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Carbon Sequestration in Sodic Grassland Ecosystems in North-Western India

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Abstract: The aim of this study was to analyze vegetation carbon pools and flows, soil carbon sequestration, soil aggregate carbon and clay mineralogy in sodic grassland ecosystems (located at Bichian, Saraswati Reserved Forest, Kurukshetra, 29°4' to 30°15' N and 75°15' to 77°16' E) in northwestern India. The climate of the area is semiarid and monsoonic and characterized by hot dry summers and cold winters. The soil organic carbon varied from 3.42 to 0.51g kg^{-1} in 0-100cm soil depths. The carbon pool in the primary producer compartment of the grassland ecosystems (Mg ha^{-1}) was: 4.945-1.721 aboveground plant biomass, 4.336-1.40 belowground biomass. Total aboveground net production was 12270–6070 kg ha^{-1} yr^{-1}. The carbon flux through total net primary productivity was 0. 954 – 0.375 Mg C ha^{-1} yr^{-1}. The carbon stock up to 1-m soil depth was: organic carbon 24.713- 16.649 Mg C ha^{-1}; inorganic carbon 72.685-89.895 Mg C ha^{-1}. The microaggregates (250µm- 53µm and <53 µm) formed a large fraction of soil aggregates and protected most of soil organic carbon. Montmorillonite, chlorite, illite, kaolinite and vermiculite were found to be the main clay minerals in the sodic soil. The naturally occurring grassland systems, by increasing plant biomass production and soil carbon pool, can play an important role in carbon sequestration on sodic soils.

Key words: Plant Biomass · Carbon Pool and Flows · Carbon sequestration · X-ray Diffraction · Organic carbon · Inorganic carbon

INTRODUCTION

Saline and sodic soils are of widespread occurrence in the arid and semiarid regions of northern India [1]. The sodic soils are characterized by high pH throughout the soil profile, high exchangeable sodium and low soil organic matter content and a sparse cover of the salt adapted natural vegetation [2]. Improvement of soil organic matter is critical for the maintenance of soil fertility and productivity of salt affected soils. The native grassland vegetation on sodic marginal lands has the potential for increasing soil carbon pool and biological productivity [3, 4]. Revegetation of salt wastelands has been found to ameliorate soil conditions and improve soil biological activity [5]. Carbon sequestration involves the removal and storage of carbon from the atmosphere in vegetation and soils through physical or biological processes. The soil processes regulating soil carbon stocks and fluxes and soil aggregation in salt-affected soils have been recently reviewed [6]. The soil inorganic carbon stock of soil has the potential to improve soil physical properties, establishment of vegetation and organic carbon sequestration in the soils [7]. Thus it is important to understand the role of soil organic carbon and inorganic carbon in soil carbon sequestration.

Aggregates play an important role in soil health i.e. movement and storage of water, soil aeration, physical protection of soil organic matter, prevention of erosion, root penetration and microbial activity [8]. Soil organic carbon associated with aggregates is an important reservoir of carbon, protected from mineralization and enzymatic degradation [9]. Physical fractionation techniques have been used to separate soil organic matter pools in to primary particles (sand, silt and clay), microaggregates (53-250µm) and macroaggregates (>250µm) [8]. Clay mineralogy is important in determining the quantity of organic carbon stored in soil, its turnover time and atmosphere–ecosystem carbon fluxes during long-term soil development [10,11]. However, studies on clay mineralogy of salt-affected soils need more attention to analyze the effect of interparticle interactions of the soil minerals and soil carbon stability.

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This study analyzes vegetation carbon pools and flows, soil organic and inorganic carbon sequestration and carbon storage in soil aggregates in the naturally occurring grassland ecosystems of sodic soils. It was also aimed to analyze clay mineralogy in a sodic soil.

MATERIALS AND METHODS

Study Site: The study was carried out in *Sporobolus marginatus* Hochst. and *Desmostachya bipinnata* (L.) Stapf, dominated grassland ecosystems on a sodic soil (located at Bichian, Kurukshetra 29° 4' to 30°15' N and 75°15' to 77°16' E) in northwestern India. The climate of the study area is semiarid characterized by hot summers (March to May) and cool winters (October to February) and rainy season from June to September. Annual rainfall was 362.0mm during March 2006 to February 2007. The mean maximum temperature varied from 29.21 to 30.66°C and mean minimum temperature varied from 18.37 to 19.98°C.

The soils of the study area are highly alkaline, a calcic hard pan at 80-120cm depth has been found to be common on these soils resulting in impeded drainage [12]. Soil carbon content varied from 0.10 to 0.16% and the soil pH from 10.0 to 10.2 in surface layer of soil in the grassland systems during the year 1991 [4].

