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Tree plantation and soil water conservation enhances climate resilience and carbon sequestration of agro ecosystem in semi-arid degraded ravine lands

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ABSTRACT

Agro ecosystems in degraded lands are subjected to climate change impacts throughout the globe. Previous work in degraded lands has focused on afforestation and soil conservation, which has obvious limitations in terms of generality and scope of application for production systems in climate change scenario. A key challenge in degraded lands is to develop climate smart systems those are resilient to extreme weather and have high potential for carbon sequestration. Therefore, we examined the effectiveness of Sapota trees (*Achras zapota*) and regional crops/grasses (annuals) combination (agroforestry) with soil water conservation (SWC) for enhancing climate resilience and carbon sequestration of agro ecosystem in semi-arid degraded lands of Western India. The experiment was conducted for eight years (2010–2017) in four systems: (i) Sapota + Crops on terrace (SCTe) (ii) Sapota on terrace (STe); (iii) Sapota and Trenches on slope (STrS); and (iv) Sole Sapota on slope (SS) and their performance was assessed during different annual rainfall events (Normal, Heavy, High, Abnormal, Drought). Our findings explained that, among all the annual rainfall events, drought resulted in the mortality of Sapota tree and reduction in biomass production of the grasses, while, terrace and trench measures reduced the tree mortality and enhanced the grass biomass production. Plant population of Cowpea and Castor crops were recorded significantly higher during normal rainfall, but a decline was observed during rest of the rainfall events. Height and diameter growth increment in Sapota was recorded higher during normal rainfall compared to the drought period. SWC measure such as terraces and trench contributed higher growth increment and biomass production in Sapota tree, compared to sole slope, under all the rainfall conditions. Rainfall variability also affected the Cowpea and Caster and their yield was recorded maximum during normal rainfall and minimum during drought period, respectively. Moreover, SWC measure such as terrace and trench enhanced fruit yield of Sapota during the drought period. These measures also improved carbon stock and carbon sequestration in Sapota and grasses during the eight years. Overall, carbon stock and carbon sequestration in plants and soil were observed greater in uncultivated terrace (STe), followed by cultivated terrace (SCTe) and trench (STr) systems, respectively, while, overall, their lower value was observed in slope system (SS). The results suggested that tree and annuals combination (agroforestry) along with soil water conservation measures enhanced agro ecosystem resilience to extreme weather and improved the carbon stock and sequestration potential. Therefore, soil and water conservation should be considered, along with only those trees and annuals, which have the capability to enhance climate resilience and potential of high carbon sequestration, in semi-arid climate change vulnerable degraded ravine landscape.

1. Introduction

Global climate change has severely affected the productivity and carbon sequestration potential of degraded lands (Kumar and Das, 2014). Researchers worldwide has observed that degraded lands are most susceptible ecosystem to climate change impacts (Henry et al., 2007). This is especially true for the semi-arid degraded ravine lands of Western India, where frequent droughts, occasional floods, high rainfall events, high summer temperature, heat waves, soil erosion, soil water limitation, infertile soil and high human-animal pressure etc. (Rao et al., 2015) contributes to ecosystem degradation. Restoring such lands through climate resilience is extremely important to conserve

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natural resources, maintain landscape sustainability, enhance greenhouse gases (GHGs) absorption, mitigate climate change, improve socio-economic conditions and to ensure food security (de MoraesSá et al., 2015; Minnemeyer et al., 2011; Perring et al., 2015; Prosdocimi et al., 2016; Roa-Fuentes et al., 2015).

Extreme climate and degraded soil environment led to reduced growth, productivity and carbon sequestration of plants in semi-arid ecosystem (Yang et al., 2000; Jiao et al., 2009; Frank et al., 2015). Afforestation of semi-arid degraded lands alone cannot sequester higher CO_2 because of high tree mortality and low productivity of surviving plants as a consequence of fluctuating climatic conditions, low soil water and high soil erosion (Singh, 2012; Kurothe et al., 2014). Under these conditions, semi-arid degraded environment needs agro ecosystem which can sequester CO_2 as well provides resilience to climate change (Altieri and Nicholls, 2013).

Agroforestry, conservation agriculture and soil and water management have the potential for enhancing agro ecosystem resilience to extreme climatic conditions (Lin, 2007; Lin 2011; Philpott et al., 2008; Reij et al., 1996; Barrow 1999; Döll, 2002). These systems also contribute to higher CO_2 sequestration in degraded lands which maintain global C balance (Basu, 2014). Degraded land world-wide can store more carbon than annual anthropogenic emissions, so climatic resilient system could further boost the large feedbacks to the global C cycle (Franzluebbers and Doraiswamy, 2007: Brahma et al., 2017). However, climate resilience, carbon sequestration and mitigation potential of agro-ecosystems have been poorly documented in degraded lands (Mattsson et al., 2009; Nguyen et al., 2013; Miguel et al., 2015; Simelton et al., 2015). A properly managed agro ecosystem can moderate/improve climatic conditions (Trabucco et al., 2008), conserve soil and water resources (García et al., 2010), improve ecosystems services (Evans et al., 2013) and absorb atmospheric GHGs (Amichev et al., 2008) in degraded lands.

Previous agroforestry experiments, particularly for climate resilience, have demonstrated great potential in enhancing productivity of degraded lands (Nambiar et al., 1990; Prajapati et al., 1993; ; Chaturvedi et al., 2014; Singh et al., 2015), while, soil and water conservation measures improve plant survival and growth in such environment as a consequence of improved soil moisture and reduced soil erosion (Altieri and Toledo, 2011; Ran et al., 2013; Hishe et al., 2017). Agroforestry have demonstrated its role individually either in climate moderation (Lin 2011), extreme weather events (Noordwijk et al., 2011) and CO_2 sequestration (Nair et al., 2009). However, the role of soil and water conservation has been underestimated in degraded environments (Mazzucato and Niemeijer, 2000). These both management systems can simultaneously provide resilience to plants against drought, flood, high temperature and extreme rainfall events (Lal et al., 2011; Lobell et al., 2011; Nguyen et al., 2013; Miguel et al., 2015; Azari et al., 2017). Agroforestry i.e. tree and annuals combination provides resilience to extreme weather conditions (Chibinza et al., 2012), while soil and water conservation sustains the plant growth during high rainfall events and drought period, respectively (Wolka, 2014).

The type of management practices for agro ecosystem may vary from location to location, but they play a vital role in maintaining the plant productivity (Iizumi and Navin, 2015). An agro ecosystem should not only be resilient to extreme climate conditions and sequester GHGs but should also be profitable, sustainable and adoptable in particular conditions. The above studies have shown that, there are rarely any reported results from field experiments that tested climate resilience and CO_2 sequestration simultaneously in agro ecosystem which is supplemented with soil and water conservation, particularly in degraded environment. Of those that are reported, the observed responses seem to be individually either for climate change (Noordwijk et al., 2011) or carbon sequestration (Nair et al., 2009). However, further studies are needed to identify management practices which can provide resilience against extreme climate and improve carbon sequestration simultaneously by conserving soil and water resources in degraded lands (Altieri and Toledo, 2011; Altieri et al., 2015). Therefore, we investigated the growth and productivity of annual and perennial plants in association with terracing and trenching during extreme weather, and simultaneously assessed their role in carbon stock and carbon sequestration in degraded ravine lands. The specific objectives of the study were to: 1) observe the impact of extreme climate on plant population, growth, biomass and economic yield and; 2 assess the effectiveness of terracing and trenching in plant growth, productivity, carbon stock and carbon sequestration in degraded lands.

