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RESEARCH ARTICLE

Changes in Soil Carbon Sequestration during Woody Plant Encroachment in Arid Ecosystems

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ABSTRACT

Carbon sequestration is one of the most important and highly recommended measures for mitigating climate change. Soil organic carbon (SOC) has potential to sequester the largest amount of carbon (C) for the longest time period in the midst of the organic C sinks in terrestrial ecosystems of the earth. In recent years, apprehension of the role of soils as sink for carbon on a wide-ranging scale has become dynamic. From last 150 years, encroachment of trees and shrubs into grasslands and the 'thicketization' of savannas have been reported and is a global phenomenon. One possibly beneficial effect could be that the shrub and tree-dominated ecosystems will sequester more carbon and will be a buffer for elevated atmospheric carbon dioxide (CO_2) levels. The question of what is impact of woody encroachment on soil carbon balance of an ecosystem has proved difficult to answer, and the results remain debatable. The magnitude and pattern of changes in the SOC with woody encroachment are exceedingly abstruse and varies from significant increases, to significant decreases to no net change in SOC. Impact of wood plant encroachment on carbon sequestration is discussed in this paper considering various studies with different results so it will lead to better understanding of the complex phenomenon. SOC sequestration is effective greenhouse gas mitigation strategy and a vital ecosystem service. Increasing SOC may helpful to mitigate negative effects of growing concentration of CO_2 in atmosphere and may be advantageous in decelerating or reversal in global climate change rate.

Keywords: Carbon sequestration, Climate change, Ecosystem, Woody encroachment.

INTRODUCTION

Encroachment is an ecological phenomenon in which density, cover and biomass of native woody or shrubby plants is increased in various grasslands, predominantly arid and semiarid grasslands (Van Auken, 2000) and is global in occurrence (Abdallah *et al.*,2020). Woody plant encroachment has been described over the past 150 years in several ecosystems of the world (Archer *et al.*, 2017). This pattern of change in vegetation structure is possibly appropriate to climatic change as it may be revealing past climate deviations and as they may impact biophysical features of land surface-atmosphere exchanges of carbon and nitrogen (Archer *et al.* 1995). Various potential reasons have been projected for woody plant encroachment like changes in climate, atmospheric CO_2, fire regime as well as herbivory, however the impact of different factors feasibly differs among various ecoregions (Van Auken 2009; Buitenwerf *et al.* 2012, Ochoa *et al.*, 2018). Arid and semiarid lands, or drylands, cover about 41% of the terrestrial surface of the Earth where around 2.4 billion people live, So it is vital to understand this phenomena (GLP, 2005). Encroachment of woody plants followed by degradation or desertification was observed in arid grasslands (10–20%) (Reynolds *et al.*, 2007). There was also alteration in distribution of plant biomass, carbon and nitrogen pools below and above ground in grasslands to increasing woodlands (McKinley *et al.*, 2008).

CO_2 and N_2O concentrations are increasing in the atmosphere, leading to increases in global temperatures and changes in the hydrological cycle (Ciais *et al.*, 2013, Naikwade 2017, Naikwade 2020a). Terrestrial vegetation is important as a volatile sink of carbon but it is seriously influenced by human activities (Aber and Melillo, 2001). Models for Africa semi-arid and mesic savannas estimated that woody C3 plants will have an accumulative advantage over C4 grasses due to elevated atmospheric CO_2 concentration (Bond *et al.* 2003). Increased CO_2 concentrations are expected to increase primary productivity in C3 plants due to the reduction of oxygenase activity of Rubisco enzyme (Lambers *et al* 2008). The impact of increased atmospheric CO_2 concentrations will vary by ecosystem (Field *et al* 1995; Naikwade 2020b). Litter quality will be also impacted as greater CO_2 concentrations will increase C:N ratios of litter and will result in reduced decomposition rate and subsequently C and N in soil will be altered (Strain and Bazzaz 1983; Mooney *et al* 1991, Naikwade, 2014).

