been identified for invasion of *P. juliflora* are river banks, irrigated cropland, roadsides and areas near the settlement areas (Shetie Gatew, 2008; Wakshum Shiferaw *et al*., 2018a). *Prosopis juliflora* is displacing grazing lands (Negussie Zeray *et al*., 2017) and it is posing a threat to wildlife conservation areas (Almaz Tadesse, 2009; Selamnesh Tesfaye, 2015). According to Helland (2015), *P. juliflora* is also the species most associated with loss of pasture and invasion into woodlands.

The key factors which are aggravating and influencing invasions and encroachments into various environments are land use changes and climate change (Pasiecznik *et al*, 2001). Increase in population pressure and overgrazing of pasture lands due to the herding of a large number of livestock in the region are also other causes increasing the invasion of the species (Hailu Shiferaw *et al*., 2019a).

Among the factors contribuing to the success of its invasiveness are growth rate (Lamarque *et al*., 2011), nitrogen fixing ability, resistance to pests, drought, and fire (Sawal *et al*., 2004). On the other hand, *Prosopis juliflora* gradually changes in form and density as one moves away from the riparian habitats along the lower seasonal watercourses to drier areas and sloppy landscapes where it appears to be stunted and dwarf (Awale and Sugule, 2006; Kaur *et al*., 2012).

Palatable grasses for livestock including *Chrysopogon plumulosus, Cenchrus ciliaris* and *Setaria verticillata*, and valuable woody species (i.e., *Acacia tortilis, Acacia senegal* and *Acacia nilotica*) are replaced in the range lands by *Prosopis juliflora* (Dubale Admasu, 2008). Moreover, *Prosopis juliflora* has resulted in multiple negative effects on food security and livelihoods of local communities.

Dispersal and germination of the seeds of *Prosopis juliflora* are mainly facilitated through animal ingestion which is subsequently defecated away into wider areas (Hailu Shiferaw *et al*., 2004; FAO, 2006; Wakshum Shiferaw *et al*., 2018b). In restoring degraded riverine forests and woodlands, the first step is to quantify the actual and potential levels of natural regeneration and examining the role of soil seed banks as propagule contributor (Gul *et al*., 2012).

Understanding phenology stages of *Prosopis juliflora* and the rate at which its progress into other land use and land cover types are useful for controlling invasivasion into grazing lands (Brownsey *et al*., 2016). Phenology is defined as the study of periodic biological events and the causes of their timing with concerning with abiotic and biotic factors and the relationships among phases of the same or different occations (Kumar *et al.*, 2014). To reverse invasion of *Prosopis juliflora*, burning and cutting of the plant to 10 cm down to the ground were tried by Ethiopian Institute of Agricultural Research (Abiyot Berhanu and Getachew Tesfaye, 2006). In addition, controlling *Prosopis juliflora* invasion through utilization like charcoal was also tried (Tewodros Wakie *et al.*, 2012; Sertse and Pasiecznik, 2014). However, most of these efforts failed to control the species.

Several quantitative assessments have been conducted in different districts of the Afar region (e.g., Shetie Gatew, 2008; Zeraye Mehari, 2008; Ashenafi Burka, 2008; Almaz Tadesse, 2009, Tamene Yohannes *et al.*, 2011; Tewodros Wakie *et al.*, 2012; Tewodros Wakie, 2014; Surafel Luleseged and Araya Asfaw, 2012; Ilukor *et al.*, 2014). However, with regards to the associations of *Prosopis juliflora* with floristic composition, its phenology, soil seed banks, and soil physicochemical properties in invaded areas were not well assessed. Thus, this study was conducted at Amibara and Awash Fentale of Zone 3; and Teru and Yalo of Zone 4 of the region.

1.2. Statement of problem and significance of the study

Afar Floristic Region is in the Horn of Africa Biodiversity Hotspot. It is the major center of diversity and endemism for several plant species. However, *Prosopis juliflora* reduces diversity and endemic plant species (EBI, 2014). Invasion of *P. juliflora* significantly weaken ecosystem services in the region (Rettberg, 2014; Hailu Shiferaw *et al.*, 2019b).

In pastoral areas, stresses on environmental caused livelihood income dynamics which enhanced demands and reduced supplies of natural resources due to the rise of population. Extensive production of livestock and movement in search for feed and water, resource exploitation for charcoal production and construction materials, and lack of institutional capacity have imposed impacts on existing natural resources particularly on woodland vegetation. These cause destruction and degradation of the vegetation resources (Dong *et al*., 2011). As a result, the socio-economic and ecological impacts of *Prosopis juliflora* are becoming serious (Yibekal Abebe).

After the introduction of *Prosopis juliflora* in the 1970's, the military (Derg) government had expanded the introduction beteween 1980 – 1986 to many areas in Afar region to combat desertification without scientific evidence (Yibekal Abebe, 2012). These had facilitated its further expansion in most districts of the region and other regions of Ethiopia. *Prosopis juliflora* reduces the effectiveness of irrigation canals, water table, movement of animals and human beings (Almaz Tadesse, 2009; EWDCA, 2015). In addition, the species has tremendous impacts on conservation areas in the Afar region. Consequently, *Prosopis juliflora* result in social instability and economic hardship, placing constraints on sustainable development, economic growth, poverty alleviation and food security in the region (Zeraye Mehari, 2008).

Pods of *Prosopis juliflora* are nutritious, palatable and form an important component of livestock feed, especially during the dry season but research reports have shown that ingestion of *Prosopis juliflora* pods by livestock causes tooth decay and death through indigestion in the absence of supplementary feeds in the dry seasons (Mwangi and Swallow, 2005; Preeti *et al*., 2015).

Woodlands in arid and semi-arid areas can provide important ecosystem services in the form of livestock production from rangelands, water production from mountain catchments, and conservation and tourism benefits from protected and other areas (Wilgen *et al*., 2012).

Quantitative information particularly ecological impacts in relation to phenology of the species and its progress towards other land use/cover detections are lacking. Furthermore, *Prosopis juliflora* invasion, phenology of the plant, and extent of ecological impacts are important for planning for management of *Prosopis juliflora*. Thus, it is imperative to quantify its ecological impacts and plan for management of the species for biodiversity conservation and ecosystem restoration.

Therefore, this study is focused on four selected districts of Afar region including Amibara and Awash Fentale from Zone 3; and Teru and Yalo of Zone 4 (Figure 2). In these districts, the species has severely invaded and has caused many ecological impacts. Thus, we set the following objectives in order to address the impacts of *Prosopis juliflora*.

1.3. Objectives of the study

1.3. 1. General objectives

- To investigate of the level of *Prosopis juliflora* invasion, phenology and its ecological impacts in Afar region, Northeast Ethiopia

1.3.2. Specific objectives

1. To quantify the land use/cover changes in Awash Fentale and Amibara districts.
2. To investigate the effects of climate variability on the phenology of *Prosopis juliflora* in Awash Fentale and Amibara districts.
3. To assess the effects of *Prosopis juliflora* invasion on species composition and diversity in Awash Fentale and Amibara districts.
4. To investigate the effects of *Prosopis juliflora* on soil physicochemical properties in Teru and Yalo districts
5. To assess the effects of *Prosopis juliflora* on the spatial distribution, soil seed bank diversity, and density in Awash Fentale, Amibara, Teru and Yalo districts.

1.4. Research questions

1. What are the effects of *Prosopis juliflora* on the magnitude of land use/land cover changes of Awash Fentale and Amibara districts?
2. Does the phenology of *Prosopis juliflora* vary across contrasting climatic conditions in Awash Fentale and Amibara districts?
3. What are the impacts of *Prosopis juliflora* on species composition and diversity of native plant species in Awash Fentale and Amibara districts?
4. What are the impacts of *Prosopis juliflora* on soil physicochemical properties in Teru and Yalo districts?
5. Do *Prosopis juliflora* impacts on soil seed bank composition, diversity and density in Awash Fentale, Amibara, Teru and Yalo districts?

1.5. Research hypothesis

$H_0$1: Land use/cover in Amibara and Awash Fentale districts did not change as a result of invasion by *Prosopis juliflora*.

$H_0$2: Phenological patterns of *Prosopis juliflora* did not vary across contrasting climatic conditions.

$H_0$3: *Prosopis juliflora* invasion did not change the composition and diversity of native species.

$H_0$4: Invasion by *Prosopis juliflora* did not alter soil physicochemical properties.

$H_0$5: Invasion by *Prosopis juliflora* did not influence the density and composition of soil seed banks.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Ecological impact and interactions

Composition, richness, dominance, and interaction among organisms have detrimental or beneficial impacts in all ecosystems since species always differ in some of their functional traits; in terms of the growth rate, density/cover, germination, biomass, and survival (Dangles and Malmqvist, 2004; Hejda *et al*., 2009; Archer *et al*., 2017). Plant species affect the structure of any plant community, plant and soil biomass, soil fertility, below ground flora, hydrology, and carbon stock, terrestrial, and aquatic primary productivity. Kumar and Mathur (2014) also suggested that invasion of plants especially woody perennials in grazing lands has been viewed both positively and negatively, positively as a source of browse and shelter to grazing animals, and negatively as competitors for nutrients, water, and space with existing vegetation.

2.2. History of invasive alien plants

Invasive species are introduced either purposely or naturally which are the second threat of global biodiversity loss next to land-use changes (Miranda *et al*., 2011a). A species is considered an invasive alien plant when it spreads beyond its natural area of distribution, causes harm or is likely to cause harm to the environment, people, economy or human health (Richardson *et al*., 2003). Biological invasions by alien species are now considered as one of the main factors in biodiversity loss and endangered species listings worldwide. This is because the natural bio-geographical barriers of oceans, mountains, rivers, and deserts, which provided the isolation essential for unique species and ecosystems to evolve, have lost their effectiveness, due to the increase in economic globalization (Borokini and Babalola, 2012).

Biodiversity loss, particularly the decline of plants has been associated with deforestation, land degradation, climate change effects, land use/land cover changes, and spread of invasive alien plants. Some of these invasive species have caused considerable disasters in East African dry vegetation and rangelands (Obiri, 2011). According to Richardson *et al*. (2003), Kueffer *et al*. (2004) and Shine *et al*. (2009), the causes for the introduction invasive alien plants are two types: For example, human intentional introduction such as that of *Prosopis juliflora* in Ethiopia, and naturally by unintentional introduction such as that of *Parthenium hysterophorus* in India, Kenya, Ethiopia. Invasion of plants can be a man-made and slow onset disaster that is least noticed, often forgotten and neglected. Several reasons are given as to why disasters caused by invasive plant species are often neglected. These include the fact that the disaster-impacts arising from invasive plants are often considered not high enough to attract the attention of the media and disaster managers. Another factor is that disasters of invasive plants are often misunderstood (Pasiecznik *et al*., 2006).

Thousands of plant species have been and continue to be transported by humans to areas far from their natural habitats. Some are moved accidentally, but more important are the many species that are intentionally introduced and cultivated to serve human needs (Richardson *et al*., 2003). In many parts of the world, some invasive alien plants cause problems as invaders, spreading from sites of introduction and cultivation to invade natural or semi-natural ecosystems, where they sometimes cause widespread damage (Wilson *et al*., 2018).

According to McNeely *et al.* (2001), there are three steps for invasion of invasive alien species: (1) introduction (intentional or unintentional), (2) establishment (survives but doesn’t spread), and (3) spread: (3a) naturalization (becomes part of the flora/fauna of its new habitat) (3b) invasion (expands and impacts on species, ecosystems, people and development). Species invasions have three main elements: (1) Source population, (2) pathways and, (3) destinations. Climate change also aggravates invasive alien species to colonize easily and invasive alien species are facilitating climate change (Masters and Norgrove, 2009; Dzikiti *et al*., 2013).

Invasive alien plants are of great concern in Ethiopia, posing particular problems on biodiversity of the country with great economic and ecological consequences (Wakshum Shiferaw *et al*., 2018a). Foremost among these are *Parthenium* weed (*Parthenium hysterophorus*), *Prosopis* (*Prosopis juliflora),* water hyacinth (*Eichhornia crassipes*), and lantana weed (*Lantana camara)*. They have been identified by the EP and NBSAP as a major threat to biodiversity of the country and economic wellbeing of the people. *Prosopis juliflora, Parthenium hysterophorus* and *Eichhornia crassipes* are the three worest invasive alien species in Ethiopia (EBI, 2014). *Prosopis juliflora* is one of the worst among three invasive alien plants such as which have been categorized as number one priority weed for eradication by NBSAP in Ethiopia.

Although *Prosopis juliflora* exists in thickets in areas of Central America and the Caribbean, it is not so often classified a weed in these parts of the native ranges. Only in Colombia and Venezuela, where *P. juliflora* has invaded pasture, it has been declared a weed by ranchers. *Prosopis juliflora* has survived where other tree species have failed, and in many cases became a major trouble and cause for land cover changes. *Prosopis juliflora* has invaded and continues to invade, millions of hectares of rangeland in South Africa, East Africa, Australia and coastal Asia (Pasiecznik *et al*., 2001).

Prosopis juliflora had been proclaimed until 2000 as weedy and as invasive alien species in Australia, Caribbean, Eritrea, India, Iraq, Pakistan, South Africa, Sudan, and the Western Africa islands. Since then several other countries have understood the invasiveness of the plant (Shetie

Gatew, 2008). As a result, the *Prosopis juliflora* species is known as invasive weed over millions of square kilometers all over the arid and semi-arid regions where it is stated to drastically reduce the cover of forage plants and threatens crop cultivation and grazing lands. Invasive plant species and woody plants, in particular, have major impacts on ecosystem structure and functioning (Maitre *et al*., 2015).

Nevertheless, several studies have shown that invasive plants also have positive economic, social and ecological contributions and that these need to be considered when assessing the costs resulting from invasions (Semenya *et al.*, 2012). Most developing countries face controversies to either eradicate or accept invasive alien plants. To compromise these controversies prior evaluation, interpretation, and documentation are very important about the impacts of ecological and its behavior in phenological events with relation to climatic variablity. Thus, based on the scientific inveastigantions, management or use of the resources so that long term land uses planning will be designed in the invaded habitats.

2.3. Biological characteristics of *Prosopis juliflora*

Prosopis juliflora belongs to the family Fabaceae (Leguminosae), subfamily Mimosoideae and genus *Prosopis*, and section algaroba that has six series. Specifically, it belongs to the series Chilensis that contain eleven species and many varieties. The chromosome numbers of most recognized species of *P. juliflora* have been ascertained and all taxa are diploid with a haploid number of n = 14 (2n = 28), with the exception of *P. juliflora* which also has tetraploid forms (2n = 56) (Pasiecznik *et al*., 2001).

The species could be a tree or shrub and is armed with stipular spines 0.5–5 cm long. Leaves have 1–2 (-4) pair of pinnae; the number of leaflets could be 6–29 pairs with sizes 6–23 mm × 1.5–5.5 mm and glabrous surfaces (Pasiecznik *et al*., 2001). Flowers are yellowish in spiciform racemes, 5–15 cm long. The pod is pale brown, linear, straight or slightly curved, 8–29 cm × 0.8–1.7 cm, compressed and with a sugary-pulpy mesocarp. Immature pods are green in color, becoming commonly straw yellow when fully mature. The fruit is an indehiscent legume, straight with an incurved apex, sometimes falcate or sub-falcate, with or without parallel margins (Hedberg and Edwards, 1989).

The formation of polyploid forms tends to occur in rapidly expanding or hybridizing populations, both of which are observed in genus *Prosopis*. Stabilization of tetraploid forms has been suggested as an evolutionary process increasing adaptability to new or changing environments. Chromosome numbers within various populations of the *Prosopis juliflora – Prosopis juliflora* complex are generally consistent but tend to differ between regions (Pasiecznick *et al*., 2001).

The stem of *Prosopis juliflora* is green-brown, sinuous and twisted with axial strong thorns. The thorns of *P. juliflora* are very much varying in appearance, number and size. Thorns can be found in pairs, solitary or both on the same branch. The plant is predominantly xerophilous spiny and sometimes unarmed evergreen tree with a height of 3–15 m depending on genetic difference and other environmental factors, but under favorable environmental conditions some individuals may reach up to 20 m (Shetie Gatew, 2008). *P. juliflora* landraces often have multi-stemmed, coppiced and prostate shrub forms with long branches and a crown that even touches the ground and have erect, flat-topped and decumbent tree forms. *P. juliflora* produced coppices except those stumped at 10 cm below the ground (Hailu Shiferaw *et al*., 2004).

Seeds of the *Prosopis juliflora* are epigeous in germination. The fleshy cotyledons are the first seed leaves, persisting after the first true leaves have formed, being green or somewhat pale-green in color. Once germinated, most energy is expended on rapidly developing a root system and locating a water source as soon as possible. In the first months, root length and biomass increases are much greater than shoot biomass leading to a high root: shoot ratio (Pasiecznik *et al*., 2001; Solis-Dominguez *et al*., 2011).

Roots of *Prosopis juliflora* develop rapidly following germination and can reach a depth of 40 cm in eight weeks. There are two distinct root systems which are formed under normal conditions of unimpeded root development. These are characteristically a deep root system, and superficial horizontal root systems both having different functions during different seasons. The deep root system is made up of one, two or three (rarely more) main tap roots, which may divide at lower depths. They have the function of anchoring the tree but are primarily for sourcing groundwater reserves, whether a water table or other subsurface supply. They can become very thick and tens of meter long until a permanent water source is found (Gallaher and Merlin, 2010).

2.4. Ecology of *Prosopis juliflora*

Prosopis juliflora is also salt-tolerant, growing near water holes and along river tributaries at low altitude in the Great Rift Valley of Ethiopia (Wakshum Shiferaw *et al*., 2018a). It is now widely cultivated in the tropics for shade, timber, and forage (Mwangi and Swallow, 2008; Samuel Getachew *et al*., 2012; Selamnesh Tesfaye, 2015; Patnaik *et al*., 2017).

The habitats of *Prosopis juliflora* are grass land, shrub land, and dry forests. *Prosopis juliflora* is a salt and drought tolerant species. Moreover, it is nitrogen-fixing, has deep reaching roots and tolerates dry soils. The tree rapidly forms dense thorny thickets that reduce native species richness and wildlife habitats. The tree re-sprouts easily after damage. Thus, invaded grasslands are transformed to woodland and forests (Weber, 2003).

Prosopis juliflora is generally found in areas where water and poor soil fertility are the principal agents limiting plant growth and are able to survive and even flourish on some of the poorest land, unsuitable for any other tree species (Pasiecznik *et al*., 2001). *Prosopis juliflora* is one of the most economically and ecologically important tree species in arid and semi-arid zones of the world. It is an important species because of its high nitrogen-fixing potential in very dry areas and in drought seasons (Dave and Bhandari, 2013).

Prosopis juliflora trees have been noted to fix nitrogen under conditions of high pH and survive in high salinity and water deficits (Tewari *et al*., 2011). *Prosopis juliflora* species are seen to survive and grow with salinity levels equal to that of seawater and in soils with a pH of 10.5 (Pasiecznik *et al*., 2001). For example, the *P. juliflora* has been successfully raised using saline irrigation water, with an electrical conductivity of 20 dS m^{-1} in India. *P. juliflora* is also particularly able to tolerate alkaline soils, with a marginal reduction in growth up to pH 9, and will survive and grow in soils of pH 11 but performs much better following soil amendments *P. juliflora* is very effective in surviving and reclaiming highly sodic and copper toxic soils by restoring productivity and fertility (Tewari *et al*., 2011; Patnaik *et al*., 2017).

Prosopis juliflora, however, appear to be not well suited to acidic soils, and the possibility that low pH is a limiting factor to the distribution has been suggested for *Prosopis glandulosa* but not specifically for *Prosopis juliflora* (Mohamed, 2014). Poor drainage or waterlogging can have effects on tree growth and survival, with low oxygen content in the soil thought to affect root growth. Altitude does not appear to be a factor directly limiting distribution of the *P. juliflora* species. Due to wide ecological adaptation, the plant occurs on large varieties of soils including marginal lands that are not productive and over a wide range of altitudes (Mainz, 2008; Beresford-Jones *et al*., 2009).

Prosopis juliflora can be found even at higher altitudes. The *Prosopis juliflora - Prosopis pallida* complex is also generally well adapted to different altitudes. The climate of its natural range is characterized by hot temperature averaging 20^0C, but the whole temperature ranges from -1.5 to 50^0C. It grows under mean annual temperature of 14 to 34°C. The major limitation of the distribution of *P. juliflora* is the mean minimum temperature and the frequency and duration of winter frost (Pasiecznik *et al*., 2001). Frost severely damage seedlings and young trees of *Prosopis juliflora*. The *Prosopis juliflora - Prosopis pallida* complex grows in a wide range of rainfall zones, from 100 mm mean annual rainfall or less in dry coastal zones to 1500 mm in the Andean region.

2.4.1. The distribution of *Prosopis juliflora* in other African countries

Africa is a home to many invasive alien species which have been introduced both intentionally and accidentally. Many of these species are included on the global list of the 100 worst invasive alien species (Turpie and Jurk, 2012; Turbelin *et al*., 2017). The magnitude of their impact varies from country to country, and from ecosystem to ecosystem. For instance, the problems caused by these invasive species are more severe in Africa due to different reasons (UNEP, 2002) such as: (1) policy environment is fragmented and weak, (2) information required by the different stakeholders is not available (3) Implementation for prevention and control programs is slow or inadequate, and (4) capacity to do its georefrenced distribution is also lacking by scholars.

2.4.2. Distribution of *Prosopis juliflora* in Ethiopia

Because of natural conditions, there are a number of native and exotic species found within the diverse ecosystem of the country (EBI, 2014). Since the 1980s the plant has spread rapidly in eastern Ethiopia, from the Middle Awash Valley into the Upper Awash Valley and Eastern

Hararghe, Dire Dawa and some localities of Raya Azebo plains of South Tigray (Wakshum Shiferaw *et al*., 2018a). The invasion is also reported in the town of Arba Minch, South Omo and neighboring localities in the South region of the country (Shetie Gatew, 2008; Wakshum Shiferaw *et al*., 2018a; Elias Adege and Abraham Jemberu, 2018).

2.5. Potential benefits of *Prosopis juliflora*

2.5.1. Economic benefits of *Prosopis juliflora*

Introducing species to new locations has had tremendous contributions to societal development Dix *et al*., 2009). Human welfares have been improved due to the introduction of different sources of plant and animal reproductive parts out of their native range. Among the invasive species pathways, global trade has largely enabled modern societies to benefit from the unprecedented movement and establishment of species around the world (McNeely *et al*., 2001). Wood sources of *Prosopis juliflora* are used either as fuel wood or structural material. As a fuel, it can be burned directly or made into charcoal, and as a timber, it can be used as poles or made into furniture (Mwangi and Swallow, 2005). *P. juliflora* pods and seeds are consumed by a wide variety of animals, both in their native range and where introduced, and are often an important part of mammalian diets when trees are present in large numbers (Pasiecznik *et al.,* 2001). A study by Ilukor *et al*. (2014) in Afar region of Ethiopia, for example, showed that about 12% and 39% of the households feed animals with *Prosopis juliflora* leaves and pods, respectively. However, the same findings have also shown that feeding animals only *P. juliflora* leaves and pods causes milk and weight loss (Getachew Gebru, 2008).

Prosopis juliflora branches are widely used as fencing posts, while its pods which are high in protein and sugars may be important or food for humans (Mwangi and Swallow, 2005). *P. juliflora* species have also an ameliorating effect on the soil under natural and semi-natural systems because of nitrogen fixation and because leaf litter incorporated into the soil improves the soil physical and nutritional status. High mineral content and rapid decay of small leaves are favorable characteristics for the use of foliage as a soil ameliorant. Compost making can detoxify its allelochemical effects on germination and growth of plants (Noor *et al*., 1995; Getahun Asrat and Ali Seid, 2017). When added to agricultural and forestry fields, leaf compost of the species replaces the cost incurred to commercial fertilizers in various countries (Pasiecznik *et al.,* 2001).

Another use of *Prosopis juliflora* is its flowers for the supply of nectar and pollen as bee forage for the production of honey. Flowers of *P. juliflora* are small, yellow and gathered on long inflorescences producing pollen and nectar that is high in protein and sugars (Pasiecznik *et al.*, 2001). Although *P. juliflora* has diverse economic values, use of the plant is limited. For example, local communities in the invaded areas are using the plant only for animal feed, fuel wood, charcoal and construction purposes in Ethiopia (Wakshum Shiferaw *et al*., 2018a).

2.5.2. Ecological benefits of *Prosopis juliflora*

2.5.2.1. Erosion control

The most beneficial part of the soil layer is humus of the top soil, which takes many years to develop. Topsoil is rich in plant nutrients and beneficial soil microorganisms. This topsoil is prone to water and wind erosion. Loss of soil can be controlled by putting up windbreaks, planting cover crop, and cultivation practices (Walter, 2011). A shelter belt of *Prosopis juliflora* is planted around fields in many semi-arid regions to reduce wind speed. This reduces wind-induced soil erosion, decreases desiccation by reducing transpiration and consequently increases plant and animal production (Tewari *et al*., 2013). *Prosopis juliflora* is a dry land plant growing in arid to semi-arid environments in many tropical areas. They have extensive lateral root systems to capture surface water after rain and deep tap roots allowing them to survive prolonged drought by accessing the water table (Pasiecznik *et al.*, 2001).

There are many instances where *Prosopis juliflora* has been planted where soil fixing or improvement is an important consideration (Zeila, 2005; Pierret *et al*., 2016; Mohammed Mussa *et al*., 2017). They have proved particularly suitable for stabilizing sand dunes and easily erodible soils. This is because of their ability to survive and grow on poor sites that few other species can tolerate, and the extensive lateral root system which binds soil particles, particularly in the upper 60 cm. Induced changes in the microclimate from the shade and shelter provided, offers physical protection, and combined with improved soil conditions, this favors the growth of other herbaceous species further controling soil erosion

The capacity to block the flow of wind depends upon height, density, and thickness of the stands. Apart from preventing the loss of fertile soil, *Prosopis juliflora* reduces wind damage to crops, loss of soil moisture and improves the microclimate. Report by Mwangi and Swallow (2005) in Sudan showed that wind speed inside five years old *P. juliflora* plantation reduced by an average of 14%, while potential evaporation was reduced by 22%.

Furhermore, *Prosopis juliflora* is a rapidly growing wind resistant plant which can be planted successfully to control soil erosion and can serve as shade and shelter that positively affects water balance by increasing relative humidity and temperature; and reducing evapotranspiration (Pasiecznik *et al*., 2001). In low land areas of Central Sudan, Al-Amin *et al*. (2010) showed that *Leptadenia pyrotechnica* provides relatively good protection windward against consequences from erosion than *Prosopis juliflora*. Another study in Central Sudan by Al-Amin (2011) pointed out that growth of *Prosopis juliflora* in clusters can be more effective against wind protection than individual trees/shrubs.

2.5.2.2. Soil fertility management and rehabilitation

Woody species within pastures and savannas are often associated with ‘resource islands’, characterized by higher fertility and organic matter levels under the tree canopies ((Tiessen *et al*., 2003). In silvopastoral systems, trees are included in cultivated fields or pastures in order to maintain soil fertility, cycle nutrients, improve microclimate, manage water table and improve overall system productivity (Tiessen *et al*., 2003). Improved fertility under tree canopies can result from litter fall or dung inputs from sheltering animals (Tiedemann and Klemmedson, 1973). Trees enrich surface soils by recycling leaf litter that contains nutrients which may have been taken up at depth or nitrogen which may have been fixed. Forest soils commonly have a steep gradient of organic matter and associated nutrients with depth. When tropical forests are replaced by pastures, for instance soil organic matter and associated nutrient levels may change (Tiessen *et al*., 2003).

Soil properties vary across the landscape, and this may determine plant distribution. This spatial variability needs to be taken into account before the effects of vegetation and vegetation change on soil properties can be examined. For instance, findings by Tiessen *et al*. (2003) showed that *Prosopis juliflora* have enriched the topsoil under their canopies with 24.6% SOC, 16% total P, 24.5% total N and 56.5% available P on the top soil surface in semiarid Northeast of Brazil. Mwangi and Swallow (2005) revealed that in Kenya the standing biomass of understory plant species was five times lower under the canopy of *Prosopis juliflora*. Organic carbon and total nitrogen concentrations in soils under *P. juliflora* were 13% and 45% higher than in the open grassland areas, respectively.

Shrubs/trees take water and nutrients from deep soils, which is beneficial to the herbaceous plant species. Thus, removal of trees from the savannah ecosystems, which usually have alternating wet and dry season and often support large numbers of grazers, could endanger the survival of the shallow-rooted herbaceous plants during the dry periods, as they are unable to access water from the deep soil horizon (Kahi *et al*., 2009).

Study by Tiedemann and Klemmedson (1973) showed that in upland desert grassland site of the Santa Rita Experimental Range South of Tucson, in Arizona; soil organic matter, total N, available P, total S, total soluble salts, total potassium were higher underneath *Prosopis juliflora* than beyond its canopy at surface 0-45 cm soil depth with total sodium increasing with soil depth. Other research made by Muturi *et al.* (2013) who reported that soil characteristics (e.g. sand%, clay%, N, P, K, Mg, Mn, Fe, and Cu) under *P. juliflora* species and mixed species (*Acacia* and *Prosopis juliflora*) canopies were similar except that pH (7.5±0.03) and calcium (8.3±0.78 meq) were higher. On the other hand, silt (14.1±2.19%) and carbon (0.39±0.068%) were lower than soil under *Acacia* canopy which were 27.2±3.30% and 0.68±0.058% for silt and carbon, respectively at Turkwel riverine forest in Kenya.

The ameliorating effects of *Prosopis juliflora* also in terms of soil salinity, neutralizing alkaline, sodic soils and improving soil nutritional status and physical properties (e.g. soil moisture, bulk density, soil texture etc). These are primarily due to complex interactions between the effects of nitrogen fixation, incorporation of leaf litter, changes in microclimate, and changes in the floral soil fauna and soil microbial populations (Pasiecznik *et al*., 2001).

2.6. Adverse effects of *Prosopis juliflora*

Invasive alien plants and other native invasive plants can affect entire systems in Ethiopia. Accordingly, natural and agro-ecosystems are largely affected by the invasive alien plants (Rezene Fessehaie and Taye Tessema, 2014). Invasive exotic plants are implicated in the decline of threatened and endangered species, because they alter ecosystem processes, change vegetation structure and displace native species, often because they reach high densities and biomass (Surendra *et al*., 2013). Yibekal Abebe (2012) indicated that *P. juliflora* is threatening native plant species in Afar region of Ethiopia, such as *Acacia prasinata*, *Boswellia ogadensis*, *Euphorbia doeloensis, Euphorbia ogadensis,* and *Indigofera kelleri*. These habitats which harbor threatened plant species also harbor many globally threatened and vulnerable mammal and bird species.

In Afar region, wild animals are further endangered due to the disruption of ecosystem integrity. Abyot Berhanu and Getachew Tesfaye (2006) also reported that *Prosopis juliflora* replaced the local biodiversity in several spots in the Afar region, mainly rangelands and dry riversides. In such areas, the grasslands are no more used for grazing and more importantly changing the ecosystem function from rangeland to *Prosopis juliflora* thicket. Consequently, the local Afar pastoralists in Ethiopia moved further from their home and pasture fields aggravating food and feed shortage. A study by Shetie Gatew (2008) at Amibara district in the Afar region of Ethiopia indicated that *Prosopis juliflora* has severely invaded dense *Acacia* woodlands, riverine forest and agricultural lands of the study area. For instance, in the 16 years period (1986 to 2001), land use/cover changes showed that *P. juliflora* were displaced 9.91 km^2 areas of *Acacia* woodland.

Prosopis juliflora has been blamed for many disaster effects such as replacing grasses, herbs, and shrubs which are consumed by local livestock, injuring livestock with its poisonous thorns and causing goat teeth to rot and fall out because the small seeds get stuck between the teeth. Thousands of goats have been rendered toothless and died from starvation following teeth loss which has been decreasing their number and threatening goat breed in the region (Obiri, 2011).

The chemical investigation of the extracts showed that the allelopathic chemical compounds are phenolic or antioxidant capacity in nature. Slow decomposition and heavy accumulation of leaf litter below *Prosopis juliflora* may possibly result in accumulation of toxic substances in the soil layers, inhibiting the growth of other species (El-Keblawy and Al-Rawai, 2007). El-Keblawy (2012) and Kaur *et al.* (2012) reported that there was a noticeable accumulation of litter underneath the *P.juliflora* compared with *Prosopis cineraria* canopies in the hyper-arid habitats of the UAE and other native Indian plants respectively.

El-Keblawy and Al-Rawai (2007) found lower species richness, evenness, and frequency of the associated native species in plots under canopies of *Prosopis juliflora* in UAE. However, it has no allelopathic effect on its own seedlings growing underneath the canopy. A study by Muturi *et al*. (2013) reported that *P. juliflora* species canopy would hinder the regeneration of native species. Findings by Samueal Getachew *et al*. (2012) in Middle Awash, Southern Afar region of Ethiopia depicted that leaves of *P. juliflora* have greater inhibitory effects than roots and barks. Muturi *et al*. (2013) also indicated that bark seemed to contain the least inhibitory compounds. But, shoot and root growth of the study species were inhibited by leaf and root extracts at higher concentrations.

Prosopis juliflora has both positive and negative interactions with plant communities in naturalized areas or ecosystems (Mwangi and Swallow, 2008; Samuel Getachew *et al*., 2012; Yibeltal Abebe, 2012; Selamnesh Tesfaye, 2015; Wakshum Shiferaw *et al*., 2018a; Hailu Shiferaw *et al*., 2019b). However, studies conducted in many parts of the world showed that problems of *P. juliflora* are outweighing positive ones ecologically, socio-economically, and in health aspects. Furthermore, some studies indicated that standing biomass, frequency, and cover of understory plant species was significantly higher under non-invaded grazing lands than under the canopies of *P. juliflora* (Kahi *et al*., 2009).

Invasive species can modify composition of native plant species, deplete species diversity and affect ecosystem processes. In Ethiopia, the invasive species can be driver of land use/cover changes and associated losses of ecosystem services (Hailu Shiferaw *et al*., 2019b). For example, *Prosopis juliflora* canopy showed strong negative effects on species richness of associated native species (Kaur *et al*., 2012). Conversely, in arid grazing lands, Kumar and Mathur (2014) showed that more species richness and evenness were recorded in all land uses of the *Prosopis juliflora* invaded sites than the non-invaded ones. Moreover, Singh *et al*. (2008) also depicted that species dominance and evenness were the highest under *Acacia nilotica* and *Prosopis juliflora,* whereas species diversity index and richness were the highest under native species.

With respect to plant species composition, numbers of plant species recorded under *Prosopis juliflora* canopy were lower than other native species (Nisar *et al*., 2013). Other effects of *Prosopis juliflora* are associated with soil related properties. Shrubs and trees take moisture and nutrients from deep soils, which are beneficial to the herbaceous plant species. Moreover, soils under the tree canopies had significantly higher organic carbon than those in adjacent open grasslands, due to high biomass of the invaded *Prosopis juliflora* (Kahi *et al*., 2009). In most sites, studies showed that soil nutrients such as soil organic carbon, N, P, EC, K, Ca, soluble salts, and S have increased (Tiedemann and Klemmedson, 1973; Maghembe *et al*., 1983; Nisar *et al*., 2013), but pH, Na, bulk density have declined. On the other hand, with spatial and temporal dynamics, Mg has sometimes either increased or declined (Maghembe *et al*., 1983; Nisar *et al*., 2013).

2.7. Vegetation of Ethiopia

We might expect biotic communities to distribute as discrete units, with rapid turnover of species as we move along an environmental gradient from one community to the next. If the environmental discontinuity is rapid and severe, most of the species living together will be limited almost simultaneously when they encounter unwelcoming conditions (James and Mark, 1998).

Afar region is characterized by desert and semi-desert scrubland; and *Acacia-Commiphora* woodland and bush land vegetation types. The vegetation types where this study conducted were *Acacia-Commiphora* woodland and *Acacia-Commiphora* woodland, desert and semi-desert scrubland with vegetation subtype *Acacia-Commiphora* woodland and bushland proper. The characteristic herbaceous vegetations consist of species *Chrysopogon, Sporobolus, Dactyloctenium, Cymbopogon,* and *Cynodon* species. The woody vegetation is mainly composed of *Acacia senegal, Acacia nubica, Acacia nilotica, Acacia tortilis, Acacia mellifera*, *Acalypha acrogyna*, *Cadaba rotundifolia*, *Dobera glabra, Grewia tenax, Salvadora persica*, *Balanites aegyptiaca*, and *Ziziphus spina-christi* (Friis *et al*., 2010).

2.7.1. Soil seed bank

Soil seed bank is important in shaping the composition, diversity, structure, and regeneration of plant communities and thus restoration of vegetation ecosystems. This in turn greatly depends on spatial distribution of vertical and horizontal seeds of different species and vegetation communities. The spatial distribution of seeds in the soil is primarily a function of the dispersal process (Wakshum Shiferaw *et al*., 2018b). The number of seeds that falls on a particular area also depends on another large number of factors, concentration of the seed source, seed dispersal, nature and activity of dispersal agents and spatial heterogeneity of the parent plants in the field.

These variations may reflect differences among the species in terms of seed longevity in the soil, modes of seed dispersal and subsequent movement, seed predation, and probable differences in the slope of the landscape and local edaphic conditions where the seeds land (Uasuf *et al*., 2009).

The reproductive strategy involves allocating a given fraction of resources to reproduction, striking a balance between sexual and vegetative/asexual reproduction, fruiting at the appropriate time and producing the optimum number of seeds of optimum size. It has been long noticed that most invasive/weedy plants produce many small seeds, and it is this characteristic that makes them so successful in the struggle for living space (Hailu Shiferaw *et al.*, 2004). Many species in ecosystems all over the world make use of seed banks as part of their regeneration strategy. In general, soil seed banks are dominated by seeds of herbaceous species, although they can be highly variable in features such as species number and composition, seed longevity and viability, germination strategies and depth distribution of seeds in the soil (Demel Teketay, 1998).

Both underground soil seed bank and aboveground vegetation should be given attention, because of its importance in determining the soil seed bank characteristics. As access to the seed bank by researhers can be hampered by the fact that seeds are buried in the soil, knowledge of relationships between underground seed bank characteristics and aboveground vegetation could simplify seed bank inventories in specific situations, by creating the opportunity to draw conclusions on seed bank characteristics based on aboveground information, without the need to heavily disturb the soil itself (Reubens *et al.*, 2007). Seed populations in the soil are incorrectly assumed to be homogeneous and normally distributed. The problem in describing the seed distribution in soil is associated with its inherent heterogeneity (Flugge, 2014; May *et al*., 2016).

The seeds of *Prosopis juliflora* are characterized by a seed coat-imposed dormancy and establishing a huge persistent seed bank in the soil. Goats, sheep, cows and wild animals, attracted by the green foliage eat ripened pods and disperse the seeds. Dispersal and successful germination of the seeds of *Prosopis juliflora* are mainly through the process of endozoochory, the dispersal of seeds through animal ingestion. Seeds are subsequently defecated away from the parent plant. The pods are also transported by flood waters and run-off (FAO, 2006).

Land use/cover changes, competition over resources, and climate change are key factors that are influencing the probability of *Prosopis juliflora* invasion (Pasiecznik *et al*., 2001; Wakshum Shiferaw *et al*., 2018a). When an invasive species becomes firmly established, its control can often be difficult and eradication is usually impossible. Moreover, its impact on biodiversity and ecosystem processes can be very serious (Hailu Shiferaw *et al*., 2004).

Soil seed bank has been considered as a promising and cost-effective method for restoring vegetation but its influencing factors have not yet been fully understood (Li *et al*., 2017). Thus, the possibility of vegetation restoration using the soil seed banks is basically dependent on its seed density and species composition (Duncan *et al*., 2009; Gonzalez and Ghermandi, 2012). Moreover, seed dispersal is very important for species diversity, composition, and density. For instance, studies showed that both livestock and wildlife species played a critical role in the dispersal of *Prosopis juliflora* and other native species (Mworia *et al*., 2011).