2. Materials and methods

2.1. Experimental site

The experiment was conducted for eight years (2010-–17) on 0.72 ha area in climate change vulnerable degraded ravine landscape of Western India, (22°16′ N; 72°58′ E; elev. 25 m). The site is a large gully, well drained, with a 14% land slope and had been previously under few scattered trees and bushes. Soils are deep and less productive, highly eroded with low soil water, identified as fine loamy mixed calcareous hyperthermic Fluventic usto chrepts (Associated with Inceptisols) group. The mean annual temperature was 25 °C, with monthly mean temperatures ranging from 17 °C in January to 31 °C in May, and the mean annual precipitation is ~870 mm, approximately 90% of which is received during June–September months of each year (Fig. 1). Rainfall received during experiment period, its characteristics and description are explained in Table 1.

2.2. Research design

The degraded sloping ravine landscapes was re-shaped to terraced land for soil water conservation, while, in the rest of the plots, slopes were maintained uniformly. Terraces and slopes were considered because both land patterns are common throughout the ravine landscapes. In one of the slopes, trenches were designed; because these are considered as a cost effective measure for SWC. The regional land use comprise of crops and trees (boundary) on the terrace, while scattered trees and bushes (natural) on the slopes, both constitutes as the dominant land use components in these ecosystems. Therefore, keeping in consideration above points, the four systems selected for the study were : (i) Sapota + Crop cultivation on terrace (SCTe) (ii) Sapota on terrace (STe); (iii) Sapota and Trenches on slope (STrS); and (iv) Sole Sapota on slope (SS). These system were considered to assess their climate resilience and CO_2 sequestration potential in degraded ravine lands. Each system was executed in a 72 m x 24 m sized plots, each separated by earthen bund. In Sapota and Trenches on slope (STrS) system, 2.0 m x 0.5 m x 0.5 m sized staggered contour trenches were designed for soil and water conservation.

2.3. Annuals and tree cultivation

To observe the response of crop and grasses during extreme weather conditions, and to assess their carbon sequestration potential, Castor (*Ricinus communis*) and Cowpea (*Vigna unguiculata*) crops were grown annually in 1:2 ratios by adopting conventional tillage method in combination with Sapota (*Achras zapota*) for eight years (2010–2017) The castor and cowpea were considered, because both crops constitute as the dominant cropping systems in these regions. Cowpea (15 cm line spacing) was sown at interspaces of castor (45 cm line spacing) during July month at onset of the rainy season. The Cowpea was harvested during September (after 3 months), while Castor was harvested during March (8 months) of the following year. The regional recommended agronomic practices were followed for both the crops. These dry degraded ravines are characterized by the greater dominance of low-value native trees and the paucity of native commercial trees led the selection

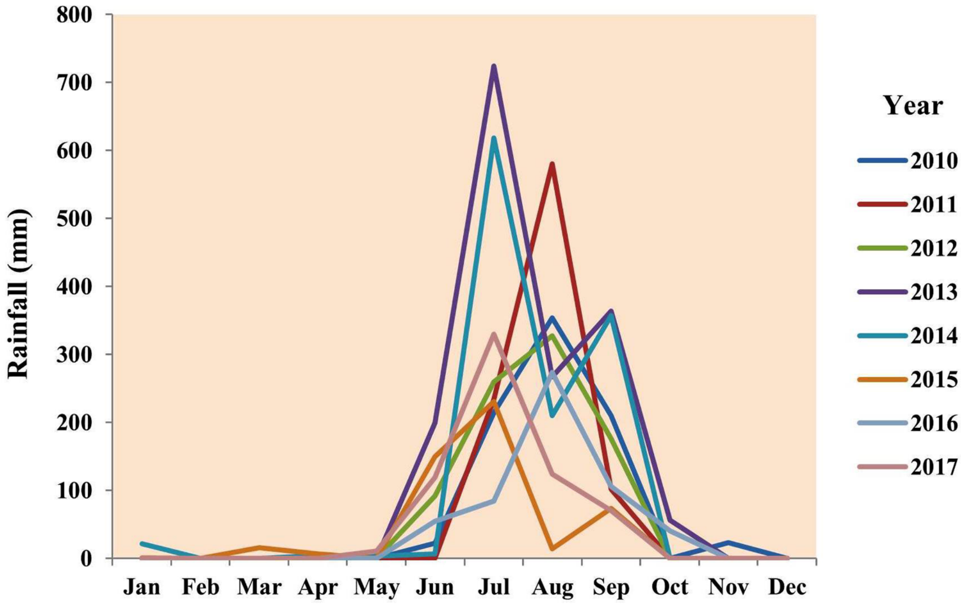

Fig. 1. Monthly rainfall received at the experimental site different during different years (2010–2017).

of *Achras zapota* (Sapota) to improve climatic and economic benefits in such lands. Sapota is an exotic tree, which is evergreen, deep-rooted, drought resistant, soil binder and highly economical (fruit); hence it is an excellent species to reclaim the ravine lands. Six months old seedlings of Sapota were planted at 8 × 8 m distance in each system during 2010. *Dichanthium annulatum* and *Cenchrus ciliaris* were observed growing naturally in three systems (STe, STrS, SS) which constitutes as the dominant grasses of the region. The annuals (crops and grasses) plant populations, above ground harvested biomass (annuals) and pods (Cowpea) and seed (Castor) yield determined in 1 × 1 m sized plots in each system.

2.4. Climate resilience assessment

The effect of extreme weather was observed on plant population, growth, biomass and economic yield of crops, Sapota tree and grasses. The year wise data of daily rainfall was recorded to determine normal rainfall, heavy rainfall events and drought etc. We recorded daily rainfall and calculated the sum of the daily precipitation amount (cm) between January 1 and December 31 of each year. Drought period was considered when total rainfall in a season was less than 75% of the long term average annual rainfall of the region (Mathai, 1979). In order to record annuals performance, eight 1 × 1 m sized sample plots were laid and number of plants (population), cowpea pods, Caster seed yield and grass biomass were recorded as per methodology explained by Chang et al. (2015) with partial modification for these systems. The plant populations (annuals and trees) and yields (crops only) in different year were compared with the base year (2010); because this year region received approximately normal rainfall (824 mm). Rainfall during this year was near to long term (50 years) average annual rainfall (870 mm) and also this year was without any extreme rainfall event. The plant population, biomass and their yield varied in different years when were compared with the year 2010 as a consequence of varied rainfall during that year. In different system mortality and fruit yield of Sapota was recorded to observe its response to drought under different SWC. Increment in height and diameter were recorded annually (2010–17) and means of all the sysetms computed to observe the effect of annual rainfall on Sapota growth. Mean increment in height and diameter were calculated to analyze Sapota growth response to SWC in different systems.