The *Desmostachya bipinnata* grassland, occurring on soils at pH of 9.29 in surface layer, is comprised of *Cynodon dactylon* (L.) Pers. (density= 23.4 tillers m^{-2}), *Cyperus rotundus* L. (density= 3.6 plants m^{-2}), *Desmostachya bipinnata* (density= 381.8 tillers m^{-2} *Erigeron linifoleus* Willd. (density= 5.60 plants m^{-2}), *Leptochloa panacea* (density= 6.60 plants m^{-2}) and *Rumex dentatus* L. (density= 1.0 plants m^{-2}). The *Sporobolus marginatus* Hochst. grassland (soil pH 9.11) is composed of *Sporobolus marginatus* (density= 818 tillers m^{-2}), *Cynodon dactylon* (L.) Pers. (density= 30.40 tillers m^{-2}), *Dichanthium annulatum* (Forsk.) Stapf (density= 11.0 plants m^{-2}) and *Digitaria sanguinalis* (density= 12.60 plants m^{-2}). The number of forbs (non leguminous plant species) was more on the *Desmostachya bipinnata* grassland site (8-9 plant species) as compared to that of the *Sporobolus marginatus* site (4-5 plant species).

During March 2006 to February 2007, the soil pH varied from 9.29 to 10.23 in the soil profile from 0-100cm soil depth. Soil organic carbon of the two grassland sites ranged from 3.42 to 0.51g kg^{-1} across soil depths (Table 1).

Analysis of Vegetation Carbon Pool and Flows: Seasonal variations in the plant biomass of the grassland system were studied by the harvest method using 1×1m harvest plots during March 2006 to February 2007. All aboveground parts were clipped at ground level and placed in paper bags and separated into live and standing dead. The litter from the ground surface was collected from each harvest plot subsequent to clipping, washed by floatation method and oven-dried at 65°C. Root biomass was determined by excavating soil cores from the centre of the harvest plots. The roots were separated from soil by soaking the soil cores in water and washing under a fine jet of water. The biomass was determined on oven dry weight basis.

Estimates of aboveground net primary productivity (ANP) were made using trough peak analysis of the seasonal biomass data on live and dead shoots [13]. Belowground net production (BNP) was calculated by summing all positive changes in belowground biomass as recorded during different months.

Table 1: Some physical and chemical soil characteristics at different soil depths in *Sporobolus marginatus* and *Desmostachya bipinnata* natural grassland systems on a sodic soil. (± Standard error)

Sites/ soil depth	Soil pH	Organic C (g kg^{-1})	Inorganic C (g kg^{-1})	Bulk density (g cm^{-3})
Sporobolus marginatus grassland				
0-15cm	9.60±0.04	2.55±0.10	1.0±0.090	1.55±0.020
15-30cm	10.03±0.04	1.2±0.16	1.1±0.130	1.64±0.010
30 – 45cm	10.13±0.04	1.05±0.06	2.15±0.14	1.58±0.020
45 – 60cm	10.19±0.04	0.75±0.06	5.55±0.23	1.62±0.021
60- 100cm	10.23±0.05	0.51±0.04	9.5±0.130	1.74±0.010
Desmostachya bipinnata grassland				
0-15cm	9.29±0.05	3.42±0.11	0.87±0.04	1.53±0.01
15-30cm	10.01±0.05	1.72±0.11	0.95±0.06	1.61±0.02
30 – 45cm	10.05±0.07	1.55±0.06	1.42±0.08	1.56±0.02
45 – 60cm	10.08±0.02	1.15±0.06	4.87±0.08	1.56±0.02
60- 100cm	10.12±0.03	0.72±0.08	7.5±0.200	1.73±0.01

Carbon pool in aboveground and belowground plant components was calculated using the averaged seasonal plant biomass during 2006 and 2007 and their mean seasonal carbon concentrations.

Analysis of Soil Aggregates and Clay Mineralogy: The sub-samples of replicated field moist soil samples (0-5 cm, 5-15 cm and 15-30 cm soil depths) were gently crumbled manually and sieved (>8mm) to remove root and were air dried for analysis of soil aggregates.

The soil aggregate size classes were studied using the wet sieving method [14]. Soil aggregates were wet sieved into four size classes (>2mm, 2mm-250μm, 250μm-53μm and <53μm) by using sub samples of soil. The sub samples of aggregate size fractions were oven dried at 80°C to represent the aggregate soil weight on oven dry weight basis.

