Journal of Biology, Agriculture and Healthcare
ISSN 2224-3208 (Paper) ISSN 2225-093X (Online)
Vol.6, No.8, 2016

Cactus Pear (Opuntia ficus-indica L.) a Valuable Crop for Restoration of Degraded Soils in Northern Ethiopia

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Abstract
Opuntia ficus-indica (L.) commonly referred to as cactus pear is a dicotyledonous angiosperm plant. It belongs to the Cactaceae family and is characterized by its remarkable adaptation to arid and semi-arid climates in tropical and subtropical regions of the globe. *Opuntia* species have developed phenological, physiological and structural adaptations for growth and survival in arid and semi-arid environments where severe water stress hinders the survival of other plant species. Among these adaptations, the asynchronous reproduction and CAM metabolism of cactus stands out, which combined with structural adaptations such as succulence, allow them to continue the assimilation of carbon dioxide during long periods of drought reaching acceptable productivity levels even in years of severe drought. In the present stud soil physical and chemical properties are considerably improved under the canopies of cactus pear compared to adjacent open areas. The generalized linear model showed that soil organic carbon, soil total nitrogen, soil available phosphorus, soil bulk density, soil moisture, and electric conductivity of soil samples were positively and significantly influenced by cactus pear canopy cover compared to adjacent open areas.
Keywords: Cactus pear, land degradation, restoration, physical property, chemical property, northern Ethiopia

1. Introduction

Drylands cover over 40% of the earth's land surface, and are home to more than a third of the world's population–many of whom are the poorest of the poor (IUCN, 2008). Drylands as tropical and temperate landscapes and regions with an aridity index value of less than 0.65 includes: dry sub-humid, semi-arid, arid, and hyper arid (IUCN, 2008b). Land degradation occurs in all continents and affecting livelihoods of millions of people including a large proportion of the poor in the drylands (Nefzaoui *et al*., 2014). Land degradation triggered by population increase and over exploitation of the natural resources is a major threat to sustainable land use in Ethiopia (Hurni *et al*., 2005). Regardless of the geographic locations, arid and semi-arid areas are characterized by specific vegetation and climatic conditions. Vegetation in arid and semi-arid lands includes plants with mechanisms of resistance and/or adaptation to water stress, such as cactus, mesquites, bushes etc. (Nobel, 2009). Climatically arid and semi-arid lands are characterized by extreme temperature conditions and torrential precipitation events with short duration and high intensity (Wei *et al*., 2007). Vegetation plays an important role in regulation of soil erosion and improvement of the physical, chemical and biological properties of soils (Wei *et al*., 2007).

In arid and semi-arid lands, the degradation of plant communities (vegetation structure and species diversity) is concomitant with the degradation of physicochemical and biological properties of soil (Requena *et al*., 1996). However, the functioning and stability of terrestrial ecosystems are primarily depending on the composition and species diversity of vegetation cover (Tilman *et al*., 1996). Arid and semi-arid ecosystems are considered as very fragile systems since they are susceptible to various forms of degradation (Ferrol *et al*. 2004). *Ountia ficus-indica* (L. Mill.) commonly referred to as cactus pear belongs to the dicotyledonous angiosperm plants. It belongs to the Cactaceae family, a family that includes about 130 genera and 2000 species (Shedbalkar *et al*., 2010). *Opuntia ficus-indica* is the most widely known genus of this family. It is characterized by its remarkable adaptation to arid and semi-arid climates in tropical and subtropical regions of the globe (Griffith, 2004: El-Mostafa *et al*., 2014). Cactus pear plants are remarkable for their diversity of growth forms and their ability not only to grow but also to thrive under environments recognized as stressful for most plant species. They are evolved to grow into water scarce environments (Shedbalkar *et al*., 2010).

Opuntia ficus-indica exhibits Crassulacean Acid Metabolism (CAM), with nocturnal stomata opening and CO_2 uptake occurring typically from dusk to dawn. Many reasons may account for the great interest devoted to cactus pear. The multipurpose use of this plant species and their ability to grow in harsh environments are the main reasons. The establishment of sustainable production systems based on cactus pear may contribute to food security of populations in agriculturally marginalized areas and to soil improvement (Nefzaoui *et al.*, 2014). *Opuntia* species have developed phenological, physiological and structural adaptations for growth and survival in arid environments where severe water stress hinders the survival of other plant species. Among these adaptations, the asynchronous reproduction and CAM metabolism of cactus stands out, which combined with structural adaptations such as succulence, allow them to continue the assimilation of carbon dioxide during long periods of drought reaching acceptable productivity levels even in years of severe drought (Nefzaoui *et al.*, 2014). CAM plants can use water much more efficiently with regard to CO_2 uptake and productivity than do C_3 and C_4 plants (Nobel, 2009). Biomass generation by CAM plants per unit of water is on average 5 to 10 times greater than C_4 and C_3 plants respectively.