2.5. Biomass and carbon stock determination

To estimate growth of Sapota, eight trees per treatment were randomly selected and height and diameter measured every year (2010–2017). Biomass and carbon stock in the tree was estimated at the end of year 2017. For that, twenty five branches of varying diameter harvested, leaves and wood component separated, and oven dried to compute dry branch biomass. The relationship between branch diameter and branch dry biomass (wood + leaves) established to compute the dry branch biomass of sampled trees as per the procedure described by Poudel et al. (2015). The stem volume of sampled tree determined to estimate above ground biomass using methodology adopted by Tomar et al. (2015). The wood specific gravity (0.93 g cc^{-1}) and root-shoot ratio (0.31) was estimated manually in Sapota as per methodology elaborated by Navar (2010). The stem biomass were determined by multiplying stem volume with the wood specific gravity. The above ground biomass computed by summing branch biomass and stems

Table 1
Characteristics and description of rainfall received during the study period.

Year	Annual rainfall(mm)	Rainfall characteristics	Description
2010	823.8	Normal (N)	Normal rainfall throughout the rainy season
2011	915.9	Normal (N)	,,
2012	852.4	Heavy events (HE)	High rainfall events received during rainy season
2013	1611.0	High (HA)	High annual rainfall received than normal rainfall
2014	1221.1	Abnormal (AB)	Low rainfall at the initial and high rainfall in later of the season
2015	475.0	Drought (D)	Less rainfall received during these years compared to normal rainfall
2016	560.0	Drought (D)	,,
2017	658.0	Drought (D)	,,

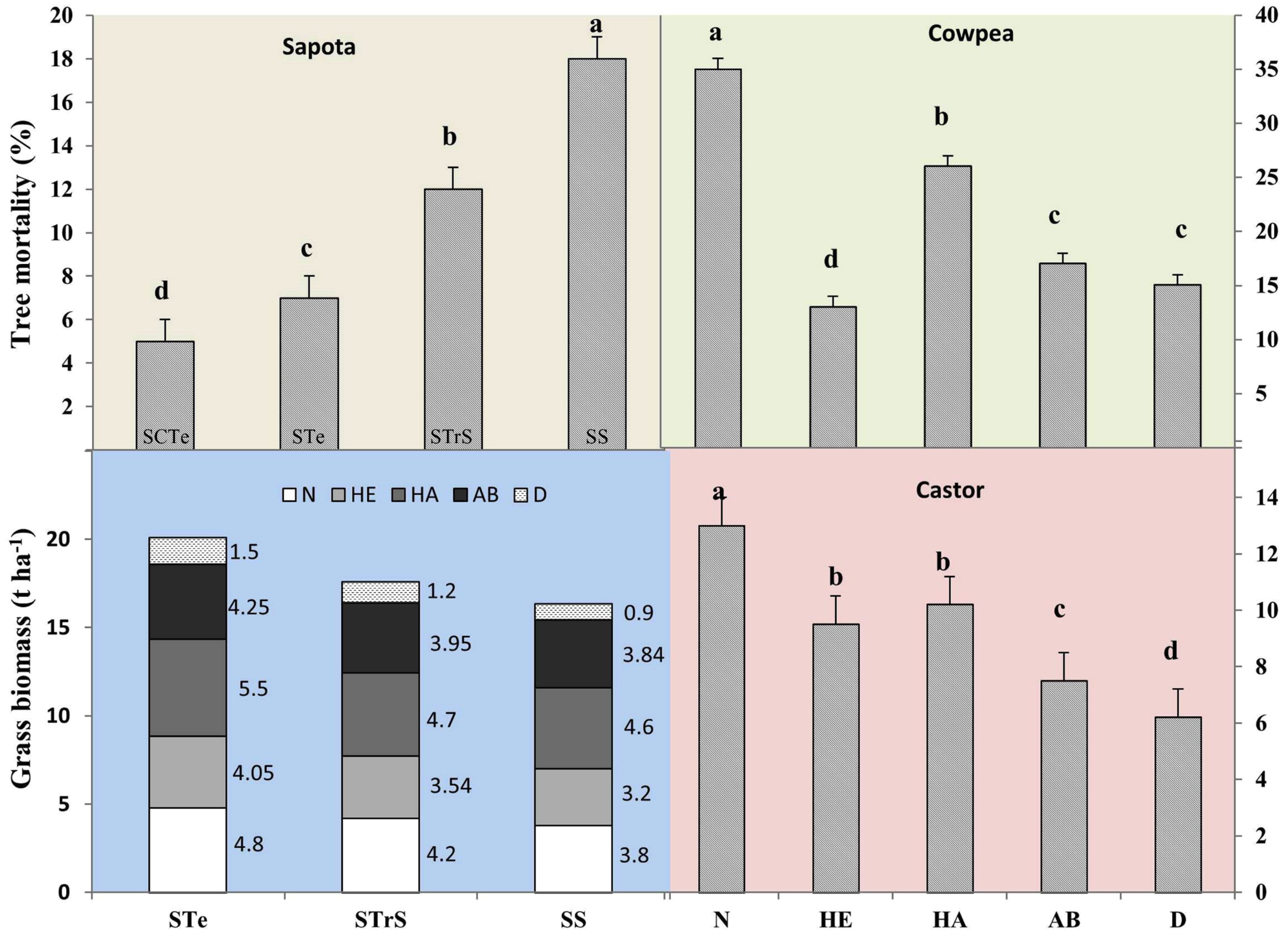

Fig. 2. Effect of drought period on tree mortality under different SWC measure. Grass biomass production under different SWC measure and rainfall conditions. Effect of rainfall conditions on plant populations of Cowpea and Castor at the experiment site. The error bars denote ± 1SE. Bars with same letters are not significantly different at $P \leq 0.05$. SCTe: Sapota and crops on terrace, STe: Sapota on terrace, STrS: Sapota and Trenches on slope, SS: Sole Sapota on slope. N: Normal rainfall, HE: Heavy rainfall events, HA: High rainfall, AB: Abnormal rainfall, D: Drought period.

biomass, while, below ground biomass computed by multiplying above ground biomass with the root-shoot ratio value of 0.31. The total tree biomass estimated by summing the above ground biomass (stem wood, branch wood and leaves) and below ground biomass (root). The carbon stock (CS) calculated by multiplying total tree biomass with the constant factor 0.50 (Petersson et al., 2012), while CO_2 sequestration (COS) was determined by multiplying the carbon stock with the constant factor 3.67 (IPCC, 2003). The shoot biomass of crops (Cowpea and Castor) and grasses was harvested and oven dried to determine above ground biomass. The below ground biomass of both components computed by multiplying above ground biomass with a constant factor 0.26 (IPCC, 2003). Likewise, CS and COS in crop and grasses were determined by using above mentioned factors. The soil organic carbon was determined by wet digestion method (Walkley and Black, 1954).