The < 2μm clay fraction that was wholly separated from the soil of the *Sporobolus marginatus* grassland site and used to examine the clay mineralogical composition by the X-ray diffraction (XRD) method [15]. Oriented separated clay samples were prepared to determine the clay mineral constituents. Two pre-treatment were made for each, glycolated, glycolated-heated (at 550° C for 4 hrs) treatments. The XRD analysis was performed using XPERT-PRO model diffractrometer with Cu as anode material using CuKα radiations at 45KV and 40mA and at a scanning speed of 0.017 in a continuous scanning mode over a range of 4° 2θ to 40° 2 θ (untreated samples) and 4° 2θ to 60° 2θ position (glycolated samples). Relative mineral contents in clay fractions were semi quantitatively estimated on the basis of XRD peak intensities by assuming the relative proportion of the minerals of samples normalized to 100% and the same proportionality between the peak intensity and the content for each mineral.

Soil Organic Carbon and Inorganic Carbon: Organic carbon in plant samples and sub-samples of air-dried soil was analyzed following the method of Kalembasa and Jenkinson [16]. The amount of organic and inorganic carbon in soil was estimated from the bulk density, soil depth and organic and inorganic carbon concentration in soil of the respective soil depth.

Statistical Analysis: Data on plant biomass and soil carbon were analyzed using one way analysis of variance using SPSS. Least significant difference (LSD) values at the 5% levels of significance ($p \leq 0.05$) were calculated following Gomez and Gomez [17].

RESULTS AND DISCUSSION

Plant Biomass and Productivity: There were marked seasonal variations in biomass of different primary producer compartments (live shoots, dead shoots, litter and roots) in the *Sporobolus marginatus* and *Desmostachya bipinnata* grassland systems during March 2006 to February 2007 (Table 2). The live shoot biomass of *Sporobolus marginatus* and *Desmostachya bipinnata* was high in the rainy season and declined during winter and summer months. The increase in live shoot biomass during June to September was higher in the *Desmostachya bipinnata* grassland than in the *Sporobolus marginatus* grassland. The average live shoot biomass in different seasons ranged from 966.66 to 2032.5 kg $ha^{-1}$for the *Sporobolus marginatus* grassland system and from 2250.0 to 8510.12 kg $ha^{-1}$for the *Desmostachya bipinnata* grassland (Table 2).

The standing dead shoots attained peak values during winter and summer months; the seasonal average values ranged from 1840.14 to 6813.33 kg ha^{-1} (Table 2). The biomass of litter in the two grassland systems fluctuated throughout the year due to litter deposition from live and dead shoots and its disappearance due to the microbial activity. The litter biomass was found to vary from 1027.5 to 2905.25 kg ha^{-1} across seasons in the two grassland systems (Table 2). The seasonal average biomass of the roots and rhizomes was greater in the *Desmostachya bipinnata* grassland system (12203.64 kg ha^{-1}) than in the *Sporobolus marginatus* grassland (3968.19 kg ha^{-1}) (Table 2). The development of high belowground biomass in natural grassland systems of sodic soils is an adaptive strategy for plants to survive under moisture and salt stress conditions [18].

The annual aboveground net primary production for the two grassland systems ranged from 6070 to 12270 kg ha^{-1} yr^{-1} in different seasons (Table 3). The aboveground net productivity (ANP) was the highest during the rainy season, the values being 69.60% (*Desmostachya bipinnata*) and 51.6% (*Sporobolus marginatus*) of the total ANP. The belowground net productivity (BNP) was found to be high during winter months as compared to the rainy season possibly due to the active translocation of food reserves to the rhizomes and roots with the advent of unfavorable conditions for shoot growth. The belowground allocation of photosynthates has been found to be an important factor for improving soil carbon content. In the two grassland systems, of the total carbon input into the

Table 2: Seasonal average biomass of live shoots, standing dead, litter and belowground parts (roots and rhizomes) in the *Sporobolus marginatus* and *Desmostachya bipinnata* grassland ecosystem at Bichian

	Biomass (kg ha^{-1})			
Site/ season	Live shoots	Standing dead	Litter	Roots and rhizomes
Sporobolus marginatus				
June-Sep. Rainy season	2032.5±43.75	1112.5±36.81	1027.5±35.93	3385.0±54.42
Oct.-Feb. Winter season	1126.2±35.98	2162.2±46.66	1316.2±53.38	4706.2±53.81
Mar-May. Summer season	966.66±45.15	1840.14±60.47	1593.33±54.33	3813.33±59.82
Annual	1375.12	1704.94	1312.34	3968.19
Desmostachya bipinnata				
June-Sep Rainy season	8510.12±44.87	2875.25±40.76	2905.25±44.82	10517.5±24.13
Oct.-Feb. Winter season	5030.1±16.54	6366.2±53.22	2624.1±63.22	12920.1±56.38
Mar-May. Summer season	2250.0±66.00	6813.33±69.62	2466.66±34.16	13173.33±37.83
Annual	5263.34	5351.59	2665.33	12203.64

