International Journal of Science, Environment and Technology, Vol. 5, No 3, 2016, 846 – 860

ISSN 2278-3687 (O)
2277-663X (P)

CACTUS PEAR (*Opuntia ficus*-indica L): A FUTURE ASSET FOR SUSTAINABILITY OF DRYLANDS 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. Soil physical, chemical and biological 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 moisture, soil bacteria and soil fungi contents of soil samples were positively and significantly influenced by cactus pear canopy cover compared to adjacent open areas. The higher nutrient content under the cactus pear canopy was also positively associated with abundance of soil bacteria and fungi which facilitated the decomposition of organic materials.

Keywords: Cactus pear, degradation, rehabilitation, soil chemical property, soil microbes.

1. Introduction

Globally drylands occupy 41 percent (60.9 million square km) of the earth's land surface and are home to 35 percent of its population, many of whom are the poorest of the poor (IUCN, 2008). Drylands refers to arid, semi-arid and dry sub-humid areas, and, in general, exclude deserts when referred to in the context of sustainable development. 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. However, the functioning and stability of terrestrial ecosystems are primarily depending on the composition and species diversity of vegetation cover (Tilman *et al*., 1996). Dryland ecosystems are considered as very fragile systems since they are susceptible to various forms

*Received April 2, 2016 * Published June 2, 2016 * www.ijset.net*

of degradation (Ferrol *et al*., 2004). In systems where perennial plants form a discontinuous cover, such as savannas and shrub lands, the presence of canopy alters the microenvironment in ways that influence the activity of soil microbes (Hopmans, 2006).

Cactus pear (*Opuntia ficus indica* L.) is a xerophytic plant whose high moisture content is a very useful characteristic under water deficit conditions in arid regions. Therefore, given the consequences of climate change and global warming in recent years, it can substitute plants that have a high water use because of its slight water use (Sharari, *et al*., 2012). One eminent attribute of cactus pear is its high capability in converting water to dry matter and its remarkable capability of producing high quality dry matter in regions with water limitation (Felker *et a*l., 2005). Cactus pear plants have adapted perfectly to arid zones characterized by droughty conditions, erratic rainfall and poor soils subjected to erosion. They have developed phonological, physiological and a structural adaptation favorable to their development in which water is the main factor limiting the development of most plant species. Notable among these adaptations are asynchronous reproduction and Crassulacean Acid Metabolism (CAM), which combined with structural adaptations such as succulence, enables this plant to survive long periods of drought and to reach acceptable productivity levels in years of severe drought (Reynold and Aria, 2001).

Soil bacteria and fungi are among the microbial components of soil that are susceptible to desertification and their diversity and abundance are significantly reduced under arid conditions (Bethlenfalvay and Schüepp, 1994). These microorganisms play an important role in both the relationship of plant-soil and ecosystem dynamics (van der Heijden *et al.,* 1998), because they enhance the ability of the plant to establish and cope with stress situations such as nutrient deficiency, droughts and other soil disturbances. Nowadays, it is also well demonstrated that mycorrhizal symbiosis influences the soil microbial functioning via its influence on some bacterial groups involved in major biogeochemical cycles (N, C and P) (Frey-Klett *et al*., 2005). Consequently both soil characteristics and plant community are affected by mycorrhization (Hartnett & Wilson, 1999). Although new technologies are widely published through scientific literature, rehabilitation programs in Ethiopia do not value biological and symbiotic potentials of soils under native or non-native shrubs, such as the cactus pear, as an alternative to improve plant physiological performances in disturbed habitats. Hence, this research was designed to assess the effect of cactus pear on the physical, chemical and biological 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 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 & 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 (Seleshi & 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 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, chemical, and biological 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 (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. Besides, about 0.5 kg subsamples were air-dried, sieved through a 2 mm mesh and put in labeled polythene bags and stored at 4^{o}C for soil biological analysis. Physical and chemical analyses of soil samples were carried out at Mekelle Soil Laboratory Center, while soil biological analyses were carried out at Mekelle University Microbiology Laboratory Centre.

