Carbon sequestration in agroforestry and pasture systems in arid northwestern India

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Carbon sequestration has been suggested as a means to help mitigate the increase in atmospheric carbon dioxide concentration. Silvipastoral systems can better sequester carbon in soil and biomass and help to improve soil conditions. In the present study, carbon sequestration was quantified both in biomass and soil in two pasture systems (*Cenchrus ciliaris* and *Cenchrus setegerus*), two tree systems (*Acacia tortilis* and *Azadirachta indica*) and four silvipastoral system (combination of one tree and on grass) in arid northwestern India. The silvipastoral system sequestered 36.3% to 60.0% more total soil organic carbon stock compared to the tree system and 27.1–70.8% more in comparison to the pasture system. The soil organic carbon and net carbon sequestered were greater in the silvipastoral system. Thus, silvipastoral system involving trees and grasses can help in better sequestration of atmospheric system compared with systems containing only trees or pasture.

Keywords: Arid soils, carbon sequestration, grasses, Kachchh, silvipasture.

SINCE the industrial revolution, there has been drastic increase in the concentration of atmospheric carbon dioxide and other greenhouse gases (GHGs). The major reasons attributed to the global warming and associated climatic changes are increased concentration of GHGs in the atmosphere[1]. The global atmospheric CO_2 concentration increased from 280 ppm in 1750 to 379 ppm in 2005 which has been attributed primarily to fossil fuel use and land-use change[2] with a total increase of 1.9 ppm per year. Apart from CO_2, the atmospheric concentration of CH_4 has increased to 1774 ppb in 2005 from the pre-industrial value of 715 ppb (148% increase). N_2O continues to rise at the rate of 0.26% per year, measured at 319 ppb in 2005, 18% higher than its pre-industrial value[2]. In another estimate, the atmospheric CO_2 concentration is expected to double until the middle to late 21st century, with implications for a temperature rise between 1.5°C and 4.5°C (ref. 3). Current strategies for coping with global warming include reducing fossil fuel combustion as well as curbing emission of other GHGs and increasing carbon sequestration[4].

Atmospheric carbon can be sequestered in long-lived carbon pools of plant biomass both above and below ground or recalcitrant organic and inorganic carbon in soils and deeper subsurface environments[5]. Apart from offsetting CO_2 emissions and global warming, sequestration of carbon in soils also helps to improve soil quality and productivity by improving many physical, chemical and biological properties of soils such as infiltration rate, aeration, bulk density, nutrient availability, cation exchange capacity, buffer capacity, etc.[6]. Soil organic carbon sequestration is more important in arid regions, where soils are inherently low in organic carbon content. In arid environments, trees, pastures and agroforestry systems are important for carbon sequestration strategies[7,8]. Articles 3.3 and 3.4 of the Kyoto protocol provide rationale for the importance of managing dry lands to sequester carbon via restoration of desertified lands and planting perennial tree/woody components[9]. Systems involving trees act as carbon sinks due to their ability to sequester atmospheric carbon in deep soil profiles and various tree components[10,11]. According to the Kyoto protocol, only carbon newly sequestered through agroforestry practices is considered as carbon credits and can be sold to industrialized countries to meet their emission reduction targets, although there is pressure to include soil carbon also[12].

Accurate information about the spatial distribution of carbon both in soil and vegetation in the ecosystem is important for better understanding of biogeochemical processes and formulation of policies and actions. The Kachchh in arid northwestern India contains a very fragile ecosystem which is threatened by increased human activities in terms of overgrazing, urbanization and rapid industrialization. Information on carbon sequestration under various land-use systems is very meagre for this important but fragile ecosystem of northwestern India. Therefore, this study aims to quantify carbon sequestration in this predominantly arid region of northwestern India.

The study was carried out in an established pasture and silvipastoral systems in Kachchh, Gujarat in the arid northwestern part of India at the research farm of Central Arid Zone Research Institute, Regional Research Station, Kukma–Bhuj. The study area is located at 23°12′N to 23°13′N and 69°47′E to 69°48′E. The region experiences scanty, erratic and irregular rainfall of 397 mm in 11 rainy days (average for 1998 to 2013) with a coefficient of variation of 73% among years. The monsoon starts generally in the first week of July and recedes in middle of September. Drought is a regular phenomenon in the region. The annual minimum temperature ranges from 1°C to 8°C and maximum temperature ranges from 39°C to 45°C. The soils are sandy loam to loamy sand in texture and are classified as Ustochreptic camborthids. The soils are alkaline with pH 8.36 to 8.41 and non-saline (electrical conductivity 0.3 to 0.34 dSm^{-1}). Soil nitrogen