The widespread replacement of grasses by woody plants could have potentially important effects upon both the structure of the vegetation and its above-ground net primary production (Knapp *et al.* 2008; Barger *et al.* 2011). One potentially beneficial effect could be that the tree-dominated ecosystems continue to sequester C and act as a buffer for increased atmospheric CO_2 levels (Naikwade *et al.*,2017). Certainly, as grasslands and savanna ecosystems account for 30–35% of the worldwide terrestrial Net Primary Productivity (NPP) (Field *et al.* 1998), it is quite possible that an increase in C input due to shrub encroachment and subsequent changes in C storage could have global implications for the earth–atmosphere system (Knapp *et al.* 2008). Changes in tree and shrub compactness impacted the spatial distribution and carbon and other nutrient cycles by modifying soil structure, microbial biomass, soil moisture etc. (Wigley *et al.*,2020).

SOC is a principal component of the global carbon cycle (Naikwade 2019), accounting for more C than the terrestrial biomass and atmospheric pools combined (Amundson 2001). Assessment of C stored in soil is vital to develop a new conservation policy related to C sequestration and combat climate change (Meena *et al.*,2019). The yearly CO_2 fluctuation from soils to the atmosphere is ten times higher than from fossil fuel burning (Schlesinger 1997), therefore minor changes in SOC pools can affect the atmospheric CO_2 concentration and successively impact climate of the planet. Although SOC concentrations in dryland soils are normally low, widespread land cover change and human disturbances in these areas alter the fluxes between atmospheric and SOC pools. As dryland area is greater, these fluctuation changes can considered as significant source or sink of atmospheric carbon (Lal 2004). The soil organic matter reservoir generally contains nearly 90% of the carbon storage in terrestrial ecosystems (Schlesinger, 1997). Accordingly, even small changes to this large reservoir may have intense consequences for ecosystem C balance. Generally, land use and land cover change account for one quarter to one half of all terrestrial carbon losses to the atmosphere, and can cause positive as well as negative climate forcing at not only at local but also at global level (Brovkin *et al* 2004). Worldwide, grasslands sequester C in the soil at a rate of 0.5 Pg C $year^{-1}$, which is about one-fourth of the potential C sequestration in soil all-inclusive (Wu *et al.* 2014). The maintenance of C storage is also a crucial factor in the sustainability of grassland (Wang *et al.* 2014) and other ecosystems (Naikwade 2013). There is a significant correlation between aboveground vegetation properties and SOC (Solomon *et al.*,2018). The carbon ratios of living biomass and soil together make up more than 90% of total storage in all regions of the world (Tsegay and Meng 2021).

Historical estimates of the higher limits of woody encroachment contribution to the USA carbon sink range from 60 to 130 Tg C yr^{-1} (25–46%) of the carbon sink in USA at the end of last century (Houghton *et al.*, 1999; Hurtt *et al.*, 2002; Houghton, 2003). Houghton *et al.* (1999) estimates assumed areas in the U.S. that were not forested or cultivated which is approximately one-fourth of the U.S. land area were experiencing woody plant encroachment and growing C pools by 55 g C m^{-2} yr^{-1}. Hurtt *et al.*(2002) used a joint mechanistic demography model with an empirically based land use change model and developed an estimate of 130 Tg C yr^{-1} increase in C storage in non-forested and pasture ecosystems of the U.S. (one-third of the U.S. land area). Later on Houghton (2003) reduced previous assessments by half and gave more realistic estimate of 60 Tg C yr^{-1} as per his knowledge. Although these estimates underlines the potential importance of woody encroachment in the continental C budget, results from several studies suggest such accounting methods may be expanding its effect (Hicke *et al.*, 2004; Jackson *et al.*, 2002; Strand *et al.*, 2008).

The actual effect of woody encroachment on carbon balance of an ecosystem is very difficult to conclude due to controversial results (Blaser *et al.*,2014). The degree and direction of changes in the SOC with woody encroachment are extremely unclear. Considering importance of carbon sequestration in mitigating climate change, impact of wood plant encroachment on SOC sequestration is discussed in this paper considering various experiments conducted worldwide for comprehensive understanding of the field.