2.7.2. Species diversity and its related analysis

There are two approaches to measuring species diversity; species richness and evenness (equitability). One method has been to construct mathematical indices broadly known as diversity indices. The other involves comparing observed patterns of species abundance to theoretical species abundance models. Both incorporate information on the number of species/species richness. Diversity measures require an estimate of species importance in the community. The simple choices are numbers, biomass, cover, or productivity. The term heterogeneity was first applied to this concept and for many ecologists; this concept is synonymous with diversity (Legendre and Legendre, 1998). Since heterogeneity contains two separate ideas species richness and evenness it is only natural to try to measure the evenness component separately. For many decades field ecologists had known that most communities of plants and animals contain a few dominant species and many species that are relatively uncommon. Evenness measures attempt to quantify this unequal representation against a hypothetical community in which all species are equally common.

Evenness (*E'*) is calculated from the ratio of observed diversity to maximum diversity following Pielou (1966). E' is normal between 0 and 1, and with 1 representing a situation in which all species are equally abundant. Species turnover analysis is complemented by calculating the floristic similarities between all pairs of sites using Sorensen's similarity index (Magurran, 1988).

The term abundance is defined as the number of individuals of a given species per unit area in a hectare. The term frequency is described as the occurrence or absence of a given species per sampling unit. It is expressed as an absolute frequency, which refers to the percentage of the total number of sampling units containing the species to all the plots or as a relative frequency showing the percentage of absolute frequency of a species compared to the total absolute frequencies of all the plots added up (Lamprecht, 1989).

2.7.3. Application of multivariate data analysis

Multivariate data analysis is a form of statistics encompassing the simultaneous observation and analysis of more than one statistical variable. Given a sufficiently large group of objects, ecological clustering methods should be able to recognize clusters of similar objects while ignoring the few intermediates which often persist between clusters. Clustering is an operation of multidimensional analysis which consists in partitioning the collection of objects (or descriptors) in the study (Legendre and Rogers, 1972 cited in Legendre and Legendre, 1998).

Agglomerative clustering algorithms often called "bottom–up method", construct a tree-like hierarchy, which implicitly contains all number of clusters. Agglomerative clustering works by first finding the clusters of the most similar items and progressively adding less similar items until all items have been included into a single large cluster. On the one end of the hierarchy every object forms a cluster and on the other end, there is only one cluster containing all objects (Legendre and Legendre, 1998).

Hierarchical divisive clustering algorithms, often called “top–down” methods, do the opposite of agglomerative clustering: they start with all items as members of a single cluster and split the cluster is into two separate clusters, and so on for every successive cluster until each item is its own cluster. Divisive methods begin with all of the cases in one cluster, which may be broken down into sub-clusters until all cases are separated. Divisive classification may be thought as generally preferable to agglomerative hierarchical cluster analysis methods as the classification of units into broad categories is usually of far greater interest than the association among particular pairs (Legendre and Legendre, 1998).

Ordination is a multivariate method that expresses the relationships between samples, species and environmental variables in a low-dimensional space using ordination diagrams. Ordination may be viewed as Constrained Ordination (Canonical Ordination or Direct Gradient Analysis) and Unconstrained Ordination (Indirect Gradient Analysis). Unconstrained ordination techniques are not constrained by environmental factors as the name suggests (Legendre and Legendre, 1998).

2.7.4. Application of Remote Sensing and GIS for land use/cover changes

Remote sensing is the use of electromagnetic radiation sensor to record images of the environment which can be interpreted to yield useful information while GIS is a computer based system which used to capture, manage, analysis and interpret data in land cover dynamics study (Helen Merga, 2017). Then, the information is used to interpret data into usable forms to detect environmental changes for instance spatiotemoral changes in certain areas using GIS software.

2.7.5. Land use land cover change detections

Land use and land cover change studies in the region have been discussed by many researchers including Shetie Gatew (2008), Zeraye Mehari (2015), Aster Tadesse (2009), Diress Tsegaye *et al*., (2010), Surafel Luleseged and Araya Asfaw (2012), Tewodros Wakie *et al*. (2014), Yetnayet Fantaye *et al*. (2017), but updated change detection information in relation to the effects of *Prosopis juliflora* invasion is lacking. Moreover, the LULCC is a continuous process and dynamic through time (Islam *et al*., 2018). Extensive research on LULCC pattern is important for social and environmental consequences at different spatiotemporal scales.

2.8. Phenology of plants and climate variability

Studies in the phenology of plants benefit for better integrating indigenous knowledge with other sources of knowledge in making adaptive management decisions. Specifically, it was advocated that integration of traditional phenological knowledge and highlight opportunities for this knowledge to support policy and practice of adaptive management of *Prosopis juliflora* in the region (Armatas *et al*., 2016). Knowledge on the phenology of the plant could be used as input to control dispersal of its seeds towards non-invaded lands (Kaur *et al*., 2013). Both abiotic factors such as temperature and precipitation and biotic factors including herbivores, pollinators, and seed dispersers influence plant phenology (Herrera, 1998; Sakai, 2001; Gordo and Sanzi, 2010; Smith *et al*., 2012).

Periodic changes in rainfall which are caused by movements of the inter-tropical convergence zone often play important role in the phenology of tropical plants (Igboabuchi *et al*., 2018). Moreover, changes in abiotic factors such as temperature, soil moisture, nitrogen availability, light, and elevated CO_2 are all likely to affect plant phenology (Nord and Lynch, 2009). Exposure of species to such altered climatic regimes could result in modified behavior and adjusted phenology of plants (Gungula *et al*., 2003; Puppi, 2011; Monteith *et al*., 2015). Variations in plant phenology have long been used as indicators of climatic change and variability (Zhao *et al*., 2012). Moreover, site-specific factors have significant effect on the phenology and reproductive success of plants (Domenech *et al*., 2016).

Although temperature has underlying effects on water availability, both via changes in transpiration and also perhaps via changes in precipitation, although this is likely to be more variable. Furthermore, in subtropical and tropical climates, precipitation is the fundamental causes of plant seasonality than temperature (Nord and Lynch, 2009; Korner, 2006).

With regard to plant phenology, few research works were carried out in Ethiopia, for instance, phenology of seven indigenous trees in the dry Afromontane Munessa-Shashemene Forest, South Ethiopia (Getachew Tesfaye *et al*., 2011). However, almost no research works were reported in relation to the phenology of *Prosopis juliflora* in Ethiopia.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Description of the study areas

This study was conducted in Afar National Regional State in Northeastern Ethiopia. As showed in Figure (1), Afar Region has five Adminstarive Zones namely Zone 1 (Awsi Rasu), Zone 2 (Kilbet Rasu), Zone 3 (Gabi Rasu), Zone 4 (Fantena Rasu), and Zone 5 (Hari Rasu). Among the five zones of the region, two *Prosopis juliflora* invaded zones including Gabi Rasu (Zone 3) and Fantena Rasu (Zone 4) were selected for this study. Amibara and Awash Fentale districts were selected from Zone 3 for studies of LULCCs, phenology of *P.juliflora,* vegetation survey, and soil seed banks. In addition, Teru and Yalo districts were also selected from Zone 4.

The locations of the study districts are indicated in Table (1).

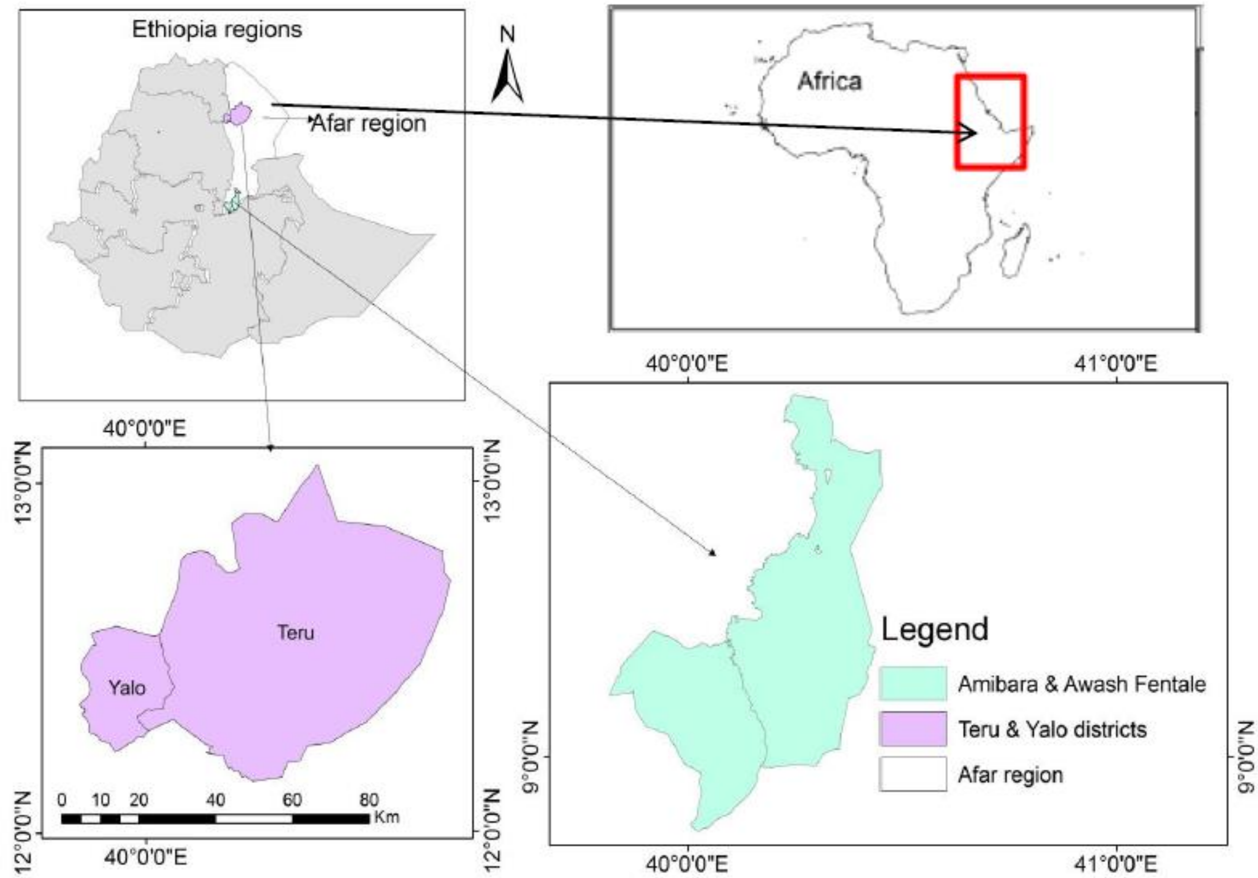


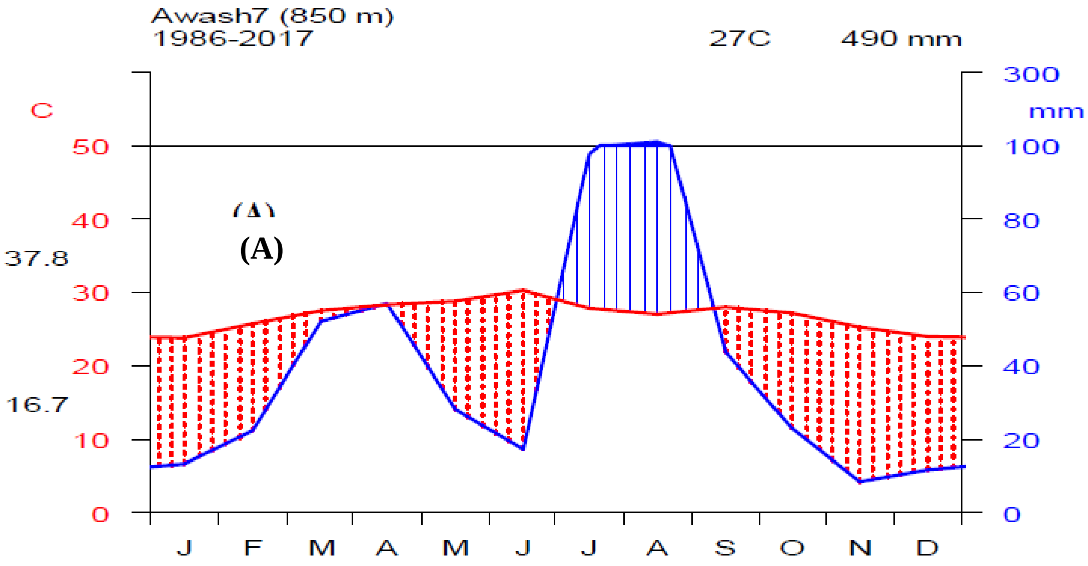
Figure 1. Map of the study sites

Table 1. Summary for location and elevation of study areas/districts

	Location		
Study districts	Latitude	Longitude	Elevation (m.a.s.l.)
Amibara	9°00'00" N to 9°19'43.83" N	40°05′51.6″ E to 40°10′51.6" E	741-746
Awash Fentale	8°98′ 50″ N 9°10' 00" N	40°03'33″ E to 40°10'56" E	700-1000
Teru	12°38'03.95"N to 13°0'.00"N	39°55'.00"E to 40°18'00.0" E	354-363
Yalo	12° 40'0″ N to12°45' 0"N	39°65'0.00″ E to 40°25'.00" E	800-829

The mean annual temperature for Awash Fentale district was 27°C (Figure 2A). Furthermore, the mean annual temperature of Amibara district was 26.8^{0}C (Figure 2B). The annual precipitation of Awash Fentale and Amibara districts were 490 mm and 416 mm, respectively (Figure 2A & B).

Moreover, climate data were taken from the nearest Chifira Meteorology Station in Afar region. The mean annual temperature of the study site was 27.5°C. The mean annual temperature ranged from 16.8°C - 39.9°C. The annual precipitation in the study site was 173 mm (Figure 3C).



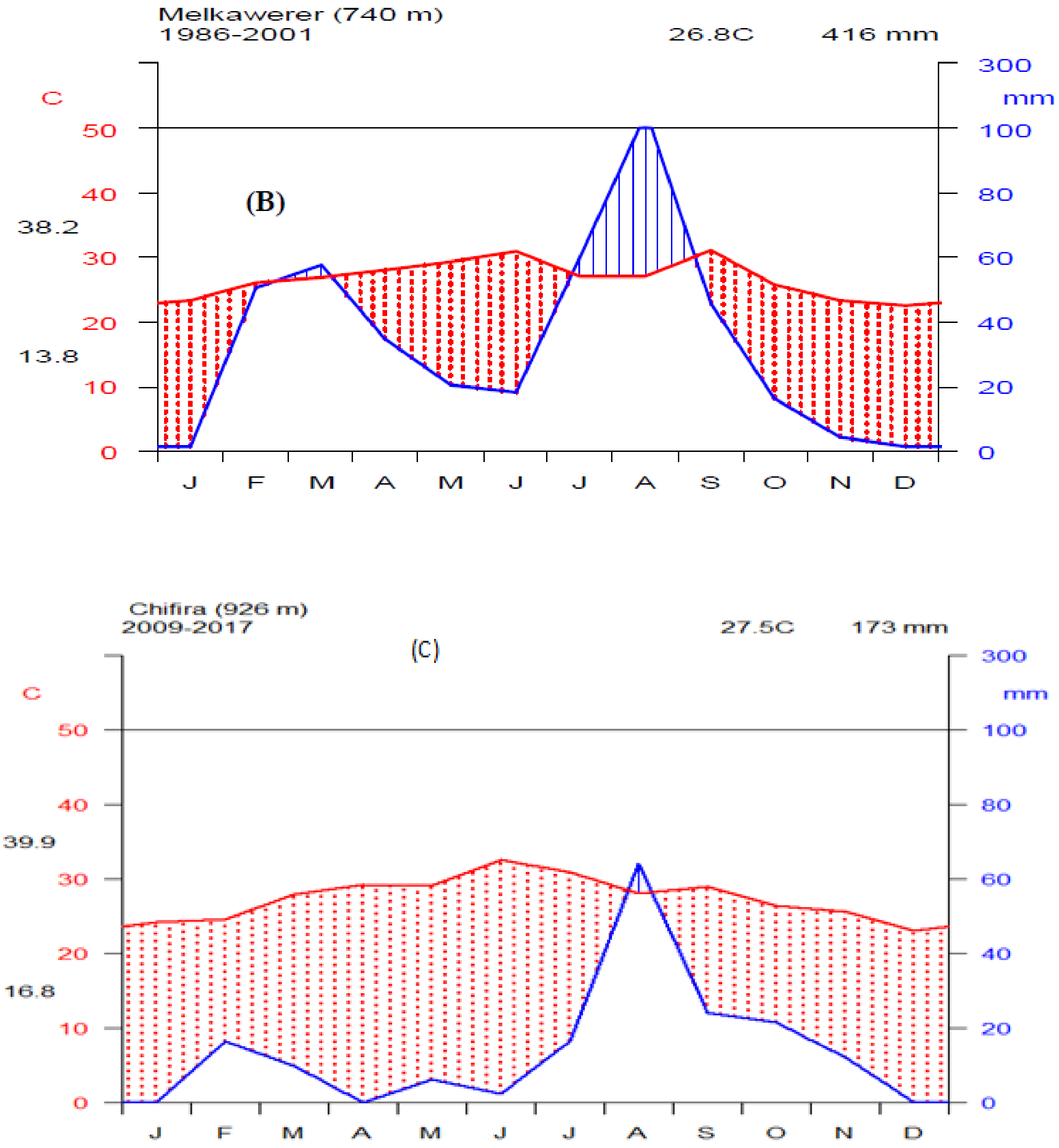


Figure 2. Climate diagram for Awash Fentale (A), fifteen years for Amibara district (B) and Ninteen years for Teru and Yalo districts (C).

The texture of the soils is usually sandy, originated from Jurassic and Cretaceous limestone and other sedimentary rocks. According to FAO soil classification and ISRIC-world soil information, soil of Afar Floristic Region is stony Leptosols are associated with the escarpments and the Afar lowlands. Arenosols are also found in arid areas of the lowlands (Friis *et al*., 2010).

About 83, 851 and 40,901 number of population were living in Amibara and Awash Fentale, respectively. Whereas 74, 559 and 52, 825 population were living in Teru and Yalo districts, respectively (CSA, 2013). Ninety percent of Afar people are pastoralists, while another 10% are considered as agro-pastoralist (Tewodros Wakie *et al*., 2014).

3.2. Land use and land cover change in Amibara and Awash Fentale districts

This study was conducted at Amibara and Awash Fentale districts in South Afar region. The required satellite images (Table 2) for the study sites were downloaded from the USGS Earth Explorer (https://earthexplorer.usgs.gov/) (Rongali *et al*., 2018).

Table 2.Satellite images used for LULCC for the study districts of Afar region in Ethiopia

Satellite	Sensor	Path/Row	Acquisition date	Spatial resolution
Landsat–5	Thematic Mapper (TM)	167/53	30/01/1986	28.5 m
		167/54	30/01/1986	
		168/54	21/01/1986	
		167/53	06/02/2000	30 m
		167/54	06 /02/2000	
		168/54	13/02/2000	
Landsat–8	OLI/TIRS	167/53	19/01/2017	
		167/54	19/01/2017	
		168/54	26/01/2017	

Seven land use/cover classes namely *Prosopis juliflora* invaded land, farmland, settlement, bare land, grazing land, woodland and water bodies were identified and described for analysis (Table 3).

Table 3. Description of different LULC of the study sites

Lists of LULC	Description
Prosopis juliflora invaded land	Areas dominated by *P. juliflora* species with more than 100 stems and the minimum area of 20 m × 20 m.
Farmland	Land under cultivation for crops (cotton, sugar cane, fruits etc.)
Settlement	The area covered with rural houses and urban buildings
Bare land	A land devoid of vegetation, pastoral houses and buildings
Grazing land	A field dominated of grass or herbage and with less than 10% canopy of woody species
Woodland	An area covered with acacia and other woody species or non-invaded area by *P. juliflora*
Water bodies	A field covered with streams and wetlands areas

Source: own description

Following Rwanga and Ndambuki (2017), processing the imagery and image interpretation for the developtent of land use and land cover maps was performed (Table 1). The pre-processed images were classified by supervised classification methods. In the supervised classification technique using the maximum likelihood, algorithm classifies the image based on the training sets (signatures) provided by the user based on field collected ground truth data. Accordingly, 50 ground truth (signatures) for each land use and land cover type used for the supervised classification. The general procedures of LULCC methods are indicated in Figure (3):

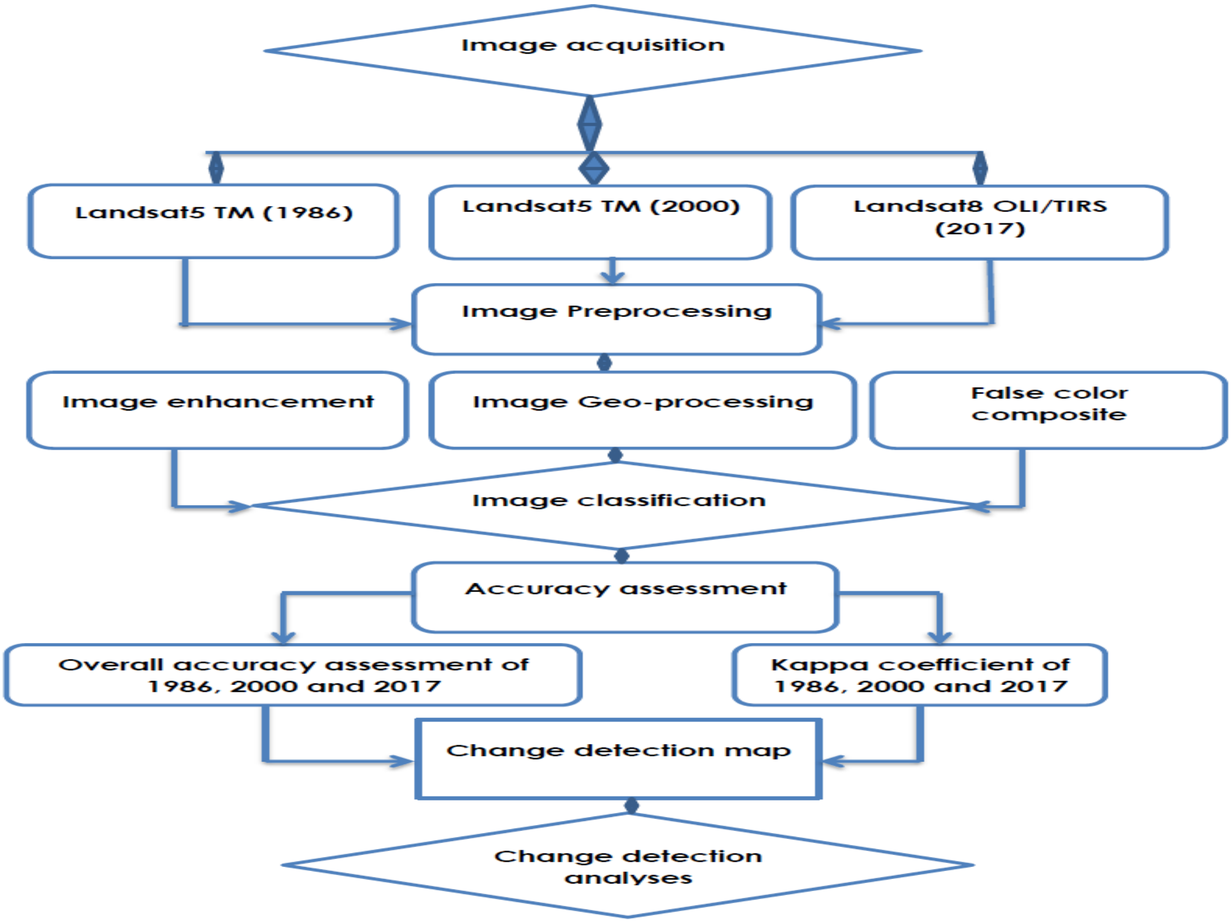


Figure 3. Framework of data analysis

The accuracy assessments for supervised land use classification were done for the years of 1986, 2000, and 2017 image by using ArcGIS. From the classifier, 350 points generated randomly each for 1986, 2000 and 2017 supervised image. Each and every point had a specific color tone and the pixel value which recognized by the software itself when the data sets trained during supervised land use classification. These values considered as reference values for land use and land cover changes. All the randomly generated points then identified by the user and assigned in different classes. The correctly identified points considered as classified values.

The overall classification accuracy = Number of correct points/total number of points. The columns of the confusion matrix in Tables (11 and 13) show to which classes the pixels is in the ground truth. The rows show to which classes the image pixels have been assigned to in the image. The diagonal show the pixels that are classified correctly. Pixels that are not assigned to the proper class are occur out of the diagonal and give an indication of the confusion between the different land use and land cover classes in the class. Producer's accuracy measures errors of omission, which is a measure of how well real world land use and land cover types can be classified. Whereas user's accuracy measures errors of commission that represents the likelihood of a classified pixel matching the land use and land cover type of its corresponding real-world location (Rwanga and Ndambuki, 2017).

An error matrix and Kappa statistics also generated from these references and classified data. The overall accuracies calculated from the error matrix by dividing the sum of the entries that make major diagonal by the total number of examined pixels. Kappa coefficients of agreement also calculated using Afify (2011).

To compute the accuracy assessment for the resent period of 2017, and previous periods of the 1986 and 2000, ground truth data with satellite imageries from Google Earth Pro v.7.1.5, and discussions with key informants of the local community were used, respectively. Satellite imageries combined manually and used to recognize different features. The magnitude of change for each LULC class calculated by subtracting the area coverage of initial year from that 2nd year as shown in Eq. (1) following Islam *et al*. (2018).

$$\text{Magnitude} = \text{Magnitude of the New Year} - \text{Magnitude of the previous year} \quad \text{-------} \ (1)$$

Percentage change (trend) for each LULC type then calculated by dividing magnitude change by the base year (the initial year) and multiplied by 100 Eq. (2).

$\text{Percentage change} = (\text{The magnitude of the change} * 100)/(\text{Base year})$ ---------- (2)

3.3. Phenology of *Prosopis juliflora* in Amibara and Awash Fentale districts

3.3.1. Sampling design and data collection

This study conducted in Amibara and Awash Fentale districts from Zone 3 of Afar region (Figure 1&4). Observation on the monthly phenology calendar of *Prosopis juliflora* were carried out at Dudub and Kurkura sites which were selected from Awash Fentale and Amibara districts, respectively. For data collection, 8 replicates of *Prosopis juliflora* stems from each site that were 16 individuals of about similar age were randomly selected from study areas.

The sampling unit for each phenological stage of *Prosopis juliflora* was individual tree in the study sites. Then proportion of biological data in percent including reproductive forms such as leaf persistence (shading and greenness), flowering (inflorescences) abundances, green pod (pod settings), and matured pods (seed dispersal) per individual tree per month were collected following Smith *et al*. (1998).

Spatial explicit data on monthly precipitation and monthly averages of minimum and maximum temperature for seasonal ranges were taken from National Metrological Agency of Ethiopia (NMA, 2018). Then, monthly mean climate data (tempreture and rainfall) of the year 2016/2017 for 12 months were used to associate with phenology stages of *Prosopis juliflora*. *Kiremt* (rainy season), *Belg* (spring), *Bega* (dry season), and *Meher* (autumn) seasons were considred for the phenology of the species with seasonal variations.

3.3.3. Data analysis

The statistical analysis of phenology stages of *Prosopis juliflora* was performed by one-way ANOVA procedure. Duncan's multiple range tests was applied to test differences among means of the phenology stages of *P. juliflora* by locations and seasons using SAS Software version 9.0 (SAS, 2002).

3.4. Floristic composition, diversity and structure in Amibara and Awash Fentale districts

3.4.1. Site selection

Two *Prosopis juliflora* invaded districts from Zone 3 of Afar region including Amibara and Awash Fentale were selected for data collection (Figures 1&4). Then, four sites Kurkura and Sedihafeghe from Amibara; Dudub and Kebena from Awash Fentale district were selected.

During preliminary reconnaissance survey, the sites were stratified into approximately similar units based on the following parameters: such as invasion levels of *Prosopis juliflora* (invasion levels were quantified based on the number individual stems of *P. juliflora* in each habitats, land use and land cover, DBH/DSH sizes of *P. juliflora*, and physiography (slope, aspect, altitude) of the sites.

Quadrats were laid at different invasion levels to collect vegetation and environmental factors (Kent and Coker, 1992). Using modified methods of Gairola *et al*. (2012) and Muturi *et al*. (2013), floristic and environmental data were collected under *Prosopis juliflora* invasion levels/habitats of:-

1. *Prosopis juliflora* thicket which contained 51–100% of *Prosopis juliflora* individual stems (PJT),

2. Mixed *P. juliflora* with native species stands in which density of *P. juliflora* was 25–50% in proportion in the patch (PJM),
3. Non-invaded woodlands (NIWLs), and
4. Open grazing lands (OGLs). Then, a total of 64 quadrats, which means 16 temporary quadrats under each habitat were laid.

Data were then collected under different *Prosopis juliflora* invasion levels using quadrat sizes of 20 m × 20 m (400 m^2) for *P. juliflora* thickets, *P. juliflora* with native species stands, and non-invaded woodland and open grazing lands. The first quadrat was started randomly and then using systematic sampling the successive quadrats were established in different adjacent patches (*Prosopis juliflora* invasion levels) and open grazing lands.

3.4.2. Data collection

In each quadrat, all trees or shrubs were measured and counted. Cover abundance was also identified and estimated for all growth forms following Van der Maarel (1979). Diameter at breath height (DBH) for trees or diameter at the stump height (DSH) for shrubs was measured in the quadrats to capture all multi-stem for each individual of shrub.

Caliper and hypsometer were used to measure tree/shrub diameter and height respectively. Individual woody categorizations were made at height less than 1 m and DSH less than 1 cm for seedlings. The height 1–2 m and DBH/DSH 1–5 cm for saplings, and height greater than 2 m and DBH/DSH greater than 5 cm for tree/shrub were measured. For seedlings and saplings, only their numbers were counted and recorded (Figure 4).

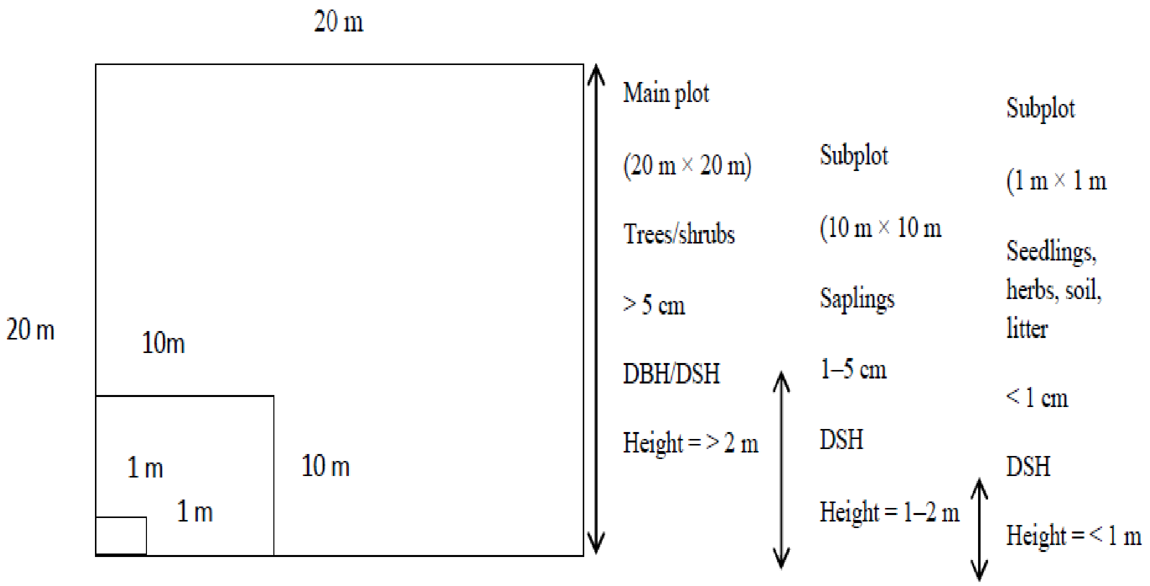


Figure 4. Quadrat design for vegetation inventory, soil and soil seed bank samples.

Any individual with its above-ground stem growing in a cluster for woody plants (shrubs) was counted and measured as a single individual for basal area calculation following fixed-area micro-plot method (Chojnacky and Milton, 2008). If a total shrub plant diameter is desired, the equivalent diameter (DSH) is recommended.

$$D_{\mathrm{SH}} = \sqrt{\sum_{i=1}^{n} D_{\mathrm{SHi}}2} \text{-------------------------------------} \quad (3)$$

Where D_{SH} is Diameter at Stump Height

Quadrats of 1 m × 1 m (1 m^2), 10 m × 10 m (100 m^2), and 20 m × 20 m (400 m^2) were used for recording seedlings/herbaceous, saplings and tree/shrub species, respectively. That was 80 sample quadrats of 1 m^2, 16 quadrats of 100 m^2, and 16 quadrats of 400 m^2 were laid in each invasion level.

The presence or absence of plant species was registered by direct counting. Percentage cover (ground cover) of herbaceous plants was estimated from the five subplots of 1 m^2 (at four corners and one in the center of the main plot) and then the mean estimates were taken (Van der Maarel, 1979). That is, all grasses and herbaceous within the marked area of the 1 m^2 were estimated, recorded, and collected for identification. For saplings, a subplot 100 m^2 in the center of each main quadrat (400 m^2) for all woody species encountered were counted and recorded.

The locations of all quadrats such as coordinates, slopes, and altitudes were also recorded. Plant specimens were brought and stored in Addis Ababa University national herbarium for further identification. Plant identification and naming was followed published flora volumes 1-8 of Ethiopia and Eritrea.

Physiographic variables such as altitude, slope, and aspects were recorded for each quadrant (Zerihun Woldu *et al*., 1989).

3.4.3. Data analysis

For analysis cover abundance, number of species under each habitat, regeneration profiles and environmental data sets were used. Accordingly, vegetation and environmental variables were organized for data analysis.

Using optimal number of clusters was determined (Zerihun Woldu, 2017). All vegetation data were verified and analyzed using the following equations. Species diversity was computed using Shannon-Wiener diversity index (H') (Magurran, 2004; Kent and Coker, 1992) Eq. (4):

$$H' = -\Sigma i(\left(\frac{\mathrm{ni}}{\mathrm{N}}\right)\ln\left(\frac{\mathrm{ni}}{\mathrm{N}}\right))\text{-----------------------------------} (4)$$

Where the $ni =$ total number of individuals in each species; $H´$ is observed index of species diversity.

$N =$ Total number of individuals in all species

Where pi, is the proportion of individuals found in the i^{th} species.

The cover/abundance values of all plant species in each plot were visually estimated using Braun-Blanquet scale (1932) a 1–9 modified scale (Van der Maarel, 1979).

Evenness (E´) was calculated from the ratio of observed diversity to maximum diversity following Pielou (1966) Eq. (5):

$$E' = \frac{H'}{H\max} = \frac{H'}{\ln S} \quad \text{-------------------------------} \ (5)$$

Where H is observed index of species diversity,

Hmax = the maximum level of diversity possible within a given population, given S species and N individuals.

Basal area of a tree/shrub was computed using Eq. (6):

$$B_{\mathrm{A}} = \frac{\pi d^2}{4} \text{ (Lamprecht, 1989)-----------------} \ (6)$$

$\Pi = 3.14$

Where D is diameter at breast height, B_A is basal area.

The Importance Value Index (I_{VI}) indicates the importance of species in the system and calculated with three components following Kent and Coker (1992) Eq. (7):

$$I_{\mathrm{VI}} = R_1 + R_2 + R_3 \quad \text{-----------------------} \ (7)$$

Where I_{VI} is Importance Value Index, R_1 is Relative Density, R_2 is Relative Dominance, and R_3 is Relative Frequency.

Then diversity of plant species was analyzed using R-software version 3.5.1 (Zerihun Woldu, 2017). All data were statistically analyzed using the GLM procedures for results under section 4.3.1. Duncan's multiple range tests was applied to test differences among means at $P < 0.05$ to test the effects of habitats, physiographic and anthropogenic factors on vegetation patterns, density and regeneration potential of woody species. For the analysis of environmental and anthropogenic variables versus vegetation relationships in section 4.3.3, Canonical Correspondence Analysis (CCA) ordination technique was used (Feyera Senbeta, 2006; Naderi and Sharafatmandrad, 2017).

Jacquard's similarity coefficient was used to determine the pattern of species turnover among the habitats to evaluate the similarity among patches/habitats following the Eq. (Kent and Coker, 1992).

$$\mathrm{Sj} = \frac{a}{(\mathrm{a+b+c})} \qquad \text{--------------------------- (8)}$$

Where "a" is the number of species common to both compared clusters, c is the number of species present in one of the clusters compared, and "b" is the number of species present in the other cluster.

The regeneration patterns of woody species for the different patches (*Prosopis juliflora* invasion levels), anthropogenic, and physiographic factors were determined based upon the population size of seedlings, saplings, and trees.

For classification of plant community types, program hierarchical clustering using similarity ratio (SR) with colored leaves and labels using R-software 3.5.1 was used. The number of clusters in the study sites was determined using elbow method. In addition, program for producing synoptic table, and analysis of indicator value were performed using R-software. Environmental variables were tested for statistical significance using ANOVA (Zerihun Woldu, 2017).

3.5.1. Soil sampling

To investigate the effects of *Prosopis juliflora* on soil physicochemical properties at Teru and Yalo districts (Figure 1&4), the following analysis methods are used for findings under section 4.4. Prior to data collection, the study sites were stratified into approximately homogeneous units based on the following parameters: such as invaded sites by *P. juliflora*, non-invaded lands adjacent to it, DBH size of *P. juliflora*, and physiography of the sites. Then, *P. juliflora* invasion and non-invaded open grazing lands (OGLs) were selected.

Soil auger and plastic bags were used for data collection in the field. Soil samples were collected in August 2018 after *Kiremt* (rainy season). A total of 52 soil samples each in Teru and Yalo districts from 0–15 cm and 15–30 cm soil depths under *Prosopis juliflora* invaded and non-invaded areas adjacent to each other (10 m apart) were taken. Then, after soil analysis the results were combined and considered for 0–30 cm soil depth. The water scheme for test plots of *P. juliflora* invaded areas at Teru district were near Teru River. But, the test plots for open grazing lands at Teru district were adjacent to *P. juliflora* invaded lands and located near Teru River. Unlikely, the water schemes for both test plots of *P. juliflora* invaded and adjacent non-invaded open grazing lands at Yalo district were far away from rivers but near villages.

Then, composite soil sample for each soil depth was taken from both districts. Finally, from the composite soil of each depth, 500g of the representative samples were labeled and sealed with a plastic bag and taken to a soil laboratory for analysis. Near the center of all plots, representative soil bulk density was also being taken only for upper soil layer (0–15 cm) using core sampler.

3.5. 2. Soil analysis

Soil sample parameters were analyzed at Ethiopia Agricultural Research Institute, Werer Research Center Soil Laboratory.

Water holding capacity (%WH_2O) on a dry mass basis expressed as percentages by mass to an accuracy of 0.1% (m/m) was calculated using the following equations, which was analyzed from a soil sample taken for bulk density.

$\%\mathrm{WH2O} = \frac{M1-M2}{M2-M0}$*100------------------ (9)

Where, WH_2O =Water content of the soil, M_0 mass of the empty container with a lid (g), M_1 mass of the container with air-dried soil or field-moist soil (g), M_2 mass of the container plus oven-dried soil (g) at 105^0C for 24 hrs (Wilke, 2005).

Typical particle densities for soils range from 2.60 to 2.75 g/cm^3 for mineral particles (Globe, 2005). The amount of pore space or porosity of the soil was calculated according to the following equation:

D_b = mass of dry soil/total volume of soil and air (g/cm^3)

D_p = mass of dry soil/volume of soil particles only (air removed) (g/cm3)

$\mathrm{Porosity} = [1 - \frac{\mathrm{Db}}{\mathrm{Pd}} * 100]$ ------------------------------ (10)

Then,

$\%\, pore\ space = 100 - [\left(\frac{Db}{Dp}\right) * 100]$------------------ (11)

Where D_b = bulk density and D_p = particle density.