Cactus pear was introduced to Tigray region of northern Ethiopia between 1846 and 1887 by missionaries (Kibra, 1992). Since its introduction it has dominated both degraded lands like the sloppy areas as well as the more favorable homestead lands. Consequently, the crop now serves as an integral part of people's food needs, livestock feed and general environmental protection. Although the importance of cactus pear as food for humans and fodder for livestock is appreciated there is comparatively very little research data available on its role in ecological restoration of degraded dryland in areas like Ethiopia where 75% of its total land area is dry. Hence, this research was designed to assess the effect of cactus pear on the physical and chemical properties of soils of two watersheds in the Tigray region of northern Ethiopia.

2. Materials and methods

2.1 Description of the study area

TIgray region is in the northern part of Ethiopia. It is located on latitude 12^o 13'-14^o 54' N and longitude 36^{o}27'-40^o 18' E, it shares borders with Eritrea in the north, Sudan in the west, Afar and Amhara regions in the east and south respectively. Tigray region has a total land area of 53,386 km^2 of which about 20% is currently under cultivation. According to the Regional Bureau of Agriculture and Rural Development, average farm size in the region ranges between 0.75 and 2.5 ha per household. It has an estimated population of 4,316,988 of which 3,472,948, representing 80.5 % are rural and 844, 040 (19.5 %) live in urban areas (CSA, 2008).

This study was conducted in two sites namely the Erob and Raya-Azeba districts of the Tigray region of northern Ethiopia. The selected areas generally represent different agro-ecological zones and soil types. Additionally, these sites experience different climatic conditions due to diverse physical and relief features. The topography of the areas is characterized by mountainous plateaus. The altitude of the study area ranges between 1,300 and 3, 250 meters above sea level with a slope along the elevation of the watersheds between 5- 40%. The climate of the study area is typical semi-arid and falls within the long-term 400 and 800 mm summer rainfall isohyets of Ethiopia (Segele and Lamb, 2005) with a bimodal rainfall pattern. The long summer rainy season (called kiremt) starts in late June and ends in early September with more than 90% of the rainfall occurring during this season (Segele and Lamb, 2005; Seleshi and Camberlin, 2006). This period, which lasts between 60 and 120 days, is the main crop growing season. Mean annual rainfall varies between 300 and 600 mm/year with an average of 562 mm/year. The mean annual minimum temperature ranges between 11^{o}C and 17 ^{o}C, and mean annual maximum temperature of 26-34 ^{o}C (Ethiopian Meteorological Service Agency, 2010).

The dry season extends from October to February, but when the short rain fails the dry season can extend up to May or June. A relatively short and stochastic rainy season (known as belg) occurs between March and April and is characterized by a coefficient of variation as high as 55% (Meze-Hauske, 2004). The dominant soil types include sandy silt, red clay loam described as Fluvisols, Lithosols, Cambisols and Regosols (FAO, 1998). The study areas have inherently low soil fertility, while rainfall is the limiting factor (Firew, 2007). The vegetation is the east African montane type that is typical of the Sudano-Sahelian transition sub zone (Le Houerou, 1989), with common plant formations that include mesophyllic deciduous woodland, mixed evergreen forest and deciduous open woodland (Feolil *et al.,* 2002).