Occurrence of woody encroachment

Woody plant encroachment into grasslands, rangelands and savannas are recognized by many scientists as speedily happening universal phenomena (Archer *et al.*, 1988; House *et al.*, 2002; Briggs *et al.*, 2005, Mbaabu *et al.*,2020). Quantitative and historical assessments suggest that woody-plant abundance has increased substantially in arid and semi-arid grasslands over the last 50 to 300 years in many parts of the world, including Africa (van Vegten 1983), India (Singh and Joshi 1979), Australia (Walker and Gillison 1982), South America (Bucher 1987), North America (Hobbs and Mooney 1986).

Grassland/savanna ecosystems occur in both temperate and tropical regions constitute over 45% of the Earth's land surface (Bailey, 1998). Throughout the previous century, spreads of woody plants have affected many savannas and grass-dominated ecosystems on earth (Van Auken 2009). Elevated levels of CO_2 have been proposed by scientists as the cause of recent C3 shrub and woody plant encroachment into grasslands throughout North America, it also includes semiarid grasslands in the southwest (Polley *et al.*, 1992 and Johnson *et al.*, 1993). Woody extension is also common in arctic and alpine ecosystems around the globe (Hallinger *et al.*, 2010; Stow *et al.*, 2004; Tape *et al.*, 2006) and in urban and peri-urban landscapes. Alterations in soil features due to encroachment of woody vegetation have been reported in the dry grasslands of the southern Great Plains (Reynolds *et al.* 1999) as well as in mesic tallgrass prairies of the eastern Great Plains (Hibbard *et al.* 2001). Woody plant encroachment has been recognized as an vital element of Australia's greenhouse gas inventory (Gifford and Howden 2001, Williams *et al.* 2005) and as a potential contributor to a U.S. carbon sink (Schimel *et al.* 2000). In past 150 years woody encroachment has basically changed many of the drylands in world (Archer 1994). Shrub encroachment is predicted to increase over the coming century (Soliveres *et al.*,2014, Ding *et al.*,2020).

Vegetation thickening and woody encroachment

Woody encroachment also called vegetation thickening or woody weeds is the invasion of grasslands or open woodlands by woody tree and/or shrub species. (Steffen *et al.*,2002). Vegetation thickening is a term used to describe increasing shrub and tree density on many grazed rangelands, woodlands and forests in which woody plant populations was not common in the past. It is one of many ecosystem changes, like post-clearing re-growth, afforestation and reforestation, which are variants of the same biological phenomenon- the recovery phase of disturbance/recovery phases that all vegetation experiences constantly (Gifford and Howden 2001). While vegetation thickening is often used to refer to increasing woody vegetation density in savannas (Noble, 1997), this phenomenon of increasing shrub and tree density following, or in association with, ecosystem disturbance is more widespread than in tropical grasslands. The impacts of woody encroachment and removal on ecosystems are highly variable and are thought to be related to the traits of the individual woody species (Eldridge and Ding 2021).

Forest thickening has been reported in several forest categories, even apparently 'mature' forest also (Lugo and Brown, 1986). It has been occurred in the Amazon rainforest (Malhi *et al.*, 1997), in tropical rainforests of Central and South America largely (Phillips *et al.*, 1998), as well as in many temperate forests in the biosphere (Pyne, 1991, Kauppi *et al.*, 1992). On a worldwide basis, according to Scholes and Hall (1996) an upper limit of C-sequestration by woody growth in tropical savannas would be about 2 Gt C per annum, if fire is not included from regions without trees.

Impact of woody encroachment on soil carbon sequestration

Previous studies investigating the response of soil C pool to woody encroachment can be divided into results showing increase in SOC, decrease in SOC and no change in SOC sequestration. So it is very interesting to see the impact of wood encroachment on soil carbon in three different patterns.

Increase in carbon sequestration

Considering past data it get cleared that majority studies showed that there in increase in soil carbon due to wood plant encroachment. One widespread ecological state transition in arid and semiarid ecosystems is from C4-dominated grassland to C3-dominated shrubland (Eldridge *et al.*, 2011). Due to this, as a beneficial change in services, some studies have shown an increase in above- or belowground ecosystem carbon sequestration (Emmerich, 2007). Carbon sequestration through woody encroachment at rate of 0.3Pg C yr^{-1} was reported by Asner and Archer (2010).