The exchangeable sodium percentage is the equivalent fraction of exchangeable Na^+ to cation exchaebale capacity multiplied by 100. It was computed) using Cannon *et al*. (2007).

$\mathrm{ESP} = ((\mathrm{Exchangeable\ Na})/(\mathrm{Cation\ excheange\ capacity}))$*100 ---------------- (12)

Sodium absorption ratio (SAR) was also computed using Cannon *et al*. (2007).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \text{-----------------------} \quad (13)$$

Where, Na^{+}, Ca^{2+}, and Mg^{2+} are sodium, calcium, and magnesium concentrations in milliequivalents per liter.

Cation Exchangeable Capacity (CEC) was also be analyzed in the labouratory by adding basic cations. After Ca, Mg and K were analyzed in the labouratory; CEC could be computed following (Ross and Ketterings, 2011):

$$\mathrm{CEC}\left(\frac{\mathrm{meq}}{100}\mathrm{g\ or}\frac{\mathrm{cmol}}{\mathrm{kg}}\right) = \frac{(\mathrm{pPJMCa})}{200} + \frac{(\mathrm{pPJMMg})}{120} + \frac{(\mathrm{pPJMK})}{390} \text{---------} \ (14)$$

Soil samples were sieved and analyzed for pH using saturated paste extract of 1:1 soil to water. Organic carbon was determined by wet oxidation method (Wakley and Black, 1934). Organic matter was estimated as organic carbon multiplied by 1.724. Soil organic carbon was calculated using Eq. (15):

Estimation of Carbon in Soil Organic Carbon (SOC**):** The carbon stock density of soil organic carbon was calculated as recommended by Pearson *et al*. (2005) from the volume and bulk density of the soil. Then, the carbon stock in soil was calculated as follows:

SOC = BD * d * % C --- (15)

Soil electrical conductivity (ECe) was carried out in the laboratory using saturated paste extract (ICARDA, 2013).

Amount of Ca and Mg in the leachate were analyzed by 1 N NH4Ac extraction method (ICARDA, 2013). K and Na were analyzed by flame emission spectroscopy using flame photometer. The textural analysis was analyzed using hydrometer method (g/cm) using USDA textural triangle (Bouyoucos, 1962).

3.5. Soil physicochemical properties in Teru and Yalo districts

4.5.3. Statistical analysis

The data analysis of different physicochemical measures in the sites was organized by arranging and recording on data sheet. All soil related data were statistically analyzed using SAS software version 9.0. Mean separation were performed using Dunnett's t tests at $P < 0.05$ between sites and land uses.

3.6. Soil seed bank diversity and density in Amibara, Awash Fentale, Teru and Yalo districts

3.6.1. Site selection

For this study, four districts including Amibara and Awash Fentale from Zone 3; and Teru and Yalo from Zone 4 of Afar region were seletcted (Figures 1&4). *Prosopis juliflora* invaded and non-invaded open grazing lands were categorized during preliminary reconnaissance survey. In Awash Fentale and Amibara districts, systematic ransom sampling method under *P. juliflora* thicket, *P. juliflora* mixed with native species stands, non-invaded woodlands and open grazing lands with above ground vegetation were used to sample soils for seed bank. For Amibara and Awash Fentale districts, soil samples were taken in the dry season in March 2018. However, for Teru and Yalo districts, the soil samples were taken in August 2018 immediately after rainy season.

Furthermore, above ground vegetation at Amibara and Awash Fentale districts were used to compare with below ground flora (soil seeds). As it seen in section 4.6, however, due to lack of finance and interest of the funding agency only soil seed banks were considered for Teru and

Yalo districts. Thus, soil seed banks and standing vegetation for Teru and Yalo districts were not associated.

3.6.2. Data collection

For soil seed study, quadrats were laid under the invasion levels of *Prosopis juliflora* used in section 3.4. Thus, data for vegetation and environmental factors, a total of 64 quadrats that means 16 temporary quadrats were laid in each habitat of *Prosopis juliflora* thickets, *Prosopis juliflora* mixed with native species, non-invaded woodlands, and open grazing lands.

Soil auger, ruler, paper bags, clinometer, and GPS were used to collect soil sample for soil seed bank. A total of 256 soil samples from 64 quadrats and animal fecal matter were collected. Fecal droppings of camels, shoats (goats and sheep) and cattle (cows and oxen) were collected from their grazing areas and corrals. At Amibara and Awash Fentale districts, soil samples for the soil seed bank were collected from the soil layer of 0–3 cm, 3–6 cm, 6–9 cm and litter layer from inside subplots of 15 cm × 15 cm. These sampling plots were set within the larger sampling quadrat of 400 m^2 used for vegetation data assessment.

For soil seed banks, one from the center, and four at four corners of 400 m^2 quadrats at Amibara and Awash Fentale in each habitat of *Prosopis juliflora* thickes, *Prosopis juliflora* mixed with native species, and non-invaded wood lands; and pentagonal ways of soil sampling at random places under open grazing lands were sampled. A total of 264 samples including animal fecal matters and soil samples were taken from the Amibara and Awash Fentale districts. The samples were constituted about 96.9% of the soil samples from the soil surface (litter layer, 0–3 cm, 3–6 cm, and, 6–9 cm) and 3.1% were from animal fecal matters.

Soil samples were carefully removed from five areas in each infection using a sharp knife (Hailu Shiferaw *et al*., 2004). Then, about 1 kg of composite and representative soil samples (about 5 cores) for each layer was put in plastic bags and labeled. The litter layers were included with the soil samples as the fourth layer because it might contain a high number of seeds. Sampling was completed within a week to avoid differences between habitats, and thus any temporal bias in seed availability and composition.

In Teru and Yalo districts, a total of 156 soil samples (13 augers × 3 soil depths × 2 land uses × 2 districts) were collected in the sites/districts. That means, 13 sample augers each in Teru and Yalo districts from soil layer of 0–3 cm, 3–6 cm, and 6–9 cm under *Prosopis juliflora* invaded and non-invaded lands were sampled. Due to lack of finance and objectives of the funding agency, the animal fecal matters were not considered at Teru and Yalo districts.

The number of viable seeds in the soil samples and animal droppings were estimated by the seedling emergence technique under conditions favorable for germination in greenhouse (Dalling *et al*., 1995; Lopez-Toledo and Martínez-Ramos, 2011). In the greenhouse, the soil from each sample was prepared and about 0.5 kg of soil was placed in plastic trays in the greenhouse at the Central Ethiopia Environment, Forestry and Climate Change Research center, Addis Ababa.
The soil in each tray was watered every day to induce germination. Seedlings were identified and counted weekly until emergence ceased. Seedling emergences were recorded for 6 months.

Specimens were transplanted on to other pots after seedlings were identified by accession numbers and local names, then removed to minimize confusion with newly emerging plants and possible density effects on further germination. Each specimen was identified in the National

Herbarium of Ethiopia, Addis Ababa University, and using the published Flora of Ethiopia and Eritrea (volumes 1-8).

At Awash Fentale and Amibara districts anthropogenic and physiographical factors such as grazing intensities, disturbances, human impacts, altitude, geographical coordinates, slope, and aspects were also recorded for each quadrat similar to subsection 3.4.2.

3.6.3. Statistical analysis

Soil seed bank density, diversity, and vertical distribution were analyzed using diversity indices to examine species seed dispersal and relate with above ground flora under different *Prosopis juliflora* invasion and in the animal fecal matters.

The species richness and evenness of soil seed bank composition in each soil profile were analyzed following methodology used by Getachew Tesfaye *et al*. (2004); and Perera (2005). Sorensen's coefficient of similarity was used to analyze the similarity between soil seed bank compositions among *P. juliflora* invasion habitats.

The similarity between the species composition of the seed bank and that of the vegetation were also calculated by the Sorensen index (Magurran, 1988). Floristic diversity was analysed using the Shannon's Diversity Index based on a natural logarithm that gives equal weight to rare and abundant species. Shannon's Diversity Index was computed using the following Eq. 16:

$$H' = -\Sigma i(\left(\frac{\mathrm{ni}}{\mathrm{N}}\right) \ln \left(\frac{\mathrm{ni}}{\mathrm{N}}\right)) \text{ -------------------------------------- } (16)$$

Where $ni =$ the total number of individuals in each species; H' is Observed index of species diversity.

$N =$ Total number of individuals in all species

Where pi, is the proportion of individuals found in the ith species.

Where H' is observed index of species diversity

Hmax= the maximum level of diversity possible within a given population, given S species and N individuals.

E' is normal between 0 and 1 and with 1 representing a situation in which all species are equally abundant (Eq. 17):

$$E' = \frac{H}{H\max} = \frac{H}{\ln S} \quad \text{------------------------------------} \quad (17)$$

Sorensen similarity index: it was used to determine the pattern of species turnover among the habitats to evaluate the similarity among habitat types in woodland vegetation. It was determined using Eq. 18 (Sorensen, 1948):

$$\mathrm{Sj} = \frac{2a}{(2a+b+c)} \quad \text{--} \quad (18)$$

In this equation, “a” is the number of species common to both compared clusters, “c” is the number of species present in one of the clusters compared, and “b” is the number of species present in the other cluster.

Species data were organized in spreadsheets using Microsoft Excel 2010. Importance Value Index (I_{VI}) for each species computation was performed using the following Eq. 19 (Muller-Dombis and Ellenberg, 1974):

Absolute Frequency (AF) = number of sampling units with species presence/total number of sampling units

Relative Frequency (RF) = species absolute frequency/sum of all absolute frequencies * 100

Absolute Density (AD) = species total number of individuals/total sampled area

Relative Density (RD) = species absolute density/sum of all absolute densities * 100

Absolute Abundance (AAb) = species total number of individuals/total number of sampling units that contained the species

Relative Abundance (RAb) = species absolute abundance/sum of all absolute abundances * 100

$I_{\mathrm{VI}} = R_F + R_D + R_{Ab}$ --- (19)

Where Index of Importance Value (I_{VI}) = Relative Frequency (R_F) + Relative Density (R_D) + Relative Abundance (R_{Ab}).

The composition and density of seeds in the soil were determined by data obtained from germination. The density of seeds was derived from the total number of seeds recovered from the soil samples. On the other hand, to analyze the depth distribution of seeds in each, the number of seeds recovered in similar layers were combined and converted to provide the density of seeds/m^2 at that particular soil depth following methodology used by Aster Tadesse (2009) and Hailu Shiferaw *et al*. (2004).

At Awash Fentale and Amibara districts, all data were statistically analyzed using the one-way analysis of variance (ANOVA) procedures. Dunnett's t-tests were applied to test differences among means at $P < 0.05$. The statistical analysis was performed using SAS version 9.0 (SAS, 2002). Canonical correspondence analysis (CCA) was also performed to evaluate soil seed bank association in terms of abundance of species with sites, habitats, and environmental factors using R-software (Zerihun Woldu, 2017). The effects of livestock type on soil seed bank diversity in their fecal matter was analysed using the one-way analysis of variance (ANOVA) procedures. Duncan’s multiple range tests was also applied to test differences among means at $P < 0.05$. Moreover, effects of land uses, locations, and soil depth on density of seed bank in Teru and Yalo districts were analyzed using GLM of SAS software version 9.0.

CHAPTER FOUR

4. RESULTS

4.1. Land use and land cover changes

4.1.1. Classification and accuracy assessment

The overall accuracies for the year 1986, 2000, and 2017 were 81.4%, 84.6%, and 84.9% with Kappa statistics of 0.80, 0.81, and 0.82 in that order (Table 3, 4 & 5). Producer's and user's accuracies of individual classes of the classified map ranged for the year 1986 from 64% for settlement areas to 96% for farmlands (Table 4). Moreover, the producer's and user's accuracies of individual classes of the classified map ranged for the year 2000 were also from 70% for settlement areas to 98% for farmlands (Table 5). Furthermore, the producer's and user's accuracies of individual classes of the classified map ranged for the recent year of 2017 were from 60% for settlement areas to 100% for farmlands, and 66.2% for grazing lands to 100% for settlement areas, respectively (Table 6).

Table 4. Error matrix of classification accuracies for 1986

					Real data					
	Land use category	WB	PJ	BL	WL	GL	ST	FL	Total	PA (%)
Predicted data	WB	**42**	2	0	1	2	0	3	50	84.00
	PJ	2	**45**	0	1	2	0	0	50	90.00
	BL	0	2	**35**	3	10	0	0	50	70.00
	WL	0	6	1	**40**	1	2	0	50	80.00
	GL	1	2	1	3	**43**	0	0	50	86.00
	ST	2	2	3	2	9	**32**	0	50	64.00
	FL	1	1	0	0	0	0	**48**	50	96.00
	Total	48	60	40	49	67	34	51		
	UA (%)	87.5	75.0	87.5	81.6	64.2	94.1	94.1		

Overall accuracy = 81.43%; Kappa statistic = 0.81, UA is Users Accuracy, PA is Producers Accuracy, WB is water body, PJ is *P. juliflora* invaded land, BL is bare land, WL is woodland, GL is grass land, ST is settlement, FL is farmland

Table 5. Error matrix of classification accuracies for 2000

					Real data					
	Land use category	WB	PJ	BL	WL	GL	ST	FL	Total	PA (%)
cted	WB	**43**	2	0	1	2	0	2	50	86.0
	PJ	1	**47**	0	1	1	0	0	50	94.0

BL	0	1	**36**	1	12	0	0	50	72.0
WL	0	5	1	**41**	1	2	0	50	82.0
GL	0	1	1	3	**45**	0	0	50	90.0
ST	1	2	2	2	7	**35**	0	50	70.0
FL	0	1	1	0	0	0	**49**	50	98.0
Total	45	59	41	49	68	37	51		
UA (%)	95.6	79.7	87.8	83.7	66.2	94.6	96.1		

Overall accuracy = 84.57%; Kappa statistic = 0.82, UA is Users Accuracy, PA is Producers Accuracy, WB is water body, PJ is *P. juliflora* cover, BL is bare land, WL is woodland, GL is grass land, ST is settlement, FL is farm land

Table 6. Error matrix of classification accuracies for 2017

		Real data								
	Land use category	WB	PJ	BL	WL	GL	ST	FL	Total	PA (%)
Predicted data	WB	**49**	0	0	1	0	0	0	50	98
	PJ	1	**47**	0	2	0	0	0	50	94
	BL	0	0	**35**	4	11	0	0	50	70
	WL	1	5	1	**41**	1	0	1	50	82
	GL	0	0	1	4	**45**	0	0	50	90
	ST	4	0	2	3	11	**30**	0	50	60
	FL	0	0	0	0	0	0	**50**	50	100
	Total	55	52	39	55	68	30	51		
	UA (%)	89.1	90.4	89.7	74.6	66.2	100	98		

Overall accuracy = 84.86%; Kappa statistic = 0.82, UA is Users Accuracy, PA is Producers Accuracy, WB is water body, PJ is *P. juliflora* invaded land, BL is bare land, WL is woodland, GL is grass land, ST is settlement, FL is farmland

4.1. 2. The spatial extent of land use and land cover types in Amibara and Awash Fentale districts

In Amibara, a total of seven LULC types were extracted in the study landscapes in the different reference years of 1986, 2000 and 2017 (Figure 5). In 1986, out of 201,047 ha of LULC, grasslands were the dominant making up 54.8% followed by woodlands (36%), farmlands (7.7%) and bare lands (1.09%). However, water bodies and *P. juliflora* invaded lands shared a small proportion of 0.48% and 0.02%, respectively of the entire area (Table 7).

In 2000, LULC of the district was also dominated by grasslands (62.5%) followed by woodlands (27%), farmlands (7.6%), and *P. juliflora* (1.3%). Water bodies, bare lands, and settlement areas accounted for 0.53%, 0.68%, and 0.007% of the total area. Grasslands continued to dominate the LULC (70.2%) in 2017. Woodlands and farmlands were the second and the third dominant

LULC types covering 18% and 8.6%, respectively. Other small proportion of the landscape was shared by *P. juliflora* (1.57%), water bodies (1.07%), bare lands (0.47%), and settlement areas (0.03%) in 2017 (Table 7).

In Awash Fentale district, the same reference years 1986, 2000 and 2017 were also used to classify the district into existed LULC types. Accordingly, seven LULC types making up a total area of 104,596 ha were classified in the district (Figure 7). In 1986, grazing lands and woodlands were dominated in the district making up 50% and 48.8%, respectively. Meanwhile, farmlands, bare lands, *P. juliflora*, and water bodies were shared the remaining 1.1% in the district (Table 8).

The spatial extent showed that the same trend for grazing lands (65.5%) and woodlands (31.9%) in 2000. But, the increasing trend for the grazing lands and decreasing for woodlands LULC type in the same period. In 2000, *P. juliflora* cover increased by 1.4% of the entire area of the land. The remaining small land areas, about 1% were shared by farmlands, water bodies, bare lands and settlement areas. During this, the result showed that the same size of farmland areas was noticed for cultivation in the study area. In 2017, the same trends of change for grazing and woodlands were observed. In this period, 67% and 24% for grazing land and woodland areas respectively were detected. Moreover, grazing lands were insisted to rise but woodlands declined in the study area during the same period (Table 8 and Figure 7).

Table 7. Spatial extent and change of land use types at Amibara district in 1986, 2000 and 2017

Land use category	Land use in 1986		Land use in 2000		Land use in 2017	
	Area (ha)	% of total	Area (ha)	% of total	Area (ha)	% of total
Farmland	15487	7.7	15355	7.64	17366	8.64
Water bodies	954	0.48	1055	0.53	2151	1.07
P. juliflora invaded land	32	0.02	2668	1.33	3164	1.57
Bare land	2186	1.09	1364	0.68	947	0.47

Woodland	72312	35.97	54980	27.35	36247	18.03
Grazing land	110076	54.75	125610	62.48	141115	70.19
Settlement	0	0	15	0.01	57	0.03
Total	201047	100	201047	100	201047	100

Table 8. Spatial extent and change of land use types in Awash Fentale district in 1986, 2000 and 2017

Land use category	Land use in 1986		Land use in 2000		Land use in 2017	
	Area (ha)	% of total	Area (ha)	% of total	Area (ha)	% of total
Farmland	976	0.93	976	0.933	5234	5.0
Water bodies	28	0.03	9	0.01	1063	1.02
P. juliflora invaded land	79	0.08	1479	1.41	2614	2.5
Bare land	92	0.09	277	0.27	37	0.04
Woodland	51070	48.83	33337	31.87	25050	23.95
Grazing land	52351	50.05	68515	65.5	70538	67.44
Settlement	0	0	3	0.003	60	0.06
Total	104596	100	104596	100	104596	100

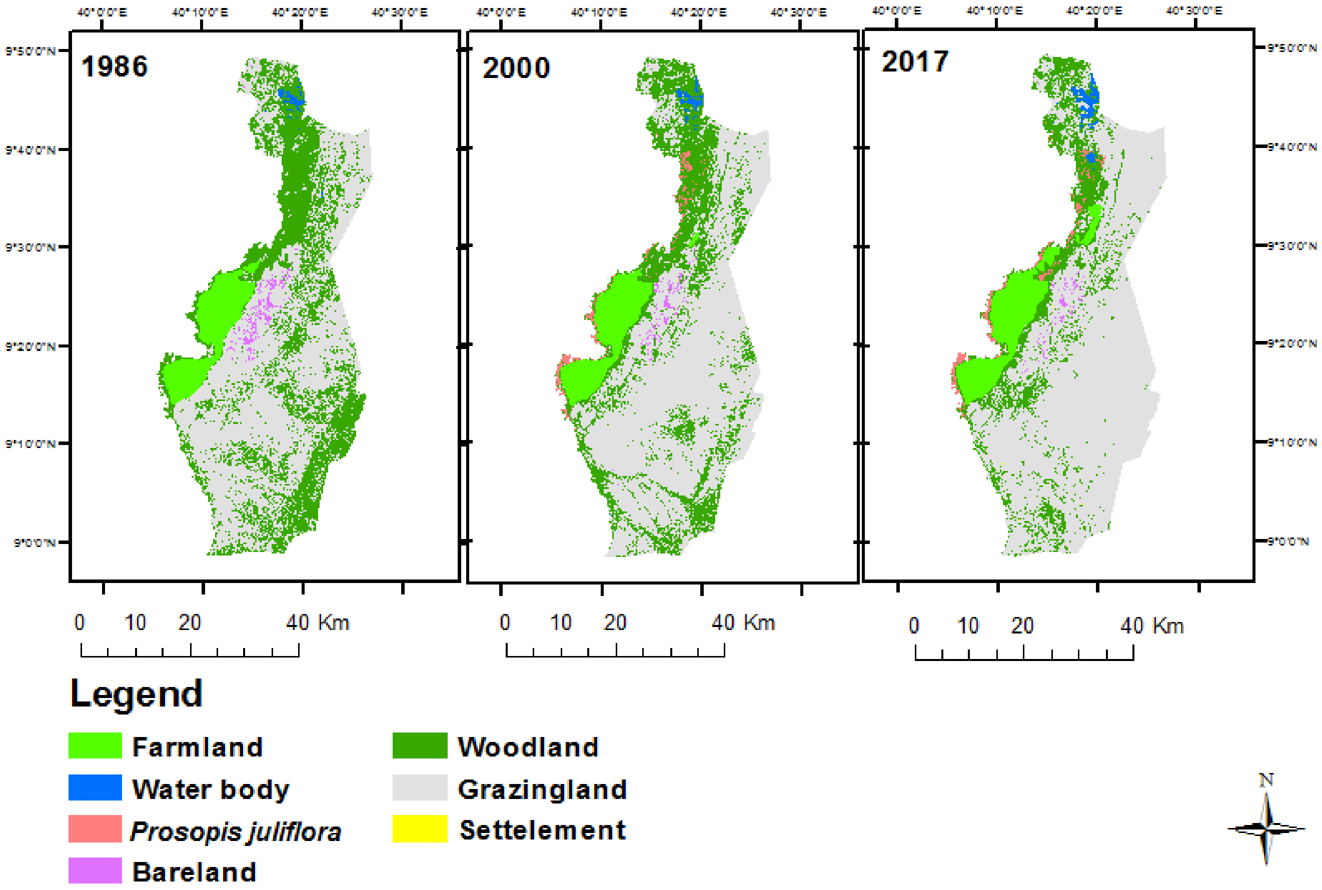


Figure 5. Land use and land cover classification of Amibara district in 1986, 2000 and 2017

4.1.3. Magnitude of land use and land cover changes in Amibara district

In the first period from 1986 to 2000, water bodies, cover of *P. juliflora*, and grasslands increased by 10.6%, 8237.5%, and 54.7% in order. Meanwhile, farmlands, bare lands and woodlands decreased by -0.85%, -37.6% and -24% (Table 9 and Figure 6). In the second period from 2000 to 2017, farmlands, water bodies, *P. juliflora* cover, grasslands, and settlement areas were showed positive changes by 13%, 104%, 18.6%, and 280%. However, bare lands and woodlands continued to show negative trends by -30.6% and -34.1 %. The overall magnitude of change of LULC types in 31 years (1986-2017) showed positive trends for farmlands, water bodies, *P. juliflora* cover, and grassland areas by 12%, 125.5%, 9787.5%, and 28% at Amibara district. However, the trends of bare lands and woodlands were also showed negative by -56.7% and -50%, respectvely (Table 9).

Table 9. Land use change relative to the reference year in Amibara district based on time frame data (1986–2017).

Land use category	Between: 1986 and2000			Between 2000 and2017			Between 1986 and2017		
	MA (ha)	% change	ARC (ha/year)	MA (ha)	% change	ARC (ha/year)	MA (ha)	% change	ARC (ha/year)
Farmland	-132	-0.85	-9.43	2011	13.1	118.3	1879	12.13	60.6
Water bodies	101	10.6	7.2	1096	103.9	64.5	1197	125.5	38.6
P. juliflora invaded land	2636	8237.5	188.3	496	18.6	29.2	3132	9787.5	101.03
Bare land	-822	-37.6	-58.7	-417	-30.6	-24.5	-1239	-56.7	-40
Woodland	-17332	-24	-1238	-18733	-34.1	-1101.9	-36065	-49.9	-1163.4
Grazing land	15534	54.8	1109.6	15505	12.3	912.1	31039	28.2	1001.3
Settlement	15	NA	1.1	42	280	2.5	57	NA	1.8
Total	201047	100		201047	100			100	

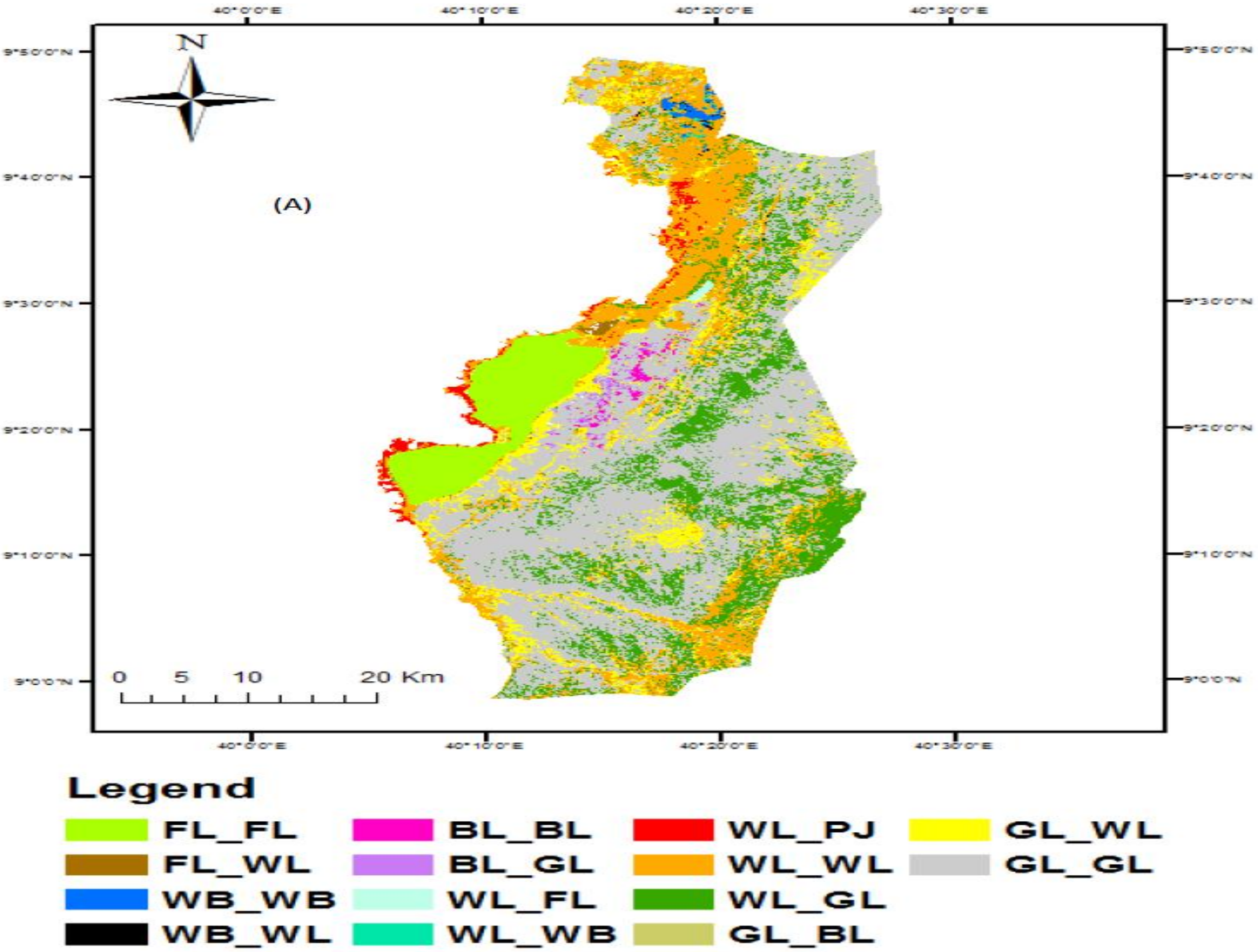
4.1.4. Change matrix of land use and land cover types in Amibara district

The change matrix analysis shows that from 1986 to 2000, about 57,953 ha (52.7%) of the land within the study landscape experienced LULC changes in one or another way in 14 years period. During this period, the level of changes differed among LULC types. For instance, out of 72,312 ha woodlands in 1986, only 35,547 ha (49%) remained unchanged during this period and 36,765 ha (50.8%) of the woodlands were converted to other LULC types. Of the 50.8% converted woodland areas, 91.5%, and 7% were converted to grazing lands and *P. juliflora*, respectively. The remaining < 1% area of woodland conversion was shared by farmlands, water bodies, and bare lands in the district (Table 10 and Figure 6A).

During the same period in 1986, out of 110,076 ha (54.8%) grazing lands, 90,739 ha (82%) remained unchanged areas. The remaining 17.6 % of grazing land areas were converted to other LULC types. Of these converted grazing land areas, 97% were encroached by woodlands; 2% and 0.2% were converted to barelands and *P. juliflora* cover, respectively. The rest small proportion about 0.2% of grazing land area conversion was shared by farmlands, settlement areas and water bodies in the study area (Table 10 and Figure 6A).

Table 10. Change matrix of LULC from 1986 to 2000 of Amibara district

		1986							
	Land use category	Farmland	Water bodies	*P. juliflora* invaded land	Bare land	Woodland	Grazing land	Settlement	Total
2000	Farmland	**15066**	0	0	0	268	21	0	15355
	Water bodies	0	**789**	0	0	264	2	0	1055
	P. juliflora invaded land	2	0	**23**	0	2601	42	0	2668
	Bare land	0	0	0	**930**	3	431	0	1364
	Woodland	377	162	9	58	**35547**	18827	0	54980
	Grazing land	42	3	0	1198	33628	**90739**	0	125610
	Settlement	0	0	0	0	1	14	**0**	15
	Total	15487	954	32	2186	72312	110076	0	201047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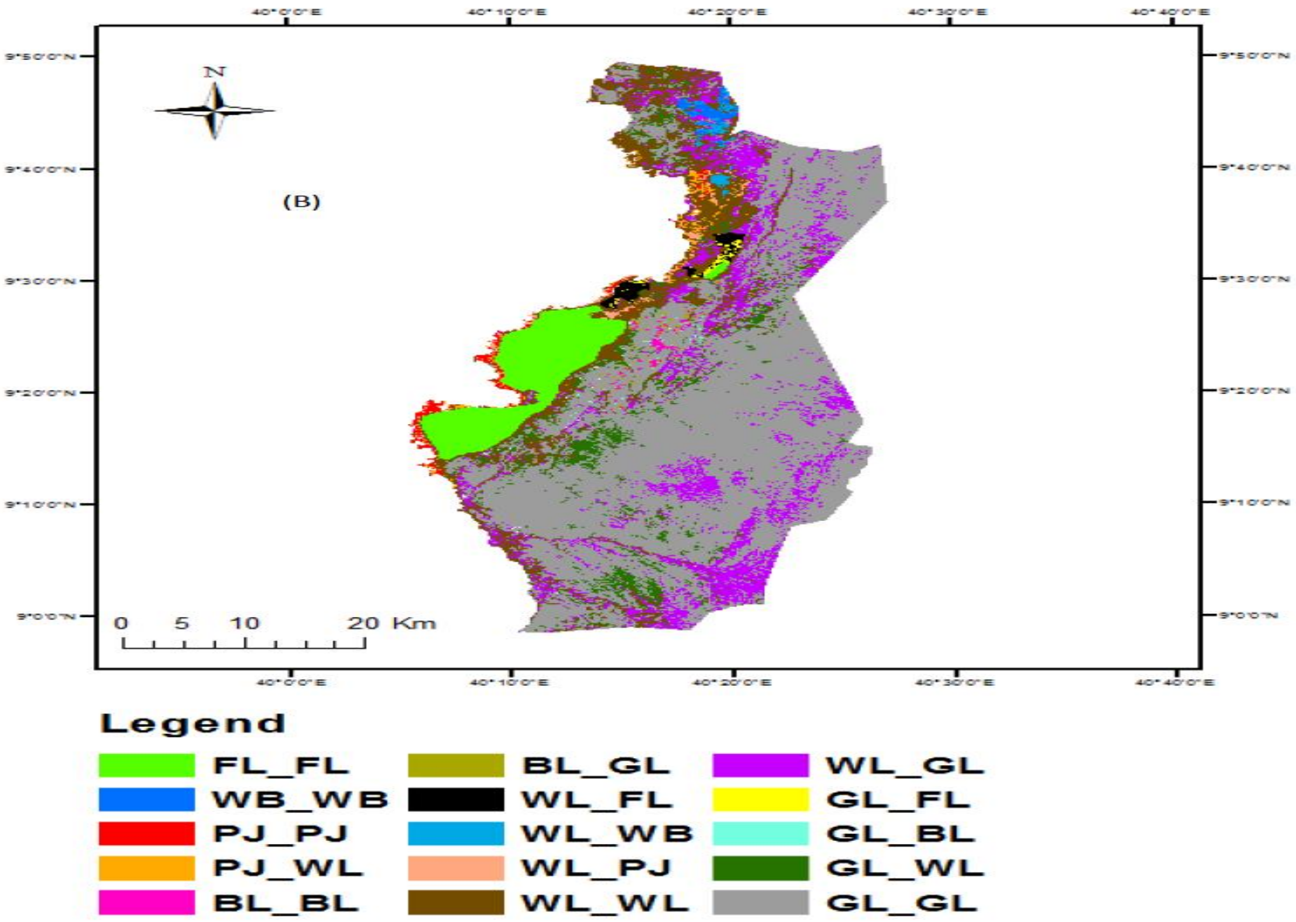

Figure 6A and B. Change map of Amibara district in A=1986-2000, B=2000-2017 (Similar letters indicate unchanged but different letters indicate changes of land uses into other).

During the second 2000 to 2017 period, change matrix analysis showed that about 43,352 ha (21.6%) of the land were converted to other LULC types in 17 years' time. For instance, out of 125,610 ha grazing lands in 2000, about 91% remained unchanged. Of the 8.9% converted grazing land areas, 24% and 1% of land areas were converted to woodlands and farmlands respectively (Table 11 and Figure 6B).

The small proportion (0.6%) of the grazing land areas were converted to *Prosopis juliflora* invaded lands. Out of 54,980 ha woodlands in the same period, only 19.6% of the land areas remained unchanged. The remaining woodland areas were converted to other LULC types. Out of the total converted woodland areas, 85.6%, 5.4%, 5.3%, and 3.6% were converted to grazing lands, *P. juliflora*, farmlands, and water bodies respectively in the district. Meanwhile, the smallest proportion of woodlands was converted to settlements and bare lands (Table 11 and Figure 6B).

Table 11. Change matrix of LULC from 2000 to 2017 of Amibara of district

		2000							
	Land use category	Farmland	Water bodies	*P. juliflora* invaded land	Bare land	Woodland	Grazing land	Settlement	Total
2017	Farmland	**15329**	0	1	0	1600	436	0	17366
	Water bodies	0	**1046**	0	0	1105	0	0	2151
	P. juliflora invaded land	0	0	**1512**	0	1638	14	0	3164
	Bare land	0	0	0	**698**	5	244	0	947
	Woodland	26	9	1102	26	**24657**	10422	5	36247
	Grazing land	0	0	53	640	25961	**114452**	9	141115
	Settlement	0	0	0	0	14	42	**1**	57
	Total	15355	1055	2668	1364	54980	125610	15	201047

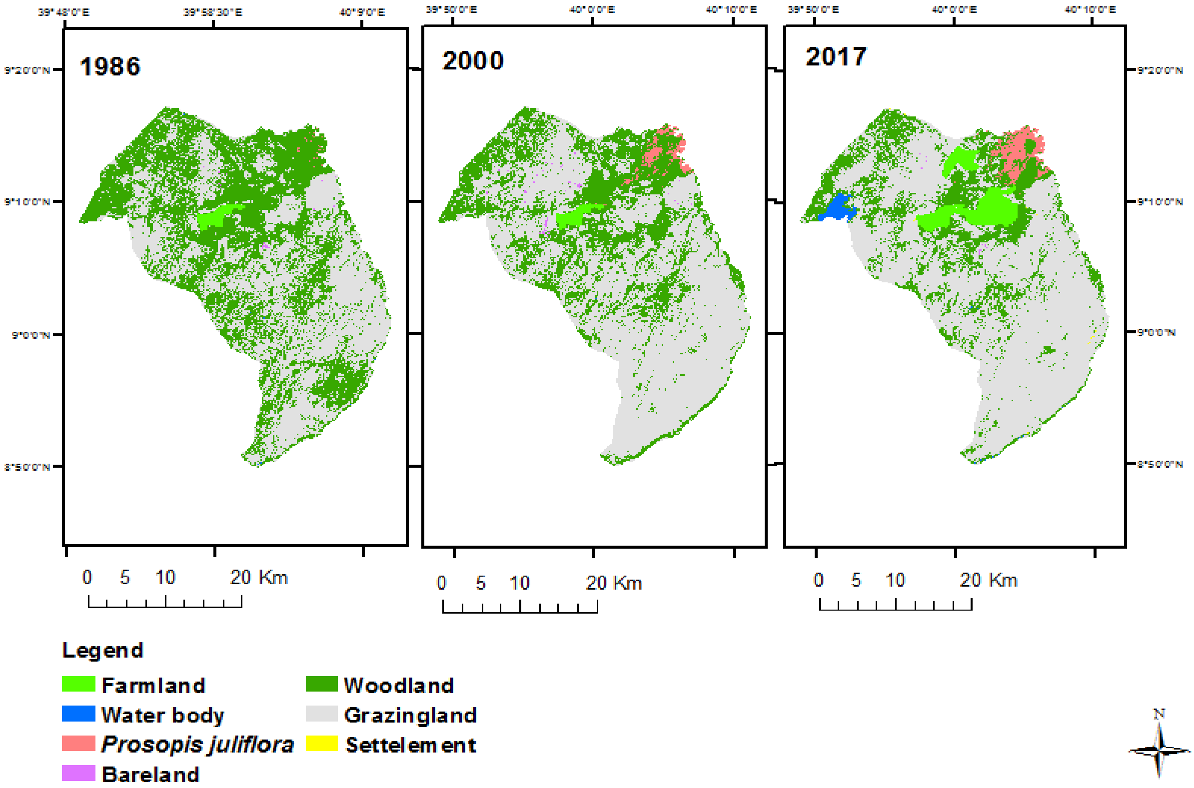

Figure 7. LULCC classification of Awash Fentale district in 1986, 2000 and 2017

4.1.6. Magnitude of land use and land cover in Awash Fentale district

Relative change in LULC of the district was assessed based on data presented in Table (12) and Figure (7). LULC from 1986-2000 showed that positive magnitude of changes for *P. juliflora*, barelands, and grazing lands by 1,772%, 201%, and 30.9%. On contrary, water bodies and woodlands showed negative trends by -67.9% and -34.7%. In the second period from 2000-2017, farmlands, water bodies, grazing land, and settlement areas showed positive increment by 436%, 11,711%, 3%, and 1,900% in that order.

Although, land covered by *P. juliflora* showed a positive trend (76.7%) but declined by 39% relative to 1986-2000. In this period, bare lands radically declined than previous and showed negative trend by -86.6%. But, an increasing trend of woodland areas was noticed than earlier period though negative change by -24.9%. In general, the overall LULCC for 31 years (1986-2017) showed positive trends for farmlands, water bodies, *P. juliflora*, and grazing lands by 436%, 3696%, 3208.9%, and 34.7%. However, bare lands and woodlands showed negative trends by -59.8 % and -51.0 % in that order (Table 12 and Figure 7).