2.3 Laboratory analyses of soil physical and chemical properties

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 & 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 & Mulvaney, 1982) was used to quantify the total soil nitrogen content. Phosphorus availability was determined by bicarbonate extraction P-Olsen's method (Olsen & Sommers, 1982).

2.4 Laboratory analyses of soil biological properties

Colonies of bacteria and fungi were counted by the dilution plate count method (Parkinson *et al.,* 1971). One gram of air-dried soil from each soil sample was aseptically weighed and transferred to dilution bottles containing 100 ml of sterilized distilled water to make the primary suspension. Bottles were allowed to stand on a magnetic stirrer for 15 minutes and then the soil was dispersed with the magnetic stirrer bar. Immediately following dispersion, series of 10-fold dilutions of the suspension were prepared by pipetting 1 ml aliquots into tubes containing 9 ml of sterilized distilled water up to (10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5}). Final dilution was up to 10^{-5} fold for bacteria and 10^{-3} folds for fungi (Cuppucino & Sherman, 1983).

To count total aerobic–mesophillic-hetrotrophic bacteria 0.1 ml aliquot of the final dilutions were transferred to 9 cm diameter sterile Petri dishes (replicated twice), with 20 ml of molten medium plate count agar at 45°C. Diluted samples were spread over the Agar Plates with an alcohol dipped, flamed sterile bent glass rod spreader "hockey stick". Plates were put in an incubator under inverted condition at 25°C to grow the microbial colony properly. Colony forming units (cfu) of bacteria and fungi were counted after 48 hours by using a colony counter with magnifying lens and glass marking pens. To count total yeast and filamentous fungi a similar procedure was followed using potato dextrose agar (PDA).

2.5 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

3.1 Analysis of physical and chemical properties of soils in the study watersheds

Table 3.1, 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). The distribution of soil moisture was also influenced by transect effect. In addition soil moisture content was influenced by the "transect*plot" interaction effect.

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 3.1 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
Ava. P (ppm)	16.08 (15.10)	7.02 (4.78)	11.638	0.001
pH	5.97 (1.05)	6.21 (1.11)	1.349	0.249
Soil moisture (%)	9.49 (7.50)	6.74 (6.10)	34.274	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). 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 for soil pH. 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.

3.2 Soil microbial analysis

In both the under the cactus pear canopy and open area soils, the number of bacteria and fungi quantified using the dilution plate count method were higher (Table 3.2). A comparison of bacterial count from under canopy and open soil samples revealed that the mean number of bacteria were significantly higher (p<0.01) in the under the cactus pear canopy samples than those in the open area soils. The mean number (107.5 cfu 10^6) of bacteria recorded was higher in transect one followed by transect three (106.00 cfu 10^6) for the under the cactus canopy soils. In contrast, the mean number (88.50 cfu 10^6) of bacteria was higher in transect four followed by transect one (88.00 cfu 10^6) for the open soils. However, all transect values were statistically non-significant (p>0.05). Further, the abundance of soil bacteria was marginally positively correlated with soil organic matter, total nitrogen, and soil moisture contents ($r_{(78)}$ = 0.054, (p>0.05); $r_{(78)}$ = 0.004, (p>0.05); $r_{(78)}$ = 0.201, (p>0.05) respectively.

Table 3.2 Mean (SD) values, *F*-test and *p*-values recorded for microbial counts (cfu 10^6/gm of soil for bacteria and cfu 10^4/gm of soil for fungi) under the canopy of cactus pear and in the open areas in the study watersheds

Parameters	Mean (SD) values			
	Under canopy	Open	*F*-test	*p*-value
Bacteria (cfu 10^6)	102.42(25.86)	84.45(24.12)	10.052	0.002
Fungi (cfu 10^4)	25.25(6.04)	19.95(5.29)	17.819	0.000

The cactus pear plant canopy recorded significantly higher mean count values (p<0.001) than the open areas (Table 2). The mean counts were higher in transect four (26.90 cfu 10^4) followed by transect three (26.40 cfu 10^4) for the under cactus pear canopy soil samples. Similarly mean counts were higher in transect four (22.50 cfu 10^4) followed by transect three (21.30 cfu 10^4), for open areas. Both values were statistically non-significant (p>0.05). However, correlation analyses showed that soil moisture content was positively correlated with soil fungal count ($r_{(78)}$=0.349, p<0.05).