In lower Wisconsin River Valley, Scharenbroch *et al.* (2010) studied encroachment areas of prairie, and nearby *Pinus resinosa* plantation to decide the impact of woody cover on carbon dynamics. By using linear encroachment model it was projected that 100% encroachment of the 6.0 ha prairie will occur in 50 yr. Total ecosystem C was greater in pine and encroachment areas (71.8 Mg C ha^{-1}) as compared to prairie (48.3 Mg C ha^{-1}). Zavaleta and Kettley (2006) estimated impact of *Baccharis pilularis* encroachment into coastal California grasslands and found that total biomass increased along the chronosequence drove where N and C sequestration was increased about 700% and 125% respectively.

A study was carried out to determine the effect of woody plant encroachment on SOC, to a depth of 15 cm along a 42 year chronosequence in a northern Great Plains grassland. Results showed that total soil carbon was amended through the chronosequence from grassland (5,070±250 g C m^{-2}) to woodland (6,370± 390 g C m^{-2}) at 0–15 cm soil depth. At the ecosystem-level, C accumulation at 0–15 cm soil depth was occurred at a rate of 18 g m^{-2} year^{-1} (Springsteen *et al.* 2010).

Wheeler *et al* (2016) estimated SOC in native California sage scrub, non-native grassland and recovering California sage scrub habitats for two seasons. More C and N were stored in intact and recovering California sage scrub than grassland habitats significantly. Preserving and restoring California sage scrub habitat provides habitat for native biodiversity, as well increases carbon and nitrogen storage potential even without restoration to intact sage scrub.

An experiment was carried out by Blaser *et al.*, (2014) to study effects of *Dichrostachys cinerea* shrub in a mesic savanna in Zambia on pools of soil N, P, and carbon. Results showed that storage of soil carbon increased significantly under *D. cinerea* and did not have any effect of shortages of N or P. The total soil carbon pool was directly proportional to cover but not age. Encroached site exhibited a slightly significant increase in C with age, at rate of 14 (12–16) g Cm^{-2}year^{-1}.

Gill and Burke (1999) studied the amount, quality, and distribution of soil C below woody vegetation and grasses at three rangelands in Texas, New Mexico, and Utah. At the La Copita Research Area in south-central Texas more soil C was found under *Prosopis glandulosa*, a dominant woody plant as compared to grasses significantly. Mean SOC content to 1 m was 7.2 kg C m^{-2} under *Prosopis glandulosa* and 6.0 kg C m^{-2} under grasses. By studying stable carbon isotopic composition it can be concluded that extension of *P. glandulosa* in savannas in Texas impacts carbon cycling throughout the soil profile but first at surface soils and deep soil later. At third site the Sevilleta National Wildlife Refuge in central New Mexico, results showed that as compared to *Bouteloua* spp. more soil carbon (10 cm depth) of soil profile was found under *Larrea tridentate*. By using stable carbon isotopic composition it was concluded that the extension of *L. tridentata* impacted carbon cycling all over the soil profile.

McCulley *et al.*, (2004) compared soil carbon pool, in remnant grassland communities and neighboring woody plant communities which was established on grassland from last century. Mean SOC in the upper 20 cm of the profile was two times greater in wooded communities (3382 g/m^2) than in remnant grasslands (1737 /m^2). Improved fluxes of soil C and N were complemented by increases in SOC and N pools and total SOC mean residence time advocates that changes from grass to woody plant encroachment have increased labile and recalcitrant pools of SOC. Considering extensive wood plant encroachment in drylands in recent years the observed net increase in soil carbon storage possibly accompanies that this alteration could have worldwide effects for C and N cycling and the climate system.

Woody plants in subtropical savanna parkland/ thorn woodland system markedly increased the near-surface (0–10 cm) soil C and N pools in the five to seven decades since their establishment in heavily grazed grasslands. The rate and extent of change was statistically comparable for three woody habitat types that differed with respect to soils, topography, and vegetation structure. Relative to near surface (0–10 cm) soils of remnant grass-dominated patches, soils associated with woody plant patches had higher SOC (0.8% vs. 1.4–2.3%), than herbaceous patches. The mean rates of annual C accretion in these fertile islands that have developed subsequent to tree/shrub establishment in grass patches ranged from 8 to 23 g C/m^2 (Hibbard *et al.* 2001).