Table 12. Land use change assessment of Awash Fentale district based on time frame data (1986–2017)

Land use category	Between: 1986 and 2000			Between 2000 and 2017			Between 1986 and 2017		
	MA (ha)	% change	ARC (ha/year)	MA (ha)	% change	ARC (ha/year)	MA (ha)	% change	ARC (ha/year)
Farmland	0	0	0	4258	436.3	25.7	4258	436.3	137.4
Water bodies	-19	-67.9	-4.9	1054	11711	688.9	1035	3696	33.4
P. juliflora invaded land	1400	1772.2	126.6	1135	76.7	4.5	2535	3208.9	81.8
Bare land	185	201.1	14.4	-240	-86.6	-5.1	-55	-59.9	-1.8
Woodlan**d**	-17733	-34.7	-2.5	-8287	-24.9	-1.5	-26020	-51	-839.4
Grazing land	16164	30.9	2.2	2023	3	0.2	18187	34.7	586.7
Settlement	3	NA	0	57	1900	111.8	60	NA	1.9
Total	104596	100		104596	100		104596	100	

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4.1.7. Change detection matrix of LULC types in Awash Fentale district

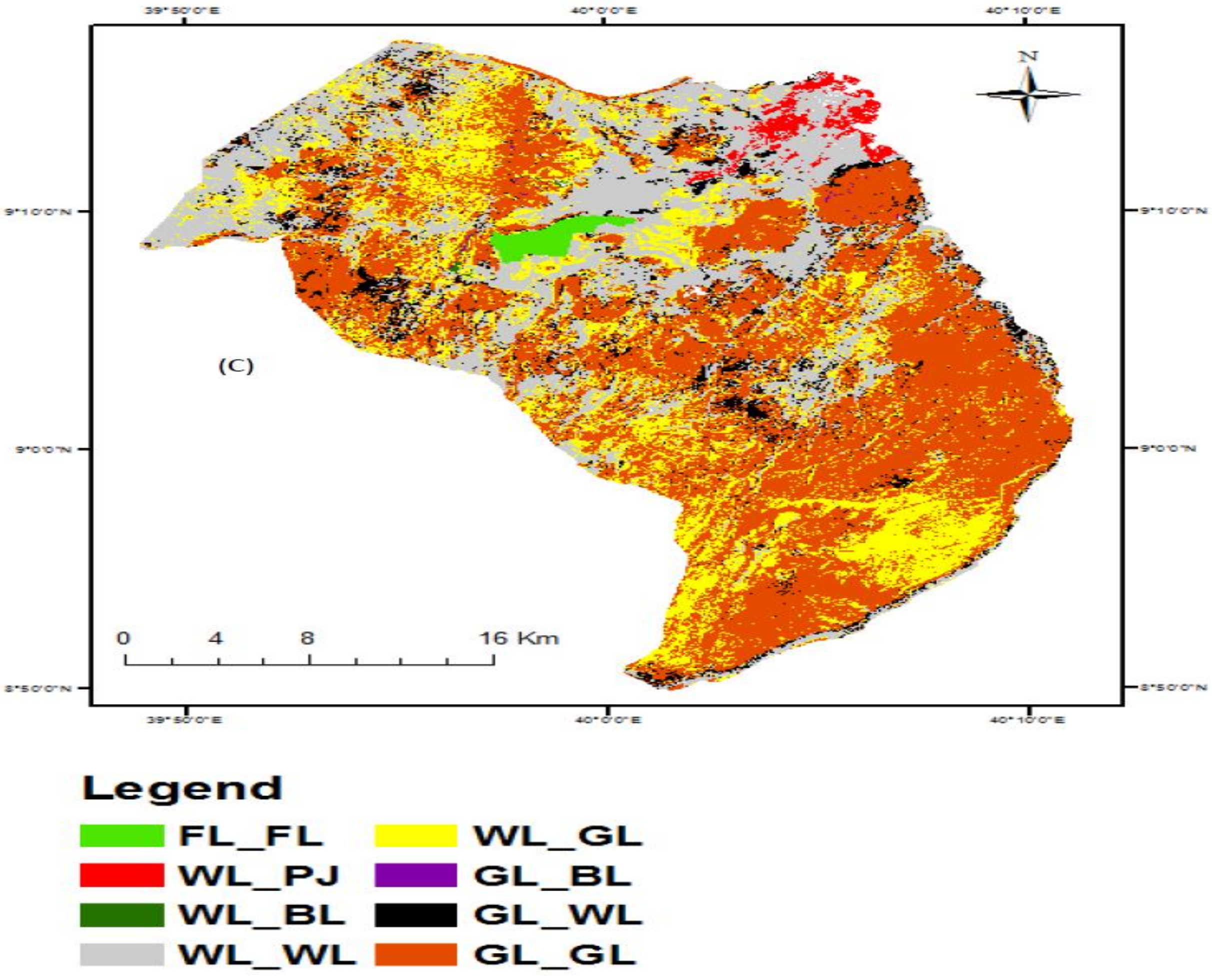
In the first 14 years from 1986-2000, the change matrix shows that 31, 858 ha (30%) areas of land were converted to other LULC types. The level of changes varied among the LULC types. For instance, results showed that 72.6%, 4.4%, and 0.4% of woodlands were converted to grazing lands, *P. juliflora*, and bare lands in order. Furthermore, in the same period, 21.6% and 0.4% of grazing lands were converted to woodlands and barelands, respectively. During this period, only 16 ha (17%) of bare lands remained unchanged. But, 0.2% and 0.1% bare lands were converted to grazing land and woodland areas. Moreover, about 0.1% for *P. juliflora* and water bodies each was converted to woodlands in the district (Table 13 and Figure 8C).

During the 2000 to 2017 the change matrix indicated that the overall area of land conversion was declined by 7,562 ha (23.7%) than the first period (1986-2000). In the later period, 24, 296 ha (23.2%) areas of land were converted to other LULC types. During the second reference period, only 8,975 ha (13%) of grazing lands were converted to other LULC types. In the same time 23.7%, 10.7%, 1.7%, and 0.3% grazing land areas were converted to woodlands, farmlands, water bodies, and *P. juliflora* in the district (Table 13 and Figure 8D).

The remaining small proportion (0.3%) of grazing lands conversion was shared by bare lands and settlement areas. Whereas, out of 14,503 ha (59.7%) converted woodland areas most the areas about 73% was converted to grazing LULC type in the district. Furthermore, 11.6%, 10.5%, and 4.4% of woodland areas were also converted to farmlands, *P. juliflora*, and water bodies in 2000 (Table 13 and Figure 8D).

Table 13. Change matrix of LULC from 1986 to 2000 of Awash Fentale **district**

		1986							
	Land use category	Farmland	Water bodies	*P. juliflora* invaded land	Bare land	Woodlan**d**	Grazing land	Settlement	Total
2000	Farmland	**969**	0	0	0	6	1	0	976
	Water bodies	0	**2**	0	0	7	0	0	9
	P. juliflora invaded land	0	0	**48**	0	1395	36	0	1479
	Bare land	0	0	0	**16**	134	127	0	277
	Woodlan**d**	6	24	31	9	**26392**	6875	0	33337
	Grazing land	1	2	0	67	23134	**45311**	0	68515
	Settlement	0	0	0	0	2	1	**0**	3
	Total	976	28	79	92	51070	52351	0	104596



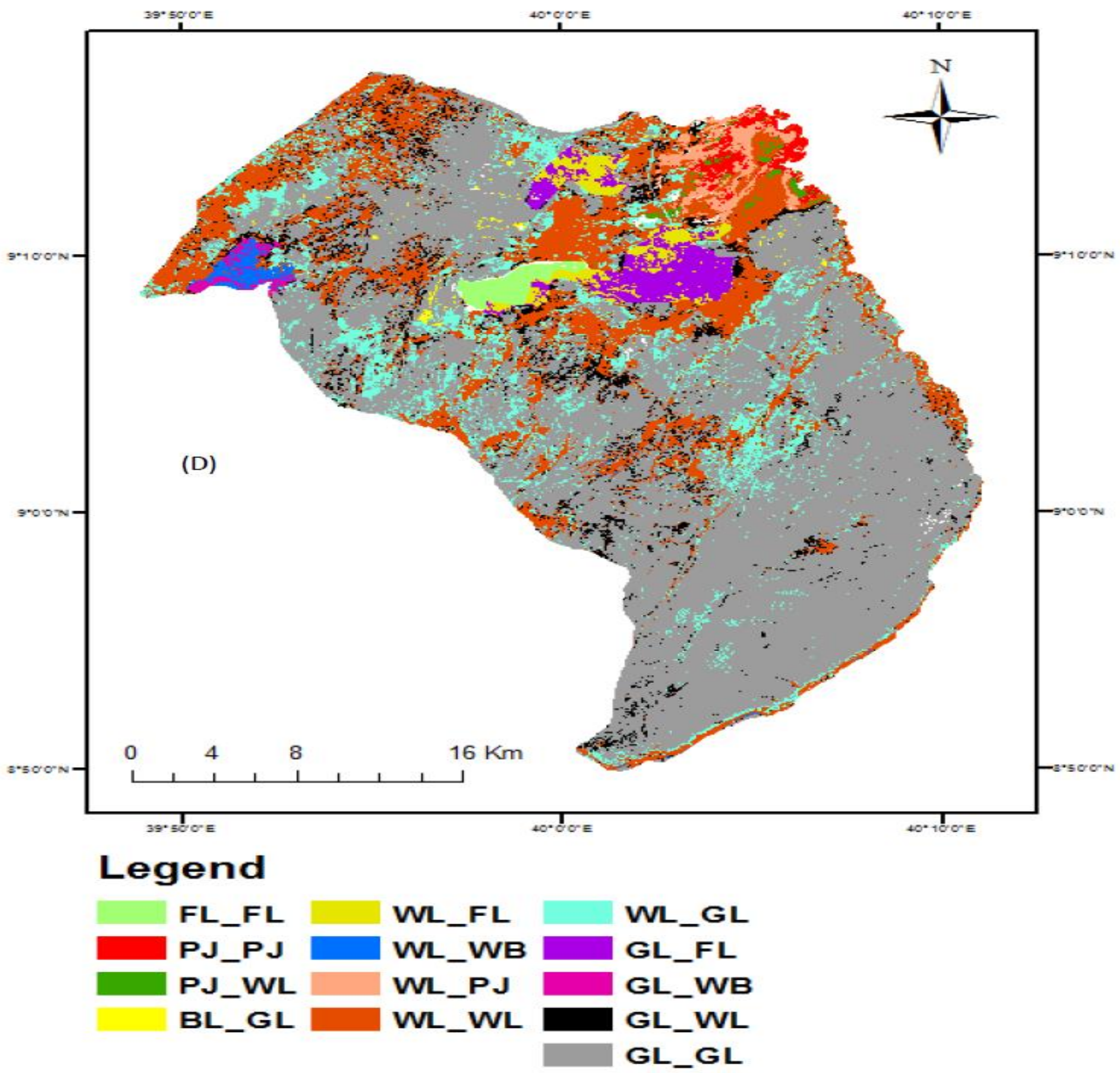


Figure 8C and D. Change map of Awash Fentale district in C=1986-2000, D=2000-2017 (Source: https://earthexplorer.usgs.gov/) (Similar letters indicate unchanged but different letters indicate changes of land uses into other).

Furthermore, in the second period (2000-2017), out of 463 ha (1.9%) converted *P. juliflora* 85% and 14.5% areas of land were converted to woodlands and grazing lands, respectively. In the same period, out of 75 ha (0.3%) converted farmlands the major areas were replaced by woodlands (68%), whereas 29% and 2.7% of farmland areas were replaced by grazing land and *P. juliflora* areas, respectively in the study area (Table 14 and Figure 8D).

Change matrix also showd that major areas of bare lands (98%) converted to other LULC types. For instance, in the same period, out of 272 ha (1%), 94%, 2.9%, 2.6%, and 0.4% barelands were converted to grazing lands, woodlands, farmlands, and water bodies in the order. As the result, quantitative change of analyses for 31 years (1986-2017) revealed that areas of farmlands, water bodies, cover of *P. juliflora*, bare lands, woodlands, grazing lands, and settlement areas were changed in magnitude by 6 ha, 137 ha, 2,232 ha, 5,667 ha, -1,294 ha, -62,085 ha, 49, 226 ha, and 117 ha (Table 14 and Figure 8D).

Table 14. Change matrix of LULC from 2000 to 2017 of Awash Fentale district

		2000							
	Land use category	Farmland	Water bodies	*P. juliflora* invaded land	Bare land	Woodlan**d**	Grazing land	Settlement	Total
2017	Farmland	**901**	0	2	7	1683	2641	0	5234
	Water bodies	0	**4**	0	1	640	418	0	1063
	P. juliflora invaded land	2	0	**1016**	0	1518	78	0	2614
	Bare land	0	0	0	**5**	0	31	1	37
	Woodlan**d**	51	5	394	8	**18834**	5758	0	25050
	Grazing land	22	0	67	256	10651	**59540**	2	70538
	Settlement	0	0	0	0	11	49	**0**	60
	Total	976	9	1479	277	33337	68515	3	104596

4.2. Patterns in phenology of *Prosopis juliflora*

The results indicated that phenology of *Prosopis juliflora* such as proportion of flowering and green pods per tree significantly differ between the two study sites. On the other hand, it was found that no significant difference in proportion green leaves per tree between the two study areas (Appendix 1).

In Amibara district, proportion of green leaves per tree (91%), flowering (15%), green pods (9%) and mature pods (2%) were higher than that in the Awash Fentale district. The proportion green leaf per tree (84%), flowering proportion (7%), green pods (1%) and mature pods (0.2%) in the Awash Fentale district were less by 8, 53, 91, and 90%, respectively than proportion of Amibara district (Table 15).

4.2.1. Seasonal variations in the phenology of *Prosopis juliflora*

Proportion of flower per tree and mature pods of *Prosopis juliflora* did not significantly vary with seasons. On the other hand, proportion of green pods per tree showed significant season to season variations ($F = 4.07$, $P < 0.008$). Higher proportion of green leaves, flower proportion and mature pods per tree were recorded in *Belg* compared to the other three seasons. The lowest proportions of mature and green pods per tree were recorded in the *Bega* season while the highest was recorded in spring. The highest in the proportion of inflorescence time were recorded in the months of November and December, and the lowest in the months of January and February (Figure 9).

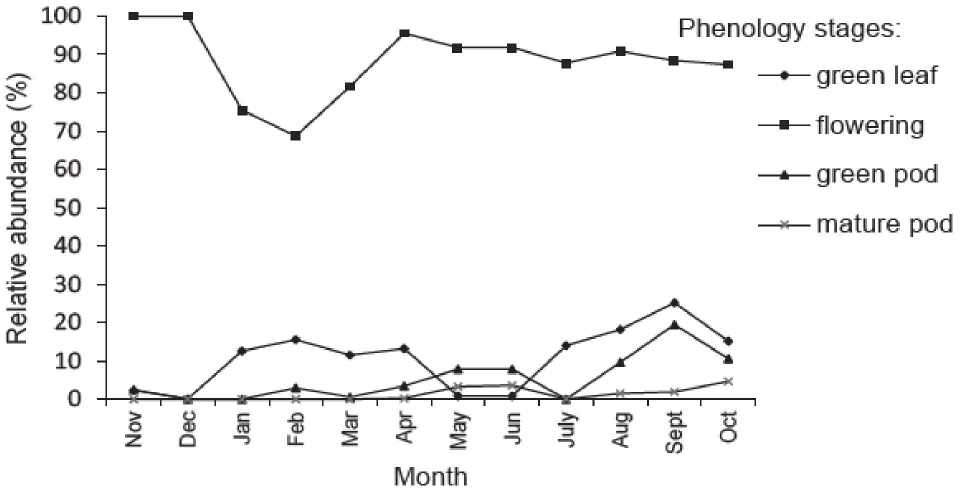


Figure 9. Phenology of *Prosopis juliflora* at Amibra and Awash Fentale districts in months of the years 2016/2017

The lowest proportion of green leaves per tree was record in December, May, and June, but the highest records were in July, August, and September. Meanwhile, the lowest percentage of green pods was recorded in December, January, March and July. But, the highest records in percentages of the green pods were in August and September. The proportion of the mature pods did not show any clear patterns (Table 15).

Table 15. Proportion (%) of phenological stages of *Prosopis juliflora* as influenced by site and season

		Proportion of phenology stages of *P. juliflora* per tree (%)			
Variables	Sites (see Figure 11)	Green leaf	Flowering	Green pod	Mature pod
	1 Awash Fentale (N=56)	84±4a	6.79±2.5a	0.81±0.57a	0.232±0.18a
	2 Amibara (N=83)	90.64±2.04a	14.55±2.58b	8.88±1.82b	1.97±0.72b
Seasons	Summer (N=36)	90.06±3.2a	11.39±3.05a	5.6028±2.5ba	1.486±1.001a
	Spring (N=35)	90.97±3.32a	15.57±4.72a	11.7714±3.06a	2.41±0.97a
	Dry season (N=34)	80.26±5.83a	9.94±3.92a	1.0362±0.75b	0±0a
	Autumn (N=34)	89.82±3.24a	8.68±2.99a	3.9324±1.88b	1.13±1.03a

4.3. Floristic composition, diversity, and structure

4.3.1. Floristic composition

In total 157 plant species belonging to 34 families were recorded (Appendix 2). Growth form distribution among the different families showed high variability; 29 (18.5%) species were belonged to Poaceae, 13 (8.3%) belonged to Fabaceae and 7 (7%) species each belonged to the families Acanthaceae and Malvaceae **(**Appendix 2).

In the study sites, the highest proportion were species in the form of forbs (50%), but the lowest proportion (3.9%) of growth forms were climbers (Figure 10)

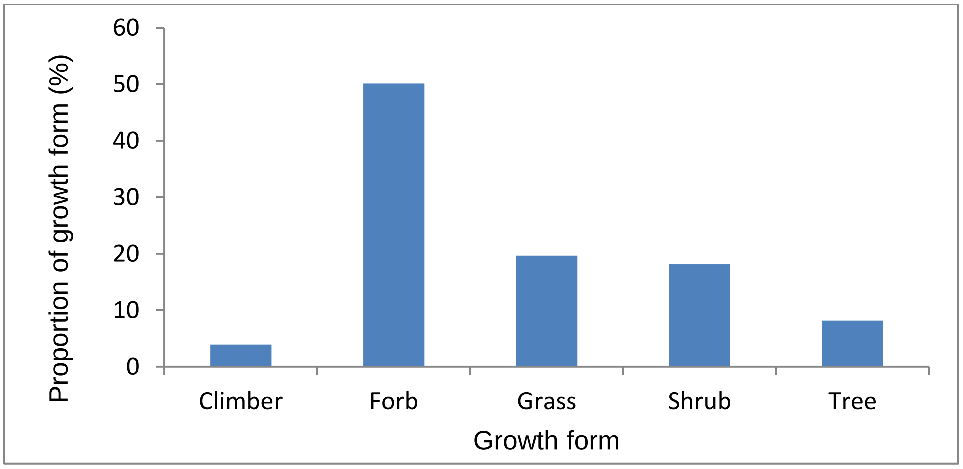


Figure 9. Proportion of growth forms in Amibara and Awash Fentale districts

Among recorded growth forms, 82 species (25.8%) of the growth forms were found under *Prosopis juliflora* thicket, 79 (24.8%) of growth forms were under *Prosopis juliflora* mixed with native species stands, 87 (27.4%) under non-invaded woodlands, and 70 (22%) were in open grazing lands. Under *Prosopis juliflora* thicket and non-invaded woodlands, the dominant growth form was forb species which accounted for 13.8% of all growth forms. The share of growth forms under *Prosopis juliflora* with native species were forbs (13.2%), shrubs (6%), and grasses (5%) (Figure 11).

The highest proportion of climbers species (1.6%) was recorded under *Prosopis juliflora* thickets, on the other hand, the lowest proportion of climbers were recorded under open grazing lands which contained 2 (0.6 %) of the total growth forms. Higher proportion of grass species were recorded under *Prosopis juliflora* with native species stands with 17 (5.3%), 16 (5%) under *Prosopis juliflora* thicket and under non-invaded woodlands each. A relatively lower number of species, 14 (4.4%) were recorded under open grazing lands. In addition, 9 (2.8%) tree species were recorded under *Prosopis juliflora* occurring with native species stands, and 7 (2.2%) tree species under non-invaded woodlands. On the other hand, 5 tree species (1.6%) were recorded under *Prosopis juliflora* thicket and open grazing lands each (Figure 11).

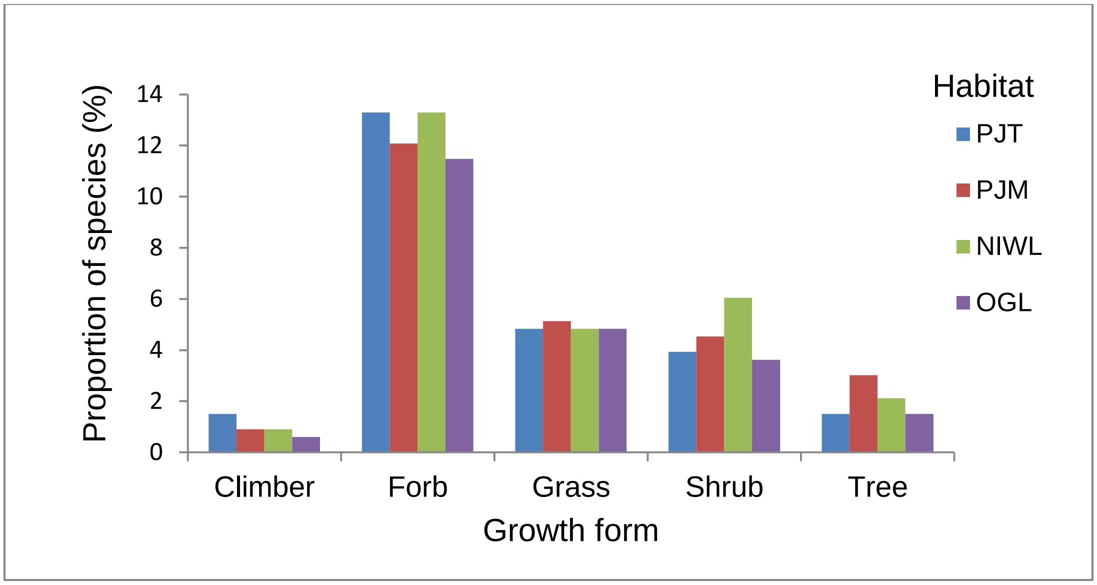


Figure 11. Proportion (%) of plant species in each habitat (PJT is *Prosopis juliflora* thicket, PJM is *Prosopis juliflora* mixed with naïve species, NIWL is non-invaded woodland, OGL is open grazing land)

4.3.2. Similarity among *Prosopis juliflora* invaded and non-invaded habitats

The Jacquard's similarity coefficient between open grazing land and *Prosopis juliflora* thicket; open grazing land and *Prosopis juliflora* mixed with naïve species were 0.21 which were lower than Jacquard's similarity coefficient between *Prosopis juliflora* mixed with naïve species and *Prosopis juliflora* thicket; *Prosopis juliflora* mixed with naïve species and *Prosopis juliflora* thicket; *Prosopis juliflora* mixed with naïve species and *Prosopis juliflora* mixed with naïve species; and open grazing land and non-invaded woodland (Table 16).

Table 16. Jacquard's similarity coefficient ratios among habitats

Habitats	*P. juliflora* thicket	Mixed (*P. juliflora* + native woody species stands	Non-invaded woodland	Open grazing land
Mixed (*P. juliflora* + native woody species stands	0.24			
Non-invaded woodland	0.23	0.23		
Open grazing land	0.21	0.21	0.23	

4.3.3. Classification of plant community types

In this study, three community types were determined by the Elbow method (Figure 14). For this section, 153 species were used for data analysis. Three plant community types, *Prosopis juliflora*

- *Acacia tortilis*, *Cadaba rotundifolia* - *Acacia mellifera,* and *Acacia senegal* - *Aerva javanica (P < 0.05)* which were represented by 24, 16, and 24 quadrats, in that order. Furthermore, the dendrogram also illustrated that communty types were separated at similarity ration (SR) of 1.5 (Figure 12).

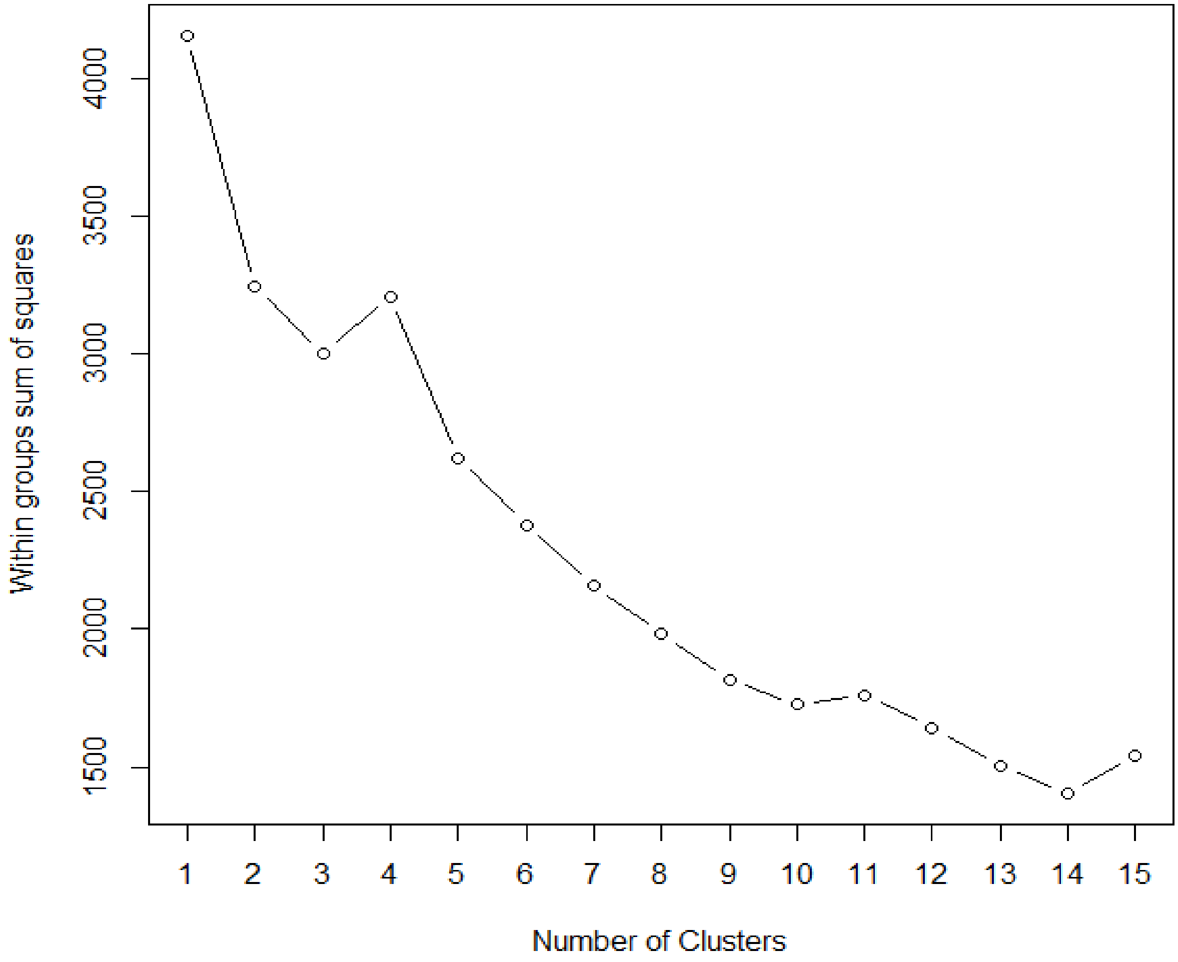


Figure 14. Optimal number (Elbow) of clusters (communities) at Amibara and Awash Fentale distrcits

Results showed that three community types were differed in species diversity (Table 20). The *Prosopis juliflora - Acacia tortilis* community had a higher *H'* (3.92) than *Cadaba rotundifolia - Acacia mellifera* (3.1), and *Acacia senegal - Aerva javanica* (2.4).

The species richness of *Prosopis juliflora - Acacia tortilis* community (114; 49.14%) was higher than *Cadaba rotundifolia - Acacia mellifera* (86; 37.07%), and *Acacia senegal - Aerva javanica* (32; 13.79%) communities (Table 19). The numbers of individuals were largely represented by *Prosopis juliflora* in the community. That means about 60.8% and 33.5% importance value index of the community were constituted by *Prosopis juliflora* and *Acacia tortilis,* respectively (Table 17).

Table 17. Summary for the indicator species of plant communities

	Indicator value			
Species	Community1	Community2	Community3	*P-value*
Prosopi juliflora	**60.8**	25.6	4.75	0.0002
Acacia tortilis	**33.5**	19.9	5.33	0.0248
Salvadora persica	31.1	13.3	5.05	0.0102
Sida rhombifolia	28.9	16.7	5.55	0.0358
Hypoestes forskaolii	27.2	24.9	5.79	0.2865
Cynodon dactylon	23.8	16.1	5.51	0.0916
Commelina benghalensis	19.9	9.1	4.37	0.0254
Cenchrus ciliaris	18.8	10.9	4.59	0.0662
Peristrophe paniculata	14.8	13.5	5.15	0.2919
Solanum incanum	14.4	7.9	3.96	0.1008
Senna obtusifolia	13	6.3	3.39	0.0462
Cryptostegia grandiflora	13	6.3	3.42	0.0564
Acacia nilotica	11.2	7.2	3.88	0.1418
Leptadenia hastata	8.7	5.4	2.89	0.1592
Clematis longicauda	8.7	5.5	2.94	0.164
Digitaria abyssinica	8.7	5.5	3.02	0.1848
Ziziphus spina-christi	4.3	4.7	1.56	0.5605
Eriochloa fatmensis	19.4	84.6	5.23	0.0002
Kosteletzkya adoensis	27.6	61.9	5.25	0.0002
Leucas deflexa	13.1	52.5	4.81	0.0002
Cadaba rotundifolia	24.5	**48.3**	5.1	0.0008
Acacia mellifera	12.1	**23.4**	4.89	0.0304

Erucastrum arabicum	9.5	42.8	4.22	0.0004
Parthenium hysterophorus	20.4	41.1	5.26	0.0044
Jatropha glauca	8	38.5	4.12	0.0004
Sida ovata	22.2	36	5.8	0.0268
Cordia sinensis	16.9	30.3	5.04	0.0208
Barleria homoiotricha	14.1	18	4.79	0.1892
Dactyloctenium scindicum	12.7	14.4	4.88	0.2817
Euphorbia piscidermis	8.8	14.3	4.14	0.1044
Acacia oerfota	7.2	8.6	3.81	0.2987
Cynodon nlemfuensis	4.7	7.7	1.54	0.197
Pavonia schweinfurthii	4.7	7.7	1.54	0.197
Vernonia adoensis	4.7	7.7	1.54	0.197
Dyschoriste radicans	4.7	7.7	1.55	0.2004
Setaria verticillata	4.7	7.7	1.55	0.201
Eragrostis minor	4.7	7.7	1.55	0.201
Achyranthes aspera var argentea	4.7	7.7	1.56	0.2024
Cynodon aethiopicus	4.7	7.7	1.56	0.2024
Hibiscus aethiopicus	4.7	7.7	1.56	0.2024
Jatropha ellenbeckii	4.7	7.7	1.56	0.2024
Aerva javanica	25.1	5.45	**45.5**	0.0036
Acacia senegal	16.4	5.21	**45.2**	0.0002
Chrysopogon plumulosus	10	4.61	25	0.0128
Eragrostis cylindriflora	13.3	4.97	23.5	0.0432
Sida ogadensis	11.5	4.88	18	0.1022
Grewia tenax	16.1	5.36	16.6	0.3585
Setaria verticillata	8.9	4.31	16.4	0.0708
Achyranthes aspera	11.5	4.48	16.4	0.171
Solanum marginatum	11.6	4.54	16.4	0.1724
Dobera glabra	9.3	4.6	15.7	0.1044
Ocimum forskoli	10.6	4.61	12.9	0.2895
Pupalia lappacea	10.7	4.36	12.1	0.2388
Gutenbergia somalensis	5.4	2.88	7.1	0.3481
Cadaba glandulosa	5.4	2.95	7.1	0.3491
Commelina diffusa	5.5	2.98	7.1	0.3551
Tragus racemosus	5.9	2.88	7.1	0.5133
Maerua angolensis	8	4.06	5.9	0.7121
Eragrostis cilianensis	8.1	4.07	5.9	0.7209
Tetrapogon cenchriformis	7.5	3.94	5.7	0.4951

Community 1: *Prosopis juliflora - Acacia tortilis*

This community was found in *Prosopis juliflora* thickets and *P. juliflora* mixed with other native species habitats. The most dominant species in this community were *P. juliflora* (P = 0.0002) and *Acacia tortilis* (P = 0.02). The main associated species were *Salvadora persica, Acacia nilotica, Senna obtusifolia, Grewia villosa,* and a woody climber *Cryptostegia grandiflora* and *Lepidagathis hastata* in the middle story, and herbaceous species *Seddera bongshawei, Hypoestes forskaolii, Cynodon dactylon Commelina diffusa*, and *Cenchrus ciliaris* in the understory (Table 17).

Community 2: *Acacia mellifera-Cadaba rotundifolia*

In order to compare the diversity status of the Southern Afar Region woodland vegetation with the diversity of other wood lands, it is necessary to analyze the overall diversity indices of the vegetation. The results show that the vegetation had an overall species richness of 153, Shannon diversity index of 3.85, and Shannon evenness of 0.78 (Table 17).

Community 3: *Acacia senegal - Aerva javanica*

In this community, proportions of woody species were declining. Results revealed that proportions of the *Acacia senegal* and *Aerva javanica* species in the community were low relative to the first and second communities. As the result, the I_{VI} values were 45.2% and 45.3%, respectively for the *A. senegal* and *A. javanica*. The most dominant tree species were *Acacia senegal (P = 0.0002) - Aerva javanica (P = 0.004)* in the canopy layer. Meanwhile, tree species *Grewia tenax*, *Berchemia discolor, Ziziphus spina-christi* and *Dobera glabra* and climber *Capparis tomentosa* were the characteristic tree species which were associated with this community in middle layer. *Achyranthes aspera, Chrysopogon plumulosus*, *Indigofera coerulea,* *Eragrostis cylindriflora*, *Panicum coloratum* and *Setaria verticillata* were the characteristic understory herbaceous species in this community type (Table 17).

Table 18. Diversity indices of plant communities at Amibara and Awash Fentale districts

Diversity indices	Community 1	Community 2	Community 3	ODI
Richness	114	86	32	153
Shannon-Wiener diversity	3.92	3.07	2.41	3.85
Shannon evenness	0.83	0.69	0.69	0.78

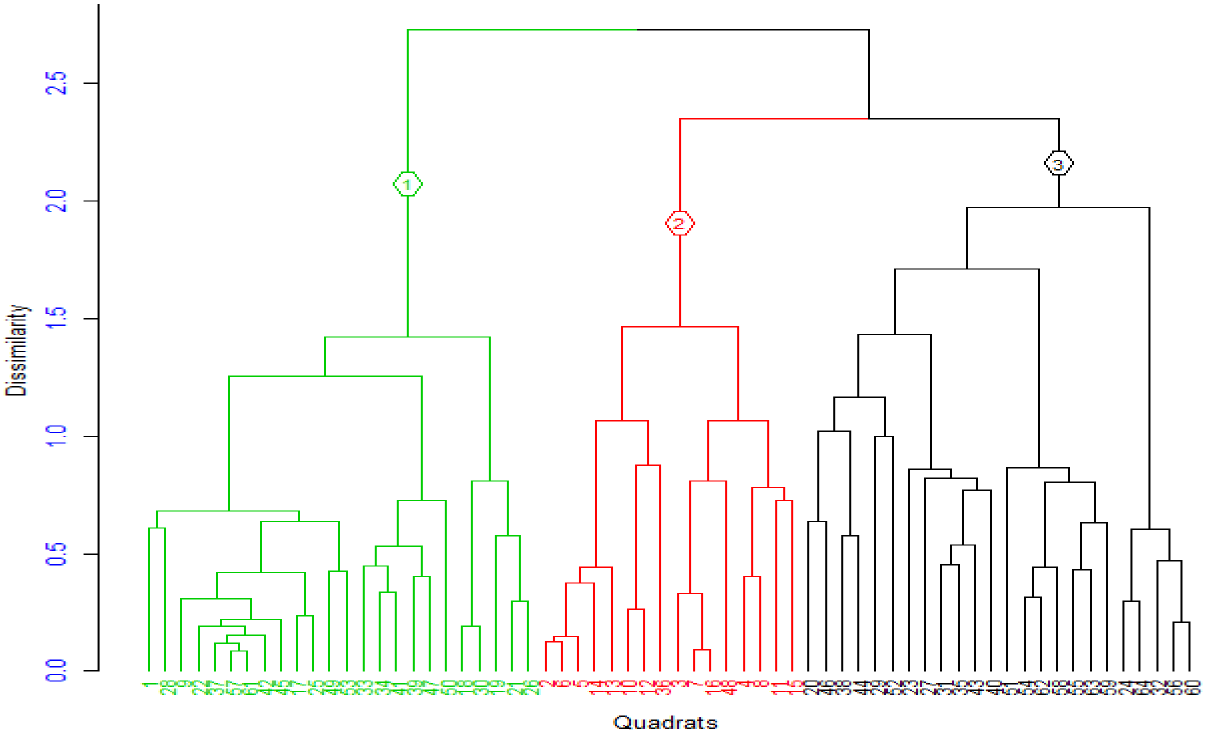


Figure 13. Agglomerative hierarchical cluster analysis using library similarity ratio (SR) with colored leaves and labels

Using ordination method (showing the effects of the environmental factors and invasion levels (habitats) on the overall vegetation patterns) is misleading unless environmental effects are treated separately for each of the vegetation variables (Figure 13). For instance, altitude (*F*=

3.89; *P* = 0.001), *Prosopis juliflora* invasion levels (*F* = 10.90; *P* = 0.001), and slope (*F* = 2.06; *P* = 0.02) had affected the vegetation patterns in the South Afar rangelands (Table 19).

Nevertheless, the length of arrow of other variables such as aspect, grazing intensity and disturbance intensity became short indicating that their effects on vegetation patterns were insignificant (Table 19; Figure 14). These methods of analysis are only useful for showing the effects of the environmental factors on the overall vegetation patterns. Thus, in order to investigate the effects of each environmental variable on each vegetation pattern in detail, it is advisable to investigate the effects of each environmental variable for each vegetation pattern separately; like the effects of the environmental factors on Shannon diversity index, species richness, and Shannon evenness in certain vegetation types and ecosystems.

Table 19. ANOVA showing environmental factors on vegetation patterns in Amibara and Awash Fentale districts

Some environmental factors	DF	Sum of squares	Means of squares	F model	R^2	Pr (>F)
Prosopis julifora invasions	1	1.78	1.78	10.90	0.13	0.001***
Slope	1	0.56	0.56	2.06	0.02	0.02**
Aspect	1	0.29	0.29	1.09	0.01	0.34
Grazing intensity	1	0.19	0.19	0.71	0.001	0.76
Altitude	1	1.05	1.05	3.89	0.05	0.001***
Disturbance intensity	1	0.45	0.45	1.67	0.02	0.06
Residual	56	14.93	0.27		0.71	
Total	63	22.68			1.00	

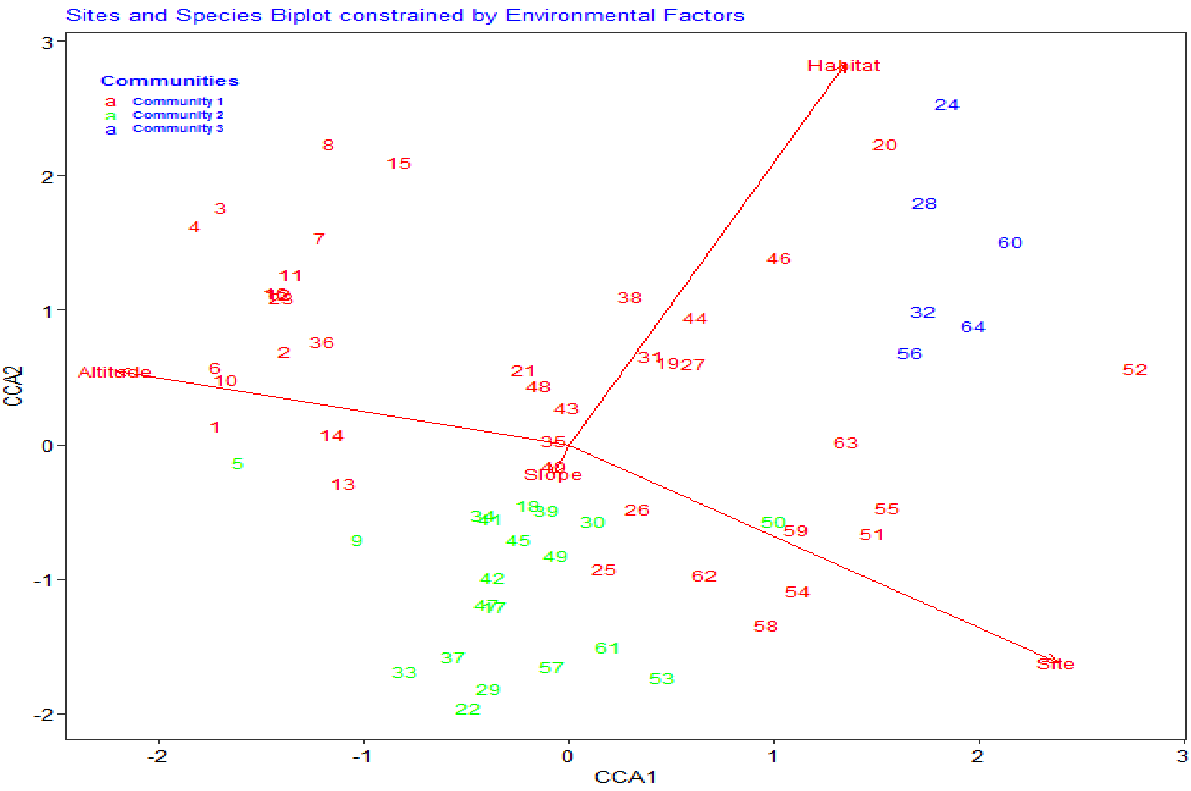


Figure 14. Canonical correspondence analysis CCA of sites constrained by some environmental variables affects patterns of above ground vegetation.