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values varied from 141.1 to 252.9 kg ha^{-1}, P_2O_5 8.9 to 17.2 kg ha^{-1} and K_2O 159.9 to 187.1 kg ha^{-1}. Due to limited rainfall, grasses and forestry along with arable farming are the major farming systems of the region. The major crops grown in the area are cotton, groundnut, castor, pearl millet, wheat and mustard and the major horticultural crops are date palm, mango and sapota. For this study, three major land-use systems prevailing in the region were selected: trees, grasses and a combination of the two. Eight systems were selected; two with trees namely acacia (*Acacia tortilis*) and neem (*Azadirachta indica*), two with grass species namely *Cenchrus ciliaris* and *Cenchrus setegerus* and four silvipastoral systems with combinations of one tree and one grass. The tree and grass components were planted in the rainy season of 1998. The tree species were planted at a spacing of 6 × 6 m and grasses were subjected to controlled grazing every year.

Biomass estimation of trees was carried out by harvesting four randomly selected trees from each tree system and silvipastoral system during October 2008. The trees were cut at ground level. Each harvested tree was partitioned into stem, branches and foliage and fresh weight was recorded for each component; and samples were collected for moisture determination. For estimation of below ground biomass of trees, the roots in 1 m^3 soil volume were excavated and fresh weight was recorded, along with collection of samples for moisture determination. All the samples were oven dried at 65°C and the oven dry weight was used for determining the stand biomass on a hectare basis.

In grasses, the biomass production was measured manually by harvesting the above ground biomass by cutting at the ground level and below ground biomass by excavation method. Four randomly selected 1 m^2 quadrants were harvested in each system. Dry biomass was determined by drying the freshly harvested grass in hot air oven at 65°C. Harvesting of trees and grasses was carried out during post-monsoon season in October to include the maximum biomass attainable by each component by making use of rainfall. Major changes in growth of trees and grasses were not expected in the system as they were already established and therefore biomass estimation was carried out only during first year of the study.

Randomly collected plant samples of leaves, stems and roots of neem and acacia and shoots and root samples of grasses were dried and ground to pass through 0.2 mm sieve. They were analysed for total carbon using CHN–O rapid auto analyser at Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almora, Uttarakhand, using standard methods. The total vegetation carbon stock (Mg ha^{-1}) was then calculated by multiplying carbon concentration with the biomass.

Composite soil samples were collected from five different depths (0–5, 5–10, 10–20, 20–40 and 40–100 cm) under each land-use system. These depths are commonly used in studies on soil organic carbon pools[13,14]. Soil sampling was repeated yearly during post-monsoon period of years 2008, 2009 and 2010.

Analysis of variance was used to compare carbon from different land-use systems for both biomass and soils at various depths[15].

The total biomass (stem + branches + leaves + roots) under different land-use systems ranged from 4.32 to 19.08 Mg ha^{-1} (Table 1) and varied significantly among different land-use systems ($P < 0.05$). The sole tree system contributed a total biomass of 9.64 Mg ha^{-1} (neem) to 15.3 Mg ha^{-1} (acacia). Under the sole cropping of trees above ground portions of acacia and neem respectively, contributed to 83.5% and 80.8% of the total system biomass. The below ground biomass contribution to the total biomass was less due to less root growth, owing to the presence of hard pan in subsoil layers. Among the two sole pasture stands studied, the maximum average annual biomass was obtained for *C. ciliaris* with the above ground portions contributing 57.1% of the total biomass. In *C. setegerus*, the above ground contribution to the total biomass was 61.4%.