2.2 Soil sampling

Soil samples were collected from two selected watersheds namely Hallo (Erob district) and Bobotiya (Raya-Azebo district) in Tigray region representing areas of high cactus pear growth and distribution compared to other semi-arid areas of the region to analyze soil physical and chemical properties. A systematic plot sampling design approach was employed to collect soil samples from the two watersheds. In each watershed two bottom-top extended parallel transect lines of 1000 m in length each and spaced at distance of 100 m were designated. Transects were laid out parallel to one another and to the topography of the landscape. Twenty 10 m x 10 m plots/transect (a total of 80 plots) were laid at equal distance of 50 m interval. In each 10 m x 10 m plot four 1 m x 1 m subplots, with two under the cactus pear canopy and two on open adjacent areas, were laid out for soil sampling. After removal of surface litter, soil sample from upper 0-20 cm depth were collected at the centre of each subplots. Soil samples were taken from under the canopy cover of the cactus pear at distance of about 30 cm from the cactus pear stem base and from adjacent open space 5 meters away from the cactus pear stem base. Composite soil samples at the frequency of one sample for four subplots were produced for each sample category along each transect after combining and thoroughly mixing the soil in a bucket to package representative samples.

A total of eighty composite samples were collected from all transects i.e., two samples from cactus pear canopy covered area and adjacent open area x four transects x ten replicates. About 1kg composite soil samples were air-dried, sieved through a 2 mm mesh to remove roots, large organic residues and stones and put in labeled polythene bags and stored at room temperature for soil physical and chemical analyses. A total of 80 undisturbed core samples, one from beneath of the cactus pear canopy cover and one from adjacent open area were also obtained from the center of the subplots for bulk density determination using steel cylinders of 100 cm^3 volumes, i.e., 5 cm in height and 5.04 cm diameter. Soil core samples were transported in heavy padded containers or suitcases to the laboratory. Physical and chemical analysis of soil samples were carried out at Mekelle Soil Laboratory Center.

2.3 Laboratory analyses of soil physical and chemical properties

Soil bulk density was determined on the undisturbed soil samples using the core method (Blake and Hartge, 1986). The moisture content of soil samples were determined by oven-drying at 105^{o}C until constant mass was attained. Soil pH was measured at soil:water ratio of 1:2.5. Organic carbon content of soil samples was determined using the Walkely and Black method (Nelson and Somers, 1982), and soil organic matter content of soil samples was then obtained by multiplying the organic carbon concentration by 1.724. The Kjeldahl method (Bremner and Mulvaney, 1982) was used to quantify the total soil nitrogen content. Phosphorus availability was determined by bicarbonate extraction P-Olsen's method (Olsen and Sommers, 1982), while basic cations such as Ca^{2+} and Mg^{2+} were analyzed by complexometric titrations using ethylenediamine tetraaceticacid (EDTA) (Dipak and Abhijit, 2005). The potassium content was estimated using the Flame photometry method (Bremer, 1965), while the electric conductivity was determined by measuring electrical resistance of 1:2.5 soil:water suspension. The turbidemetric procedure was used to estimate total sulfur in the soil samples by spectrophotometric barium sulfate precipitation method (Dipak and Abhijit, 2005).

2.4 Statistical analysis

Laboratory analyzed soil data were subjected to analysis of variance (ANOVA) using the Generalized Linear Model (GLM) available in SPSS version 17.0. Tukey's HSD test was used to detect significant differences among means at the $p<0.05$ level of significance. Pearson's correlation coefficients were calculated for the relationship between soil parameters.

3. Results

Table 1, presents the mean (SD) values for selected physico-chemical soil parameters under the cactus pear canopy and adjacent open areas. Cactus pear plants had significant impacts on the physical and chemical properties of sampled soils. The values for most parameters varied with sampling sites (under the cactus pear canopy and opened areas), with the exception of Mg and carbon/nitrogen ratio (C:N) which remained similar. The distribution of total sulfur, available potassium, calcium, pH, bulk density and soil moisture was also influenced by transect effect. In addition soil moisture content was influenced by the "transect*plot" interaction effect.

The Analysis of variance result demonstrated that cactus pear had significant effect on bulk density Table 1. Bulk density was higher in soils sampled from the open area compared to soils sampled from under the cactus pear canopy. Results showed that cactus pear plant reduced soil bulk density significantly ($p<0.01$) compared to adjacent open areas. Besides, the Tukey's HSD revealed that significantly higher mean value for bulk density ($p<0.01$) was observed in transect 4 in Bobotiya watershed compared to transect 1 and transect 2 in Hallo watershed. In addition, transect 3 in Bobotiya watershed had significantly higher bulk density ($p<0.01$) compared to transect 1 in Hallo watershed. The effect of cactus pear canopy on soil moisture content in the study sites was highly significant. A significant increased ($p<0.01$) in soil moisture content was found under the cactus pear canopy (9.50%) compared to adjacent open areas (6.74%). In addition, mean soil moisture contents were significantly influenced ($p<0.01$) by transects and values were higher in Transect 3 and transect 4 compared to transect 1 and transect 2. The interaction for "transect* plot" were also higher ($p<0.05$) in transect 3 and transect 4 compared to transect 1 and transect 2.