In new Juniperus woodlands, slight change in availability of nitrogen can cause carbon and nitrogen stocks increase in plant biomass and soils (McKinley and Blair, 2008). An increase in soil carbon was observed beneath cut Juniper trees (Bates *et al*., 2002). The source of this carbon may originated from decomposing of juniper litter substrates and/or from the increase in the efficiency of the herbaceous constituent (Bates *et al*., 2000). Similar pattern of positive reply of SOC to woody encroachment was observed at several other places (e.g. Archer *et al*., 2001; Hibbard *et al*., 2001) and likely originate from increased organic matter input and depressed loss rates. Mesic savanna influenced by shrub species can represent a carbon sink for some decades. Wood plant encroachment in mesic savannas has increased and it is projected that if CO_2 concentrations is doubled it will increase by 70% (Bond *et al*. 2003), as a result this ecoregion have potency to act as a carbon sink in upcoming many years also. Woody plant encroachment of Juniper into a sagebrush community increased carbon stocks (including soil carbon) from 13.5–30.2 Mg C ha^{-1} (Throop and Lajtha, 2018).

Connin *et al* (1997) investigated the effects of shrub expansion in New Mexico using δ13C natural abundance to partition soil organic matter (SOM) into C4 (grass) and C3 (shrub) sources. δ13C analyses indicated that SOM consequent from mesquite shrub was highest under shrub canopies and 3 m outside canopy boundaries, due to spreading of roots. It can be suggested that mesquite may increase soil carbon storage than grasses after comparing turnover rates in grass and mesquite soils. At the ecosystem level, wood plant encroachment in semiarid grasslands will influence changes in root biomass, litter yield, and SOM cycling which in turn impact on nutrient content availability and long-term soil carbon sequestration.

At the continental scale, Knapp *et al*. (2008) suggested 7.02 % proportional change in soil organic C due to shrub encroachment but it differs from results from earlier experiments (Jackson *et al*., 2002; Wessman *et al*., 2004; Briggs *et al*., 2005). Barger *et al* (2011) reported an estimated time since encroachment, rates of soil carbon varied from decrease of 80 g C m^{-2} yr^{-1} to addition of 29 g C m^{-2} yr^{-1} with a mean of 2.2 g C m^{-2} yr^{-1}.

SOC pools would be greater in soils under *Prosopis* canopies than in soils in the surrounding grassland matrix (Virginia 1986). SOC pools were consistently higher in soils associated with *Prosopis* plants in comparison with soils in the grassland matrix, consistent with observations on other desert grassland sites in the area (Biggs *et al*. 2002, Biedenbender *et al*. 2004). Bradley *et al*. (2006) showed that shrub communities store more C than grassland communities.

Barron-Gafford *et al*. (2012) found higher carbon sequestration in mesquite dominated woodland than grassland in the Sonoran Desert. Considering this feature, the shrubland carbon pool is predicted to persist and increase in future. Semiarid ecosystems have significant effect on interannual variability in terrestrial carbon sequestration globally (Poulter *et al*., 2014). Observations in southern Texas (Boutton *et al*., 1998; Geesing *et al*., 2000; McCulley *et al*., 2004) and Arizona (Tiedemann and Klemmedson, 2004) proved that encroachment by *Prosopis* shrub increased near-surface soil C and N pools.

Gonzalez-Roglich *et al*. (2014) reported that *Prosopis caldenia* encroached ecosystem produced three times more total ecosystem carbon than grassland ecosystem. Increase in SOC stocks also reported by Chiti *et al*.,(2017) in the Lopé National Park, Gabon, South Africa.

Carbon storage in litter, roots, and soils averaged across all age states within each landscape element was studied in a Subtropical Savanna by Boutton *et al* (2009). Carbon stocks in roots of all wooded landscape elements (1000–1500 g C m^{-2}) was higher than remnant grasslands (< 400 g C m^{-2}). Total SOC of the soil profile was 1000 g C m^{-2} in remnant grasslands was lesser than 3000 g C m^{-2} in drainage woodlands.