Total plant biomass was highest in the silvipastoral system involving acacia + *C. ciliaris* followed by acacia + *C. setegerus*. Trees grown in silvipastoral systems had lower total biomass compared to sole tree plantations. Acacia recorded a total biomass of 10.9 Mg ha^{-1} under silvipastoral system with *C. ciliaris* and 13.3 Mg ha^{-1} with *C. setegerus* against 15.3 Mg ha^{-1} under sole tree plantation. Neem when combined with grasses such as *C. ciliaris* and *C. setegerus*, recorded a total biomass of 7.3 and 9.4 Mg ha^{-1} respectively. The sole stands grew faster than those in the silvipastoral systems owing to the greater availability of nutrients and moisture[16]. Under silvipastoral systems, the contribution of above ground biomass of acaia to the total biomass was reduced to 74.3% when the grass component was *C. ciliaris* and to 80.0% when the grass component was *C. setegerus* compared to 83.5% in sole cropping. The reduction in above ground biomass contribution to the total biomass might be due to the competition between grasses and trees for the below ground resources such as nutrients and water[17] and increased growth of below ground parts. On average, below ground contribution to the total biomass in acacia was higher in silvipastoral system (20.2% in acacia + *C. ciliaris* and 20.6% in acacia + *C. setegerus*) compared to sole tree cropping (16.5%). Under stress induced by silvipastoral system, it is reported that more biomass allocation occurs to the below ground portions in nutrient poor environment[18,19]. In neem, the contribution of above ground biomass to the total biomass was 79.5% with *C. ciliaris* and 79.8% with *C. setegerus*.

The maximum biomass of grass component under silvipastoral system was recorded for acacia + *C. ciliaris* (7.6 Mg ha^{-1}) followed by neem + *C. ciliaris* (5.55 Mg ha^{-1}). The above ground contribution of biomass of grasses to the total biomass in these cases was 64.7% and

Table 1. Biomass (Mg ha^{-1}) and carbon stock (Mg ha^{-1}) in selected land-use systems in Kachchh

	Above ground biomass	Below ground biomass	Total biomass	Carbon stock (above ground)	Carbon stock (below ground)	Total plant carbon stock
Acacia	12.78	2.52	15.30	5.03	0.98	6.02
Neem	7.79	1.85	9.64	2.92	0.71	3.64
CC	6.26	4.70	10.96	2.44	1.82	4.26
CS	2.78	1.75	4.53	1.04	0.71	1.74
Acacia + CC	12.93	4.49	17.41	5.08	1.75	6.82
Acacia + CS	12.55	3.14	15.69	4.91	1.24	6.15
Neem + CC	9.60	3.79	13.39	3.53	1.39	4.91
Neem + CS	9.35	3.12	12.48	3.65	1.22	4.87
MS	38.53	3.71	50.17	6.13	0.54	7.88
$F_{7,23}$	21.85	16.73	16.80	21.65	14.75	16.88
LSD 5%	2.30	0.82	2.99	0.92	0.33	1.18

CC, *Cenchrus ciliaris*; CS, *Cenchrus setegerus*.

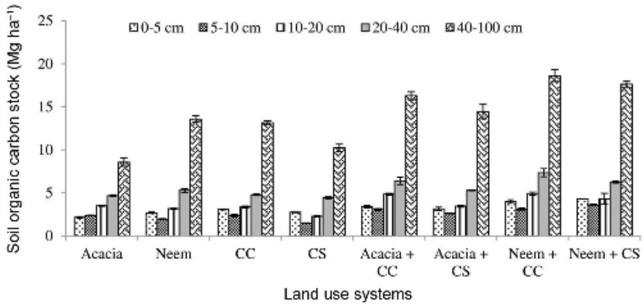

Figure 1. Soil organic carbon stock (Mg C ha^{-1}) in various land-use systems at different soil depths in Kachchh, India.

62.5% respectively. *C. setegerus* recorded a total biomass of 3.65 Mg ha^{-1} when planted in silvipasture combination with acacia and 3.75 Mg ha^{-1} with neem, with the above ground contribution of 62.7% and 60.5% respectively. In contrast to the tree component of the silvipastoral system, the contribution of above ground parts to the total biomass of grasses was more compared to the sole pasture. The root biomass contribution to the total biomass of grasses was more under sole pasture (42.9% for *C. ciliaris* and 38.6% for *C. setegerus*) compared to grass in the silvipastoral system. The plant component of silvipastoral system invests higher proportion of growth into the development of the root system compared to those growing singly[17].

The total carbon stock under the sole tree system varied from 3.64 Mg C ha^{-1} (neem) to 6.02 Mg C ha^{-1} (acacia) (Table 1). The contribution of above ground portions to the total carbon was 83.6% in case of acacia and 80.2% in case of neem. The sole stand of *C. ciliaris* could sequester 4.26 Mg C ha^{-1} and *C. setegerus* 1.74 Mg C ha^{-1}. The above ground contribution in sole pasture to the total carbon stock was 57.3% for *C. ciliaris* and 59.8% for *C. setegerus*.