Table 1. Mean (SD) values, *F*-tests and *P*-values recorded for selected physico-chemical soil parameters under the cactus pear canopy and adjacent open areas in the study watersheds

Parameters	Mean values (SD)			
	Under canopy	Open	*F*-test	*p*-value
OC (%)	2.48 (0.85)	1.82 (0.77)	12.762	0.001
OM (%)	4.27 (1.47)	3.14 (1.32)	12.772	0.001
TN (%)	0.25 (0.16)	0.18 (0.05)	6.832	0.011
C:N	11.56 (5.77)	10.23 (3.44)	1.488	0.226
Ava. P (ppm)	16.08 (15.10)	7.02 (4.78)	11.638	0.001
TS (ppm)	221.43 (15.97)	217.63 (14.01)	1.728	0.193
Ava.K (meq/100gm)	0.13 (0.06)	0.11 (0.06)	2.944	0.091
Ca (meq/litre)	7.92 (5.11)	7.66 (5.76)	0.299	0.634
Mg (meq/litre)	4.32 (3.36)	5.05 (3.52)	0.900	0.346
pH	5.97 (1.05)	6.21 (1.11)	1.349	0.249
EC (dS/m)	0.13 (0.11)	0.08 (0.04)	4.948	0.029
Soil moisture (%)	9.49 (7.50)	6.74 (6.10)	34.274	0.000
Bulk density (gm/cm^3)	1.39 (0.17)	1.53 (0.10)	31.764	0.000

Compared to the open sites the under cactus pear canopy samples had significantly higher ($p<0.01$) organic carbon and organic matter contents. Average organic carbon content in soils of the open adjacent areas increased by 36% from 1.82% to 2.48% in soils from under cactus pear canopy. There was a significant increase in total nitrogen ($p<0.05$) levels under the canopy of the cactus pear than the open sites. The average total nitrogen content was 0.18% for soils in open area, increasing to 0.25% for soils from under the cactus pear canopy. Values for total nitrogen content correlated positively with soil organic matter content ($r_{(78)} = 0.505$, $p<0.05$). The results of the analysis of variance showed that soil phosphorus was affected by cactus pear canopy and mean value of phosphorus under the cactus pear canopy soil samples was significantly higher ($p<0.01$) than the open sites. Available phosphorus content was also positively correlated with soil organic matter content ($r_{(78)} = 0.417$, $p<0.05$).

In contrast to significant differences in soil organic carbon, soil organic matter, total nitrogen, available phosphorus, soil moisture and bulk density contents, there was no significant difference ($p>0.05$) in total sulfur contents in soils sampled from the two sites . On the contrary, mean total sulfur was significantly higher ($p<0.05$) in transect 2 compared to transect 1 (Hallo), and transect 3 and transect 4 (Bobotiya) while other transects remained similar. Potassium content of soil samples from the study areas were 0.13 meq/100 gm under cactus pear canopy soils and 0.11 meq/100 gm in open area soils. Results showed that there was no significant difference ($p>0.05$) in the potassium content between the sampling sites. In contrast, mean available potassium was detected to be significantly higher ($p<0.05$) in transect 2 compared to transect 3 and transect 4. The statistical analysis of variance indicated that calcium and magnesium contents were not significantly different ($p>0.05$) between the sampled soils. However, Tukey's HSD revealed that mean calcium values were significantly higher ($p<0.01$) in transect 3 and transect 4 compared to transect 1 and transect 2.

The soils of the study areas were moderately acidic ranging between 5.97 in the cactus pear canopy soils and 6.21 in open area soils. The analysis of variance showed no significant difference ($p>0.05$) between sampled soils. These results showed cactus pear had no effect on soil pH. However, mean soil pH values were significantly higher ($p<0.05$) in transect 3 and transect 4 compared to transect 1 and transect 2 in Hallo watershed and the pH values were almost neutral. The electric conductivity of the soils were found to be 0.13 dS/m for under the cactus pear canopy soils and 0.08 dS/m for the open area soils. The statistical analysis result showed a significantly higher value of eclectic conductivity under the cactus pear canopy soils compared to the open area soils, the difference being significant ($p<0.05$) between the sampled soils.