2.6. Statistical analysis

The Tukeys HSD (honest significant difference) was performed in randomized block design with eight replications to detect differences in plant populations, grass biomass, tree height and collar diameter increment (both annual and mean), fruit yield, CS and COS and, economic yield. The significance among the treatments was tested at 5% level of significance. All these statistical analysis was performed using the SPSS 16.0 software.

3. Results

The ravine landscapes are severely affected by the rainfall aberration, soil erosion and water limitations that resulted in the reduced plant productivity and enhanced resource degradation. Therefore, performance of annual and perennial plants has been assessed along with soil and water conservation (SWC) measures in the following headings:

3.1. Plant populations

Our results showed that drought period resulted in 5–18% decline ($P < 0.05$) in tree populations, while normal, heavy rainfall event, high rainfall and abnormal rainfall resulted in no effect on tree population. During drought period, the performance of SWC showed that uncultivated terraces (STe; 5%), cultivated terrace (SCTe; 7%) and trenches (STrS; 12%) resulted in the lesser tree mortality compared to slope (SS; 18%) (Fig. 2). In case of grasses, high annual rainfall contributed to greater ($P < 0.05$) biomass production followed by normal rainfall, heavy rainfall event, abnormal rainfall and least was observed during drought conditions. During these rainfall conditions, terrace produced higher ($P < 0.05$) biomass (1.5–4.8 t ha^{-1}) in grasses followed by trench (1.2–4.2 t ha^{-1}) and least (0.9–3.8 t ha^{-1}) was produced in slope. Drought, high rainfall event, high annual rainfall and abnormal rainfall had moderate to high effect on castor populations compared to normal rainfall. Likewise, cowpea populations were significantly higher

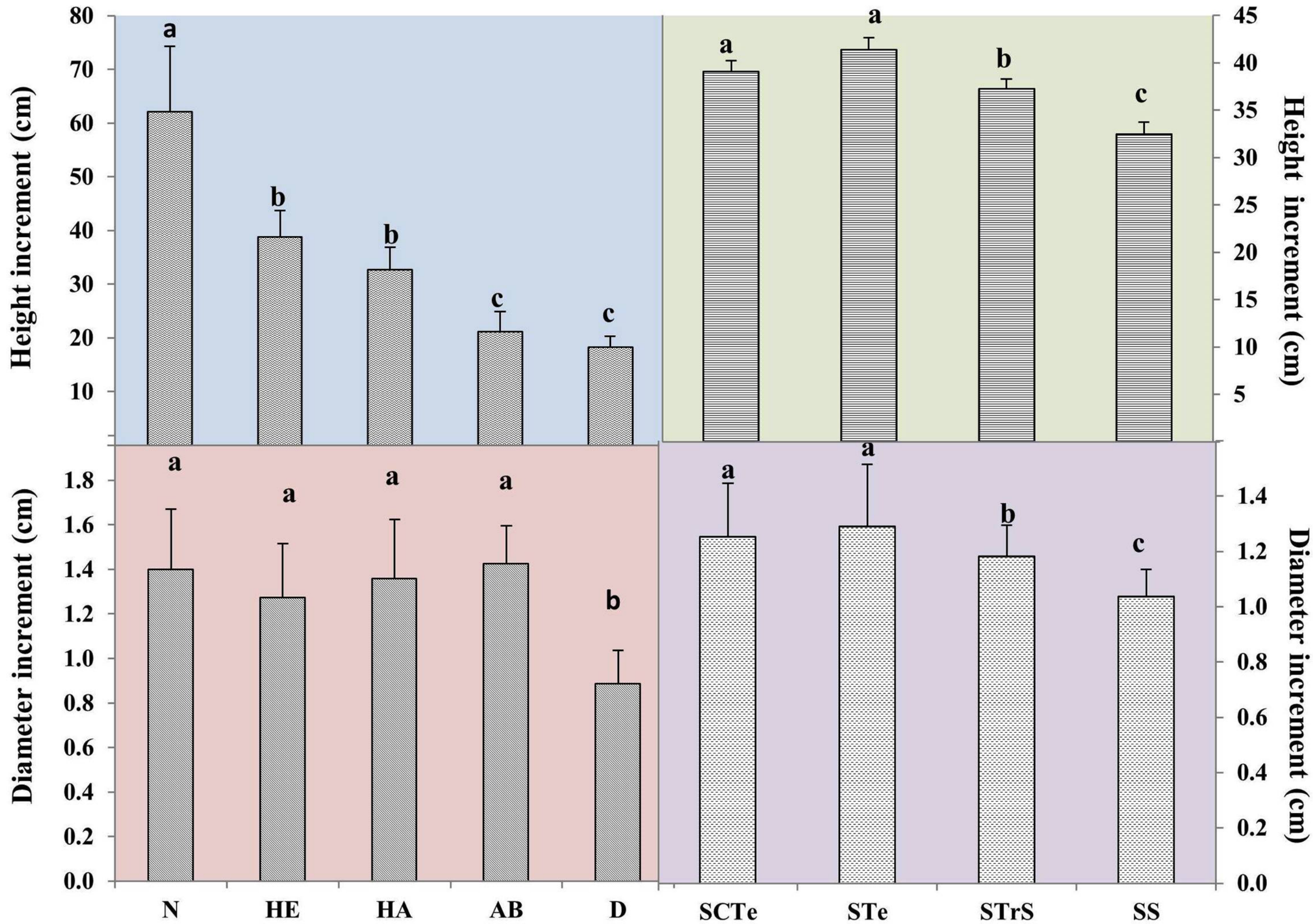

Fig. 3. Effect of rainfall conditions on annual height and diameter growth increment in Sapota. Mean height and diameter growth increment in Sapota under different SWC measure after eight years. The error bars denote ± 1SE. Bars with same letters are not significantly different at $P \le 0.05$. SCTe: Sapota and crops on terrace, STe: Sapota on terrace, STrS: Sapota and Trenches on slope; SS: Sole Sapota on Slope. N: Normal rainfall, HE: Heavy rainfall events, HA: High rainfall, AB: Abnormal rainfall, D: Drought period.

($P < 0.05$) during normal rainfall compared to rest of the rainfall events. Therefore, rainfall variability negatively affected the plant population and biomass, while, terrace and trench reduced the tree mortality and enhanced the grass biomass production.