4.3.4. Invasion of *Prosopis juliflora* and species diversity

As depicted in (Table 20), *Prosopis juliflora* invasion levels had significantly affected Shannon diversity index, species richness, and Shannon evenness (P = 0.05). The mean value of Shannon diversity index in Figure (15) under *Prosopis juliflora* mixed with native species (H' =2.22±0.10) and non-invaded wood lands (H' =2.23±0.08) were significantly higher than *P. juliflora* thicket (H'=1.96±0.12) and open grazing lands (H'=1.84±0.09). Moreover, the average values of species richness in Figure (16) under *Prosopis juliflora* mixed with native species (R= 13.94±1.22) showed significantly higher than open grazing lands (R = 9.56±0.83. In addition, the Shannon evenness of non-invaded wood lands (0.87±0.01) was significantly higher than *Prosopis juliflora* thicket (0.83±0.02) and open grazing lands (0.83±0.01) (Figure 17).

Table 20. GLM showing effects of *Prosopis juliflora* invasion levels on vegetation patterns in Amibara and Awash Fentale districts, Ethiopia

Habitat × variable	Source	Df	Sum of squares	Mean square	F-value	Pr > F
Habitat × Shannon diversity index	Model	3	1.86	0.62	3.74	0.02
	Error	60	9.92	0.17	-	-
	Corrected total	63	11.77	-	-	-
Habitat × species richness	Model	3	191.42	63.81	3.52	0.02
	Error	60	1086.81	18.11	-	-
	Corrected total	63	1278.23	-	-	-
Habitat × Shannon diversity eveness	Model	3	0.01997	0.0067	2.41	0.08
	Error	60	0.166	0.0028	-	-
	Corrected total	63	0.186	-	-	-

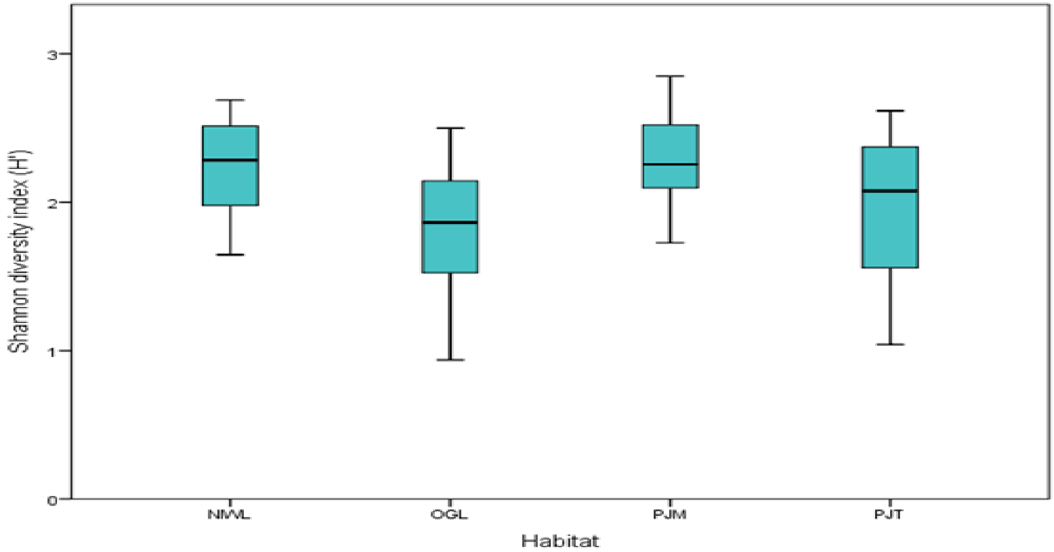


Figure 15. Shannon diversity indices (*H'*) in each *Prosopis juliflora* invaded levels in Amibara and Awash Fentale districts (PJT is *Prosopis juliflora* thicket, PJM is *Prosopis juliflora* mixed with native species, NIWL is non-invaded wood land, OGL is open grazing land)

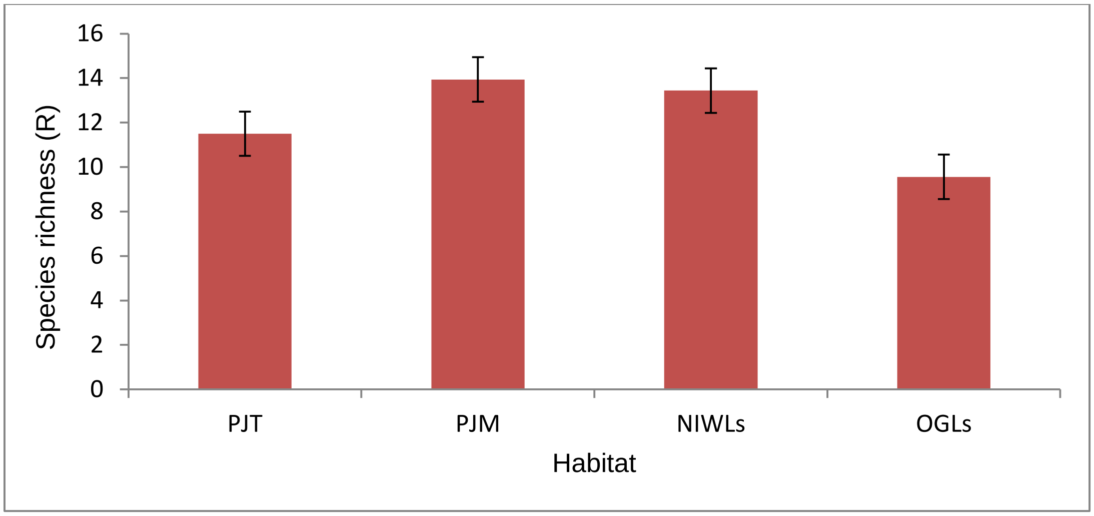


Figure 16. Species richness in each *Prosopis juliflora* invaded habitats in Amibara and Awash Fentale districts

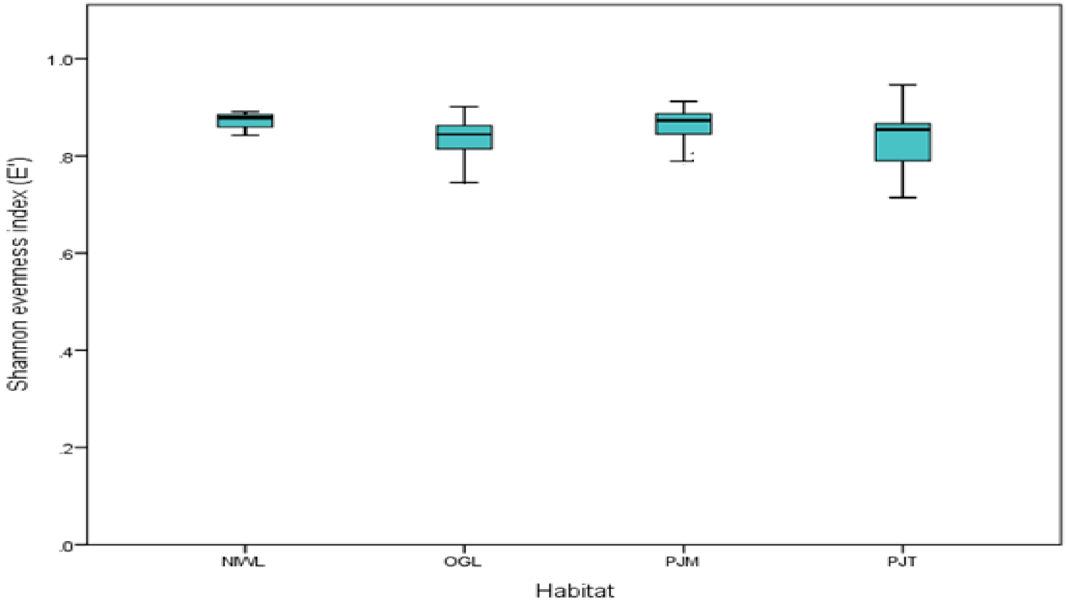


Figure 17. Shannon evenness index in each *Prosopis juliflora* invaded levels in Amibara and Awash Fentale

4.3.5. Regeneration status of woody species

As could be seen from the result in (Table 21) tree and seedlings stages are shown to be statistically affected by the invasion of *Prosopis juliflora* at the different invaded habitats (*P* = 0.05). But, sapling stages were not affected by the invasion of *P. juliflora* in the study sites.

Table 21. General Linear Model showing the effects of *Prosopis juliflora* invasion levels on regeneration status of woody species in Amibara and Awash Fentale districts, Ethiopia

Response variables	Source	Df	Sum of squares	Mean square	F-value	Pr > F
Habitat × Trees	Model	2	36907.7	18454	0.94	0.41
	Error	21	410318.9	19539	-	-
	Corrected total	23	447226.7			
Habitat × Saplings	Model	2	32.66	16.33	0.71	0.49
	Error	1592	36640.01	23.01	-	-
	Corrected total	1594	36672.67	-	-	-
Habitat × Seedlings	Model	2	69.28	34.64	1.06	0.35
	Error	1592	51796.23	32.53	-	-
	Corrected total	1594	51865.51	-	-	-

As could be seen from the result in (Table 21) tree, saplings and seedlings are shown to be statistically affected by the invasion of *Prosopis juliflora* at the different invaded habitats (*P* = 0.05). The lowest total densities of trees were recorded under *Prosopis juliflora* thicket (102 stems/ha).But, the highest total densities of trees were recorded under non-invaded wood lands (1252 stems/ha). Moreover, the highest total density of seedlings were recorded under *Prosopis juliflora* mixed with native species (358 stems/ha). However, the lowest total densities of seedlings were recorded under *Prosopis juliflora* thickets (153 stems/ha) (Table 22).

Table 22. Density of the regeneration of woody species in *Prosopis juliflora* invaded and non-invaded habitats at Amibara and Awash Fentale districts, Ethiopia in stems/ha)

Growth Stages	Habitat		
	PT	PM	NIWL
Trees	102a	585b	1252b
Saplings	151a	334b	324c
Seedlings	153a	358b	242c

4.3.6. Location and regeneration status of woody species

The mean values of density of trees, saplings and seedlings at all sites were significantly different among each other ($P < 0.05$). Thus, the total density of 957 stems ha^{-1} of individual trees at Sedihafeghe was significantly higher than that of the rest of the sites. The density of trees at the other sites were 428 stems ha^{-1} (Dudub), 814 stems ha^{-1} (Kebena) and 456 stems ha^{-1} (Kurkura). In addition, the number of saplings at Dudub (522 stems ha^{-1}) were the highest of sites namely Kebena (487 stems ha^{-1}), Kurkura (137 stems ha^{-1}), and Sedihafeghe (174 stems ha^{-1}). Moreover, the number of seedlings at Kebena (1443 stems ha^{-1}) were the highest of sites namely Dudub (365 stems ha^{-1}), Kurkura (157 stems ha^{-1}), and Sedihafeghe (39 stems ha^{-1}) in the study areas (Figure 18).

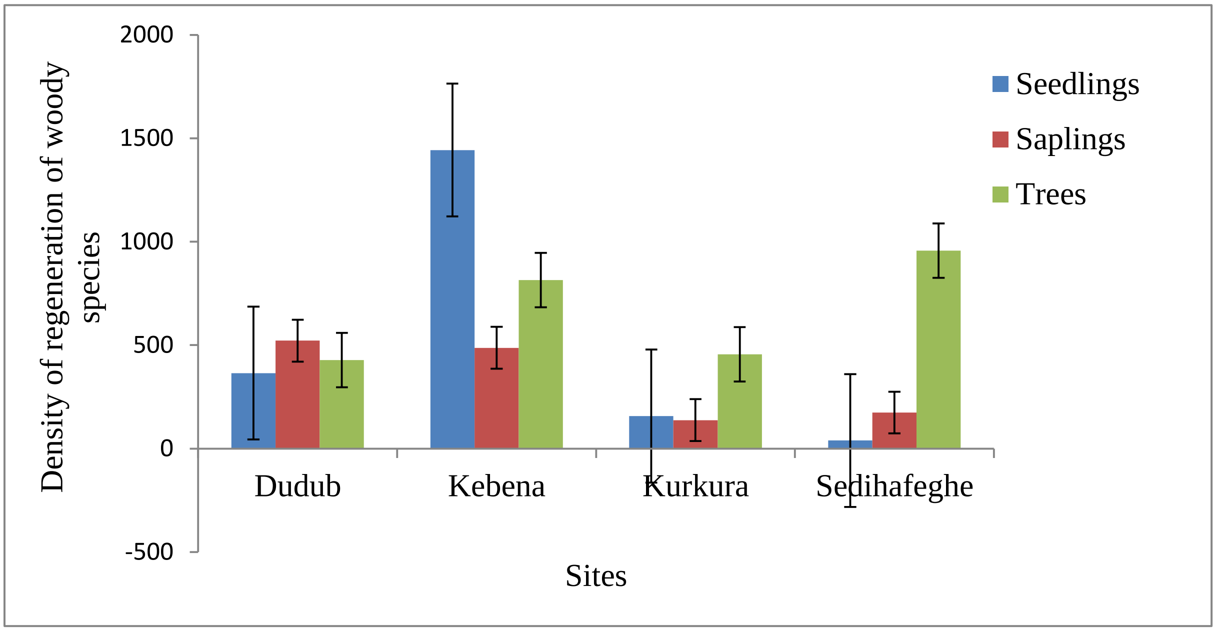


Figure 18. Effects of sites/location on regeneration of woody species in Amibara and Awash Fentale

Results revealed that out of 2608 stems ha^{-1} (49.5%) trees under *Prosopis juliflora* thicket, 2506 individual stems ha^{-1} (96%) were *Prosopis juliflora* whereas 102 stems ha^{-1} (3.9%) were native woody species, including *Acacia nilotica*, *Acacia senegal*, *Acacia tortilis*, and *Cadaba rotundifolia*. Moreover, from 1321 individual stems ha^{-1} (25%) trees under *Prosopis juliflora* mixed with native species, 735 individual stems ha^{-1} (56%) were *Prosopis juliflora* but the rest 585 individual stems ha^{-1} (44.4%) were other native species (Figure 19, Appendix 3).

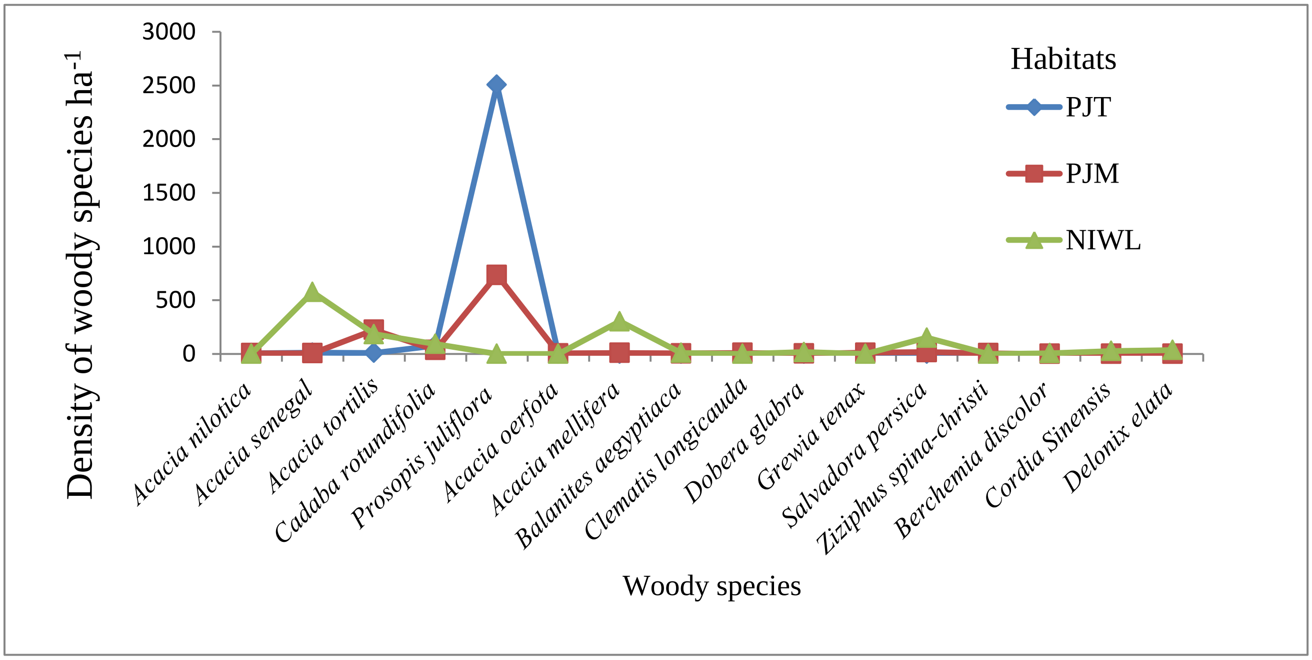


Figure 19. Density of woody species in PJT (*Prosopis juliflora* thicket), PJM (*Prosopis juliflora* mixed with native species stands), and NIWL (non-invaded wood lands) for DBH/DSH > 2 cm

4.3.7. *Prosopis juliflora* invasion and abundances of woody species

The quantitative data for the effects of *Prosopis juliflora* invasion, sites and other environmental effects on abundances of woody species are presented in (Table 23). General Linear Model revealed that *P. juliflora* invasion on abundance, density and importance value index of woody species ($P < 0.05$).

Table 23. General Linear Model showing the effects *Prosopis juliflora* on abundances woody species in Amibara and Awash Fentale districts

Ecological availability	Sum of Squares	Df	Mean Square	F	Pr > F
Abundance	31377.92	2	15688.96	13.91	<0.0001

Basal area	0.0003	2	0.0002	0.01	0.99
Density	19151.56	2	9575.78	13.91	<0.0001
Importance Value Index	197.0	2	98.50	5.07	0.008

As showed in Table (24), the mean values of basal areas of woody species showed significant variations among sites ($P < 0.05$). Among the sites, the value of basal area was the highest at Kebena site (4.62 m^2). But, the lowest mean value of basal area was recorded at Dudub (1.2 m^2). Moreover, abundances of woody species also showed significantly affected by sites ($P < 0.05$). Results depicted that values of abundances of woody species at Sedihafeghe (943 stems ha^{-1}) was the highest of all sites. On the other hand, value of abundance for woody species at Dudub (390.1 stems ha^{-1}) was the lowest values in the study areas (Table 24).

Table 24. General Linear Model showing the effects site on abundances woody species in Amibara and Awash Fentale districts

Ecological availability	Sum of Squares	Df	Mean Square	F	Pr > F
Abundance	11871.14	3	3957.05	2.91	0.04
Basal area	0.33	3	0.11	5.93	0.01
Density	7245.57	3	2415.19	2.91	0.04
Importance Value Index	278.219	3	92.74	4.96	0.003

Results also indicated that values of densities of woody species were significantly varied among sites ($P < 0.05$). Thus, value of density of the woody species at Sedihafeghe (736.7 stems ha^{-1}) was the highest of all sites considered for the study. On the other hands, value of density of woody species at Dudub (304.8 stems ha^{-1}) was the lowest record value in the study landscape. Moreover, the mean of importance value index showed significant variations among sites. Among the sites, the mean of importance value index at Kebena (9.29%) was the highest, but the mean of importance value index at Dudub (4.56%) was the lowest (Table 25).

The mean values of abundances, density and importance value index of woody species had shown significant variations among levels of *Prosopis juliflora* invasions. However, the invasion of *Prosopis juliflora* did not show significant effects on basal areas of woody species ($P < 0.05$).

Results indicated that mean value abundance of woody species under *Prosopis juliflora* thicket (1252 stems ha^{-1}) was the highest of all habitats, but the abundances of the woody species under *Prosopis juliflora* mixed with native species (645stems ha^{-1}) was the lowest in the study areas. Moreover, the mean of importance value index of woody species under *Prosopis juliflora* thicket (9.27%) was the highest relative to other habitats, but the mean of importance value index under *Prosopis juliflora* mixed with native species (5.55% was the lowest (Table 25).

Table 25. The mean density of woody species affected by *Prosopis juliflora* invasion and location in Amibara and Awash Fentale districts

Explanatory variables		Response variables			
		BA	Ab	D	I_{VI}
Sites	Dudub	1.15d	390d	305d	4.56±0.33d
	Kebena	4.62a	805b	629b	9.29±1.49a
	Kurkura	2.50b	429c	335c	5.55±0.68b
	Sedihafeghe	2.07c	943a	736a	7.01±0.86c
Habitat	*P. juliflora* thicket (N = 20)	2.20a	1252a	978a	9.27±1.49a
	Mixed *P. juliflora* + native woody species (N = 41)	4.51a	645c	504c	5.55±0.58c
	Non-invaded woodland (N = 31)	3.41a	670b	524b	6.03±0.60b

4.3.8. Environmental factors and abundances of woody species

Results in Table (26) showed that altitude had shown significant effects on basal area, abundances, and I_{VI} of woody species ($P < 0.05$). Thus, the mean value of basal area of woody species at lower altitudinal range (4.2 m^2) was the highest values of other altitudinal ranges. But, at medium altitude (4.0 m^2), value of basal area of woody species was the lowest in the study areas. Moreover, value of the abundance of woody species at medium altitude (943 stems ha^{-1}) was the highest, but at lower altitude was the lowest (791 stems ha^{-1}) in the abundance value of woody species. Whereas value of density woody species at medium altitude (736.7 stems ha^{-1}) was the highest, but at lower altitude (617.9 stems ha^{-1}) was the lowest of all altitudinal ranges (Table 27).

Table 26. General Linear Model showing the effects Aspect, slope and altitude on abundances woody species in Amibara and Awash Fentale districts

Ecological availability	Sum of Squares	Df	Mean Square	F	Pr > F
Aspect × Ab	14179.03	7	2025.58	1.447	0.20
Aspect × BA	0.089	7	0.013	0.57	0.78
Aspect × D	8654.2	7	1236.31	1.45	0.20
Aspect × I_{VI}	145.23	7	20.75	0.98	0.45
Slope × Ab	5857.74	2	2928.87	2.07	0.13
Slope × BA	0.08	2	0.04	1.99	0.14
Slope × D	3575.28	2	1787.64	2.07	0.13
Slope × IVI	68.10	2	34.50	1.65	0.20
Altitude × Ab	13846.47	2	6923.24	5.23	0.007
Altitude × BA	0.29	2	0.14	7.62	0.0001
Altitude × I_{VI}	293.36	2	146.68	8	0.001

Notes: Ab is Abundance, BA is Basal area, D is Density, I_{VI} is Importance Value Index

With regard to the effects of aspect of the study areas in Table (26), for both abundances (basal area, abundances, density and I_{VI}) of woody species, aspects did not significantly affect the availability of the species ($P < 0.05$). Value of basal area of woody species on northeast side (5.32 m^2) was the highest, but the lowest on southeast (0.14 m^2) of the study areas. Moreover, of abundances of woody species on northeast side (1144.9 stems m^{-1}) was also the highest, but the lowest on southeast (110 m^{-1}) of the study areas. On the other hand, values of density were similar the trends to that of basal area and abundances of woody species. However, the highest mean value of I_{VI} was recorded on southeast sides of landscape, but the lowest I_{VI} was recorded on western sides of the study areas (Table 27).

Table 27. Density of woody species affected by altitude, aspect and slope in Amibara and Awash Fentale districts

Explanatory variables		Response variables			
		BA	Ab	D	I_{VI}
Altitude	Lower (N=19)	0.22±0.05a	41.63±14.30a	32.52±11.17a	9.66±1.61a
	Medium (N=23)	0.09±0.02b	41.00±8.42b	32.03´±6.58b	7.01±0.86b
	Higher (N=50)	0.08±0.02c	16.66±2.22c	13.02±1.73c	5.10±0.39c
	North (N=11)	0.05±0.02e	19.82±5.86f	15.48±4.58f	4.66±0.74f

Aspect	Northeast (N=38)	0.14±0.03ba	30.13±7.81c	23.54±6.10c	7.19±0.93c
	Northwest (N=12)	0.10±0.03c	29.08±9.49d	22.72±7.41d	6.39±1.01d
	East (N=6)	0.10±0.03c	53.00±18.49b	41.41±14.45b	8.37±2.05b
	West (N=5)	0.08±0.04d	13.40±5.90h	10.47±4.61d	4.68±1.21f
	Southeast (N=1)	0.14±0.00a	110.00±0.00a	85.94±0.00a	13.19±0.003a
	Southwest (N=10)	0.10±0.04c	21.70±5.56e	16.95±4.34e	5.82±0.96e
	South (N=9)	0.12±0.06b	15.89±5.91g	12.41±4.62b	5.97±1.41e
Slope	Lower (N=68)	0.11±0.02b	32.34±5.37a	25.26±4.20a	6.74±0.63b
	Moderate (N=15)	0.09±0.03c	11.07±2.68c	8.65±2.10c	4.71±0.61c
	Higher (N=9)	0.20±0.05a	22.44±7.82b	17.53±6.11b	7.88±1.09a

Notice**:** Values with the same letter are not significantly different, P=0.05, BA is basal area, Ab is abundance of woody species, D is density of woody species, I_{VI} is importance value of woody species.

In the present study, abundances of woody species were significantly affected by slope ($P < 0.05$). Thus, value of basal area on the lower slope (7.48 m^2) was the highest, but value of basal area on the moderate slope (1.35 m^2) was the lowest value in the study landscapes. Meanwhile, the mean value of abundances of woody species on lower slope (2199.12 stems ha^{-1}) was the highest, but on moderate slope (166.05 stems ha^{-1}) the value was the lowest. The same trends in the mean values of density and I_{VI} of woody species were recorded by slope ranges in the study areas (Table 27).

Results designated that abundance of *Prosopis juliflora* species were higher under *Prosopis juliflora* thicket (1203) than *Prosopis juliflora* mixed with native species (353) and non-invaded woodland (0). However, higher abundances of *Acacia senegal* were recorded under non-invaded woodland (276) than *Prosopis juliflora* mixed with native species (136) and *Prosopis juliflora* thicket (5) *Prosopis juliflora* invasion levels. Meanwhile, higher abundances of *A. tortilis* were recorded under *Prosopis juliflora* mixed with native species (107) than under habitats of non-invaded woodland (88) and *Prosopis juliflora* thicket (4) in this study. Moreover, lower abundances of *Acacia mellifera* individuals were recorded under *Prosopis juliflora* thicket (0) than *Prosopis juliflora* mixed with native species (4) and non-invaded woodland (145) habitats (Appendix 3).

On the other hand, higher abundances for *A. nilotica* were recorded under *Prosopis juliflora* thicket and *Prosopis juliflora* mixed with native species 3 individuals each than that of non-invaded woodland (0). But, the lowest abundances of *Acacia oerfota* were recorded under *Prosopis juliflora* thicket and non-invaded woodland (0) each and relatively higher abundances were recorded under *Prosopis juliflora* mixed with native species (2). While no abundance of *Ziziphus spina-christi* was recorded under *Prosopis juliflora* thicket and *Prosopis juliflora* mixed with native species habitats, 3 individuals of this species were recorded under non-invaded woodland habitat in the study areas (Appendix 3).

Results also revealed that higher abundances of *Cadaba rotundifolia* were recorded under non-invaded woodland (44) than *Prosopis juliflora* thicket (37) and *Prosopis juliflora* mixed with native species (17). But, higher abundances of *Salvadora persica* were recorded under non-invaded woodland (72) than *Prosopis juliflora* mixed with native species (8) and *Prosopis juliflora* thicket (0). Similarly, relatively higher abundances of *Dobera glabra* were observed under non-invaded woodland (8) than under *Prosopis juliflora* mixed with native species (1) and *Prosopis juliflora* thicket (0) over the study landscapes (Appendix 3).

Importance value index values of species varied from 0.5% under *Prosopis juliflora* mixed with native species for *Balanites aegyptiaca* to 83% for *Prosopis juliflora* under habitat of *Prosopis juliflora* thicket. With regards to importance value index of woody species, higher I_{VI} values of *Prosopis juliflora* were recorded under *Prosopis juliflora* thicket (83%) than *Prosopis juliflora* mixed with native species (45%) and non-invaded woodland (0). However, lower importance value index of *Acacia nilotica* were recorded under non-invaded woodland (0%) than *Prosopis* *juliflora* mixed with native species (2.5%) and *Prosopis juliflora* thicket (2.2%) in the study areas. The importance value index of *Acacia senegal* were higher under non-invaded woodland (23.1%) than *Prosopis juliflora* mixed with native species (15.5%) and *Prosopis juliflora* thicket (1.5%). Whereas 37% importance value index of *Acacia tortilis* recorded under *Prosopis juliflora* mixed with native species were higher than non-invaded woodland (25.9%) and *Prosopis juliflora* thicket (2.5%) habitats (Appendix 3).

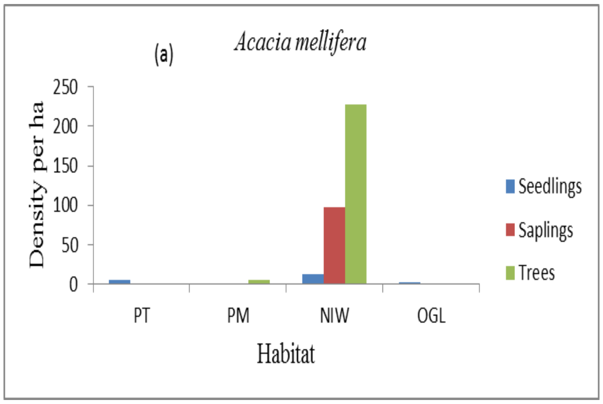
No importance value index were recorded under *Prosopis juliflora* thicket and non-invaded woodland habitats which were relatively lower than under *Prosopis juliflora* mixed with native species (1.2%). Moreover, higher *Cadaba rotundifolia* importance value index were recorded under non-invaded woodland (8.2%) than *Prosopis juliflora* mixed with native species (4.3%) and *Prosopis juliflora* thicket (3%) over the study landscapes. But, no importance value index of *Cocculus hirsutus* species were recorded under *Prosopis juliflora* thicket and non-invaded woodland habitats which were lower than that of *Prosopis juliflora* mixed with native species (2.9%).

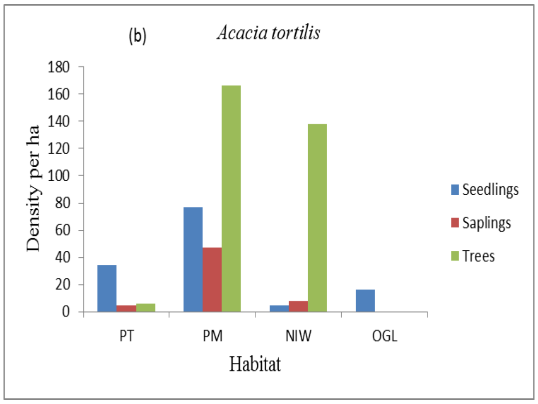
On the other hand, higher importance value index of *Acacia mellifera* species were recorded under non-invaded woodland (14%) than *Prosopis juliflora* mixed with native species (1.3%) and *Prosopis juliflora* thicket (0%). Similar trends of importance value index were recorded for *Dobera glabra* and *Salvadora persica*. As a result, importance value index of *Dobera glabra* were higher under non-invaded woodland (3.7%) than *Prosopis juliflora* mixed with native species (0.3%) and 0 I_{VI} values were computed under *Prosopis juliflora* thicket. Whereas 5.1% of importance value index of *S. persica* were computed under non-invaded woodland which were relatively higher than that of under *Prosopis juliflora* mixed with native species (1.5%) and *Prosopis juliflora* thicket (0%) in the study sites (Appendix 3).

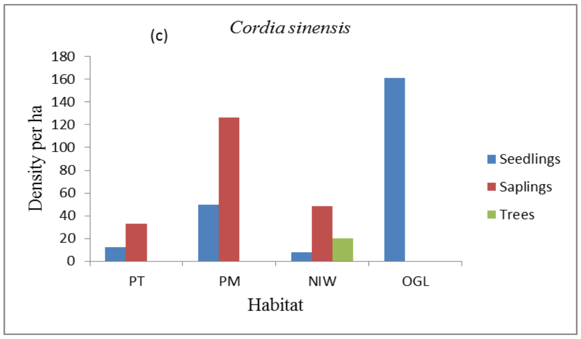
4.3.9. Invasion of *Prosopis juliflora* and regeneration of selected population of woody species

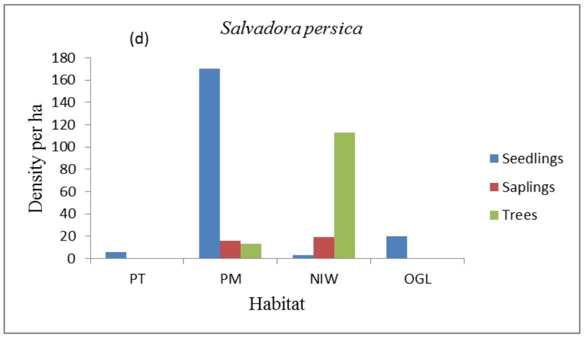
Results showed that pattern of population structure for a given species can be roughly grouped in one of four basic types (I, II, III & IV). Type I is a pattern in which a diameter size class distribution displays a greater number of smaller trees than large ones. Type II is characteristic of species that show discontinuous, irregular and or periodic recruitment. Type III reflects species whose regeneration is severely limited. Type IV is characteristic of species that show a lower number of saplings or mid class distribution than seedlings and trees.

The results in Figure 23b&f showed that the population of *Prosopis juliflora* and *Acacia tortilis* both under *Prosopis juliflora* mixed with native species, their regeneration patterns had U-shaped (Type IV) type. Meanwhile, population of *Cordia sinensis* under non-invaded woodland; *Cadaba rotundifolia* and *Grewia tenax* under *Prosopis juliflora* mixed with native species showed that regeneration patterns bell-shaped type (Type II) (Figure 20 i&j).

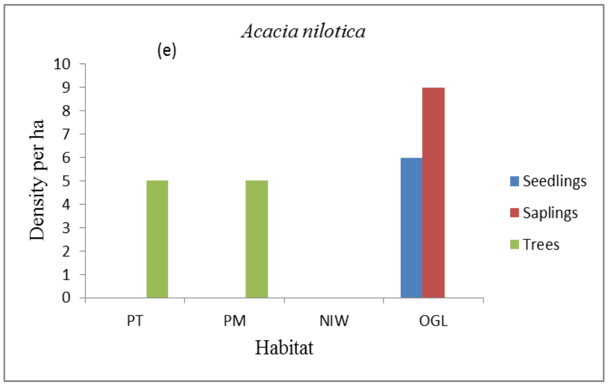


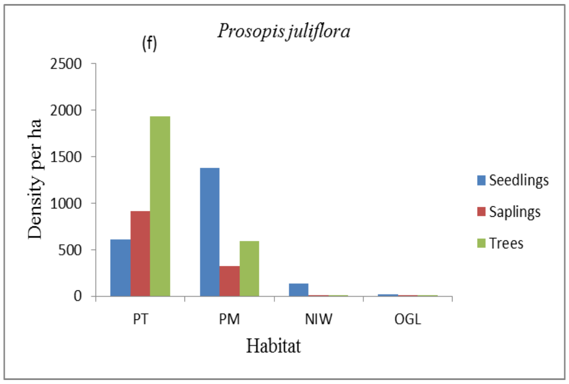


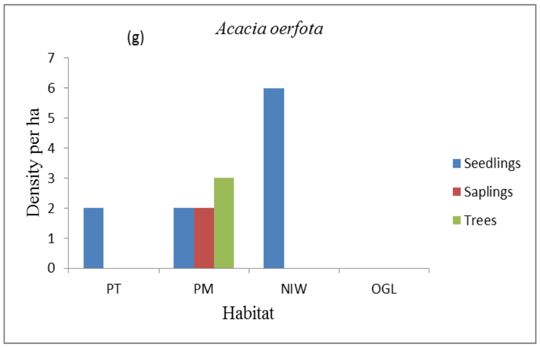


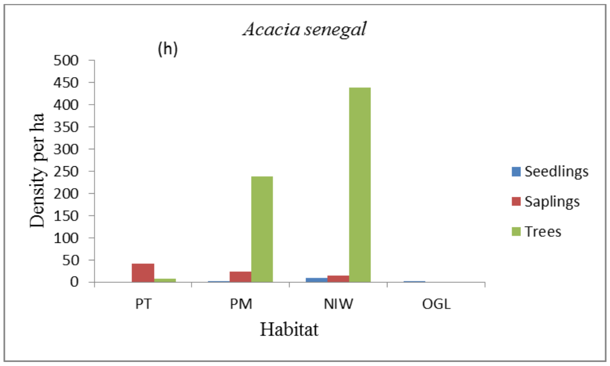


Using Appendix (3), in Figure 22d&j the population of *Cadaba rotundifolia* under non-invaded land, and *Salvadora persica* under *Prosopis juliflora* mixed with native species were showed the regeneration patterns of inverted J-shape (Type I). On the other hand, the population of *Acacia mellifera*, *Salvadora persica* and *Acacia tortlis* under non-invaded woodlands; and *Prosopis juliflora*, *Grewia tenax*, *Acacia oerfota*, *Acacia sengeal*, *Acacia mellifera* and *Cadaba rotundifolia* under *Prosopis juliflora* thicket; and *Acacia nilotica* under non-invaded woodlands and woody species like *Acacia mellifera*, *Acacia oerfota*, *Acacia tortilis*, *Grewia tenax*, *Salvadora persica*, *Cadaba rotundifolia* under open garzing lands were resembled the limited regeneration patterns of J–shape (Type III) in the study areas (Figure 20 b, d, g, h, i & j).









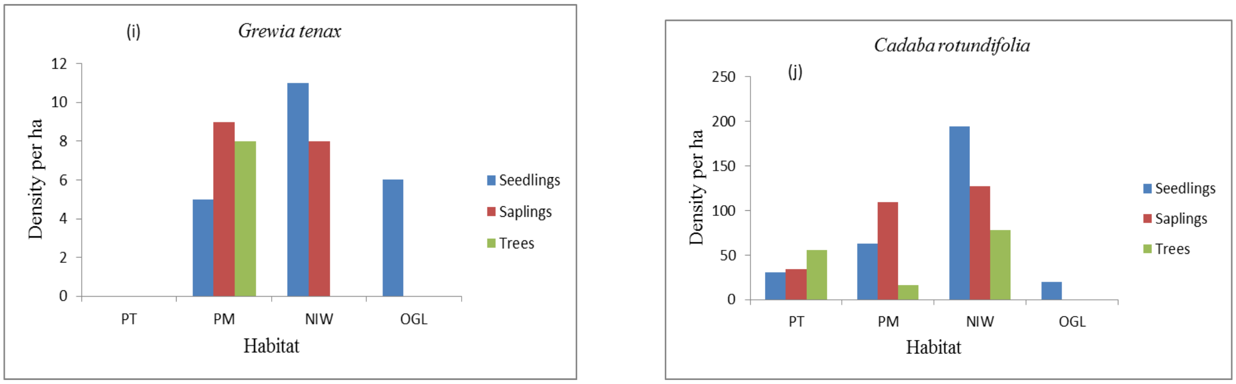


Figure 22a-j. Regeneration of ten species population in each habitat (PJT = *Prosopis juliflora* thicket stands, PJM = *Prosopis juliflora* with native species stands, NIWL = non-invaded woodland, OGL = open grazing land).