Zhou *et al* (2017) found that woody encroachment into landscape at subtropical savanna in the Rio Grande Plains, USA increased SOC storage throughout the upper 1·2 m of the soil profile, and 30% of the C sequestered following encroachment was stored below 30 cm. In general, woody clusters and groves accrued 12·87 and 18·67 Mg C ha^{-1} more SOC than grasslands.

Decrease in carbon sequestration

Jackson *et al* (2002) investigated woody plant encroachment along a precipitation gradient (200 to 1,100 mm yr^{-1}) by estimating carbon and nitrogen resources and soil d13C profiles among 6 pairs of neighboring grasslands. In the pair one pair is selected where wood encroachment was reported 30 to 100 years ago. They found strong negative connection between precipitation and changes in C and N content in soil when grasslands were occupied by woody vegetation, with increase in soil organic carbon at drier locations and decrease at wetter locations. Losses of soil organic carbon at the wetter sites were significant enough to offset increases in plant biomass carbon, signifying that current land-based assessments may overvalue carbon sinks. However he did not quantified woody roots (>1 cm diameter) in this C pool study. Wheeler *et al*. (2007) and Geesing *et al*. (2000) observed a similar negative relationship within a narrower range of mean annual precipitation in arid or semiarid ecosystems.

Oelofse *et al* (2016) conducted an experiment at South Africa encroached by *Acacia mearnsii*, fast growing tree species. Carbon stocks in soil and litter on a chronosequence of *Acacia* stands of varying ages (up to >50 years) were analyzed and compared these with adjacent native grassland. The results showed that at one location woody encroachment of grassland had an insignificant effect on SOC stocks. However at another location, decrease in combined soil and litter carbon stocks was reported where woody plant encroachment occurred before 50 years.

Mbaabu *et al* (2020) assessed impact of grassland degradation and 25–35years of *Prosopis* encroachment or grassland restoration on SOC in tropical semi-arid region in Kenya. SOC stocks in pristine and in restored grasslands were higher than those in *Prosopis* invaded sites. Pristine grasslands showed the highest total SOC stock at 1 m depth (49.76 ± 2.28 t C ha^{-1}), followed by restored grasslands (44.68 ± 3.77 t C ha^{-1}), high *Prosopis* densities (40.05 ± 1.28 t C ha^{-1}) and low *Prosopis* densities (36.99 ± 2.51 t C ha^{-1}).

Mureva *et al* (2018) calculated the changes in C and $\delta^{13}C$ values in encroached and neighboring open grassland sites along a precipitation gradient from 300 mm to 1500 mm per annum in South Africa. Results indicated negative relationship between changes in soil organic C stocks in the 0–100 cm soil layer and mean annual precipitation (MAP). Among shrub-encroached sites, most humid site (1500 mm MAP) had less C in while the drier sites (300–350 mm MAP) had more C than adjacent open grasslands.

In a study of woody encroached and adjacent grassland plots along a rainfall gradient of 300–1500 mm MAP in South African savannas, Mureva *et al.*, (2021) studied changes in SOC at depth of 1 m, in soil physical fractions. The 0–10 cm soil layer of the 1500 mm MAP site lost 26% of SOC stocks due to shrub encroachment. Contrastingly, the 300 and 350 mm MAP sites gained 24% and 27% total SOC, respectively, due to shrub encroachment. In the soil fractions, the largest changes in SOC, ranging within 2.64–464%, were in the coarse particulate organic matter and the lowest in the silt and clay fraction (6–32%) across all sites and depths.

No Change in carbon sequestration

Hughes *et al* (2006) estimated net primary productivity and carbon, nitrogen pools in aboveground biomass and surface soils on shallow clay and clay loam soils experiencing *Prosopis glandulosa* extension in the Southern Great Plains, US. While aboveground carbon and nitrogen pools increased considerably with *Prosopis* stand development, no equivalent change in surface soil carbon and nitrogen pools (0–10 cm) was observed. This is in accordance with observations for *Juniperus* extension in Kansas prairie (Smith and Johnson, 2004).