4. Discussion

In present the study values for soil bulk density were greater for sample sites without cactus pear canopy cover. Soil bulk density decreased by 17% for soil samples under the cactus pear canopies as compared to soil samples from open areas. These low values for soil bulk density under the cactus pear canopy were in agreement with the findings of: Molley and Charle (1996), and Rebeca *et al*. (2010) who in similar work recorded low values of soil bulk density under the cactus pear canopy cover as compared to open areas. The difference in soil bulk density values between open areas and cactus pear canopy cover could be due to the accumulation of organic matter from cactus pear under its canopy leading to improved soil structure and therefore enhancing soil porosity. This therefore, tends to decrease soil compaction and soil bulk density. Decrease in soil bulk density could also be due to root channeling and litter decomposition as reported by Callaway *et al*. (1991), Joffre and Ramball (1993) thus making it easier for water penetration.

The result from the present study indicated that on average soil moisture content increased by 41%

(6.74 vs 9.49%) for soil samples from under the cactus pear canopy cover than open areas. This was in agreement with the findings of earlier investigators such as Maestre and Cortina (2003), Pugnaire *et al*. (2011), who in similar work recorded higher values for soil moisture content under the canopy compared to open ground areas. The lower soil moisture content values outside the cactus pear canopy cover may be due to poor vegetation cover, exposure to trampling and compaction by animals and higher soil bulk density, which may lead to reduced infiltration rate and increased surface runoff. The higher moisture content under the canopy cover of cactus pear may be due to reduced thermal stress and water loss through evapo-transpiration as reported by Moro *et al.* (1997a).

Soil organic carbon is the material in the soil that is directly derived from plants and animals and it supports most important micro fauna and micro flora in the soil. It is largely responsible for much of the physical and chemical fertility of soils (Charman and Roper, 2007). In the present study soil organic carbon generally showed a declining trend from the cactus pear canopy cover to adjacent open areas. This result was consistent with that of: Le Houerou (1996), Rodriguez et *al*. (2006), Neffar *et al.* (2013) and Nefzaoui *et al.* (2014), who reported 20 to 40% increase in soil organic carbon under the cactus pear canopy cover compared to adjacent open areas. The difference in soil carbon content between the cactus pear canopy cover and open areas may be due to the fact that cactus pear plants have the ability to effectively trap fine soil materials and plant detritus from nearby unprotected lands and deposited them under their canopy. In addition, the increase in soil organic carbon content under the cactus pear canopy could be attributed to other various processes, such as accumulation of litter, deposition and subsequent stabilization of wind and waterborne soil particles under the cactus pear canopy. In a similar work Armbrust and Bilbro (1997) and Carrilo-Garcia *et al.* (2000a) have reported that the soil carbon content under the shrub canopy improves the soil texture and creates microhabitats for communities of organisms such as insects, reptiles, birds and other animals. Furthermore, soil organic carbon can be obtained from organic matter and nutrients that are concentrated near the soil surface and removed and deposited by storm runoff under the canopy of plants. Storm runoff can carry considerable amount of detritus rich in organic matter and nitrogen and deposited it under plant canopies. Soil organic carbon accumulation can also be caused by carbon inputs and soil management practices (Six and Justrow, 2002; Barbera, *et al*., 2010). The increased soil organic carbon in the study watersheds may be due to more carbon inputs from the root biomass and litter under the cactus pear canopy cover. Furthermore, the lower carbon content in the open areas could be attributed to small carbon inputs (Novara *et al*., 2012b).

In the present study it was found that the difference in total nitrogen contents between the cactus pear canopy cover and open area soil samples was more than 77% (0.30% vs 0.17%). This result is consistent with previous studies by Rodriguez *et al*. (2006) and Nefzaoui *et al*. (2014) who reported higher concentration of total nitrogen (30-200%) in soils under the cactus pear canopy than open areas. In addition Molley and Charles (1996) and Rebeca *et al*. (2010) also reported similar pattern of enrichment of soil total nitrogen under canopies of other cactus pear shrubs. Moreover, in their study on soil characteristic under individual tree canopy in Kenyan savannas, Belsky *et al.* (1989) reported higher levels of nitrogen underneath the canopy of plants compared to open savannas.