4.4. Effects of *Prosopis juliflora* on soil physicochemical properties in Teru and Yalo districts

4.4.1. *Prosopis juliflora* and soil chemical properties

Invasion of *Prosopis juliflora* had significantly affected soil pH, exchangeable Na^+, water soluble $Ca^{2+} + Mg^{2+}$, water soluble Na^+, and ESP in Teru and Yalo distrcits of Afar region. On the other hand, the effects of *Prosopis juliflora* invasion on ECe, exchangeable $Ca^{2+} + Mg^{2+}$, Ex K^+, water soluble K^+, sodium absorption ratio, organic carbon, and total organic carbon were not statistically significant in Teru and Yalo distrcits ($P < 0.05$). The mean values of pH under *Prosopis juliflora* invaded areas were increased by 1.5% than in non-invaded open grazing lands. But, the mean values of exchangeable Na^+ were decreased under *Prosopis juliflora* invaded lands by 24.2% than in non-invaded open grazing lands (Table 28).

In addition, results showed that under *Prosopis juliflora* invaded sites, the mean values of exchangeable $Ca^{2+} + Mg^{2+}$ decreased by 2.2% than under non-invaded open grazing lands. The mean values of water soluble $Ca^{2+} + Mg^{2+}$ were decreased by 39.9% in *Prosopis juliflora* invaded lands than in non-invaded grazing lands. Meanwhile, the mean values of ESP were decreased by 21.6% under *Prosopis juliflora* invaded areas. Moreover, the mean values of water soluble Na^+ was decreaded by 21% than lands in non-invaded areas of open grazings (Table 28).

Table 28. Effects of *Prosopis juliflora* on soil physicochemical properties in Teru and Yalo districts

		0–30 cm			
Types and units	Soil properties	*Prosopis juliflora* invaded (A)	Non-invaded grazing land (B)	P value of t-test	% change (100%(A-B)/B)
-	pH	8.15	8.03	0.0002	1.49
dS m-1	ECe	1.17	1.35	0.36	-13.33
Exchangeable cations (Cmol kg-1)	Ca^{2+} + Mg $^{2+}$	47.17	48.25	0.45	-2.24
	Na+	0.5	0.66	<0.0001	-24.24
	K+	1.44	1.24	0.08	16.13
% wt/wt	Clay	21.44	17.36	0.003	23.50
	Sand	28.5	34.05	0.04	-16.30
	Silt	50.06	48.59	0.73	3.03
	Textural class	Loam	Silt loam	0.25	Silt loam
Water soluble cations (meq L-1)	Ca^{2+} + Mg^{2+}	4.32	7.19	0.004	-39.92
	Na+	1.83	2.32	0.002	-21.12
	K+	0.32	0.35	0.65	-8.57
-	SAR	1.35	1.4	0.38	-3.57
%	OC	0.76	0.78	0.10	-2.56
	TOC	1.02	1.04	0.1	-1.92
	ESP	1.05	1.34	0.48	-21.64

4.4.2. Effects of *Prosopis juliflora* on soil physical properties

With respective to soil physical properties, it was found that clay and sand showed significant variations in the study areas. But, the silt content of the soils was not statistically significant with land use systems ($P < 0.05$). In this study, the mean value of clay content for *Prosopis juliflora* invaded lands was increased by 23.5% than in non-invaded open grazing lands. But, the mean value of sand content for *Prosopis juliflora* invaded areas was decreased by 16.3% than lands in non-invaded adjacent lands (Table 28).

In Teru district, bulk density and moisture content for *Prosopis juliflora* invaded lands were 1.1 g/cm^3 and 81.0 %, respectively. But, the mean values of bulk density and moisture content for non-invaded open grazing lands were 1.2 g/cm^3 and 97.7 %. In Yalo district, bulk density, and moisture content for *Prosopis juliflora* invaded areas were 2.2 g/cm^3 and 147.9 %, respectively. But, the mean values of bulk density and soil moisture content for non-invaded open grazing lands were 1.5 g/cm^3 and Mc of 87.5 % (Table 29).

Table 29. Some soil physical properties of Teru and Yalo districts

District	Habitat	Bulk density (g/cm^3)	Soil moisture content (%)
Teru	*Prosopis juliflora* invaded lands	1.1	81.0
	Non-open gazing lands	1.2	97.7
Yalo	*Prosopis juliflora* invaded lands	2.2	147.9
	Non-open gazing lands	1.5	87.5

4.4.3. Spatial variations of soil chemical properties at Teru and Yalo districts

It was found that ECe, exchangeable Ca^{2+} + Mg^{2+}, exchangeable Na^+ exchangeable K^+, water soluble Ca^{2+} + Mg^{2+}, water soluble K^+, SAR, OC, TOC and ESP were significant variations with study districts ($P < 0.05$). But, spatially pH and textural class did not reveal significant variations between the study districts. In Teru district, the mean value of ECe was increased by 54.6% than in Yalo district. In addition, the mean values of exchangeable Ca^{2+} + Mg^{2+} was increased by 17.8% than in the Yalo district (Table 30).

Furthermore, the mean values of exchangeable Na^+ in Teru district was increaed by 34% than inYalo district. But, the mean values of exchangeable K^+ in Teru district was decreased by 20.8% than in Yalo district. In addition, the mean value of water soluble Ca^{2+} + Mg^{2+} in Teru district was decreased by 36.2% than in soil of Yalo district. Moreover, the mean values of watersoluble K^+ in Teru soil was decreased by 48.9% than in soil of Yalo district. In addition, the mean value of total organic carbon for Teru district was decreased by 20% than in Yalo district. The mean value of organic carbon in Teru district was decreased by 19.8% than in Yalo soils. But, the mean value of ESP in Teru district was increased by 11.4% than inYalo district (Table 30).

4.4.4. Spatial variations of physical properties in Teru and Yalo districts

It was found that sand and silt showed significant variations between districts. But, clay content of the soils was not statistically significant between the study areas ($P < 0.05$). In Teru district, the mean value of sand content was decreased by 29.3% than in the soil of Yalo district. But, the mean value of silt content in Teru district was increased by 20% than Yalo district (Table 30).

Table 30. Spatial variations of soil physicochemical properties

Type and unit	Soil properties	Teru (A)	Yalo (B)	P value of t-test	% change (100%(A-B)/B)
-	pH	8.11	8.06	0.25	0.62
dS m-1	ECe	1.53	0.99	0.02	54.55
Exchangeable cations (cmol kg-1)	$Ca^{2+} + Mg^{2+}$	51.56	43.77	0.0002	17.80
	Na^+	0.67	0.5	< 0.0001	34.00
	K^+	1.18	1.49	0.01	-20.81
% wt/wt	Clay	20.15	18.21	0.27	10.65
	Sand	26.24	37.13	<0.0001	-29.33
	Silt	53.61	44.67	<0.0001	20.01
	Textural class	Silt loam	Silt loam	0.61	Silt loam
Water soluble cations (meq L-1)	$Ca^{2+} + Mg^{2+}$	4.62	7.24	0.03	-36.19
	Na^+	2.25	1.94	0.03	15.98
	K^+	0.23	0.45	<0.0001	-48.89
-	SAR	1.6	1.14	<0.0001	40.35
%	OC	0.69	0.86	0.002	-19.77
	TOC	0.92	1.15	0.002	-20.00
	ESP	1.27	1.14	0.04	11.40

4.4.5. Vertical variations of soil physicochemical properties in Teru and Yalo districts

In both soil layers, 0-15 cm and 15-30 cm down the soil profile, except exchangeable K^+ the rest of soil physicochemical properties considered did not significantly vary across the soil depths. The trends of ECe dS/m, exchangeable $Ca^{2+} + Mg^{2+}$ meq/L, and water soluble $Ca^{2+} + Mg^{2+}$ meq/L decreased down the soil depth in the study areas. On the other hand, results depicted that soil pH, exchangeable Na^+ cmol kg^{-1}, exchangeable K^+ cmol kg^{-1}, water soluble Na^+ meq L^{-1}, water soluble K^+ meq L^{-1}, SAR, % organic carbon (OC), % total organic carbon (TOC), and %

ESP increased vertically the soil depths. In the study areas, both % clay and % silt increased vertically down the soil profile, but contents of % sand decreased. The textural classes across the soil depths showed that varied from silt loam to loam in 0–15 cm to loam in the lower 15–30 cm (Table 31).

Table 31. Effects of soil depth on soil physicochemical properties in Teru and Yalo districts

Type and unit	Soil properties	0–15 cm (A)	15–30 cm (B)	P value of t-test	% change (100%(A-B)/B)
-	pH	8.12	8.06	0.07	0.74
dS m-1	ECe	1.09	1.36	0.32	-19.85
Exchangeable cations (cmol kg-1)	$Ca^{2+} + Mg^{2+}$	47.1	48.16	0.62	-2.20
	Na^{+}	0.59	0.57	0.61	3.51
	K^{+}	1.48	1.22	0.04	21.31
% wt/wt	Clay	20.39	18.53	0.15	10.04
	Sand	30.27	32.63	0.29	-7.23
	Silt	49.34	48.84	0.81	1.02
	Textural class	Loam	Silt loam	0.69	Silt loam
Water soluble cations (meq L-1)	$Ca^{2+} + Mg^{2+}$	4.8	6.21	0.07	-22.71
	Na^{+}	2.07	2.06	0.95	0.49
	K^{+}	0.36	0.31	0.09	16.13
-	SAR	1.44	1.31	0.16	9.92
%	OC	0.82	0.73	0.1	12.33
	TOC	1.09	0.97	0.09	12.37
	ESP	91.29	76.66	0.22	19.08

Simple linear regressions establish functional relationships between variables. In Teru district, for 0-15 cm soil depth in *Prosopis juliflora* invaded areas, sodium absorption ration (SAR) did not show functional relationships with ECe (r^2 =0.09). In addition, SAR did not also show functional relationships with ECe in the district (Figure 21a&b).

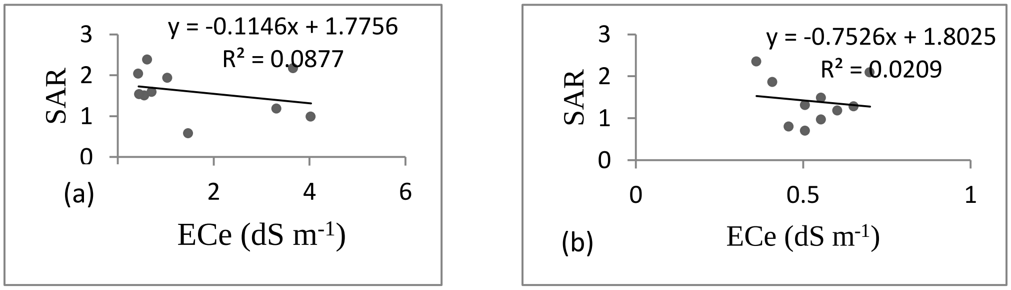


Figure 21a&b. Simple linear regressions between ECe and SAR for *Prosopis juliflora* invaded areas in Teru district at 0-15 cm (a) and 15-30 cm (b)

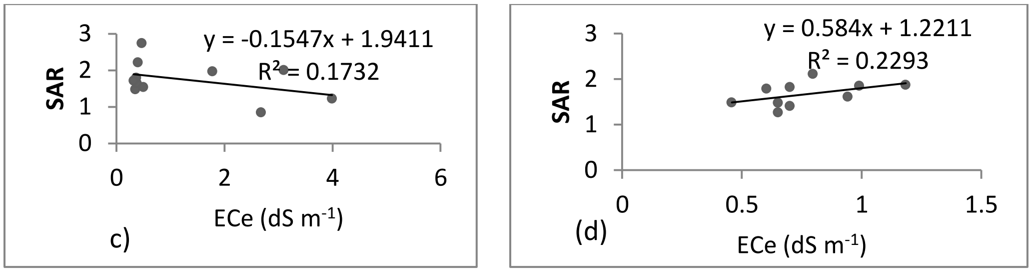


Figure 22c&d. Simple linear regressions between ECe and SAR for non- *Prosopis juliflora* invaded areas in Teru district at 0-15 cm (c) and 15-30 cm (d)

Moreover, in Teru district, the correlation coefficient between sodium absorption ration (SAR) and ECe did not reveal functional relationships at 0-15 cm soil depth (r^2 = 0.17), but functional relationships between SAR and ECe (r^2 =0.23) were observed in the 15-30 cm (Figure 22c&d).

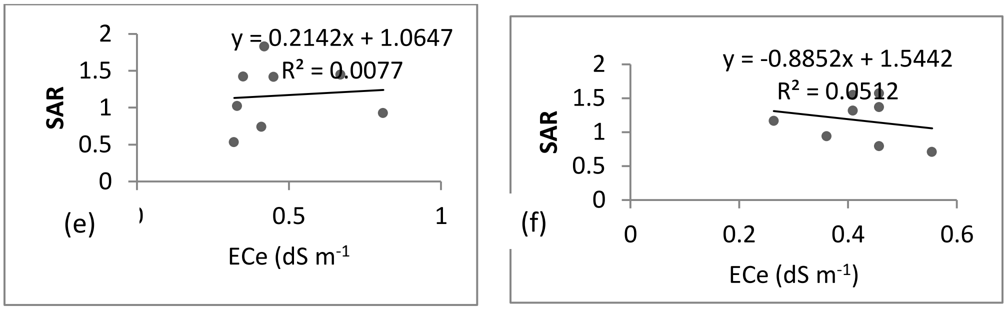


Figure 23&f. Simple linear regressions between ECe and SAR for *Prosopis juliflora* invaded areas in Yalo district at 0-15cm (e) and 15-30 cm (f)

In Yalo district, the correlation coefficient between sodium absorption ration (SAR) and ECe showed functional relationships for 0-15 cm soil depth (r^2 = 0.021), but for the 15-30 cm soil depth, the soil depths did not show functional relationships at r^2 =0.05, respectively for *P. juliflora* invaded areas (Figure 23e&f).

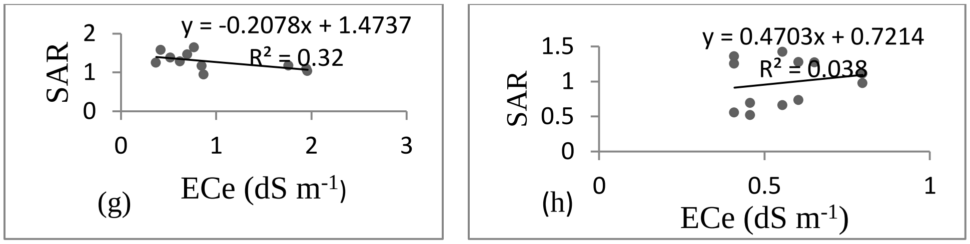


Figure 24 g&h. Simple linear regressions between ECe and SAR for non- Prosopis juliflora invaded lands in Yalo district at 0-15 cm (e) and 15-30 cm (f).

In non- *Prosopis juliflora* invaded areas of adjacent open grazing lands in Yalo district, the correlation coefficient between sodium absorption ration and ECe showed non-functional relationships for 0-15 cm soil depth (r^2 = 0.32) but for the 15-30 cm soil depth, they showed functional relationships at r^2 =0.038) (Figure 24g&h).

4.5. Composition and of density soil seed bank in Amibara and Awash Fentale districts

4.5.1. Composition of soil seed bank

Nineteen plant species belonging to 11 families were identified in soil seed banks, while 157 plant species, belonging to 34 families were identified in the above-ground flora. Although results indicated that several families and plant growth habits were not significantly affected by *Prosopis juliflora* invaded levels. Numerically the mean values of habitats revealed variations in the study areas. From the total of 11 families recorded from the soil seed banks, 8 (72.7%), 7 (63.6%), 9 (81.8%) and 7 (63.6%) were recorded in *Prosopis juliflora* thicket, *Prosopis juliflora* mixed with native species, non-invaded woodlands, and open grazing lands, in that order (Appendix 5).

The three top frequent families in the study areas were Poaceae, Asteraceae, and Lamiaceae which had contributed 12 (25%), 8 (16.7%) and 6 (12.5%) species in the soil seed bank. Fabaceae and Solanaceae together contributed to 25% of the total species while the rest of the families contributed to 20.8%. Other families contributed (for instance Convolvulaceae, Rhamnaceae, and Cyperaceae) contribute to only 2.1% in *Prosopis juliflora* thicket, *Prosopis juliflora* mixed with native species and non-invaded woodlands (Appendix 7).

Twenty nine (60.4%) of the germinated seedlings were identified as forbs while 13 (27.1%), 3 (6.3%) and 3 (6.3%) were grass, climber, and tree (woody) species, respectively. The number of species collected from the different habitats were 15 (non-invaded woodlands) 12 (open grazing lands), 11 (*Prosopis juliflora* thicket) and 10 (*Prosopis juliflora* mixed with native species). Graminoid species were most frequent (8.3%) in non-invaded woodlands. In the rest of the habitats, graminoid species were equally distributed. A very low proportion of climbers and woody species were identified from all habitat types (Table 32, Appendix 7).

Table 32. Distribution of growth forms in each habitat in Amibara and Awash Fentale districts

		Habitat									
		PJT		PJM		NIWL		OGL		Total	
		Frequency	%	Frequency	%	Frequency	%	Frequency	%	Frequency	%
Life form	Forb	5.0	10.4	6.0	12.5	11.0	22.9	7.0	14.6	29.0	60.4
	Grass	3.0	6.3	4.0	8.3	3.0	6.3	3.0	6.3	13.0	27.1
	Climber	2.0	4.2	0.0	0.0	1.0	2.1	0.0	0.0	3.0	6.3
	Tree	1.0	2.1	0.0	0.0	0.0	0.0	2.0	4.2	3.0	6.3
Total		11.0	22.9	10.0	20.8	15.0	31.3	12.0	25.0	48.0	100.0

Notice: PJT is *Prosopis juliflora* thicket, PJM is *Prosopis juliflora* mixed with native species, NIWL is non-invaded woodland, and OGL is open grazing land

Results revealed that invasion of *Prosopis juliflora* had highly significant effects on soil seed bank Shannon diversity index and species richness. But, habitats did not show significant effect on Shannon evenness. In addition, no significant variations were observed between *Prosopis juliflora* thickets and *Prosopis juliflora* mixed with native species stands (Table 33, Appendix 4).

Table 33. Effects of *Prosopis juliflora* invasion levels on soil seed bank patterns in Amibara and Awash Fentale districts

Habitat	Shannon diversity index	Species richness	Shannon evenness index
Prosopis juliflora thicket	1.18±0.03c	3.94±0.15bc	0.93±0.01a
Prosopis juliflora mixed with native species stands	1.19±0.04c	3.83±0.013c	0.94±0.01a
Non-invaded wood land	1.46±0.04a	5.13±0.15a	0.93±0.01a
Open grazing land	1.30±0.05b	4.3±0.17b	0.94±0.01a

4.5.2. Spatial distribution of soil seed bank at Amibara and Awash Fentale districts

It was found that sites had shown significant effects on Shannon diversity index, species richness and Shannon evenness index (Appendix 4). In Amibara district, Shannon diversity index was increased higher by 10.4% than in the Shannon diversity index in Awash Fentale district. Moreover, the mean value of species richness for Amibara district was higher than those of Awash Fentale district, but Shannon evenness index of Awash Fentale was higher than Amibara district. Moreover, Shannon diversity index of Kebena site was higher than Dudub, Sedihafeghe, and Kurkura sites, respectively. However, Species richness at Kurkura site was higher than Dudub, Kebena, and Sedihafeghe sites, respectively. Moreover, Shannon evenness index of SSB in Sedihafeghe site was higher than Dudub, Kebena, and Kurkura sites in that order (Table 34).

Table 34. Effects of sites and district on values of soil seed bank patterns at Amibara and Awash Fentale districts

	Locations	Shannon diversity index	Species richness	Shannon evenness index
Districts	Awash Fentale	1.20±0.03b	3.93±0.1b	0.94±0.006a
	Amibara	1.34±0.02a	4.63±0.11a	0.92±0.006b
Sites	Dudub	1.02±0.03b	3.2±0.12c	0.95±0.008ab
	Kebena	1.38±0.03a	4.65±0.04b	0.93±0.009b
	Kurkura	1.37±0.04a	5.07±0.15a	0.87±0.01c
	Sedihafeghe	1.32±0.04a	4.28±0.14b	0.96±0.005a

4.5.3. Vertical patterns of soil seed bank

Soil seed bank did not show significant variations in species diversity indices among soil layers. Numerically the 6–9 cm soil depth showed higher mean values of Shannon diversity index and species richness than the rest of soil layers. But, about the same Shannon evenness was recorded in both soil layers (Table 35).

Table 35. Effects of soil layer on mean values of soil seed bank patterns

Soil Layer	Shannon diversity index	Species richness	Shannon evenness index
Litter layer	1.28±0.03a	4.29±0.12a	0.93±0.01a
0–3 cm	1.25±0.03a	4.2±0.14a	0.93±0.01a
3–6 cm	1.29±0.05a	4.39±0.21a	0.94±0.01a
6–9 cm	1.32±0.06a	4.44±0.24a	0.94±0.01a

In this study, a total of 73,155 seedlings of 19 species/m^2 emerged from the SSB and 168 seedlings of 6 species/kg emerged from animal fecal matter (Appendix 6, Table 39). Overall results showed that 33, 911seeds/m^2 was recorded from the litter layer. Out of these, 25,822 seeds/m^2, 8311 and 5289 seeds/m^2 was recorded in soil layer of 0–3 cm, 3–6 cm, and 6–9 cm seeds/m^2, respectively (Appendix 6, Figure 25).

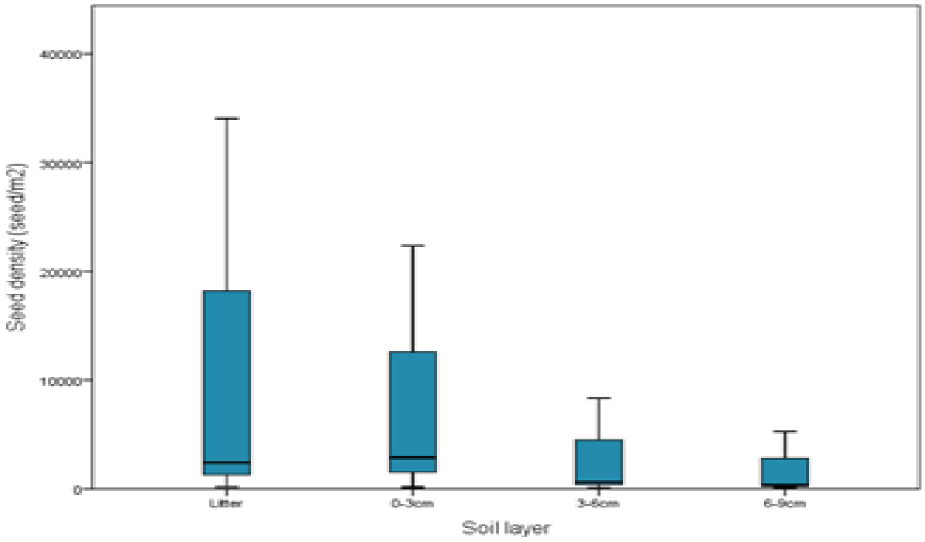


Figure 25. The vertical distribution of density of soil seed bank at Amibara and Awash Fentale districts

In CCA, the length of the arrow indicated that density and composition of seeds in the soil highly determined by altitude, disturbance and grazing intensities (Figure 26).

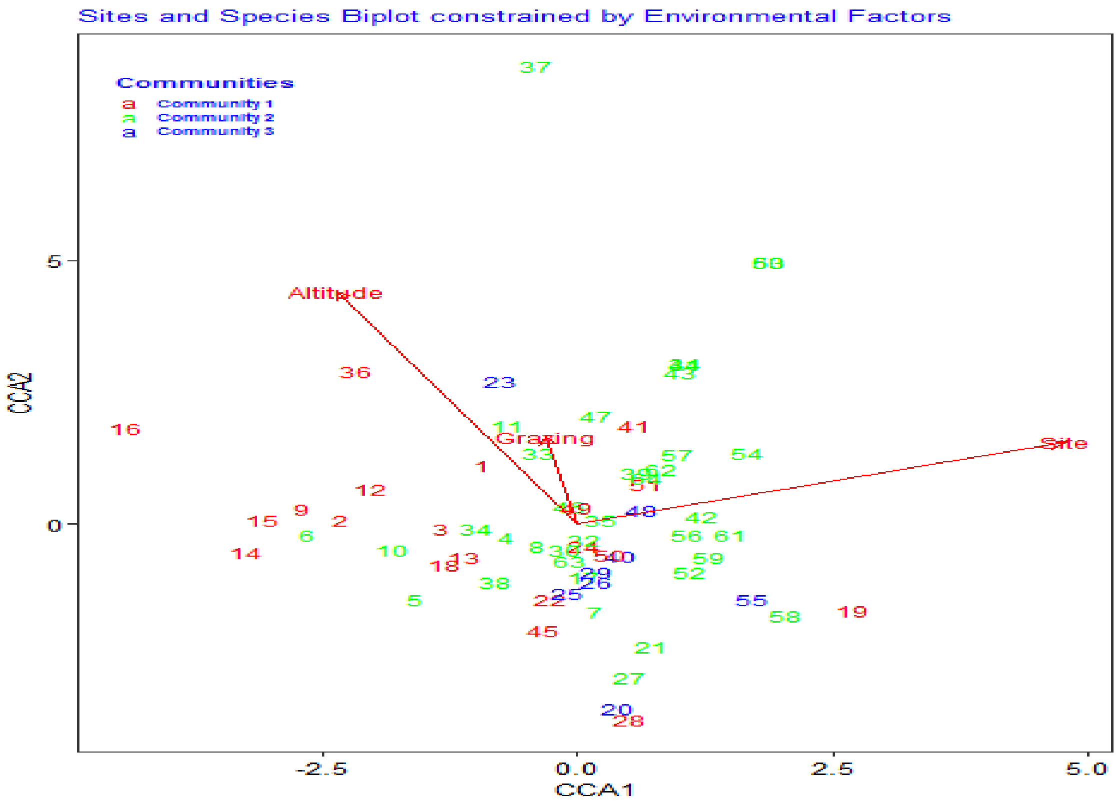


Figure 26. Canonical correspondence analysis (CCA) of sites constrained by some environmental variables

For CCA displaying sites constrained by some selected environmental variables, results revealed that site (Dudub, Kebena, Kurkura, and Sedihafeghe), altitude and grazing intensity had correlated by 95% and 31%, respecively with quadrats. For instance, 95% of soil seed bank patterns were constrained by sites in CCA1 and 31% in the CCA2. In addition, 88% of soil seed bank patterns were constrained by altitude in CCA2 and 33% in the CCA2 (Table 36, Figure 26).

Table 36. Biplot scores for constraining variables on soil seed bank patterns in Amibara and Awash Fentale districts

Environmental variable	CCA- axis		
	CCA1	CCA2	CCA3
Site	0.95	0.31	-0.04
Altitude	-0.47	0.88	-0.1
Grazing intensity	-0.07	0.33	-0.94

Results showed that 13,333 seeds of the species *Brachiaria leersioides*, 6,178 seeds of the species *Parthenium hysterophorus* and 5,689 seeds of the species *Eragrostis aethiopica* were recorded from the litter layer. These figures were higher than those obtained for *P. juliflora* (222 seeds/ m^2) and *Ziziphus spina-christi* (89 seeds/ m^2). A total 44 of seeds/m^2 of *Solanum incanum, Crotalaria pycnostachya*, *Trifolium simense,* and *Eragrostis aethiopica* each were identified. In addition, 14,178 seeds of *Brachiaria leersioides*, 4,533 seeds of *P. hysterophorus*, 2,667 seeds of *Eragrostis aethiopica* and 1,556 seeds of *Bidens pilosa* were seedlings per m^2 were recorded from the 0-3 cm soil layer. Likewise, 44 of seeds/m^2 each for *Ipomoea blepharophylla, Fuirena leptostachya*, *Heliotropium longiflorum* and *Coccinia grandis* were identified from the same layer (Appendix 6).

Results show a decrease in density of soil seed bank with depth. Accordingly, a density 3,289 of seeds/m^2 of *Brachiaria leersioides,* 2,578 of seeds/m^2 for *Parthenium hysterophorus* and 1,022 of seeds/m^2 of *Amaranthus thunbergii* species were recovered from soil samples in 3-6 cm soil layer. These values were far higher than 44 of seeds/m^2 for *Potamogeton crispus, Ipomoea indica* and *Cenchrus ciliaris.* No *Prosopis juliflora* seedling in the 3-6 cm soil layer. Meanwhile, 2, 444 and 1, 1022 of seeds/m^2 were recorded in that order for *Brachiaria leersioides* and *P. hysterophorus* in 6-9cm soil depth. But, 44,133 and 178 of seeds/m^2 were recovered in soil depth of 6-9 cm for *Trifolium simense, Physalis lagascae* and *Biden pilosa,* respectively. Moreover, 89 of seeds/m^2 each for *Cenchrus ciliaris* and *Crotalaria pycnostachya* were recovered from soil samples in the 6-9cm soil layer (Appendix 6).

Concerning ecological availability of seeds in soil seed banks, results revealed the same importance value index patterns with that of the density of species as aforementioned seeds which existed in the upper and subsoils. For instance, higher importance value index was computed for *Brachiaria leersioides*, *Eragrostis aethiopica*, *Crotalaria pycnostachya* and *Parthenium hysterophorus* in both layers whereas lower importance value index which were computed for *Prosopis juliflora*, *Solanum incanum*, *Trifolium simense*, *Potamogeton crispus*, *Coccinia grandis*, *Fuirena leptostachya*, *Heliotropium longiflorum*, *Cenchrus ciliaris*, *Ipomoea indica*, and *pycnostachya pycnostachya* seeds in litter layer and across soil depths (Appendix 6).

4.5.4. Soil seed bank versus standing vegetation at Amibara and Awash Fentale districts

Results showed that a much larger number of species occur in the above ground vegetation than represented in the soil seed bank. The Sorensen similarity coefficient revealed that above-ground vegetation species under *Prosopis juliflora* thickets were low similarity with below ground flora under the habitats of *Prosopis juliflora* with native species stands, non-invaded wood lands, and open grazing lands, respectively. Meanwhile, species in the above ground flora under non-invaded woodlands was low similarity with the below-ground flora under open grazing lands and above-ground species under *Prosopis juliflora* with native species stands was similar to soil flora of non-invaded wood lands and open grazing lands (Table 37).

Table 37. Sorensen similarity ratio between soil seed bank and extant vegetation

		Standing vegetation			
		Prosopis juliflora thickets	*Prosopis juliflora* mixed with native species	Non-invaded woodlands	Open grazing lands
Soil seed bank	*Prosopis juliflora* mixed with native species	0.02			
	Non-invaded woodlands	0.06	0.08		
	Open grazing lands	0.01	0.08	0.06	

4.5.5. Physiographic factors and soil seed bank diversity

The physiographic effects on plant species diversity are presented in Appendices 4&7. It showed that Shannon diversity, species richness, and Shannon evenness were significantly affected by altitude. Moreover, Shannon diversity, species richness, and Shannon evenness were significantly affected by the slope. Moreover, Shannon diversity, Species richness, and Shannon evenness were also significantly affected by aspect. The mean values for altitudinal ranges revealed that Shannon diversity index at lower altitude ranges (740–790 m.a.s.l) was higher by 12.4% than at higher altitudes (> 841m.a.s.l.).

Moreover, the mean value of species richness and Shannon evenness at lower altitudes was also higher by 10.3% and 5.2%, respectively than the upper altitudes. On the other hand, the mean values of Shannon diversity index at northwest and east-facing slopes were greater by 44.7% and 42.1%, respectively than in the southeast. The mean values of Shannon diversity index at northwest and east were found to be greater than in the southwest. The mean values of Shannon diversity index at northwest and east were also higher by 31.4% and 28.3%, respectively than in the northeast (Appendix 7).

Concerning the species richness and Shannon evenness values, similar trends of higher mean values were observed in the study areas. The mean value of slopes for Shannon diversity index and species richness was the greatest at higher slopes. On the other hand, the mean values of

Shannon evenness values were the greatest at slower slopes. But, the lowest mean values of Shannon evenness values were recorded at 6% slope. Results revealed that the overall trends of Shannon diversity index, species richness and Shannon evenness values were not consistent with slopes (Appendix 7).

4.5.6. Anthropogenic activities and soil seed bank diversity

Results indicate that Shannon diversity index and Shannon evenness are significantly affected by human impacts, soil seed bank patterns such as species richness and Shannon evenness were affected by human activities ($P < 0.05$). As a result, human impacts had shown significant effects on species richness and Shannon evenness. Moreover, grazing intensities had significant effects on Shannon diversity index, species richness and Shannon evenness. Meanwhile, disturbance intensities had also significant effects on Shannon diversity index, species richness and Shannon evenness in the study landscapes at $P < 0.05$ (Appendix 4).

The variations in mean values of diversity indices between soil seed bank patterns are shown in Appendix (8). For instance, the mean species richness values of non-human impacted ones were higher than mean values of moderate and heavy impacts. Meanwhile, species richness values of low disturbance were higher by 14.4% and 5.0% than moderate and heavy impacts, respectively. Moreover, the mean in Shannon diversity values of relatively non-grazing zero grazing and low grazing intensities were greater by 6.6% and 10.5%, respectively from the moderately grazed ones (Appendix 7).

The mean values of zero grazing and low grazing were also higher by 24.8% and 28% respectively than under heavy grazing intensity. Whereas similar trends for the values of species richness which computed throughout the study landscapes. The mean value in Shannon evenness for moderately grazed areas was higher by 3.1% than under zero grazing and low grazed areas. But, moderate grazing was higher than heavy grazed areas in the study areas. With respect to disturbance intensity, the impact of mean zero disturbances for Species diversity values were higher by 5.9% and 22.8% than under moderate and heavy disturbances respectively. Meanwhile, under low disturbance regime, species diversity value was higher by 9.9% and 26.1% than under moderate and heavy disturbances, respectively (Appendix 7).

On the other hand, the mean value of zero disturbances for species richness was higher by 13.2% and 26.4% than under moderate and heavy disturbances. The mean values of low disturbances were also higher by 14.4% and 27.4% than moderate and heavy disturbances. But, the mean values of heavy disturbance in Shannon evenness were lower by 5.3, 6.3% and 6.3% than low, moderate, and heavy disturbances, respectively (Appendix 7).

4.5.7. Composition, density, and diversity of seeds in animal fecal matter

ANOVA depicted that livestock had significant effects on Shannon diversity index, species richness, and Shannon evenness of the seeds in soils at $P < 0.05$ (Appendix 8). The mean Shannon diversity value of seeds in small ruminant (sheep and goats) fecal matter was higher than cattle but the mean value of species richness in the fecal matter of cattle was higher by 20% than that of shoats. Moreover, the mean value in Shannon evenness of small ruminants was higher by 27.7% than that of cattle in their fecal matter (Table 38).

Table 38. Effects of livestock droppings on soil seed bank patterns

Livestock	Shannon diversity index	Species richness	Shannon evenness index
Cattle	0.94±0.00a	4.0±0.0a	0.68±0.0b
Small ruminants	1.07±0.03b	3.2±0.2b	0.94±0.06a

Results revealed that the highest density of seeds in cattle fecal matter for *Prosopis juliflora* were 132 seeds/kg (78.6%). The lowest proportion of seeds in cattle fecal matter was accounted for by

Amaranthus thunbergii and *Biden pilosa* (3.6%) collectively. The rest (10.7%) is accounted for by *B. leersioides.* On the other hand, 3.6% of *P. juliflora* were recovered from the fecal matter of small ruminants, 3.6% seeds/kg were accounted by *Ipomoea indica* and *Ocimum urticifolium* seeds. As a result, a large proportion of seeds/kg (92.9%) was recovered from cattle fecal matters. No seeds were recovered from camel fecal matter in the study landscapes (Table 39, Figure 27).

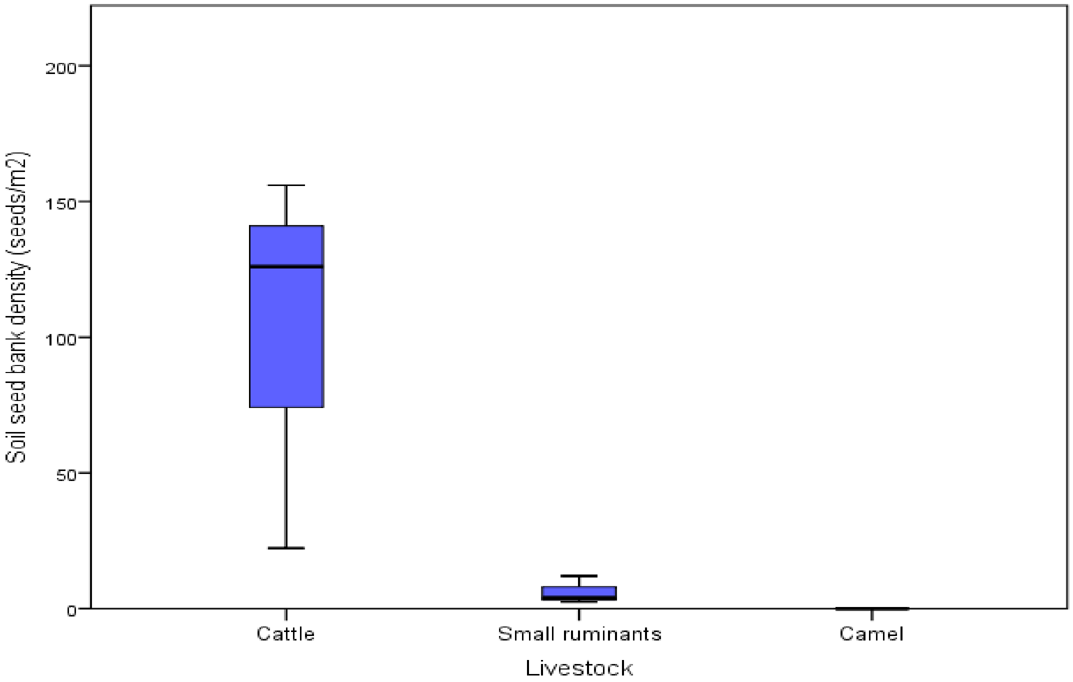


Figure 27. Total density of soil seed bank in animal fecal matter

Table 39. Distribution of seeds types in animal droppings

Animals	Scientific name	Number of animals	Soil seed bank abundance/0.5kg	Soil seed bank density/kg	%
Cattle	*Biden pilosa*	50	2	4	2.4
	Prosopis juliflora		66	132	78.6
	Brachiaria leersioides		9	18	10.7
	Amaranthus thunbergii		1	2	1.2
Small ruminants	*Ipomoea indica*	150	2	4	2.4
	Prosopis juliflora		3	6	3.6
	Ocimum urticifolium		1	2	1.2
Total			84	168	100

4.6. Soil seed banks in Teru and Yalo districts

4.6.1. Composition of soil seed bank

In the study sites, 10 species of plants were germinated from soil seed banks. Most of these species were herbaceous 9 (90%) and the rest 10% of the species was woody species. These plant species were distributed to 8 families of plants. Out of the 10 species, 4 (40%) of the species were common to the 0–3 and 6–9 cm soil depths. These species include *Galinsoga parviflora*, *Lipocarpha rehmannii*, *Physalis lagascae,* and *Eragrostis cilcilianensis.* Meanwhile, the other 2 (20%) were found in both the 0–3 and 3–6 cm soil depths. These were *Lipocarpha rehmannii* and *Eragrostis cilcilianensis.* But, *Prosopis juliflora* seedlings were recorded only in the soil depth of 0–3 cm (Table 40).