McCarron *et al.* (2003) assessed the effects of shrub encroachment in a mesic grassland in Kansas (USA) under shrub communities (*Cornus drummondii*) and nearby undisturbed grassland locations. In this study, shifting of grassland to shrubland caused reduction in annual soil CO_2 flux upto 16% (4.78 kg CO_2 m^{-2} $year^{-1}$ for locations where shrub was dominating as compared to 5.84 kg CO_2 m^{-2} $year^{-1}$ for grassland locations) however no differences were found in total carbon and nitrogen in soil. Smith and Johnson (2003) did not found noteworthy differences between woodlands and grasslands in long-term (82-week) laboratory incubations of potentially mineralizable soil C and short-term incubations for microbial biomass carbon. It was predicted that as compared to grasslands turnover of woodland soil carbon stocks may be slowed by 15 years. Woody plant encroachment into South African grasslands did not caused significant increase in total ecosystem carbon pools (Coetsee *et al.*, 2013).

In a study at paired watershed in central Oregon where western juniper trees were cut in one watershed considered as treated, and were left intact in another as untreated (Abdallah *et al.*,2020). Thirteen years after control, soil carbon stocks at both 0-25 cm and 25-50 cm depth were not affected by juniper control. In general, total ecosystem C stocks (average 137.6 Mg C ha^{-1}) did not varied among water-sheds. Rau *et al.* (2011) reported no gains in soil carbon resulting from woody plant encroachment in the Great Basin of North America.

By analyzing results of various experiments conducted at various locations of the world, it is noticed that majority of the studies showed increase in SOC due to woody plant encroachment while some studies showed decrease or no change in SOC. It was reported that woody encroachment in grasslands increased soil C pools in drier regions, but decreased it in regions with mean annual precipitation (MAP) greater than 500 mm·$year^{-1}$ (Jackson *et al.* 2002). Nevertheless, Barger *et al.* (2011) recognized that changes in SOC pools with tree encroachment were inversely proportional to MAP and responses to shrub encroachment were highly variable and without any correlation with MAP.

The methodologies used to estimate SOC in various experiments are different, soil samples are also collected from various depths, at some sites SOC is also influenced by drought, grazing, wildfire, pathogen outbreaks and land management practices. The various sites where studies were conducted showed different stages of encroachment. So it very mystifying to conclude trend of SOC sequestration in arid ecosystem under wood plant encroachment. SOC sequestration have a tendency to be greater in arid locations than in wetter locations (Jackson *et al.* 2002; Barger *et al.* 2011), however it is greatly influenced by several factors like shrub species, % clay content, soil bulk density etc. The physical properties of soil influence soil carbon cycle. If bulk density is higher, more carbon is lost from soil (Barger *et al.* 2011) but if soil contains more clay percentage then more SOC is sequestrated (Liao *et al.*,2006). Soil structure formed by combination of physical particles and organic matter enhances soil carbon storage at fine scales. Root systems of shrubs and trees are very well developed which extract nutrients from the soil, result in recycling of C and N and better biomass production associated with organic matter accumulation (Zhou *et al* 2017).

Grasses may acquire nutrients mainly from upper soil, while shrubs belonging to Leguminosae family can obtain nitrogen through symbiotic fixation and phosphorus from deeper soil. It was noticed that several encroaching woody plants fix nitrogen symbiotically (Eldridge *et al.* 2011) and so can add more N into the ecosystem (Cech *et al.* 2010). Nevertheless these shrubs require high phosphorus for the growth. As per some field experiments (Blaser *et al.* 2013; Sitters *et al.* 2013) shrubs with nitrogen fixation capacity and with greater canopy increase phosphorus in the top layer of soil. This phosphorus may be absorbed by shrubs from deeper soil layers as shrubs have deeply rooted system than grasses. Also shrub species belonging to leguminosae family have one more benefit than grasses is, shrubs have greater root phosphatase activity, so they can absorb organic form of phosphorus from the soil. Availability of nutrients increases more biomass which on decomposition release more carbon in soil beneath shrubs. C sequestration at woody plant encroachment areas is not limited by a scarcity of nitrogen. Greater SOC fluxes are found under canopies of woody plants due to addition of biomass to the soil, higher microbial populations, larger plant and microbial activity than in plant interspaces.