3.2. Sapota growth and biomass production

In the present study, an increasing trend in diameter and height growth was observed in the eight years of experimentation. Height growth increment during normal rainfall was significantly ($P < 0.05$; Fig. 3) higher (62 cm) compared to heavy rainfall event (38 cm), high rainfall (32 cm), abnormal rainfall (21cm) and drought (18 cm), respectively. Likewise, increment in diameter growth was recorded higher ($P < 0.05$) during normal rainfall (1.40 cm) compared to drought year (0.89 cm). During these rainfall conditions, uncultivated terrace (STe; 41 cm) and cultivated terrace (SCTe 39 cm) and trench (STrS; 37 cm) contributed higher ($P < 0.05$) mean height increment compared to sole slope (SS; 32 cm), after eight years. The mean diameter increment was also observed greater ($P < 0.05$) in uncultivated terrace (1.29), followed by cultivated terrace (1.29 cm) and trench (1.18 cm) compared to sole slope (1.04 cm). The positive effect of SWC on Sapota growth resulted in marked influence on the biomass production which was also observed higher ($P < 0.05$) in uncultivated terrace, followed by cultivated trench and least on sole slope, respectively (Fig. 4). These results showed that SWC enhances the growth increment and biomass production of Sapota as affected by the rainfall variability.

3.3. Rainfall variability affects crop yield

Our results showed that the significant ($P < 0.05$; Fig. 5) effect of rainfall were observed for cowpea and castor economic yields during eight years (2010–2017). Cowpea yield (pods) was ranged maximum of 14.97 q ha^{-1} during normal rainfall year and minimum of 0.40 q ha^{-1} during heavy rainfall event (year), respectively. Likewise, castor yield (seed) was recorded greater (10.92 q ha^{-1}) during normal rainfall and lesser (2.53 q ha^{-1}) during drought period, respectively. These results explained that rainfall variability significantly affected crop yield during the experiment period.

3.4. Effect of SWC on fruit yield

The effect of SWC on fruit yield was recorded during the drought period (2015–2017). During this period, fruit yield of Sapota ($P < 0.05$; Fig. 4) was observed in order of STe > SCTe > STrS > SS, respectively. Sapota plantation on un-cultivated terrace (STe) produced higher fruit yield followed by cultivated terrace (SCTe) and trench (STrS), while, least fruit yield was observed in sole slope (SS), respectively. These results demonstrated that SWC measures enhanced the fruit yield of Sapota during drought period.

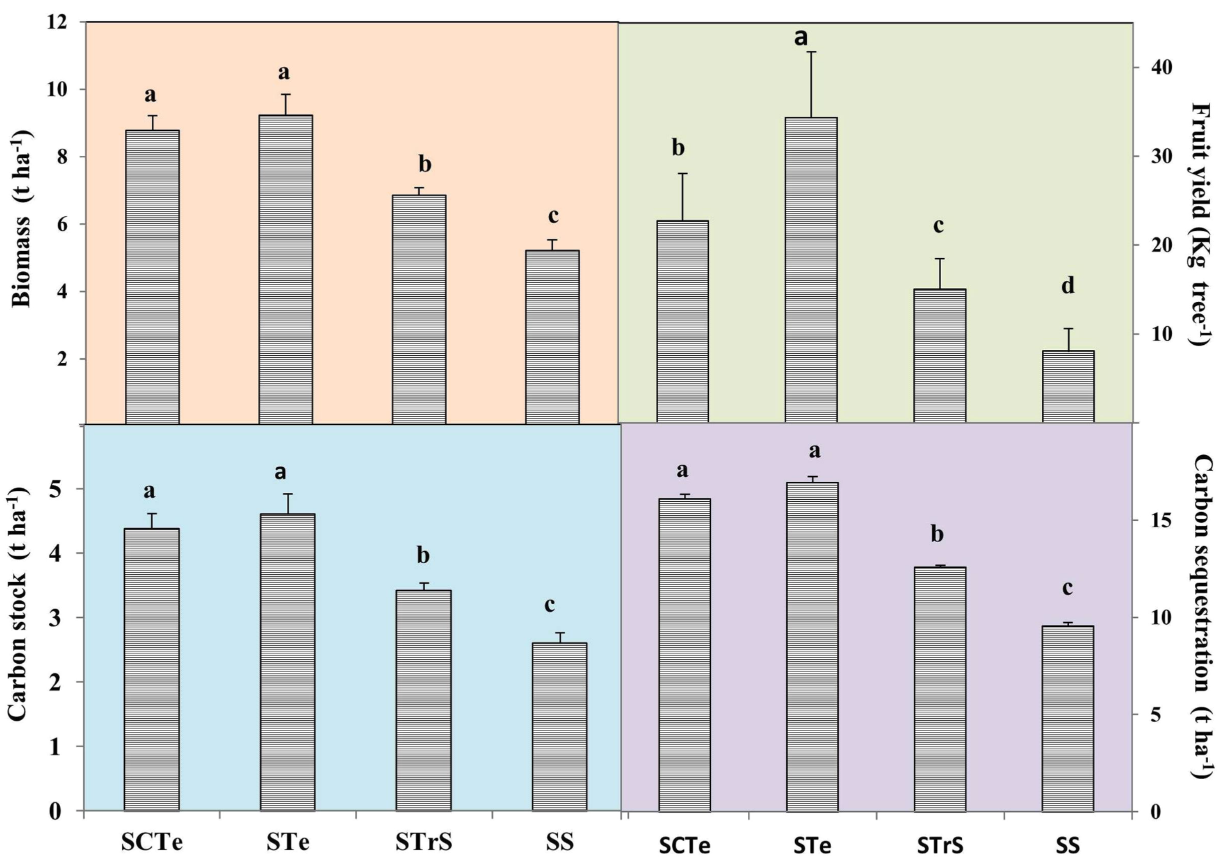

Fig. 4. Effect of SWC measure on biomass production, fruit yield, carbon stock and carbon sequestration in Sapota. The error bars denote ± 1SE. Bars with same letters are not significantly different at $P \leq 0.05$. SCTe: Sapota and crops on terrace, STe: Sapota on terrace, STrS: Sapota and Trenches on slope, SS: Sole Sapota on slope.

3.5. Carbon stock (CS) and CO_2 sequestration (COS) in Sapota

CS and COS were estimated in four systems in eight years in perpetuity. Analysis of change in systems indicated that there was significant change between systems ($P < 0.05$; Fig. 4) based on calculated mean value. CS and COS in STe, SCTe, STrS and SS systems was ranged maximum and minimum between 2.61–4.61 t ha^{-1} and 9.57–16.93 t ha^{-1}, respectively. CS and COS showed the largest increase in STe compared to SS systems. In absolute terms, cultivated terrace (SCTe), trench (STrS) and sole slope (SS) recorded 4.8, 25.8, and 43.4 percent lower CS of Sapota compared to uncultivated terrace (STe), respectively. Likewise, COS found to decline significantly ($P < 0.05$; Fig. 4) in cultivated terrace (0.83 t ha^{-1}), trench (4.36 t ha^{-1}) and in sole slope (7.36 t ha^{-1}) compared to uncultivated terrace. Overall, Sapota grown on uncultivated terrace (STe) resulted in maximum CS and COS of 76%, followed by cultivated bench terrace (SCTe) of 68% and trench (STrS) of 31%, respectively, compared to sole slope (SS). These results indicate that terraces and trenches improved the carbon stock (CS) and CO_2 sequestration (COS) in Sapota.