Table 40. Composition and density seed bank in Teru and Yalo districts of Afar region

District	Soil depth (cm)	Species	Soil seed bank density /m^2	Family
Teru	0–3	*Galinsoga parviflora Cav.*	44	Asteraceae
	6–9	*Galinsoga parviflora*	44	Asteraceae
	0–3	*Prosopis juliflora (Sw.) DC.*	44	Fabaceae
	0–3	*Lipocarpha rehmannii (Ridl.) Goetgh.*	1422	Cypercaeae
	3–6	*Lipocarpha rehmannii*	2978	Cypercaeae
	6–9	*Lipocarpha rehmannii*	3778	Cypercaeae
	0–3	*Physalis lagascae Roem. & Schult.*	133	Solanaceae
	6–9	*Physalis lagascae*	3111	Solanaceae
	0–3	*Eragrostis cilcilianensis (All.) Vign. Ex Janchen*	5422	Poaceae

	3–6	*Eragrostis cilcilianensis (All.) Vign. Ex Janchen*	6000	Poaceae
	6–9	*Eragrostis cilcilianensis*	1289	Poaceae
	6–9	*Kalanchoe glaucescens Britten.*	222	Crassulaceae
Yalo	0–3	*Galinsoga parviflora*	89	Asteraceae
	0–3	*Bidens pilosa L.*	133	Asteraceae
	3–6	*Oxalis anthelmintica A. Rich.*	356	Oxalidaceae
	6–9	*Brachiaria ovalis Stapf*	44	Poaceae
	6–9	*Amaranthus thunbergii Moq.*	89	Amaranthaceae

Results also revealed that the highest soil seed banks were recorded for *Eragrostis cilcilianensis* 6000 seedlings/ m^2, and 5422 seedlings / m^2 in the depth of the 3–6, and 0–3 cm, respectively in the study sites. Whereas the lowest soil seeds were recovered for *Galinsoga parviflora* that were 44 seedlings/ m^2 for the 6–9 cm and *Brachiaria ovalis* were 44 seedlings/ m^2 for 6–9 cm soil depths; and *Prosopis juliflora* (44 seeds/ m^2) only in the 0–3 cm soil depth. Furthermore, Cypercaceae and Poaceae were the highest frequent families recorded in the study landscapes of the districts. But, the lowest frequency families in soil seed banks were recovered for the Crassulaceae, Oxalidaceae and Amaranthaceae families (Table 40).

4.6.2. Density of soil seed banks in Teru and Yalo districts

In this study, the highest densities of soil seed banks (1037±633 seedlings/ m^2) were recovered in the soil depth of 3–6 cm. However, the lowest densities of soil seed banks were recovered in soil depth of 0–3 cm (461±315 seedlings/ m^2). The density of soil seed banks did not show a clear trend across the soil depths in the study landscapes (Figure 28).

In this study, ANOVA results in Appendix (9) showed that densities of soil seeds were significantly varied by soil depth, district, and habitats ($P > 0.05$).

The mean density of soil seed bank in Teru district (818 ± 267 seedlings / m^2) was significantly higher than the soil seed bank density of Yalo district (119 ± 48 seedlings / m^2). Whereas the mean density of soil seed bank under non-invaded open grazing lands (813 ± 375 seedlings / m^2)

was significantly higher than the soil seed bank density of invaded lands by *Prosopis juliflora* (545 ± 156 seedlings / m^2). Moreover, the mean soil seed bank density in the soil depth of 3–6 cm (1037 ± 633 seedlings / m^2) was the highest, but in the soil depth of 0–3 cm (461 ± 315) was the lowest soil seed bank density (Table 41).

Table 41. Statistical variations of soil seed bank densities in Teru and Yalo districts

Explanatory variable		Mean ± SE	Minimum	Maximum
District	Teru (N = 30	818±267a	44	6000
	Yalo (N = 6)	119±48b	44	89
Habitat	*Prosopis juliflora* invaded land (N = 15)	545±156a	44	2044
	Non-invaded open grazing land (N = 21)	813±375b	44	6000
Soil depth (cm)	0–3 cm (N= 16	461±315a	44	5067
	3–6 cm (N = 9)	1037±633b	89	6000
	6–9 cm (N = 11)	776±302c	44	3111

The densities of soil seed banks at Teru district were far higher than that of Yalo districts. Consequently, 589±418, 849±324, and 1122±711 seedlings/ m^2 densities of soil seed banks were recorded in 0–3, 6–9, and 3–6 cm soil depths, respectively at Teru district. Whereas 119±48, 44±0, and 356±0 seedlings/ m^2 densities of soil seed banks were recorded in 0–3, 6–9, and 3–6 cm soil depths, respectively at Yalo district (Figure 28).

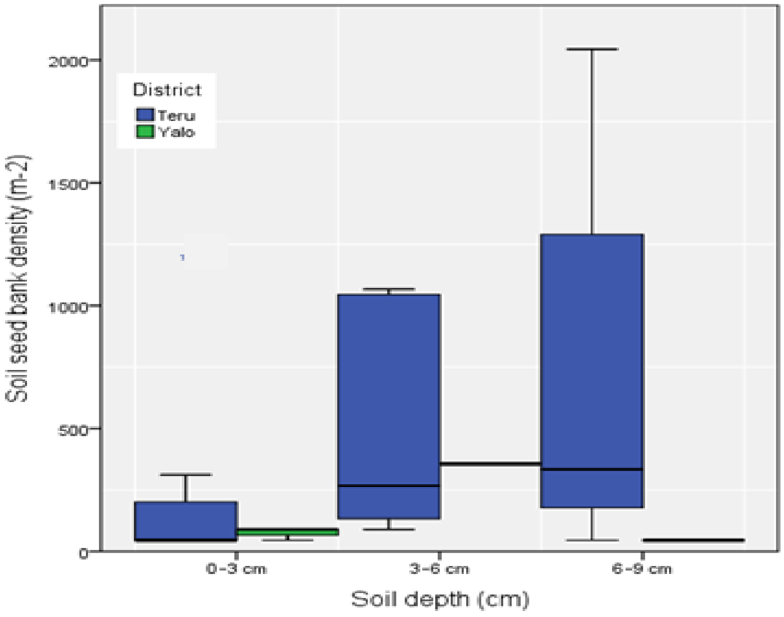


Figure 28. Soil seed banks of Teru and Yalo districts

4.6.3. Invasion of *Prosopis juliflora* and density of soil seed bank

In 0–3 cm soil depth and under non-invaded grazing lands, densities of soil seeds were 94±32 seedlings/ m^2. Whereas in the 0–3 cm soil depth, the density of soil seeds under invaded by *P. juliflora* was 828±622 seedlings/ m^2. Moreover, the density of soil seed banks in the 3–6 cm was 519±257 seedlings/ m^2 under the invaded lands, but 1296±953 seedlings/ m^2 were recovered from 3–6 cm soil depth under non- invaded areas (Figure 29).

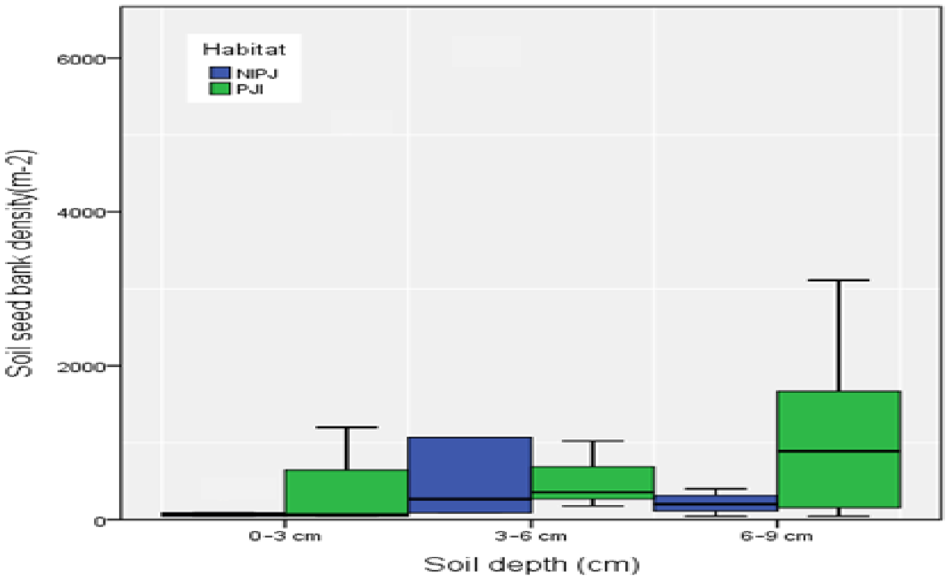


Figure 29. Soil seed banks under invaded and non-invaded by *Prosopis juliflora* in Teru and Yalo districts (Habitat indicates NIPJ = Non-invaded by *Prosopis juliflora* and PJI = *Prosopis juliflora* invaded lands)

In the 6–9 cm soil depth and under invaded lands, densities of soil seeds recovered were 1098±435 seedlings/ m^2. But, under non-invaded grazing lands, 211±73 seedlings/ m^2 were germinated in the 6–9 cm soil depth (Figure 29).

CHAPTER FIVE

5. DISCUSSION

5.1. Changes in land use/cover

The analysis revealed that land use and land cover has changed at Amibara and Awash Fentale districts. The overall accuracy assessment for the year 1986, 2000, and 2017 showed strong agreement between the classification and reference data (Haroun *et al*, 2013; Helen Merga, 2017). Kappa statistics more than 0.80 also shows better accuracy and the classification resulted from random points.

On the other hand, the confusion matrix analysis revealed that producer accuracy for settlement and bare land areas were relatively lower than other land use and land cover types for 1986, 2000, and 2017. User accuracy for grazing lands was also relatively lower than the rest for the same periods. The reduction in user and producer accuracies for the years 1986, 2000, and 2017 for aforementioned land use and land cover types could be due to their similar reflectance values of solar radiations that misclassified to either of the land use and land cover types. Moreover, the broad ranges of accuracies indicated severe confusions of bare lands and settlements with other land use and land cover types and their omission errors were greater. Accuracy assessments made by Rwanga and Ndambuki (2017) in Limpopo province of South Africa and Habtamu Tadele *et al*. (2017) in the case of Quashay watershed in the Northwestern Ethiopia argued similar trends with mensioned land use and land cover types.

The major conversions of land use and land cover types during 1986-2000 were detected in the study areas. These were attributed to the expansion of farmlands and the invasion of *Prosopis juliflora*. Similar findings were suggested by Nigussie Haregeweyn *et al*. (2013) for the cause of conversions during 1973-2004 in Amibara district. Large areas of woodlands might also be cleared fo r fuelwood purposes (Diress Tsegaye *et al*., 2010) during the 1986-2000. Furthermore, in 31 year s' time, large areas of land conversions were taken place in Amibara district in comparsion to A wash Fentale district. The reasons might be due to the the expansion of large-scale farmlands and invasion of *Prosopis juliflora* in the former district.

The reductions in areas of woodland and bare land areas at both districts were mainly attributed to the conversion of the areas into farmlands, invasion of *Prosopis juliflora,* and devastation of woodlands for construction, charcoal and firewood purposes. Findings from elsewhere also showed that such changes are common in other areas with similar settings. For instance, the land use and land cover dynamics at Merti district in Oromia region by Helen Megersa (2017) reported that shrublands and woodlands dropped by 56.8% and 26.4%, respectively in 29 years (1986–2015) time. Belay Zerga (2015) also reported similar trends for the changes of woodlands and farmlands during 1972–2007 in the Afar region of Ethiopia. Furthermore, the afromentoined author also reported increased trends of grazing lands and bare lands unlikely to the present study. This might be due to the expansion of the *Prosopis juliflora* and other woody species into grazing and bare lands. Another study in the Great Rann of Kachchousehold Biosphere Reserve of Gujarat, India during 1977-2005 also revealed that expansion of water bodies and *Prosopis juliflora* (Pasha *et al*., 2014).

The change matrix analyses showed that *Prosopis juliflora* invasion was progressing largely towards woodland and grazing land use and land cover types in both periods. Grazing land areas were largely affected by woody species (native plus *Prosopis juliflora*) encroachments, expansion of farmlands, and became barren lands in the three decades (1986–2017) in both the districts. The increases in the areas of *Prosopis juliflora* cover in districts were mainly owing to the woodland destruction and overstocking of grazing lands. Findings by Amboka and Ngigi

(2015) revealed comparable trends of land use and land cover changes for 25 years (1985–2010) in Baringo district of Central of Kenya. Shetie Gatew (2008) also reported similar patterns of land use and land cover changes in the Amibara district of Ethiopia.

The land use and land cover types at Amibara and Awash Fentale districts experienced various change detections for three decades (1986–2017). They have seen persistent changes both spatially and temporally, resulting in 51.5% of the total areas experiencing changes among land use and land cover types. This result shows that the changes were higher than the one reported by Diress Tsegaye *et al*. (2010) in Northern Afar during 1972–2007. The major conversions of land use and land cover types during 1986–2000 were attributed to the expansion of farmlands and invasion of *Prosopis juliflora.* Similar findings were suggested by Nigussie Haregeweyn *et al*. (2013) for the cause of conversions during 1973–2004 at Amibara district. Large areas of woodland might also be cleared for fuelwood purposes (Diress Tsegaye *et al*. 2010) during the 1986–2000.

5. 2. Phenology of *P. juliflora* and climatic variability

This study has demonstrated changes in the phenology of *Prosopis juliflora* significantly. Species are shifting their geographic distributions and seasonal timing of reproduction in response to climate warming (Forrest *et al.*, 2010; Ford *et al.*, 2016). Knowledge of the phenology of *Prosopis juliflora* tells us the plant is ever-green throughout the year, with minimal change in its floristic character occurring during its flowering period which roughly coincides with the rainy season (Zeila, 2005). Thus, uniform phenology of *Prosopis juliflora* throughout the year makes it more invasive and difficult to control. The patterns of flowering times for *P. juliflora* might be accounted to moisture availability for flowering (Yoda *et al.*, 2012). The results of our study also showed the occurrence of *Prosopis juliflora* is heavily associated with environmental factors in terms of soil moisture.

Moreover, Wolf *et al*. (2016) also reason out as altered precipitation regimes are the most determining factors to induce flowering time. The proportions of green leaves per trees were partially similar to findings of Shirke (2001), Ford *et al*. (2016), and Gallinat *et al*. (2015). On the contrary, for the appearance of coherent leaves, it was found that the patterns in proportions of green leaves per trees per contrasting seasons were not comparable with our findings (Parmesan and Hanley, 2015).

Variations in temperature and rainfall closely influence phenology of different tree species. Temperature is a major factor affecting the rate of plant growth (Hatfield and Prueger, 2015). Moreover, the effects of shade and flowers of invasive plant species on native plant pollination also depend on overlap in flowering (McKinney and Goodell, 2011). In the present study, the highest proportion of the green leaves per trees was recorded in lower temperature seasons than relatively medium temperatures. The reasons could be due to higher moisture content of the soil which was similar with findings of Yoda *et al*. (2012) and Wolf *et al*. (2016).

The patterns in the phenology of the plant in this study also showed the direct relationship between leaf loss and reproductive phases reflects the apportioning of the resource use for supporting these stages of plant growth (Singh and Shwaha, 2006). The structure and activity of plants in semi-arid ecosystems are strongly influenced by seasons precipitation patterns (Miranda *et al*., 2011b). However, deep rooted plants can withstand the moisture stress encountered during dry seasons.

5. 3. *Prosopis juliflora* invasion, native species diversity and regeneration

Invasion of *Prosopis juliflora* has changed the species diversity and regenetration of native species in the study areas. Knowledge of species composition is of paramount importance not only to understand the structure of vegetation but also for planning and implementation of conservation strategies (Singh *et al*., 2016). Number of families identified was comparable with researches made by Aggarwal (2012) and Hibret Demissie (2009). However, in this study, both number of species and families were higher than other reports at World Heritage Site; Keoladeo National Park in India by (Mukherjee *et al*., 2017).

The availability of forbs in *Prosopis juliflora* thickets contributes to suitable resource islands which had out-competed other species under thicket of *Prosopis juliflora* (Tiessen *et al*., 2003; Kahi *et al*., 2009). However, higher proportion of grass species under *Prosopis juliflora* with native species stands and non-invaded woodlands in comparision to *Prosopis juliflora* thickets could be due to inhabitation of light penetration and allelophytic chemicals under the thicket (El-Keblawy, 2012). The decline in species forming different growth in habitats of non-invaded woodlands and open grazing lands could also be attributed to anthropogenic impacts (i.e., exploitation of trees for firewood and construction) and browsing (Diress Tsegaye *et al*., 2010; Majumdar and Datta, 2015; Malik and Bhatt, 2016).

Species diversity has been recognized as an important component of sustainable development of *Prosopis juliflora* with native species (Tang *et al*., 2010). This is because ecosystems with diverse species resilient for competition for resources with *Prosopis juliflora*. The decline of Shannon diversity index under open grazing lands and *Prosopis juliflora* thicket compared to other habitats might be due to disturbance intensities under open grazing lands and invasive effects of *Prosopis juliflora*.

The Shannon diversity value for non-invaded woodlands and *Prosopis juliflora* with native species stands were comparable with research reports such as Belay Zerga *et al*. (2015) and Aggarwal (2012). It was found that in the present study Shannon diversity index was lower than those of Kumar and Mathur (2014). High species richness allows the provision of ecosystem services in terms of plant biomass accumulation, which ultimately sequester greenhouse gasses from the atmosphere (Ceroni *et al*., 2007). The higher species richness under *Prosopis juliflora* with native species stands and non-invaded woodlands contributes to the decline of *Prosopis juliflora* invasions and other effects including anthropogenic impacts, grazing, and disturbance intensities.

It was found that woody species abundances can account for the variations of species richness better than models involving either tree species richness or dominance (Zilliox and Gosselin, 2014). In addition, the increase in the density of individual stems in the form of tree and seedling stages under non-invaded woodlands and *P. juliflora* mixed with native species stands might be due to its allopathic substances that would inhibit the growth of associated native species (Pasiecznik *et al*., 2001; El-Keblawy and Al-Rawai, 2007; Samuel Getachew *et al*., 2012). In our study, the trend of the densities of species under canopies of *Prosopis juliflora* thicket, *Prosopis juliflora* with native species stands, and acacia woodlands were similar to results reported by Muturi *et al*. (2013) in Turkwel of Kenya.

In this study, high importance value index for *Prosopis juliflora* in *Prosopis juliflora* thickets was recorded than in other habitats in comparison to the importance value indices of native woody species. The importance value index is used for prioritizing species conservation whereby species with low importance value index need high conservation priority compared to the ones with high importance value index (Kacholi, 2014; Wakshum Shiferaw *et al*., 2018c).

Quantitative analysis of the regeneration status of woody species recorded in this study may provide baseline information to design, formulate conservation and management strategies for *Prosopis juliflora* dominated woodlands. Moreover, regeneration of vegetation is a vital process showing which old woody species die and replaced by young ones in perpetuity (Malik and Bhatt, 2016). Regeneration status of woody species of any vegetation is determined on the basis of densities of seedlings and saplings (Singh *et al*., 2016). The ratio of various age groups in a population determines the reproductive status of the population and indicates the future course (Odum, 1971).

Following Singh *et al*. (2014), contagious distribution was shown by maximum species followed by regular distribution and random distribution. Thus, it was found that about 68.8% of tree and sapling stratums were recorded under non-invaded woodlands. Moreover, 62.5% of seedlings were recorded under non-invaded woodlands which showed the highest percentage of regular patterns of distribution. The decline in the number of trees under non-invaded woodlands was accounted for the effects of human activities such as intensive livestock grazing and disturbances (Diress Tsegaye *et al*., 2010).

The distribution patterns of tree species under non-invaded woodlands and *Prosopis juliflora* with native species stands were similar to the research findings by Patel *et al*. (2012). However, the distribution of trees under *Prosopis juliflora* with native species stands were higher than non-invaded wood lands and *Prosopis juliflora* thicket which were in contrary to the findings reported by Muturi *et al*. (2013). The reason could be the variations in the management of vegetation types and age factor of *Prosopis juliflora* that might not be affected native species under *Prosopis juliflora* with native species stands in Kenya.

Regeneration is a very important phase for intervation of vegetation management by natural resource managers as it maintains the desired species composition and stocking and can be predicted by the structure of the population (Pande *et al*., 2014). Different categories of regeneration status were designated following (Pokhriyal *et al*., 2010; Pande *et al*., 2014; Khaine *et al*., 2018).

Furthermore, the regeneration patterns of some woody species such as *Salvadora persica* and *Cadaba rotundifolia* under non-invaded woodlands showed good regeneration in the study areas. In contrary to our findings, findings of Endris Ahmed *et al*. (2017) showed that *Prosopis juliflora* under *P. juliflora* mixed with native species stands and *A. mellifera* under non-invaded woodlands were good regeneration profiles in the Hallideghie wildlife reserve, Northeast Ethiopia. Furthermore, the density of seedlings for *Prosopis juliflora* and *Acacia tortilis* under *Prosopis juliflora* mixed with native species stands, non-invaded woodlands, and *Prosopis juliflora* thicket also showed different regeneration profiles in comparision to reports by Muturi *et al*. (2013).

5. 4. Invasion of *Prosopis juliflora* and soil physicochemical properties in Teru and Yalo districts

The invasion of *Prosopis juliflora* was changed the physicochemical properties of Teru and Yalo districts. The overall soil pH in *Prosopis juliflora* invaded was higher than non-invaded grazing lands. The increase of pH in *Prosopis juliflora* invaded lands reason could be due to the proximity of river particularly in Teru district that declined organic carbon stock due to runoff (Morrissey et al., 2014). In this study, soil pH of the soil was thus rated as moderate salinity in both *Prosopis juliflora* invaded and adjacent non-invaded open grazing lands (Beernaert and Bitondo 1992 cited in Asongwe *et al*., 2016).

It was found that though the soil pH critical level varies the trend of soil pH under *Prosopis* invaded and open grazing lands were similar to findings by Menezes & Salcedo (1999) in the semi-arid of Northeastern Brasil. The pH of the soil under *Prosopis juliflora* was similar to research made by Cibichakravarthy *et al*. (2011) near the Wetland Experimental Station of Tamil Nadu Agricultural University of India, and Merkineh Mesene and Tsegaye Kabtamu (2017) for the case of Dupti in Afar region of Ethiopia. However, the average value of soil pH under *Prosopis juliflora* invaded lands in comparsion to non-invaded grazing lands which contradict findings of Kahi *et al*. (2009) in Njemps Flats at the Baringo district of Kenya and similar with findings of Vallejo *et al*. (2012) in intensive silvopastoral systems of Colombia. Exchangeable Na^+ (Ex Na^+) is the sodium content in the resulting solution and ready for uptake by plant roots in the soil. Excess Ex Na^+ destroys this soil structure by causing the individual soil particles to repel each other (Harron *et al*., 1983). Moreover, Elbashier *et al*. (2016) pointed out that soluble salts affect the productivity of soils in changing the osmotic potential of soil solution and increasing the content of Ex Na^+.

In this study, the average values of was less by 24.2% than. The higer Ex Na^+ under *Prosopis juliflora* invaded lands in comparsion to non-invaded grazing lands might be due to the amelioration effects of *Prosopis juliflora* that lessen Ex Na^+ (Maghembe *et al*., 1983; Nisar *et al*., 2013). The critical values of Ex Na^+ in the soil for both land use systems were rated as medium in the study areas (Munjeb *et al*., 2018). In the present study, Ex Na^+ under *Prosopis juliflora* invaded lands and non-invaded lands were less than the same land uses in semiarid northeast of Brazil (Menezes and Salcedo, 1999). On the other hand, it was found that the mean value of Ex Na^+ was similar with 7 years old of *Prosopis juliflora* invaded lands of India, but less than 5 years age of *Prosopis juliflora* (Bhojvaid *et al*., 1996).

The increase in the mean values of water soluble Ca^{2+} + Mg^{2+} under non-invaded open grazing lands in comparsion to *Prosopis juliflora* invaded lands might also be due to the reducing effects of *Prosopis juliflora* (Basavaraja *et al*., 2007). According to Munjeb *et al*. (2018), the critical value was rated as about low for Ca^{2+} and medium for Mg^{2+} both land use systems. However, ater soluble Na^{+} was declined under *Prosopis juliflora* invaded lands was possibly due to the uptake of water soluble Na^{+} by *Prosopis juliflora* (Basavaraja *et al*., 2007). In addition, the mean value of ESP under *Prosopis juliflora* was lower than the soils under open grazing lands. The reason was due to the reclaiming capacity of salt concentrations namely Na^{+} relative to Ca^{2+} and Mg^{2+} by *Prosopis juliflora* (Tiedemann and Klemmedson 1973; Maghembe *et al*., 1983; Nisar *et al*., 2013).

The soil of both *Prosopis juliflora* invaded and non-invaded open grazing lands were non-saline (Qadir *et al*., 2002; Gonzalez *et al*., 2004). It was found that salinity status of the study areas was also varied from that of Mishra and Sharma (2003) at Uttar Pradesh, at Dehra Dun of India.

The increase in clay content under *Prosopis juliflora* invaded lands in comparsion to to non-invaded grazing lands might be due to the invasion effects of *Prosopis juliflora* which in the long run modified soil texture in study areas (Merkineh Mesene and Tsegaye Kabtamu, 2017) and low Ex Na^{+} under *Prosopis juliflora* invaded lands could also reduce the dispersion of clay materials. It was found that the clay content of *Prosopis juliflora* invaded areas was higher, but similar with non-invaded areas for 5 and 7 years old invasion of *Prosopis juliflora* in sodic soils of Haryana of India (Bhojvaid, 1998). Moreover, the mean value of clay content in the soil for both *Prosopis juliflora* invaded and non-invaded lands were less than finding by Vallejo *et al*. (2012) in Colombia.

In Yalo district the mean values of soil moisture and soil compaction were declined, but soil water content was affinity to be raised under open grazing lands than *Prosopis juliflora* invaded lands. These could be due to inputs of animal manures around homestead where the soil samples had collected in this district (Morrissey *et al*., 2014; Su *et al*., 2016). Thus, this could be the cause for the decline of soil bulk density and soil moisture content in Yalo district.

5.5. Status of soil seed bank in Afar region

The study revealed that invasion of *Prosopis juliflora* has affected soil seed banks in the study sites. The overall number of families and species in the soil seed bank were far lower than that of above-ground flora. In the present study, the number of species in the soil seed bank was comparable with a research report by Fengqin *et al*. (2017) but their findings show that less number of species and families in the above-ground flora were recorded than present results.

In this study, higher frequent families were recorded in soil seed bank of non-invaded woodlands than habitats under *Prosopis juliflora* canopies such as *Prosopis juliflora* thickets and *Prosopis juliflora* with native species stands. This might be due to the allopathic effects (Samuel Getachew *et al*., 2012; Mahdhi *et al*., 2018), the density of rhizobia organisms which able to nodulate *Prosopis juliflora* was higher than native nitrogen fixer species (Mahdhi *et al*., 2018*)* and it’s shading effects (Rotich, 2016). These effects could favor the production of large amounts of seeds for *Prosopis juliflora* which had dominated other native species under *Prosopis juliflora* thicket and *Prosopis juliflora* with native species stands than non-invaded woodlands.

The higher dominance of forbs and grass growth forms in comarsion to woody species were due to shade-tolerant properties of the forbs and grass species (Wakshum Shiferaw *et al*., 2018b). Furthermore, post-dispersal processes such as predation and removal of seeds from the above-ground caused limitation in the viability of seeds of woody species (Salazar, 2010). These findings were incomparable with a report made by Tesfaye Bekele (2000) in the dry Afromontane forest in South Wollo of Ethiopia.

Moreover, our findings were similar to soil seed banks of dry seasons, but in contrast to soil seed bank in the wet season of research made by Madawala *et al*. (2016). Furthermore, the number of growth forms in the form of forbs, climbers and woody species had similar trends both in the forest relic and closed areas to that of research works by Reubens *et al*. (2007) in dry tropical forests of Northern Ethiopia. But, the number of graminoids recorded by the authors above was in contrast to the present study of Amibara and Awash Fentale districts.

In the study sites, plant species such as *Amaranthus thunbergii, Alysicarpus rugosus, Physalis lagascae, Brachiaria leersioides, Ipomoea indica, Crotalaria pycnostachya, Euphorbia prostrate, Ocimum urticifolium* which were in the soil seed banks but absent in the standing vegetation. The reason could be the effects intensity of grazing intensity and disturbances factors which had affected those species from standing vegetation.

In restoring degraded woodlands, the first step is to quantify the actual and potential levels of natural regeneration, examining the role of soil seed banks as propagule contributor (Gul *et al*., 2012). The mean values of species diversity in terms of Shannon diversity index and species richness declined under *Prosopis juliflora* invaded patches than non-invaded woodlands. These were due to the allelopathic and shade effects of the species underneath *Prosopis juliflora* canopy which had reduced seed productivity. Furthermore, greater accumulation of litters underneath *Prosopis juliflora* canopy could explain the greater inhibition of understory vegetation to produce seeds (El-Keblawy, 2012; Kaur *et al*., 2012, El-Keblawy and Al-Rawai, 2007; Muturi *et al*., 2013). Under high invasion of *Prosopis juliflora*, less species richness was recorded in soil seed bank when we compare with Ilukor *et al*. (2016) findings in Gewane, Awash Fentale and Amibara districts.

In Awash Fentale district, the dominance of few species for instance invasion of *Prosops juliflora* attribute to lower in Shannon diversity index that produces seeds to land on/in the soil (Singh *et al*., 2008; Kumar and Mathur, 2014). The highest values of Shannon diversity index under moderate disturbance might be due to favorable environmental variables that enhance the growth of a variety of plants in an ecosystem (Gautam *et al*., 2016). Our results were also in line with findings made by Biswas and Malik (2010) in riparian and upland plant communities of Canada. The level in the effects of disturbance on species diversity in present study was also comparable with a multi-trophic perspective of Wootton (1998).

In the study sites, though soil layer did not have negatively affects Shannon diversity values and species richness of soil seed banks, the highest Shannon diversity index and species richness were recorded in the lower soil layer. The reason might be due to the small size and elongated seeds those moved down to the subsoil and persistent in the soil (Moles *et al*., 2000; Peco *et al*., 2003; Eager *et al*., 2013).

Vertically down the soil layers, the density of seedlings germinated from soil samples in the greenhouse was declined. This pattern is assumed as regular seed inputs at the surface and a more or less gradual decline in viability as seeds aged and move vertically down soil profiles (Thompson *et al*., 1997). Our findings were similar trends with that soil seed banks density distribution pattern with Cox and Allen (2008). However, the density of soil seed bank for *Prosopis juliflora* was far less than that of reports made by Hailu Shiferaw *et al.* (2004) in the litter layer in Middle Awash Rift Valley Area in Northeastern Ethiopia. These variations in the density of *P. juliflora* could be due to seasonal effects and random spatial distribution of seeds in the soil samples.

Moreover, the densities of soil seed bank in these findings were greater than for both seasons of research findings by Kellerman and Van Rooyen (2007) in selected habitat types in the Maputa Land of South Africa. However, the densities of the soil seed bank in the present findings were far less than the density of the soil seed bank by Dreber (2011) in arid rangelands of the Nama Karoo of Sothern Africa.

Results showed that seeds recovered from soil samples were low similarity to the standing vegetation in both of the habitats and the least similarity was recorded between *Prosopis juliflora* thicket and *Prosopis juliflora* with native species stands; and *Prosopis juliflora* thicket and open grazing lands. Only three species such as *Cenchrus ciliaris, Parthenium hysterophorus,* and *Prosopis juliflora* under *Prosopis juliflora* thicket and *P. juliflora* with native species stands of soil seed banks were common to the same habitats of standing vegetation. Whereas, four species such as *Leucas martinicensis, Solanum. incanum, Cenchrus ciliaris, Parthenium hysterophorus* and *P. juliflora* under non-invaded wood lands of soil seed bank were similar to (shared species) non-invaded wood lands of standing vegetations.

Furthermore, *Leucas martinicensis, Parthenium hysterophorus* and *Prosopis juliflora* were common species under open grazing lands in soil seed bank and standing vegetation. The reason might be due to the variations in the persistence of the seeds that contributed to vegetation composition of the standing vegetation and below ground flora (Hopfensperger, 2007; Gioria and Pysek, 2016). Moreover, the dissimilarity between above ground and below ground flora might also be due to the effects of grazing (Chaideftou *et al*., 2009) and increased disturbance intensities (Li *et al*., 2017).

Our findings were similar with studies reported by Degefi Sileshi, Berhanu Abraha (2014) and Mulugeta Lemnih and Demel Teketay (2006). However, in the present study patterns of similarity between above and below ground flora were different from the results of Koch *et al*. (2011) in the limestone grasslands, Valko *et al*. (2011) in the dry-mesophyllous grasslands and Sanou *et al*. (2018) around the savanna woodland watering point in West Africa.

The soil seed banks in Shannon diversity index, species richness and Shannon evenness were significantly decreased at other aspects than northwest and east facings of the study areas. These could be due to the effects of easterlies wind which had caused the seed rain to land on these facings. Moreover, due to the higher amount of solar radiation received and consequently, the increased air and soil temperature on the east-facing slopes had increased species diversity in the above-ground flora which had also favored the diverse and abundances of seeds in the soil (Eshetu Yirdaw *et al*., 2015).

Results showed that not clear variations in Shannon diversity index, species richness and Shannon evenness of vegetation patterns observed in the study areas. The reason might be due to insignificant variations in the topography of the study landscapes in Southern Afar region. However, in general variations in slopes of an area indirectly detected the variations in moisture and soil fertility which as the result affects the density of above ground and soil seed banks as well (Chapman and McEwan, 2018).

The reasons for higher seed Shannon diversity index might be due to shoats feeding habits which are different from that of cattle. That means shoats are both browsers and grazers. Other reasons might also be due to the smaller seeds which increase survival rate during gut passage in greater numbers than larger seeds in cattle gut which had contributed for high species/seed richness (Bruun and Poschlod, 2006).

Furthermore, cattle are feeding large quantities of biomass which might also cause for species/seeds richness higher. Among the dispersers, in the cattle fecal matter, the higher overall density of seeds kg^{-1} was recorded than in fecal matters of shoats. This idea was confirmed by a study of Bilal (2015) in the Netherlands. Moreover, cattle are usually fed on ground pods of *P. juliflora* which had dropped on the floor. These findings were similar to the report of Mworia *et al*. (2011) in the riverine wood lands of upper floodplain at Tana River in Kenya.

In Teru and Yalo districts, most of the species germinated were also herbaceous species like grass species (Wakshum Shiferaw *et al.*, 2018b). The patterns of the density of soil seed banks were increasing from the top soil layer towards subsoil layer. These might be due to the size of the seeds which moved down to the lower soil layers (Wakshum Shiferaw *et al.,* 2018b). Moreover, the germination of the soil seed banks in the lower soil layers might be the effects of soil depth hindered from emergence (Dalling *et al*., 1995) and insufficiency of soil moisture to reach lower soil layers (Tang *et al*., 2016). Other reasons might be due to the effects of disturbance such as grazing of the study areas and harsh climatic conditions.

In both the districts, densities of soil seed banks for *Prosopis juliflora* were few. The reason might be due to its hard seed that could not break its mechanical dormancy (Hailu Shiferaw *et al*., 2004; Aster Tadesse, 2009). With compared to the density of the soil seed banks of Teru districts, the density of soil seed banks in Yalo district found to be very low. These could be due to the variations of the effects of the grazing (Koc *et al.*, 2013), and human impact (Li *et al.*,

2017) intensities for the two districts. While the number of soil seeds recovered in both districts were also low in comparison to other sites in the region and elsewhere in Ethiopia. The reasons might be due to temporal and spatial variations of the status of seeds in the soil (Madawala *et al*., 2016), the effects in the variations of nutrient conditions (Gough *et al.*, 2015), and potential of the seeds rains in the districts (Gross and Mackay, 2014).

Moreover, lower rates of seed dispersal and unfavorable micro-climatic conditions like extreme high temperatures which contributed to higher mortality rates of seeds during rainy seasons might also be the reasons for the lower density and richness of seeds in Yalo district than Teru district (Ooi, 2012). The variations in the density of soil seed banks could also be due to the variations of altitudes in between the districts. At higher altitudes the density of seeds in soils are lower than that of low lying altitudes which is likely due to the effects of gravity and wind movement deposited seeds in lower altitudes (Jalili *et al*., 2003).

On the other hand, the number of species emerged in both Teru and Yalo districts were lower than that of findings by Zewdu Kelkay *et al*. (2017) in a semi-arid African savannaand Reubens *et al*. (2007) in Northern Ethiopia. Moreover, the number of species recovered from the soil seed banks in the present study areas was far lower than that of Dreber (2011) in arid Nama Karoo rangelands in the South Africa. The decline of abundance and density of the soil seed banks in the *Prosopis juliflora* invaded areas could also be due to the allelochemical effects of the *P. juliflora* (Pasiecznik *et al*., 2001; Samuel Getachew *et al*., 2012) and effects of shade by *Prosopis juliflora* that inhibit native species to produce sufficient seeds (Mosbah *et al*., 2018).

Findings made by Hailu Shiferaw *et al*. (2004) in the Middle Awash of Ethiopia was greater than the density of the seeds recovered from the soil seed banks in Yalo district, but lower than that of

Teru district. The density of soil seed banks in both districts was greater than research made by Aster Tadesse and Coppock (2015) in Northeastern Ethiopia in both the invaded and non-invaded areas of *Prosopis juliflora*.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

Three percent of the area of woodlands and grazing lands were converted to *Prosopis juliflora* invaded lands during 1986–2017 in the study area. It is concluded that the pastoral production system will be under increasing threat if the present land-use/cover changes are go on unmitigated. Current management practices are also not satisfactory to sustain the woodlands. Unless improved management interventions are adopted, the sustainability of ecosystem services will be at stake.

In the study sites, the phenology of *Prosopis juliflora* such as proportions of green pod and flowering per tree varied indicated that the preventaion of the invasion of *Prosopis juliflora* spatially varied. The proportions of in the phenology stages of *Prosopis juliflora* varied across seasons are indications for the successive reproduction seasons of the plant into seeds and uses of the green and mature pods for cattle feeds and ultimately reduce dispersal of its seeds. Moreover, it was found that abundances of the inflorescences and green leaf had shown insignificant variations through the seasons implied that *Prosopis juliflora* is using resources (moisture, nutrients) better than other native species.

The patterns of the phenological satges of *Prosopis juliflora* showed high leafing and flowering relatively in cool seasons. These will have implications for the integrated management in order to alleviate flourishing and invasion of the species. With respect to precipitation, it was found that inconsistent variations in different precipitation gradients. In different seasons of the year, it showed that *Prosopis juliflora* could adapt to different moisture gradients and is progressing into large areas competing for resources in the region.

The study shows that diversity of native species was declined as the density of *Prosopis juliflora* increased in invaded habitats than non-invaded habitats. These implied that invasion effects of *Prosopis juliflora* had threat on native species. Physiographic factors such as aspect, slope, and altitude had affected density of woody species. At higher altitude and slopes, the densities of woody species were lower than medium and lower slopes indicated that *Prosopis juliflora* was more severe at the lower and medium topography and altitudinal ranges. The invasion of under *Prosopis juliflora* had affected the growth of new regeneration which could pass into higher size classes. The lower the number of seedlings under the *Prosopis juliflora* thicket was implications of allopathic effects.

Between soil seed banks and standing vegetation, the Sorensen's coefficient revealed the lowest similarity. These had also indicated for the loss and degradation of below-ground flora of the grass and woodlands. Thus, these losses and other underlying effects of drought might delay the natural restoration of vegetation in the region. It was found that cattle were the most for seed dispersal agents and disseminating large amounts of individual plant seeds and *Prosopis juliflora* in the study landscapes. The overall density of soil seed bank in the *Prosopis juliflora* invaded and non-invaded areas in comparison to similar agro-ecology had implications of poor rangeland quality for animals to feed on and consequently affects the livelihood incomes obtained from livestock.