Among various land-use systems under study, maximum carbon was sequestered by silvipastoral system involving acacia + *C. ciliaris* (6.82 Mg C ha^{-1}) followed by acacia + *C. setegerus* (6.15 Mg C ha^{-1}) compared to 6.02 Mg C ha^{-1} sequestered by acacia planted alone. The silvipastoral system involving neem + *C. ciliaris* and neem + *C. setegerus* registered a total carbon stock of 4.91 and 4.87 Mg C ha^{-1} respectively, against sole cropping of neem that recorded 3.64 Mg C ha^{-1}. Silvipastoral systems help in greater accumulation of soil organic matter and thus more carbon storage when compared to grass only or tree only systems due to addition of more net biomass and better utilization of available resources[20]. Contribution from the tree component of silvipastoral system to the total carbon stock was 61.4%, 80.7%, 56.2% and 72.7% for the systems involving acacia + *C. ciliaris*, acacia + *C. setegerus*, neem + *C. ciliaris* and neem + *C. setegerus* respectively. *C. ciliaris* sequestered a carbon stock of 2.96 Mg C ha^{-1} with acacia and 2.16 Mg C ha^{-1} with neem. However, there was 30.5% and 49.3% reduction in carbon sequestered by *C. ciliaris* in combination with acacia and neem respectively, when compared to the mean carbon sequestered when grown singly. With *C. setegerus*, reduction in carbon sequestered by the grass in the silvipastoral system, in comparison to the sole pasture was 21.1% and 15.4% respectively, with acacia and 183 neem.

Analysis of the data showed a significant land use and depth interaction effect on total organic carbon stock in soil (Figure 1). Among the sole tree systems, the soil organic carbon stock was highest under neem although the biomass was more with acacia, which might be due to better degradability of neem residues than of acacia. The soil organic carbon stock under the sole pasture field of *C. ciliaris* and *C. setegerus* was correlated with their corresponding biomass. Among the silvipastoral systems, the total soil organic carbon stock was highest under neem + *C. ciliaris*, followed by neem + *C. setegerus*. In 5 cm of the soil surface, the soil organic carbon stock was highest under silvipastoral system of neem with *C. setegerus* followed by neem with *C. ciliaris*. At 0–5 cm depth, the soil organic carbon stock under silvipastoral system of neem was 33% higher in silvipastoral combination with *C. ciliaris* in comparison to neem only system. When *C. setegerus* was the grass component, 37.7%

increase in soil organic carbon stock was observed in the silvipastoral system compared to the tree only system. In 5 cm of the soil surface, soil organic carbon stock was less under sole tree cropping than under sole pasture stand. Differential influence of trees may have led to changes in root : shoot ratio, litter quality and soil organic carbon[21] as observed elsewhere also[22,23]. Due to greater soil carbon stocks and greater allocation of carbon to soil pools with longer turnover times, the potential for soil carbon sequestration is greater under pasture than under forest[24].

Total soil organic carbon stock in the 0–100 cm soil depth was highest in the system involving neem + *C. ciliaris*. The greater soil organic carbon sequestration of silvipastoral system could be due to more total root biomass offered by the system that facilitates organic matter in the top as well as deep layers, thus making carbon less prone to oxidation as observed for deep-rooted grasses[25].

Changes in soil organic carbon content during 3 years of study were very small. It was found that silvipastoral system comprising neem and *C. ciliaris* recorded the maximum increase in carbon stock during the 3-year period both at the top 5 cm (0.91 t ha^{-1}) and in the entire 1 m soil profile (2.58 t ha^{-1}). Among grasses, the increase in carbon stock was highest with *C. ciliaris* in 5 cm of the soil surface. However, overall in the soil profile, the carbon stock remains unchanged.

The study indicated the potential of silvipastoral system in offsetting the adverse effect of climate change by contributing to more sequestration of carbon in the soil as well as biomass, when compared to the sole tree or sole pasture systems. Introduction of grass components to the tree systems helped to increase the total ecosystem biomass and hence the total biomass carbon stock. Introduction of *C. ciliaris* to neem was beneficial which added 34.9% higher total plant biomass carbon compared to that of neem only system and with *C. setegerus* (33.8%). The silvipastoral system also helped improve the soil organic carbon stock. The increase in soil organic carbon stock under silvipasture system when compared with sole tree system ranged from 36.3% to 60.0%; and it varied from 27.1% to 70.8% when compared with sole grass system. The study was conducted on established experimental plots and the results may hence be indicative of the potential. The rates could be lower or higher in the real field conditions which depend on agroclimatic and environmental factors.

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