3.6. CS and COS in grasses

In the present study, CS and COS of native grasses differed significantly ($P < 0.05$) among the systems. CS and COS value was observed higher in STe (2.84 and 10.41 t ha^{-1}) compared to STrS (1.88 and 6.90 t ha^{-1}), and SS (1.81 and 6.62 t ha^{-1}), respectively, in decreasing order (Fig. 6). In general, terrace (STe) contributed 1.50 and 1.57 times higher CS and COS in grasses compared to trench (STrS) and slope (SS). Likewise, grasses grown in trench sequestered 1.04 times higher carbon compared to slope (SS). These results support the notion that SWC measure enhances the CS and COS of native grasses in degraded lands.

3.7. Overall CS and COS

Overall (Tree + crop/grass + soil) CS and COS trend differed significantly ($P < 0.05$, Fig. 7) in all the four systems. During experiment period, overall CS and COS in STe, SCTe and STrS were recorded 1.68, 1.08, 1.20 times more, respectively, compared to SS. In precise terms, cultivated terrace (SCTe) resulted in higher CS and COS by 0.37 and 1.35 t ha^{-1} respectively, compared to sole slope (SS). Likewise, Uncultivated terrace (STe) and trenching (STr) contributed higher CS (3.01; 0.89 t ha^{-1}) COS (11.14; 3.27 t ha^{-1}), respectively, compared to SS. Overall, CS and COS were observed greater in uncultivated terrace (STe), followed by cultivated terrace (SCTe) and trench (STr) systems, respectively, while, overall, lower CS and COS was observed in slope system (SS). Thus, our results indicate that SWC measures induced higher CS and COS in degraded ravine lands.

4. Discussion

Overall results explained that extreme seasonal/annual rainfall (low or high) had a low effect on trees and low to moderate effect on grass populations, while moderate to high effect on crop populations during the experiment period. Among different annual rainfall, only drought were found to have significant negative effect on tree populations and grass biomass, while all the annual rainfall negatively affected the crop populations compared to normal rainfall. Trees and grasses were observed to be more resilient compared to crops during extreme weather conditions; because former are more efficient in water and nutrient

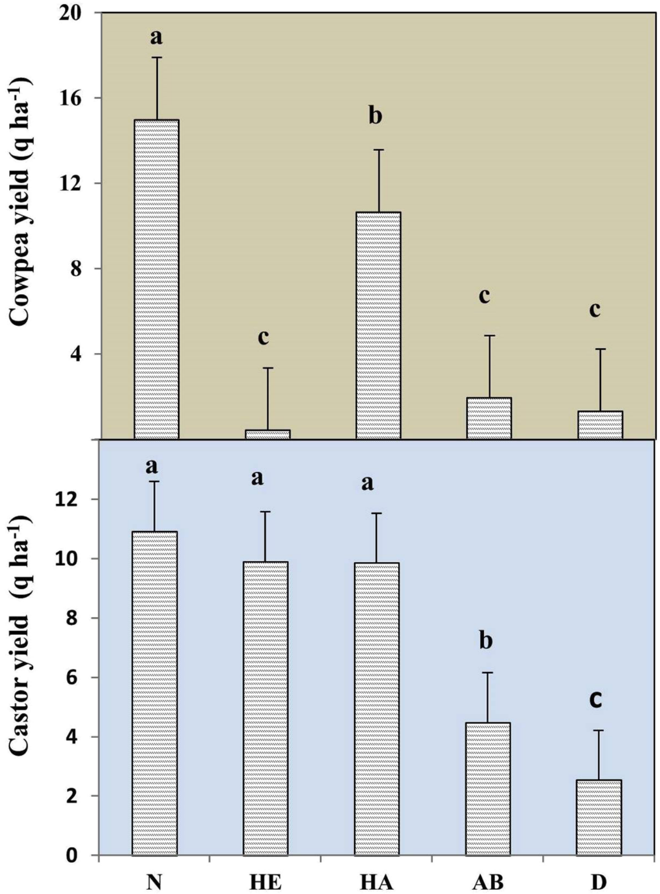

Fig. 5. Cowpea and castor economic yield during the experiment period. The error bars denote ± 1SE. Bars with same letters are not significantly different at $P \leq 0.05$. N: Normal rainfall, HE: Heavy rainfall events, HA: High rainfall, AB: Abnormal rainfall, D: Drought period.

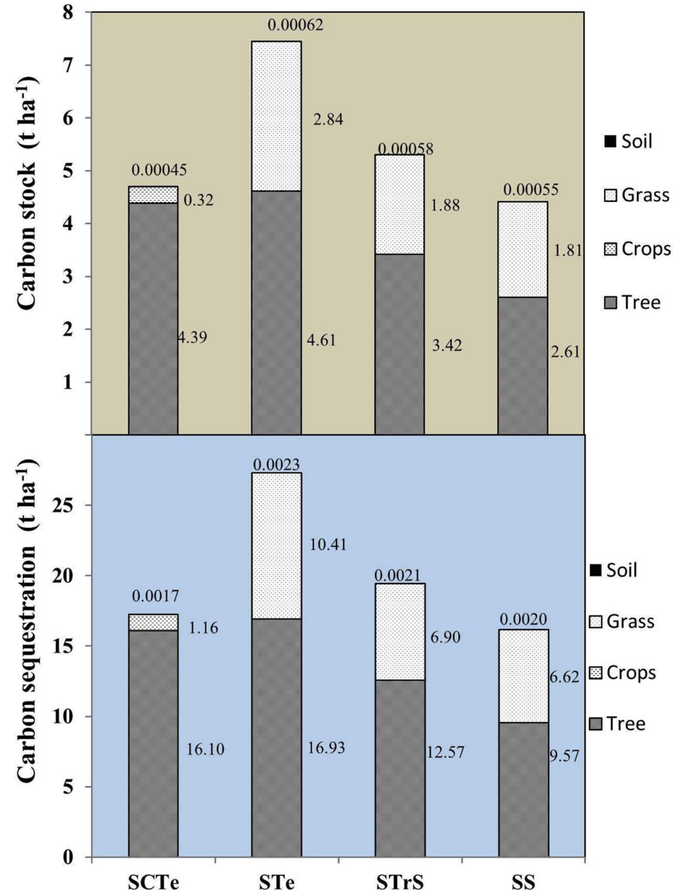

Fig. 7. Overall carbon stock and carbon sequestration in different systems. The error bars denote ± 1SE. Bars with same letters are not significantly different at $P \leq 0.05$. SCTe: Sapota and crops on terrace, STe: Sapota on terrace, STrS: Sapota and Trenches on slope, SS: Sole Sapota on slope.