Another reason for more SOC sequestration in woody encroached areas may be increased atmospheric CO_2 concentrations is beneficial to woody C3 plants than C4 grasses due to their specific metabolic pathways. One more advantage to woody plants is their additional complex canopy architecture which utilizes greater leaf area compared to grasses. The SOC sequestration depends on long-term inputs from leaves, stems, and roots of plant species. So the changes in the quantity of SOC would fluctuate with changes in the plant production.

It is also supposed that SOC sequestration depends on Annual Net Primary Productivity (ANPP) of grass and wood plant species. If encroaching shrub or tree species are more productive compared to grass communities net ANPP will increase and vice versa. Subsequently if grassland and woody plant communities are similar in productivity then net ANPP will not change. ANPP depends with MAP however SOC sequestration did not showed consistent pattern or apparent relation to MAP. Reasons are uncertain but may be nonequilibrium status of many woody encroached landscapes; changes in soils lag well behind the changes in the vegetation, plant species variances in distribution of carbon for above and below ground growth.

Precipitation, vascular plant species composition and spatial pattern, occurrence of biological soil crusts, and surface disturbance work together to regulate rates of carbon and other nutrient cycling. Soil carbon and nitrogen cycling was energy limited and increasing carbon dioxide improved nutrient availability and carbon storage. Management of grazing also increases carbon and nitrogen stocks in rangeland soils. Woody plant encroachment in mesic savannas is predicted to further increase by 70% if CO_2 concentrations doubled in future (Bond *et al.* 2003), arid ecosystem might continue to act as a carbon sink for many decades.

CONCLUSION

Findings from several studies indicated that woody plant encroachment is a potentially, but highly uncertain, carbon sink. Wood plant encroachment affected several savannas and grass-dominated ecosystems around the biosphere. Studies showed that changes in SOC in response to woody encroachment differ extensively, ranging from net SOC increase, to no change, to decrease. However majority of results are in favor of increase in carbon sequestration in soil, very few denote decline or no change due to woody plant encroachment. The effects of woody encroachment on soil carbon in ecosystem are uncertain, not only because of the multiple, interacting drivers of change, but also because the impact of woody encroachment on C distribution and storage differs considerably through ecoregions.

Significant changes in topsoil carbon stock with growing woody plant encroachment have been witnessed in many grassland or savanna ecosystems around the world, SOC accumulation rates differed from negative up to >100 g C m^{-2} $year^{-1}$ increase depending on the encroaching species, stand age, land management practice, mean annual precipitation and soil sampling depth. Variation in the result may be due to differences in soil characteristics and historical land use patterns, climate and the tree species, or the lack of appropriate methodology for estimating SOC stocks in encroached systems with complex vegetation patterns. The reason behind accretion of SOC in the drier shrub-encroached grasslands maybe, greater rates of primary productivity in the more arid sites; the encroached grasslands had greater biomass compared to open grasslands.

Though various studies on SOC sequestration in woody encroached areas reported form various countries, it is strongly recommended to balance these with data documenting brush management impacts. Standardization of methodologies is also need to develop vigorous, significant generalizations. Future research can be focused to understand of soil microbial community composition and biologically mediated processes in the carbon and nitrogen cycles, soil function, in arid ecosystems. Many earlier studies focused SOC sequestration at upper layer but it should be studied in deeper soil layers as well. For better understanding of this concept field research must be integrated with new technology such as remote sensing and modeling.

The climate future the earth depends on regulation of global water and carbon cycles by terrestrial vegetation. The arid ecosystems are likely to become net sources of carbon due to occurrence of woody encroachment, while higher rainfall zones may become net sinks. Amplified potential for SOC sequestration may be a positive outcome of woody plant encroachment that is to be considered against potential reductions in biodiversity, water yield etc. The whole world benefits from a unit of carbon sequestration regardless of where it occurs because greenhouse gases thoroughly mix in the global atmosphere. As woody plant encroachment is global phenomenon with significant magnitude, subsequent effect of it on SOC sequestration can potentially affect the global carbon budget and energy balance.

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