4. Discussion

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 is in agreement with the findings of earlier investigators such as 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).

In the present study soil organic carbon generally showed a declining trend from the cactus pear canopy cover to adjacent open areas. This result is consistent with that of: 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 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 (Barbera, *et al*., 2010). The increased soil organic carbon in the study watersheds may also 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 Rebeca *et al*. (2010) also reported similar pattern of enrichment of soil total nitrogen under canopies of other cactus pear shrubs. 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 was in agreement with 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). 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 Saleh *et al*. (2009) who reported less acid soils can contribute high microbial activities, and proper plant growth and development.

The availability of nutrients and soil moisture for plants is tightly related to microbial activity under shrubs, which at the same time is regulated by soil moisture (Whitford and Freckman, 1988). The presence, abundance and trophic relations of symbiotic microorganism and organic matter decomposers are very important in the cycling of essential elements in plant nutrition. Soil microorganisms are crucial especially when plants are in full development and their demand surpasses the rate of mineralization by microbial components (Ingham *et al*., 1985). Soil microbial communities can change in response to different ecological factors such as association with plants, plant productivity gradients, susceptibility to herbivores and biological invasions. These factors have been confirmed by Hawkes *et al*. (2005) to alter soil microbial communities. Feedback on plant-soil relationship in natural systems has commonly been shown to influence soil microbial community composition or activity and ecosystem processes. Similar observation on the influence of plant-soil relationship on microbial community and ecosystems processes were reported by previous workers such as Wardle *et al.* (2004).

Higher soil carbon, total nitrogen, available phosphorus contents under the cactus pear canopy of the current study might be associated to the abundance of soil microorganisms which facilitated the decomposition of organic materials. In present study the abundance of bacteria in the soils significantly varied spatially and was related to the amount of nutrients and soil moisture availability. On the contrary, Ogunmwonyi *et al*. (2008) found non-significant difference in bacterial counts between under the plant canopy and open areas. However, the finding of this study was consistent with Ruiz *et al*. (2008) who found higher bacterial count under the canopy of shrubs compared to the open areas. Furthermore, the results obtained for the bacteria counts from soil samples from both cactus pear canopy cover and open areas fall within the range reported by Ogunmwonyi *et al*. (2008). Differences in the distribution of soil microorganisms were clearly reflected in the number of bacteria detected in each sampling sites. Moreover, it can be said that the higher soil moisture content under the canopy of cactus pear stimulated the growth and activity of microorganisms, which in turn may facilitate the mineralization rate of organic matter favoring plant mineral nutrition availability.

Similar patterns have been observed for other arid regions of the world. For instance, Herman *et al*. (1994) found that temporary soil moisture fluctuation was the only abiotic variable accounting for the nutrient fluctuation of free-living nitrogen-fixing microorganisms in Chihuahuan desert. The difference in fungal count between cactus pear canopy cover and open area soils was as high as 27% (with high value under cactus pear canopy). This difference disagreed with the finding of Ogunmwonyi *et al.* (2008), who reported non-significant difference between the sampling site (under shrub canopy and open areas). However, this finding was in agreement with the reports by Xueli *et al*., (2002) who recorded higher fungal numbers under shrub canopies than open areas. The fungal counts in this study were within the range reported by Amir and Pineau (1998).

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, chemical and biological properties positively. Soil organic carbon, soil organic matter, soil total nitrogen, soil available phosphorus, soil moisture contents, soil bacteria and soil fungi contents of the soil samples from under the cactus pear canopy cover were significantly higher compared to the adjacent open area soil samples. 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. The presence of higher nutrient content under the cactus pear canopy was also positively associated with abundance of soil bacteria and fungi which facilitate the decomposition of organic materials. Therefore, the microbial ecology of the studied watershed soils was found to be influenced by cactus pear canopy. The increase in soil bacteria or fungi number under the cactus pear canopy may be also be due to mineralization of organic matter. 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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