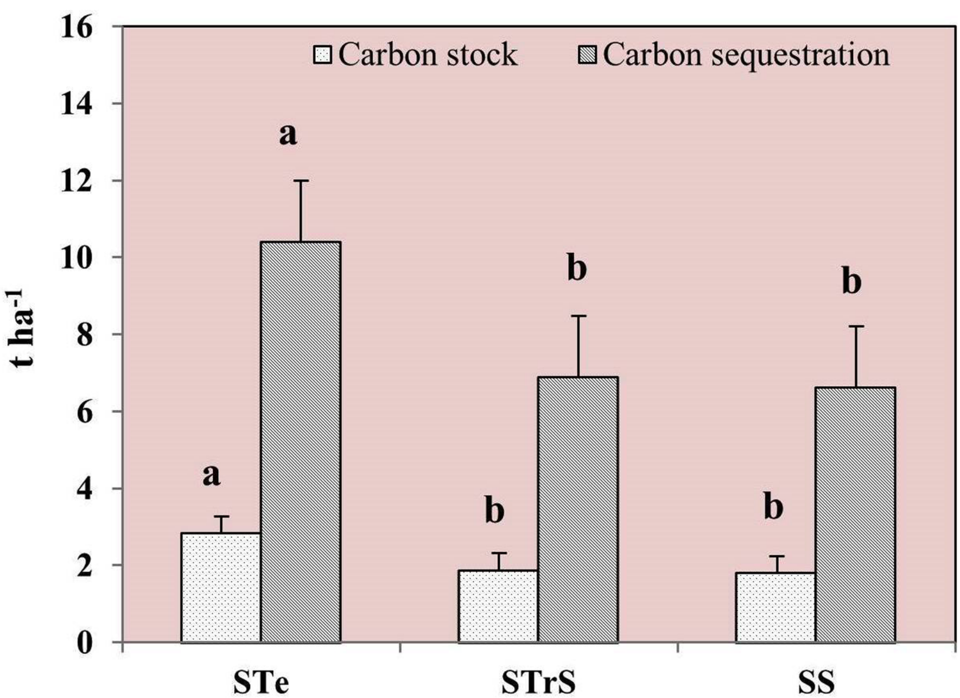

Fig. 6. Carbon stock and carbon sequestration in grasses under different systems. The error bars denote ± 1SE. Bars with same letters are not significantly different at $P \leq 0.05$. SCTe: Sapota and crops on terrace, STe: Sapota on terrace, STrS: Sapota and Trenches on slope;, SS: Sole Sapota on slope.

absorption during extreme weather compared to crops. Lobell et al. (2011) also observed that altered precipitation and extreme weather events significantly affect plant growth characteristics. Rather, crop diversification and tree plantation/ agroforestry are considered one of the strategies that reduces vulnerability to climate variability (Miguel et al., 2015). In our experiment, tree-crop/grass combination performance showed that tree component can provide resilience to agro ecosystem, even after moderate to high loss to the crops/grasses during extreme climate. For instance, Nguyen et al. (2013) in Vietnam observed that rice and rain-fed crops suffered over 40% yield loss in years of extreme drought or flood, while tree-based systems were less affected. Similarly, Sida et al. (2018) observed that *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. In addition, several researchers have also reported damage to crops during extreme weather conditions compared to trees (Eitzinger et al., 2007; Mattsson et al., 2009; Lin, 2011; Simelton et al., 2015). However, results further showed that implementing SWC measures such as terrace and trench in degraded lands reduced damage to tree and grasses during extreme climate conditions, particularly the drought. Therefore, SWC measure should be adopted for enhancing climate resilience in the degraded ravine lands (Fig. 8).

Sapota growth increment (height and diameter) during normal rainfall was observed higher compared to heavy rainfall (event), high rainfall, abnormal rainfall and drought, respectively. Under drought conditions, highest reduction in growth increment was recorded compared to rest of the rainfall conditions. The lesser water availability during growing season alters physiological functions (Penuelas et al., 2001) that subsequently affect the growth and biomass of trees (Penuelas et al., 2002). For example, rainfall aberration had also significantly affected the growth of *Pinus taeda* (Zaminet al., 2013), *Pinus pinaster* (Bogino and Bravo, 2008) and *Pinus nigra* (Andreu et al., 2007). However, irrespective of rainfall conditions, terrace and trench sustained and improved the tree growth and biomass compared to sole slope. In terrace and trench, greater soil water conservation and more nutrient availability and consequently their higher absorption contributed to the improved Sapota growth and biomass production in highly degraded conditions. The increased growth and biomass as a consequence of conservation measures eventually contributes to increased vegetation cover that rapidly ameliorates the degraded lands (Ran et al., 2013). Nevertheless, rainfall variability significantly affected the increments in Sapota growth which suggests that drought tolerant trees should be preferred along with SWC measure in climate change vulnerable regions.

Crop yield was recorded quite variable during different years as a consequence of drought, high, heavy and abnormal rainfall events during the experiment period. Although satisfactory Cowpea and Castor yield was recorded during normal rainfall in these semi-arid conditions. Change in rainfall pattern during a particular year, significantly reduced yield of both the crops. The Cowpea was observed to be highly sensitive to the change in seasonal rainfall compared to the Castor. During drought period, terraces and trench were found effective in enhancing fruit yield in semi-arid degraded lands. Uncultivated terrace (STe) was highly effective for fruit production, followed by cultivated terrace (SCTe) and trench (STrS), compared to sole slope (SS), that was due to greater soil moisture and nutrients availability in terrace and trench system. It can be interpreted from the results that in cultivated terrace, system of tree-crop combination can be win-win situation in climate venerable degraded agro ecosystem. During extreme climate, failure of crop component can be compensated through yield obtained from the second component. In Sri Lanka, Bantilan and Mohan (2014) reported that farmers are shifting from annual crops to perennial drought-tolerant plantations to avoid the risk of crop failure during drought conditions. Previous researchers have observed that incorporating trees in agriculture landscapes provides more resilience to extreme climate compared to the sole crops (Chibinga et al., 2012; Jost and Pretzsch, 2012). This suggested that trees and agroforestry based farming systems augumented with SWC should be preferred globally in degraded agro-ecosystems vulnerable to climate change (Simelton et al., 2015).