Phosphorus is an essential constituent of numerous substances involved in biochemical reactions including photosynthesis and respiration. It is a major component of adenosine diphospate (ADP) and adenosine triphosphate (ATP) (Hazelton and Murphy, 2007). In the present study cactus pear significantly influenced available phosphorus content and therefore increased the amount by 119% compared to open areas. This result is in agreement with Wezel *et al*. (2000) and Neffar *et al.* (2013) who reported values greater than 51% increase in available phosphorus under the cactus pear canopy compared to open areas. Higher concentration of available phosphorus was linked to higher concentration of soil organic carbon under shrub canopies because soil organic carbon is the most important factor in storage of nutrient in infertile soils (Wezel *et al*., 2000). Shade provided by trees and shrubs reduces soil temperature and evaporation. It can also significantly increase electric conductivity of soils of the landscape. In the current study higher electric conductivity values were recorded under the cactus pear canopy compared to open areas. This was in agreement with Neffar *et al.* (2013) who in their study on cactus pear plantation in Algeria reported higher soil electric conductivity values under the cactus pear shade, while significantly lower values were recorded for open areas. These higher values of electric conductivity for the cactus pear canopy cover could be attributed to higher microbial activities leading to the production of organic acid and subsequent ions under the cactus pear canopy. Solubility of most soil elements among other factors is influenced by electric conductivity which can also influence soil salinity. Higher soil electric conductivity implies higher salinity which intends affect plant growth and development. Electric conductivity values for the present study were low indicating that soils from cactus pear canopy cover and open areas were not saline. Therefore, soil salinity was not a problem in the study watersheds.

Soil pH is also an important soil property that affects the solubility of most elements essential for plant growth and development. It either increases or decreases the availability of elements found in the soil. It is also an indicator of the chemical processes that occur in the soil and a guide to likely deficiencies and/or toxicities.

The results from the present study showed that soil samples from both cactus pear canopy cover and open area had pH values within the range of 6.5-6.1 implying that they were less acidic. The less acidic nature of the soil of the study areas therefore would cause an increased availability of essential plant macro and micro nutrients and microbial activities. This would lead to proper plant growth and development. This result was in agreement with Marx *et al.* (1999) and Saleh *et al*. (2009) who reported less acid soils can contribute to high microbial activities, and proper plant growth and development. Despite the marked effect of cactus pear on several soil parameters of the study areas, its effect on magnesium, potassium, calcium and available sulfur content of soils was not observed in this study. This could probably due to the fact that cactus pear plants as an evergreen plant species can keep the growth limiting-nutrients in their biomass more effectively than deciduous species (Aerts, 1990).

Conclusions

Cactus pear is now part of the natural and agricultural systems of northern Ethiopia. There is an increasing interest in cactus pear as it plays a strategic role in ecosystem conservation. It has shown its adaptability to degraded ecosystems characterized by limited resources. From the ecological point of view cactus pear plants were identified as a suitable crop for the prevention of long-term ecosystem degradation. Cactus pear plants may therefore help to conserve soil quality of marginal lands and regeneration of degraded agricultural lands. Cactus pear plants were found to influence soil physical and chemical properties positively. Soil surface physical properties were improved under cactus pear canopy cover compared to adjacent open areas. Soil organic carbon, soil organic matter, soil total nitrogen, soil available phosphorus, electric conductivity, soil moisture contents of the soil samples from under the cactus pear canopy cover were significantly higher compared to the adjacent open area soil samples. A close positive relationship was found between soil organic matter content and soil total nitrogen and available phosphorus contents. Furthermore, it was evident from this study that cactus pear plants have exerted great impact on nutrient redistribution with significant accumulation of growth limiting nutrients under their canopies. Moreover, it is worthy to mention that enrichment of soils under cactus pear canopies could be attributed to the addition of waste from animals resting under its shade and decomposition of its litter. In addition the canopies of cactus pear may trap air and waterborne particles and deposit them at the base of the plant. Hence, planting cactus pear in combination with native woody plant species on steep slopes, shallow low quality soils could convert marginal soils to productive lands and mitigate land degradation in the region.

Acknowledgement

I would like to express my sincere gratitude to Professor I. K. Asante, Professor Christopher Gordon and Dr. Ted Yemoh Annang for their continuous support, guidance, valid advice and encouragement at all stages of this study. I wish also to express my deep gratitude and appreciation to Mekelle University for the generous funding of this study.

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