In this study, most results indicated that invasion of *Prosopis juliflora* had positive effects on physicochemical properties of the study areas. Therefore, the soils of the study areas were conducive for cereal crops and forage production.

6.2. Recommendations

If the present LULCC continues, pastoralists grazing lands will be lost. Therefore, the following recommendations will be suggested to conserve rangelands in the region:-

- Further studies about the phenology of *Prosopis juliflora* should be encouraged to reduce seed dispersal and reduce its invasiveness.
- To minimize the adverse effects of *Prosopis juliflora* on the native species, appropriate silvicultural management practices such as thinning, pollarding and pruning can also be applied.
- As seeds in the soil were low in the study areas, *in-situ* and *ex-situ* conservation of original plants and reseeding of grass species are recommended to sustain the grazing areas in the region.
- To minimize its progress into other land uses, mechanical clearing/uprooting of *Prosopis juliflora* seedlings and clearing by bulldozer from farmlands, grazing lands, woodlands, and urban or settlement areas.
- Thus, control of *Prosopis juliflora* by utilization can also be among another option to minimize its density from different land uses in the region.

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APPENDICES

Appendix 1. The results of ANOVA showing effects of site, season, temperature, and precipitation on proportion of *Prosopis juliflora* phenology stages at Amibara and Awash Fentale districts

Phenology stage ×variable	Sum of Squares	Df	Mean Square	*F*-value	*P*-value
Green leaf × Season	2605	3	868	1.544	0.206
Flowering × Season	933	3	311	0.641	0.59
Green pod × Season	2136	3	712	4.069	0.008*
Mature pod ×* Season	103	3	34	1.295	0.279
Green leaf × temperature	10656	10	1066	2.011	0.037*
Flowering ×temperature	7324	10	732	1.586	0.118
Green pod × temperature	4210	10	421	2.501	0.009*
Mature pod × temperature	307	10	31	1.166	0.32
Green leaf × precipitation	9015	6	1502	2.854	0.012*
Flowering × precipitation	1477	6	246	0.5	0.807
Green pod × precipitation	2053	6	342	1.905	0.085
Mature pod × precipitation	165	6	27	1.029	0.41

Appendix 2. Plant species list in Amibara and Awash Fentale districts, Ethiopia

Scientific name	Family	Life form	Vernacular name*	SCN
Abutilon anglosomaliae Cufod.	Malvaceae	Forb	Hambukto	WSC143
Abutilon figarianum Webb	Malvaceae	Forb	Hedayito	WSC154
Abutilon fruticosum Guill. & Perr.	Malvaceae	Shrub	Hambukto	WSC005
Abutilon ramosum Guill. & Perr.	Malvaceae	Forb	Hambukto	WSC144
Acacia mellifera (Vahl) Benth.	Fabaceae	Shrub	Makharto	WSC007
Acacia nilotica (L.) Willd. ex. Del.	Fabaceae	Tree	Kasalto	WSC145
Acacia oerfota (Forssk) Schweinf.	Fabaceae	Tree	Gerento	WSC115
Acacia senegal (L.) Wild.	Fabaceae	Tree	Adado	WSC104
Acacia tortilis (Frossk.) Hayne	Fabaceae	Tree	E’ebto	WSC003
Acalypha acrogyna Pax	Euphorbiaceae	Forb	Berbere	WSC063
Achyranthes aspera L. var. pubeseens *(Moq*	Amaranthaceae	Forb	Murit tabiri	WSC125
Aerva javanica (Burm.f.) Schultes	Amaranthaceae	Shrub	Olyato	WSC018
Alternanthera pungens Kunth.	Amaranthaceae	Forb	Ferengisisib	WSC040
Amaranthus dubius Thell.	Amaranthaceae	Forb	Bonket/Bunkete	WSC146
Amaranthus thunbergii Moq.	Amaranthaceae	Forb	Aburi	WSC107
Asparagus africanus Lam.	Asparagaceae	Forb	-	WSC147
Balanites aegyptiaca (L.) Del.	Balanitaceae	Tree	Udda	WSC044
Barleria acanthoides Vahl	Acanthaceae	Forb	Ganzalto	WSC004
Berchemia discolor (Klotzsch) Hemsl.	Rhamnaceae	Tree	Jajaba'ito	WSC122
Blepharis maderaspatensis (L.) Roth	Acanthaceae	Forb	Yamarukta	WSC118
Boerhavia coccinea Mill.	Nyctaginaceae	Forb	Asara	WSC167
Boerhavia repens L.	Nyctaginaceae	Forb	Asara	WSC119
Brachiaria ramosa (L.) Stapf	Poaceae	Herb (A)	Gewita	WSC075

Cadaba glandulosa Forssk.	Capparidaceae	Shrub	Ududoyta	WSC139
Cadaba longifolia (R. Br.) DC.	Capparidaceae	Shrub	Dunbiya	WSC110
Cadaba rotundifolia Forssk.	Capparidaceae	Tree	Haragali	WSC184
Calotropis procera (Ait.) Ait. f.	Asclepiadaceae	Forb	Gelato/garbaadiyita	WSC059
Capparis tomentosa Lam.	Capparidaceae	Climber	Dangayito	WSC169
Ceinfugosia somaliana Fryx	Malvaceae	Shrub	Hameresa	WSC117
Cenchrus ciliaris L.	Poaceae	Herb (P)	Serdoyita	WSC024
Centrostachys aquatica (R.Br.) Wall. ex Moq.	Amaranthaceae	Forb	Bete	WSC038
Chenopodium album L.	Chenopodiaceae	Forb	Riba	WSC073
Chrysopogon plumulosus Hochst.	Poaceae	Herb (P)	Durfu	WSC079
Cissus quadrangularis L.	Vitaceae	Climber	Ala'e	WSC149
Cissus rotundifolia (Forssk.) Vahl	Vitaceae	Climber	Al'ie	WSC106
Clematis hirsuta Perr. & Guill.	Ranunculaceae	Climber	Adayito	WSC056
Clematis longicauda Steud. ex A. Rich.	Ranunculaceae	Climber	Matamato	WSC172
Cocculus pendulus (J.R. & G. Forst)	Menispermaceae	Climber	Hayikto	WSC131
Commelina diffusa Burm.f	Commelinaceae	Forb	Mutuki	WSC070
Commicarpus plumbagineus (Cav.) Standl.	Nyctaginaceae	Climber	Yejib chama	WSC162
Commiphora coronillifolia Chiov.	Burseraceae	Shrub	File neme'a	WSC033
Cordia sinensis Lam.	Boraginaceae	Shrub	Maderto	WSC002
Cryptostegia grandiflora Roxb. Ex R. Br.	Asclepiadaceae	Climber	Halimaro	WSC046
Cucumis dipsaceus Ehrnb. ex spach.	Cucurbitaceae	Climber	Seroyita	WSC051
Cucumis prophetarum L.	Cucurbitaceae	Forb	Garaun	WSC089
Cyathula cylindrica Moq.	Amaranthaceae	Forb	Kandadaf	WSC077
Cycnium erectum Rendle	Sclrofloriaceae	Forb	Andoliva	WSC151
Cymbopogon commutatus (Steud.) Stapf	Poaceae	Herb (P)	Haragali	WSC083
Cymbopogon pospischilii (K. Schum.) C.E. Hubb.	Poaceae	Herb	-	WSC170
Cynodon dactylon (L.) Pers.	Poaceae	Herb (P)	Rareta	WSC041
Cynodon nlemfuensis Vanderyst	Poaceae	Herb (P)	Rareta	WSC037
Dactyloctenium scindicum Boiss.	Poaceae	Herb (P)	Afara mole	WSC026
Delonix elata L. Gamble	Fabaceae	Tree	Amayito	WSC134
Diceratella elliptica Guill. & Perr.	Brassicaceae	Herb	Moroe'i	WSC080
Diceratella incana Balf.f.	Brassicaceae	Forb	Atikhara	WSC103
Digitaria velutina (Forssk.) P. Beauv.	Poaceae	Herb (A)	Santkefa	WSC097
Dobera glabra (Forssk.) Poir.	Salvadoraceae	Shrub	Gersayiato	WSC154
Dregea rubicunda K. Schum.	Asclepiadaceae	Forb	Golfaha	WSC064
Ecbolium viride (Forssk.) Alston	Acanthaceae	Forb	Kinoyita	WSC120
Echinochloa colona (L.) Link	Poaceae	Herb (A)	-	WSC163
Eleusine africana Kenn.-O'Byrne	Poaceae	Herb (A)	-	WSC110
Eragrostis aethiopica Chiov.	Poaceae	Herb (A)	Ayti-adoyta	WSC074
Eragrostis biflora Hack.	Poaceae	Herb (A)	-	WSC155
Eragrostis cilianensis (All.) Vign. ex Janchen	Poaceae	Herb	-	WSC118
Eragrostis cylindriflora Hochst.	Poaceae	Herb (A)	Dankit/feresgera	WSC156
Eragrostis papposa (Roem. & Schult.) Steud.	Poaceae	Herb (P)	Bekelayso	WSC078

Eriochloa fatmensis (Hochst. & Steud.) Clayton	Poaceae	Herb (A)	Bohale	WSC019
Erucastrum arabicum Fisch. & Mey.	Brassicaceae	Forb	Ferate	WSC026
Eurphorbia longituberculosa Boiss.	Euphorbiaceae	Forb	Haliforesi	WSC034
Fagonia schweinfurthii (Hadidi) Hadidi.	Zagophyllaceae	Shrub	Adihara	WSC129
Fuirena leptostachya Oliv.	Cyperaceae	Herb	Ka'ato	WSC158
Glossonema revoilii Franch.	Asclepiadaceae	Forb	Sanga hayu	WSC081
Grewia flavescens Juss.	Tiliaceae	Shrub	Menangure/Garuwayito	WSC035
Grewia schweinfurthii Burret	Tiliaceae	Shrub	Manangurita/AdePJTo	WSC127
Grewia tenax (Forssk.) Fiori	Tiliaceae	Forb	Hedayito	WSC032
Grewia villosa Willd.	Tiliaceae	Shrub	Garawayito/legida	WSC035
Heliotropium longiflorum (A.DC. in DC.) Jaub. & Spach	Boraginaceae	Forb	Kinbira hara	WSC092
Hermannia paniculata Franch.	Sterculiaceae	Shrub	-	WSC043
Hibiscus calyphyllus Cavan.	Malvaceae	Shrub	Hambukito	WSC091
Hibiscus crassinervius Hochst. ex A. Rich.	Malvaceae	Forb	Akulito	WSC106
Hibiscus dongolensis Del.	Malvaceae	Forb	Walayneba	WSC028
Hibiscus micranthus L. f.	Malvaceae	Forb	Okelehina	WSC164
Huernia somalica N.E. Br.	Asclepiadaceae	Forb	-	WSC200
Hyparrhenia rufa (Nees) Stapf	Poaceae	Herb (P)	Isesu	WSC163
Hypertelis bowkeriana Sond.	Molluginaceae	Forb	Asara	WSC073
Hypoestes forskaolii (Vahl) R. Br.	Acanthaceae	Forb	Harawayitu	WSC006
*Hypoestes triflora (*Forssk.) Roem. & Schult.	Acanthaceae	Forb	Harawayitu	WSC180
Hyptis pectinata (L.) Poit.	Lamiaceae	Forb	Amada	WSC165
Hyptis spicigera Lam.	Lamiaceae	Forb	Amado	WSC054
Indigofera coerulea Roxb.	Fabaceae	Forb	Dunwayito	WSC126
Indigofera hochstetteri Bak.	Fabaceae	Forb	Aro	WSC060
Ipomoea cairica (L.) Sweet	Convolvulaceae	Climber	-	WSC166
Jatropha ellenbeckii Pax	Euphorbiaceae	Forb	-	WSC036
Jatropha glauca Vahl	Euphorbiaceae	Shrub	Halfolisi	WSC022
Kleinia odora (Forssk.) DC.	Astreraceae	Climber	Bisilto	WSC133
Leptadenia hastata (Pers.) Decne.	Asclepiadaceae	Climber	Hayikto	WSC012
Leucas inflata Benth	Lamiaceae	Forb	Bunketi	WSC025
Leucas martinicensis (Jacq.) R. Br.	Lamiaceae	Forb	Kurufule	WSC160
Linum strictum L.	Linaceae	Forb	-	WSC090
Linum volkensii Engl.	Linaceae	Forb	Susui	WSC140
Lipocarpha hemisphaericus (Roth) Goetgh.	Cyperaceae	Herb	Gerandoyta/Gedoyta	WSC153
Lipocarpha rehmannii (Ridl.) Goetgh.	Cyperaceae	Herb	Abuu	WSC111
Lonchocarpus laxiflorus Guill. & Perr.	Fabaceae	Forb	Halemagira	WSC143
Maerua angolensis DC.	Capparidaceae	Shrub	Dunbayito	WSC144
Megalochlamys ogadenensis Vollesen	Acanthaceae	Shrub	Gelsanto	WSC116
Megalochlamys violacea (Vahl) Vollesen	Acanthaceae	Forb	Uraurto	WSC052
Otostegia fruticosa (Forssk.) Schweinf.ex Penzig	Acanthaceae	Forb	Atihara/michi	WSC169
Monothecium glandulosum Hochst.	Acanthaceae	Forb	Kulumintili	WSC069
Nicotiana glauca R. Grah.	Solanaceae	Tree	Adihara	WSC170

Ocimum circinatum A.J Paton	Lamiaceae	Forb	Harawayitu	WSC106
Ocimum forskolei Benth	Lamiaceae	Forb	Kayidiriya	WSC085
Ocimum jamesii Sebald	Lamiaceae	Herb	-	WSC174
Ocimum americanum L.	Lamiaceae	Forb	Kaqtuhara	WSC016
Orthosiphon pallidus Royle ex Benth.	Lamiaceae	Forb	Yengula hebaki	WSC067
Otostegia fruticosa (Forssk.) Schweinf. ex Penzig	Lamiaceae	Shrub	-	WSC183
Otostegia modesta S. Moore	Lamiaceae	Forb	-	WSC121
Echinochloa colona (L.) Link	Poaceae	Herb (A)	Baruri	WSC034
Panicum subalbidum Kunth	Poaceae	Herb (A)	Heniso	WSC124
Parkinsonia scioana (Chiov). Brenan	Fabaceae	Shrub	Sosokite	WSC171
Parthenium hysterophorus L.	Astreraceae	Forb	Hari	WSC001
Paspalidium desertorum (A. Rich.) Stapf	Poaceae	Herb (P)	-	WSC019
Pavonia arabica Hochst. & Steud. ex Boiss.	Malvaceae	Forb	-	WSC091
Pergularia daemia (Forssk.) Chiov.	Asclepiadaceae	climber	Gime'ito	WSC076
Peristrophe paniculata (Forssk.) Brummitt	Acanthaceae	Forb	Aburi	WSC136
Pisonia aculeata L.	Nyctaginaceae	Climber	Dambikiso	WSC042
Portulaca quadrifida L.	Portulacaceae	Forb	Hatihara	WSC175
*Prosopis juliflora (*Sw.) DC.	Fabaceae	Shrub	Dargi-haraa	WSC010
Pupalia lappacea (L.) A. Juss.	Amaranthaceae	Forb	Sarotkefa	WSC024
Salvadora persica L.	Salvadoraceae	Shrub	Adaito	WSC056
Sansevieria ehrenbergii Schweinf. ex Baker.	Dracaenaceae	Forb	Ya'ato	WSC176
Sansevieria forskaoliana (Schult. f.) Hepper & Wood	Dracaenaceae	Forb	Ya'a	WSC123
Schoenoplectus maritimus (L.) Lye	Cyperaceae	Herb	Ka'ato	WSC053
Seddera bagshawei Rendle.	Convolvulaceae	Forb	Riba	WSC023
Seddera latifolia Hochst. & Steud.	Convolvulaceae	Forb	Adiriba	WSC114
Senna italica Mill.	Fabaceae	Shrub	Oklehina	WSC027
Senna obtusifolia (L.) Irwin & Barneby	Fabaceae	Shrub	Salilimeki	WSC109
Setaria verticillata (L.) P. Beauv.	Poaceae	Herb (A)	Delayta	WSC177
Solanum coagulans Forssk.	Solanaceae	Forb	Alulis	WSC178
Solanum cordatum Forssk.	Solanaceae	Forb	Ubabulto	WSC050
Solanum incanum L.	Solanaceae	Forb	Kurara'i	WSC066
Solanum schimperianum Hochst. ex A. Rich.	Solanaceae	Forb	Bobao	WSC015
Sporobolus agrostoides Chiov.	Poaceae	Herb (P)	-	WSS171
Sporobolus consimilis Fresen.	Poaceae	Herb (P)	Denekto	WSC180
Sporobolus panicoides A.Rich.	Poaceae	Herb (A)	Gewita	WSC009
Sporobolus pellucidus Hoehst.	Poaceae	Herb (P)	Sosokete	WSC181
Sporobolus spicatus (Vahl) Kunth	Poaceae	Herb (P)	Edolatyansi	WSC039
Tetrapogon cenchriformis (A.Rich.) Clayton	Poaceae	Herb (A)	Sabrisi	WSC045
Thunbergia ruspolii Lindau	Acanthaceae	Forb	Harawayito	WSC086
Tragus racemosus (L.) All.	Poaceae	Herb (A)	Bekelayso	WSC078
Tribulus parvispinus Presl.	Zygophyllaceae	Forb	Bunket	WSC061
Tribulus terrestris L.	Zygophyllaceae	Forb	Bunket	WSC182
Verbesina encelioides (Cav.) A. Gray	Asteraceae	Forb	Surimia	WSC062

Wissadula rostrata (Schumach. & Thonn.) Hook.f.	Malvaceae	Shrub	Delgida	WSC142
Xanthium strumarium L.	Asteraceae	Forb	Bangi	WSC030
Ziziphus spina-christi (L.) Desf. var. mitissima Chiov.	Rhamnaceae	Tree	Kusirayito	WSC132
Zygophyllum simplex L.	Zygophllaceae	Forb	Mutiki	WSC034

Notices: * is Afar language SCN is Species Collection Name, A is annual grasses, and P is perennial grasses.

Appendix 3. Abundance, basal area (m2 ha-1), density (stems ha-1), Frequency and I_{VI} of woody species in Amibara and Awash Fentale distrcits (DBH/DSH > 2 cm)

District	Site	Habitat	SN	Ab/sampled area	BA (m^{2}ha^{-1})	D (stems/ha)	RD	Dom	Rdom	F	RF	I_{VI}	A/F
1	1	1	*Acacia nilotica*	3.0	0.3	6.3	0.1	0.6	1.0	0.1	1.1	2.2	0.3
2	4	1	*Acacia senegal*	5.0	0.0	10.4	0.2	0.1	0.1	0.1	1.1	1.4	0.5
2	3	1	*Acacia tortilis*	4.0	0.1	8.3	0.2	0.1	0.2	0.2	2.1	2.5	0.2
1	1	1	*Cadaba rotundifolia*	37.0	0.1	77.1	1.4	0.3	0.5	0.1	1.1	3.0	3.7
2	4	1	*Prosopis juliflora*	1203.0	5.5	2506.3	46.9	11.5	20.1	1.3	16.1	83.1	9.3
2	3	2	*Acacia oerfota*	2.0	0.0	4.2	0.1	0.0	0.1	0.1	1.1	1.2	0.2
1	1	2	*Acacia mellifera*	4.0	0.0	8.3	0.2	0.1	0.1	0.1	1.1	1.3	0.4
2	3	2	*Acacia nilotica*	3.0	0.1	6.3	0.1	0.1	0.2	0.2	2.1	2.5	0.2
2	4	2	*Acacia senegal*	136.0	1.0	283.3	5.3	2.1	3.7	0.5	6.4	15.5	2.7
2	3	2	*Acacia tortilis*	107.0	6.4	222.9	4.2	13.3	23.2	0.8	9.7	37.0	1.3
2	4	2	*Balanites aegyptiaca*	2.0	0.0	4.2	0.1	0.1	0.1	0.1	0.3	0.5	0.2
1	1	2	*Cadaba rotundifolia*	17.0	0.1	35.4	0.7	0.2	0.4	0.3	3.2	4.3	0.6
2	3	2	*Clematis longicauda*	4.0	0.2	8.3	0.2	0.3	0.6	0.2	2.1	2.9	0.2
2	4	2	*Dobera glabra*	1.0	0.2	2.1	0.0	0.4	0.6	0.1	0.0	0.7	0.2
2	4	2	*Grewia tenax*	5.0	0.0	10.4	0.2	0.1	0.1	0.1	1.1	1.4	0.5
2	4	2	*Prosopis juliflora*	353.0	4.2	735.4	13.8	8.7	15.2	1.3	16.1	45.0	2.7
1	2	2	*Salvadora persica*	8.0	0.0	16.7	0.3	0.1	0.1	0.1	1.1	1.5	0.8
2	3	2	*Ziziphus spina-christi*	3.0	0.2	6.3	0.1	0.3	0.6	0.1	1.1	1.8	0.3
2	4	3	*Acacia mellifera*	145.0	0.8	302.1	5.6	1.7	3.0	0.4	5.4	14.0	3.6
2	3	3	*Acacia senegal*	276.0	1.3	575.0	10.8	2.8	4.8	0.6	7.5	23.1	4.6
2	3	3	*Acacia tortilis*	88.0	4.4	183.3	3.4	9.2	16.0	0.5	6.4	25.9	1.8
2	4	3	*Balanites aegyptiaca*	4.0	0.0	8.3	0.2	0.1	0.1	0.2	2.1	2.4	0.2
2	3	3	*Berchemia discolor*	3.0	0.2	6.3	0.1	0.5	0.9	0.1	1.1	2.1	0.3
1	2	3	*Cadaba rotundifolia*	44.0	0.3	91.7	1.7	0.7	1.2	0.4	5.4	8.2	1.1
1	1	3	*Cordia Sinensis*	13.0	0.1	27.1	0.5	0.2	0.4	0.1	1.1	2.0	1.3
2	4	3	*Delonix elata*	17.0	1.1	35.4	0.7	2.3	4.1	0.1	1.1	5.8	1.7
2	3	3	*Dobera glabra*	8.0	0.3	16.7	0.3	0.7	1.3	0.2	2.1	3.7	0.4
1	2	3	*Salvadora persica*	72.0	0.3	150.0	2.8	0.7	1.2	0.1	1.1	5.1	7.2
				2567	27.5	5347.9	100	57.3	100	7.8	100.0	300	

Notes: District1 is Awash Fentale, District2 is Amibara, Site1 is Dudub, Site2 is Kebena, Site3 is Kurkura, Habiat1 is *P. juliflora* thicket, Habitat2 is *P. juliflora* + indigenous plant species mixed, Habiat3 is non-invaded woodlands, SN is species scientific name, Ab is abundance, BA is basal area, D is density, RD is relative density, Dom is dominance, Random is relative dominance, F is frequency, RD is relative frequency, I_{VI} is importance value index, A/F is Abundance to frequency ration, DBH is diameter at breast height, DSH is diameter at stump height.

Appendix 4. ANOVA showing the effects of locations, *Prosopis juliflora* invasiveness, a soil layer, physiographic and human activities on soil seed patterns at Amibara and Awash Fentale distrcits

Model	Sum of Squares	Df	Mean Square	F-value	P-value
H' *district	1.982	1	1.982	13.053	0.0002**
R * district	56.193	1	56.193	21.85	<0.0001***
E' * district	0.061	1	0.061	8.381	0.004**
H' * site	10.138	3	3.379	25.281	<0.0001***
R * site	214.113	3	71.371	32.164	<0.0001***
E' * site	0.518	3	0.173	27.461	<0.0001***
H' * habitat	6.153	3	2.051	14.355	<0.0001***

R * habitat	127.473	3	42.491	17.565	<0.0001***
E' * habitat	0.003	3	0.001	0.119	0.95
H' * soil layer	0.166	3	0.055	0.353	0.79
R * soil layer	3.024	3	1.008	0.372	0.77
E' * soil layer	0.009	3	0.003	0.422	0.74
H' * altitude	2.988	2	1.494	9.971	<0.0001***
R * altitude	20.422	2	10.211	3.839	0.02*
E' * altitude	0.209	2	0.104	14.965	<0.0001***
H' * slope	14.071	11	1.279	10.078	<0.0001***
R * slope	289.955	11	26.36	12.659	<0.0001***
E' * slope	1.633	11	0.148	39.31	<0.0001***
H' * aspect	18.829	7	2.69	23.459	<0.0001***
R * aspect	453.399	7	64.771	38.512	<0.0001***
E' * aspect	0.73	7	0.104	17.851	<0.0001***
H' * Human impact	1.007	3	0.336	2.168	0.09
R * human impact	68.392	3	22.797	8.921	<0.0001***
E' * human impact	0.108	3	0.036	5.003	0.002**
H' * grazing intensity	10.423	3	3.474	26.119	<0.0001***
R * grazing intensity	162.528	3	54.176	23.171	<0.0001***
E' * grazing intensity	0.355	3	0.118	17.792	<0.0001***
H' * disturbance intensity	9.338	3	3.113	22.968	<0.0001***
R * disturbance intensity	127.942	3	42.647	17.638	<0.0001***
E' * disturbance intensity	0.271	3	0.09	13.178	<0.0001***

Notices: *H'* = Shannon-Wiener index, *R* = species richness, *E'* = Shannon eveness habitat *P. juliflora* invasion level habitats (PJT, PJM, NIWL, and OGLs), Df = the degree of freedom, * sign at $P < 0.05$, ** is the high sign at $P < 0.05$, *** = very highly sign at $P < 0.05$.

Appendix 5. Species richness and composition under different *Prosopis juliflora* invasion levels (habitats) of at Amibara and Awash Fentale distrcits

Species richness	Habitat	Scientific name	Life form	Family
1	PJT	*Amaranthus thunbergii*	Forb	Amaranthaceae
2	PJT	*Bidens pilosa*	Forb	Asteraceae
3	PJT	*Brachiaria leersioides*	Herb	Poaceae
4	PJT	*Cenchrus ciliaris*	Herb	Poaceae
5	PJT	*Coccinia grandis*	Climber	Cucurbitaceae
6	PJT	*Eragrostis aethiopica*	Herb	Poaceae
7	PJT	*Ipomoea indica*	Climber	Convolvulaceae
8	PJT	*Ocimum americanum*	Forb	Lamiaceae
9	PJT	*Parthenium hysterophorus*	Forb	Asteraceae
10	PJT	*Physalis lagascae*	Forb	Solanaceae
11	PJT	*Prosopis juliflora*	Tree/shrub	Fabaceae
1	PJM	*Amaranthus thunbergii*	Forb	Amaranthaceae
2	PJM	*Bidens pilosa*	Forb	Asteraceae
3	PJM	*Brachiaria leersioides*	Herb	Poaceae

4	PJM	*Cenchrus ciliaris*	Herb	Poaceae
5	PJM	*Eragrostis aethiopica*	Herb	Poaceae
6	PJM	*Fuirena leptostachya*	Herb	Cyperaceae
7	PJM	*Ocimum americanum*	Forb	Lamiaceae
8	PJM	*Parthenium hysterophorus*	Forb	Asteraceae
9	PJM	*Physalis lagascae*	Forb	Solanaceae
10	PJM	*Trifolium simense*	Forb	Fabaceae
1	NIWL	*Amaranthus thunbergii*	Forb	Amaranthaceae
2	NIWL	*Bidens pilosa*	Forb	Asteraceae
3	NIWL	*Brachiaria leersioides*	Herb	Poaceae
4	NIWL	*Cenchrus ciliaris*	Herb	Poaceae
5	NIWL	*Coccinia grandis*	Climber	Cucurbitaceae
6	NIWL	*Indigofera hochestetteri*	Forb	Fabaceae
7	NIWL	*Eragrostis aethiopica*	Herb	Poaceae
8	NIWL	*Fuirena leptostachya*	Forb	Cyperaceae
9	NIWL	*Leucas martinicensis*	Forb	Lamiaceae
10	NIWL	*Ocimum spicatum*	Forb	Lamiaceae
11	NIWL	*Parthenium hysterophorus*	Forb	Asteraceae
12	NIWL	*Physalis lagascae*	Forb	Solanaceae
13	NIWL	*Ipomoea blepharophylla*	Forb	Convolvulaceae
14	NIWL	*Solanum incanum*	Forb	Solanaceae
15	NIWL	*Trifolium simense*	Forb	Fabaceae
1	OGL	*Amaranthus thunbergii*	Forb	Amaranthaceae
2	OGL	*Bidens pilosa*	Forb	Asteraceae
3	OGL	*Brachiaria leersioides*	Herb	Poaceae
4	OGL	*Cenchrus ciliaris*	Herb	Poaceae
5	OGL	*Eragrostis aethiopica*	Herb	Poaceae
6	OGL	*Leucas martinicensis*	Forb	Lamiaceae
7	OGL	*Ocimum americanum*	Forb	Lamiaceae
8	OGL	*Parthenium hysterophorus*	Forb	Asteraceae
9	OGL	*Physalis lagascae*	Forb	Solanaceae
10	OGL	*Alysicarpus rugosus*	Forb	Potamogetonaceae
11	OGL	*Prosopis juliflora*	Tree/shrub	Fabaceae
12	OGL	*Ziziphus spina-christi*	Tree	Rhamnaceae

Notices: PJT is *P. juliflora* thicket, PJM is P.juliflora plus other indigenous species, NIWL is non-invaded woodland, OGL is open grazing land

Appendix 6.Vertical soil seed bank composition, abundance, density, and I_{VI} of plant species.

Soil depth	Species	Ab	SSBD m^{-2}	F	AF	R_1	AD	R_2	Aab	R_3	I_{VI}
Litter	*Amaranthus thunbergii*	39	1733	10	0.04	2.34	6.77	2.37	3.90	3.07	7.79
Litter	*Bidens pilosa*	33	1467	19	0.07	4.45	5.73	2.01	1.74	1.37	7.83
Litter	*Brachiaria leersioides*	300	13333	64	0.25	14.99	52.08	18.26	4.69	3.69	36.94
Litter	*Cenchrus ciliaris*	43	1911	6	0.02	1.41	7.47	2.62	7.17	5.64	9.67
Litter	*Coccinia grandis*	3	133	2	0.01	0.47	0.52	0.18	1.50	1.18	1.83

Litter	*Crotalaria pycnostachya*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
Litter	*Eragrostis aethiopica*	128	5689	12	0.05	2.81	22.22	7.79	10.67	8.40	19.00
Litter	*Fuirena leptostachya*	3	133	3	0.01	0.70	0.52	0.18	1.00	0.79	1.67
Litter	*Ipomoea indica*	4	178	3	0.01	0.70	0.69	0.24	1.33	1.05	2.00
Litter	*Leucas martinicensis*	4	178	2	0.01	0.47	0.69	0.24	2.00	1.57	2.29
Litter	*Ocimum spicatum*	35	1556	17	0.07	3.98	6.08	2.13	2.06	1.62	7.73
Litter	*Parthenium hysterophorus*	139	6178	23	0.09	5.39	24.13	8.46	6.04	4.76	18.61
Litter	*Physalis lagascae*	20	889	9	0.04	2.11	3.47	1.22	2.22	1.75	5.07
Litter	*Alysicarpus rugosus*	2	89	2	0.01	0.47	0.35	0.12	1.00	0.79	1.38
Litter	*Prosopis juliflora*	5	222	3	0.01	0.70	0.87	0.30	1.67	1.31	2.32
Litter	*Solanum incanum*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
Litter	*Trifolium simense*	1	44	2	0.01	0.47	0.17	0.06	0.50	0.39	0.92
Litter	*Ziziphus spina-christi*	2	89	1	0.00	0.23	0.35	0.12	2.00	1.57	1.93
0–3cm	*Amaranthus thunbergii*	19	844	11	0.04	2.58	3.30	1.16	1.73	1.36	5.09
0–3cm	*Bidens pilosa*	35	1556	12	0.05	2.81	6.08	2.13	2.92	2.30	7.24
0–3cm	*Brachiaria leersioides*	319	14178	53	0.21	12.41	55.38	19.42	6.02	4.74	36.57
0–3cm	*Cenchrus ciliaris*	12	533	3	0.01	0.70	2.08	0.73	4.00	3.15	4.58
0-3cm	*Coccinia grandis*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
0–3cm	*Crotalaria pycnostachya*	5	222	4	0.02	0.94	0.87	0.30	1.25	0.98	2.23
0–3cm	*Eragrostis aethiopica*	60	2667	13	0.05	3.04	10.42	3.65	4.62	3.63	10.33
0–3cm	*Fuirena leptostachya*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
0–3cm	*Heliotropium longiflorum*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
0–3cm	*Ocimum spicatum*	19	844	9	0.04	2.11	3.30	1.16	2.11	1.66	4.93
0–3cm	*Parthenium hysterophorus*	102	4533	15	0.06	3.51	17.71	6.21	6.80	5.35	15.08
0–3cm	*Physalis lagascae*	2	89	2	0.01	0.47	0.35	0.12	1.00	0.79	1.38
0–3cm	*Alysicarpus rugosus*	1	44	1	0.01	0.47	0.17	0.06	0.50	0.39	0.92
0–3cm	*Trifolium simense*	4	178	3	0.01	0.70	0.69	0.24	1.33	1.05	2.00
3–6cm	*Amaranthus thunbergii*	23	1022	7	0.03	1.64	3.99	1.40	3.29	2.59	5.63
3–6cm	*Bidens pilosa*	6	267	5	0.02	1.17	1.04	0.37	1.20	0.94	2.48
3–6cm	*Brachiaria leersioides*	74	3289	25	0.10	5.85	12.85	4.50	2.96	2.33	12.69
3–6cm	*Cenchrus ciliaris*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
3–6cm	*Crotalaria pycnostachya*	2	89	2	0.01	0.47	0.35	0.12	1.00	0.79	1.38
3–6cm	*Eragrostis aethiopica*	6	267	5	0.02	1.17	1.04	0.37	1.20	0.94	2.48
3–6cm	*Ipomoea blepharophylla*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
3–6cm	*Ipomoea indica*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08
3–6cm	*Ocimum urticifolium*	6	267	6	0.02	1.41	1.04	0.37	1.00	0.79	2.56
3–6cm	*Parthenium hysterophorus*	58	2578	11	0.04	2.58	10.07	3.53	5.27	4.15	10.26
3–6cm	*Physalis lagascae*	2	89	1	0.00	0.23	0.35	0.12	2.00	1.57	1.93
3–6cm	*Trifolium simense*	3	133	2	0.01	0.47	0.52	0.18	1.50	1.18	1.83
6–9cm	*Amaranthus thunbergii*	11	489	4	0.02	0.94	1.91	0.67	2.75	2.17	3.77
6–9cm	*Bidens pilosa*	4	178	4	0.02	0.94	0.69	0.24	1.00	0.79	1.97
6–9cm	*Brachiaria leersioides*	55	2444	25	0.10	5.85	9.55	3.35	2.20	1.73	10.93
6-9cm	*Cenchrus ciliaris*	2	89	1	0.00	0.23	0.35	0.12	2.00	1.57	1.93

6–9cm	*Crotalaria pycnostachya*	2	89	2	0.01	0.47	0.35	0.12	1.00	0.79	1.38
6–9cm	*Eragrostis aethiopica*	12	533	4	0.02	0.94	2.08	0.73	3.00	2.36	4.03
6–9cm	*Ocimum spicatum*	6	267	3	0.01	0.70	1.04	0.37	2.00	1.57	2.64
6–9cm	*Parthenium hysterophorus*	23	1022	8	0.03	1.87	3.99	1.40	2.88	2.26	5.54
6–9cm	*Physalis lagascae*	3	133	2	0.01	0.47	0.52	0.18	1.50	1.18	1.83
6–9cm	*Trifolium simense*	1	44	1	0.00	0.23	0.17	0.06	1.00	0.79	1.08

Notices: Ab = Abundance per soil layer/sampled quadrats, SSBD = soil seed bank density per m^2, F = frequency, AF = Absolute frequency, R_1 = relative frequency, AD = absolute density, R_2 = relative density, Aab = absolute abundance, R_3 = Relative abundance, I_{VI} = importance value index.

Appendix 7. Effects of physiographic factors on mean values of soil seed bank patterns

Physiographic factors		*H’*	*R*	*E’*
Alt (m.a.s.1)	740–790	1.37±0.04a	4.56±0.17a	0.96±0.01a
	791–841	1.36±0.04a	4.48±0.16ab	0.95±0.004a
	> 841	1.20±0.02b	4.09±0.1b	0.91±0.001b
Aspect (direction)	North	1.15±0.04b	3.81±0.17d	0.92±0.01bc
	Northeast	1.09±0.03b	3.37±0.11ed	0.96±0.005ba
	Northwest	1.59±0.00a	7.00±0.00a	0.82±0.00e
	East	1.52±0.04a	5.21±0.17cb	0.96±0.006ba
	West	1.46±0.05a	4.54±0.17c	0.98±0.006a
	Southeast	0.88±0.08c	2.91±0.32e	0.88±0.01dc
	Southwest	1.07±0.08b	3.4±0.13ed	0.87±0.04d
Slope (degree)	0	1.31±0.04bac	4.8±0.14b	0.85±0.02de
	0.1	0.69±0.00f	2.00±0.00e	1.00±0.00a
	0.2	1.12±0.08edc	4.13±.37cbd	0.88±0.01dc
	0.3	1.39±0.00bac	4.00±0.00cbd	1.00±0.00a
	0.5	1.59±0.00a	7.0±0.00a	0.82±0.00fe
	1	1.26±0.03bdc	3.99±0.13cbd	0.98±0.003a
	1.5	1.31±0.11bac	4.53±.41cb	0.91±0.06bc
	2	1.48±0.03ba	4.91±0.13b	0.96±0.005a
	2.5	1.11±0.096edc	3.41±0.3cd	0.96±0.01ba
	3	0.94±0.06ef	2.94±0.2ed	0.91±0.01c
	4	0.86±0.06ef	3.0±0.00ed	0.78±0.06f
	6	1.0±0ed	4.0±0.00cbd	0.72±0.00g
Human activities				
Human impacts	Nil	1.32±0.04a	4.74±0.17a	0.92±0.01b
	Low	1.29±0.04ba	4.41±0.14ba	0.91±0.01b
	Moderate	1.196±0.03b	3.73±0.10c	0.95±0.01a
	Heavy	1.28±0.05ba	4.19±0.19b	0.95±0.01a
Grazing intensity	Nil	1.37±0.04 ba	5.01±0.19a	0.93±0.01b
	Low	1.43±0.02a	4.74±0.10a	0.93±0.01b
	Moderate	1.28±0.04b	4.07±0.13b	0.961988a
	Heavy	1.034±0.03c	3.47±0.11c	0.89±0.01c

Disturbance intensity	Nil	1.36±0.05ba	4.78±0.20a	0.95±0.01a
	Low	1.42±0.03a	4.85±0.16a	0.94±0.01a
	Moderate	1.28±0.03b	4.15±0.11b	0.95±0.01a
	Heavy	1.05±0.03c	3.52±0.11c	0.89±0.01b

Notices: H' = Shannon-Wiener index, R = species richness, E' = Shannon eveness, $P < 0.05$

Appendix 8. ANOVA showing effects of animals on seed patterns

Model	Sum of Squares	Df	Mean Square	F-value	P-value
H' × livestock	0.049	1	0.049	23.333	0.001*
R × livestock	1.867	1	1.867	23.333	0.001*
E'× livestock	0.196	1	0.196	23.333	0.001*

Notice: H' = Shannon-Wiener index, R = species richness, E' = Shannon evenness; the same letters indicate insignificant variations at $P<0.05$.

Appendix 9. ANOVA showing effects of habitat (lands invaded or non-invaded by *Prosopis juliflora)*, location (district), and soil depth in Teru and Yalo districts

Explanatory variables	Source	DF	Sum of Squares	Mean Square	F value	Pr > F
Habitat and soil depth	Model	3	3546279.29	1182093.10	0.62	0.61
	Error	32	61157655.32	1911176.73	-	-
	Corrected total	35	64703934.61	-	-	-
District and soil depth	Model	3	3710235.08	1236745.03	0.63	0.60
	Error	31	60871104.21	1963584.01	-	-
	Corrected total	34	64703934.61	-	-	-