Our results explained that terraces (both) and trench system

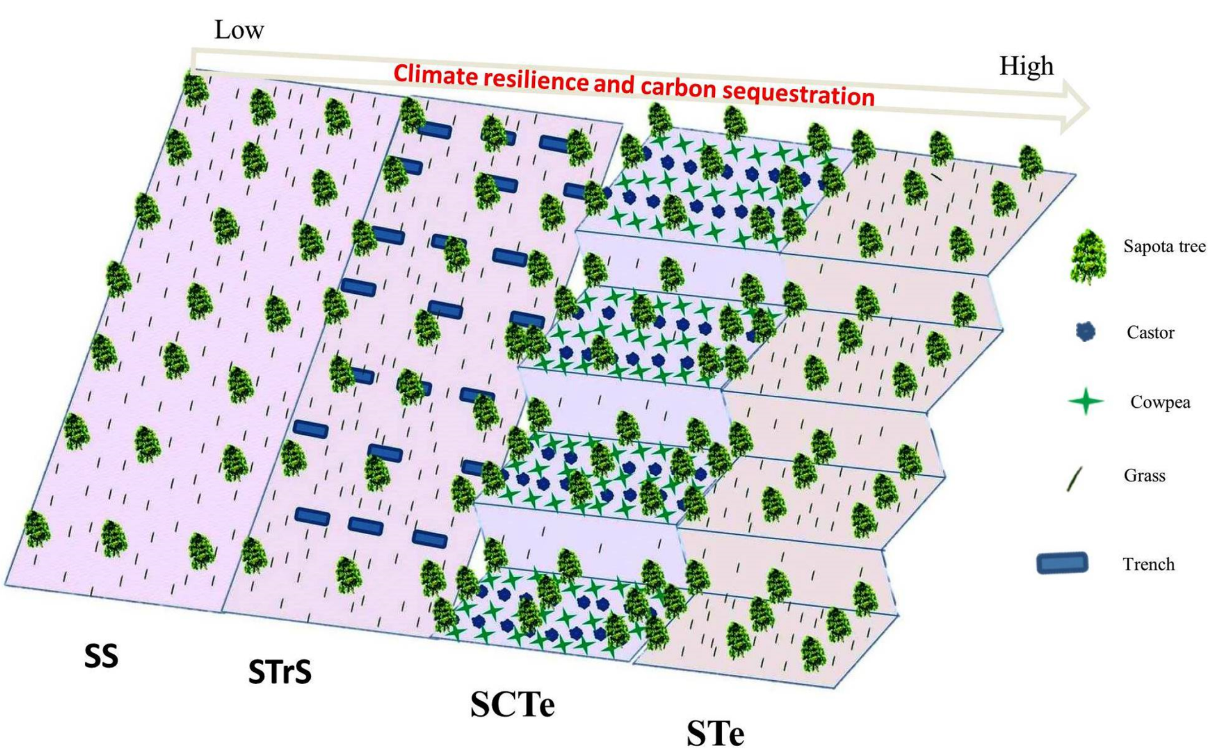

Fig. 8. Conceptual framework depicting process of enhancing climate resilience and carbon sequestration in agro ecosystem of degraded ravine lands. STe: Sapota on terrace, STrS: Sapota and Trenches on slope, SS: Sole Sapota on slope.

enhanced Carbon stock (CS) and CO_2 sequestration (COS) in Sapota. The higher CS and COS in terrace and trench clearly indicated input management in cultivated terrace (SCTe), and soil water conservation in uncultivated terrace (STe) and trench (STrS) induced the biomass production that resulted in greater carbon stock and carbon sequestration in Sapota. Uncultivated terrace was found to be highly effective, followed by cultivated terrace and trench for CS and COS (Sapota) in degraded ravine lands (Fig. 8). Similar observations were made by Lal (2015) and Deen and Kataki (2003) with regard to increased CS and COS in plants due to higher soil nutrients and water in such environment. The increased CS and COS contributes to climate change mitigation through greater CO_2 sequestration in degraded lands (Murgueitio et al., 2011).

The result explained that SWC viz. terrace and trench improved the CS and COS of grasses in degraded ravine lands. The highest CS and COS was observed in the uncultivated terrace (STe) compared to other systems that was resulted from the greater soil moisture and nutrients conservation. Likewise, in semi-arid China, Liu et al. (2010) observed that terrace increased annuals yield (27%) and drought resistance due to higher moisture content (9–15%) and nutrient use efficiencies in the soil. Vickars (2005) and Zhang et al. (2014) further confirmed that soil and water conservation improved soil moisture that enhanced plant productivity in semi-arid degraded land. Similarly, in several other species, soil and water conservation maintained the plant growth and productivity (Zhu and Zhao, 2003; Zhang et al., 2011). Moreover, soil water conservation measures improved the grass carbon stock in semi-arid degraded lands. Such measures have the great potential to improve resilience of grassland ecosystems to climate change (Chibinza et al., 2012).

In ravine ecosystem, high level of degradation coupled with extreme climate conditions leads to poor carbon stock in the vegetation and soil. The present findings explained that tree plantation along with SWC measures improved the overall (Tree + crops/grass + soil) CS and COS in semi-arid degraded ravine lands. CS and COS was observed greater in uncultivated terrace (STe) followed by uncultivated terrace (STe) and trench (STr) systems, respectively, while, overall, lower CS and COS were observed in slope system (SS). Soil and water conservation measures contributed in enhancing moisture and nutrient availability in the soil, thereby improvement in the CS and COS of plants. System of tree and perennial grass combination on terrace (STe) were found to be highly effective for CS and sequestered maximum carbon compared to other system in ravine lands (Fig. 8). Trenching on slope, crop cultivation on terrace and sole slope systems were observed almost equivalent in term of carbon stock and carbon sequestration. Peichl et al. (2006) also observed that CO_2 mitigation in agroforestry was 11–41% higher compared to sole cropping systems in Southern Ontario, Canada. In present days, researchers throughout the globe are working to develop such agro-ecosystems which can rapidly sequester more and more carbon in degraded lands for reducing the impact of global warming (Lal et al., 2011; Franzluebbers and Follett 2005; Gurian-Sherman 2011 and Del Grosso, 2010). For example, Lal et al., (2011) suggested sustainable land management (SLM) options to increase net primary production and ecosystem carbon (SOC) pool to mitigate climate change. Such management practices can be developed in global ravine ecosystems to mitigate climate change impacts. In general, tree plantation augmented with soil water conservation measures has the potential to improve carbon stock that contributes to greater CO_2 sequestration in the degraded lands (Lal 2001).

5. Conclusion

Climate change has severely affected the productivity and carbon sequestration potential of semi-arid degraded lands. Soil-water conservation and agroforestry play a key role in providing climate resilience and enhanced carbon sequestration in such lands. Sapota tree and native grasses were found better in term of survival and growth during changing rainfall conditions, except for small effect of drought on both; while native crops (cowpea and castor) were observed highly sensitive for different rainfall events. Soil water conservation measure such as terrace and trench enhanced the Sapota tree growth, grass biomass productions and fruit yield in these degraded lands, under all rainfall conditions. Terracing was found to be superior compared to trench and sole slope in ravine ecosystem. Native grass cultivation in association with Sapota tree should be preferred over crop cultivation for ravine lands. SWC measures also enhanced carbon stock and carbon sequestration of Sapota tree and grass during extreme rainfall conditions. These both agroforestry and soil-water conservation measures individually and in combination can play a significant role in providing the resilience during extreme weather events and enhanced carbon sequestration of agro ecosystem in semi-arid degraded lands. Further, the role of such systems in moderating micro and regional climatic conditions, providing resilience to extreme weather conditions and, sequestering and emitting greenhouse gases need to investigated globally in degraded ecosystems.

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There's no financial/personal interest or belief that could affect their objectivity, or if there is, stating the source and nature of that potential conflict.

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