Table 3: Aboveground net production (ANP), belowground net production (BNP) and total net production (TNP) for the *Sporobolus marginatus* and *Desmostachya bipinnata* grassland system at Bichian

	Net production (kg ha^{-1} yr^{-1})		
Season	ANP	BNP	TNP
Sporobolus marginatus			
Rainy (June - September)	3130	1030	4160
Winter (October - February)	1540	2660	4200
Summer (March - May)	1400	420	1820
Annual	6070	4110	10180
Desmostachya bipinnata			
Rainy (June - September)	8540	2870	11410
Winter (October - February)	1260	8340	9600
Summer (March - May)	2470	3360	5830
Annual	12270	14570	26840

Table 4: Carbon content in different primary producer compartments and carbon flux in aboveground net primary productivity (ANP) and belowground net primary productivity (BNP) in the *Desmostachya bipinata* and *Sporobolus marginatus* grassland systems

	Grassland System	
Plant Component	*Sporobolus marginatus*	*Desmostachya bipinata*
Carbon content (Mg C ha^{-1})		
Live shoots	0.522	1.871
Standing dead	0.677	2.020
Litter	0.522	1.054
Roots	1.400	4.336
Total	3.121	9.281
Carbon flux (Mg C $ha^{-1}yr^{-1}$)		
ANP	0.230	0.436
BNP	0.145	0.518
TNP	0.375	0.954

system, 44.87% to 46.72% was associated with belowground production and 55.13% to 53.27% with the aboveground net production.

Vegetation Carbon Pool and Flows: The carbon concentration in different primary producer compartments of *Sporobolus marginatus* and *Desmostachya bipinnata* in the grassland system were - 37.94 % to 35.54 % live shoots; 39.70 % to 37.75 % dead shoots; 39.80 % to 39.54 % litter; 35.29 % to 35.53 % root and rhizomes. The shoots had higher concentration of carbon as compared to that of roots.

Total carbon pool in the plant biomass was 3.121 Mg C ha^{-1} and 9.281 Mg C ha^{-1} in *Sporobolus marginatus* and *Desmostachya bipinnata* grassland systems, respectively (Table 4).

Carbon flow refers to the input of carbon through net primary productivity into the system and its subsequent transfer to the soil through litter and root turnover. Total carbon input in net primary productivity varied from 0.375 to 0.954 Mg C ha^{-1} yr^{-1} in the two grassland systems (Table 4). In the *Desmostachya bipinnata* grassland system, about 54% of carbon was channelised to the belowground components, whereas in the *Sporobolus marginatus* grassland, 39 % of total carbon flux was channelized belowground.

Soil Organic Carbon Pool: In the *Sporobolus marginatus* and *Desmostachya bipinnata* grassland systems on sodic soils, soil organic carbon showed marked decrease with increase in soil depth (Fig. 1).

In the two grassland system, the soil organic carbon stock (Mg C ha^{-1}) at different soil depths was: 5.812-7.803 (0-15 cm); 2.952-5.416 (15-30 cm soil); 2.495-3.584 (30-45 cm soil); 1.824-2.902 (45-60 cm soil);

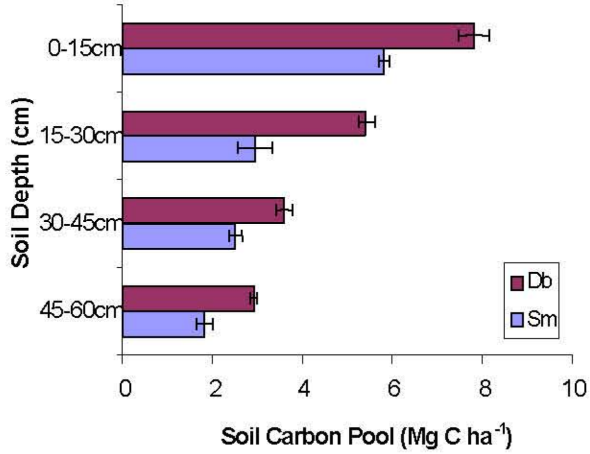

Fig. 1: Soil organic carbon pool (Mg C ha^{-1}) in *Sporobolus marginatus* (Sm), *Desmostachya bipinnata* (Db) on sodic soils at Bichian

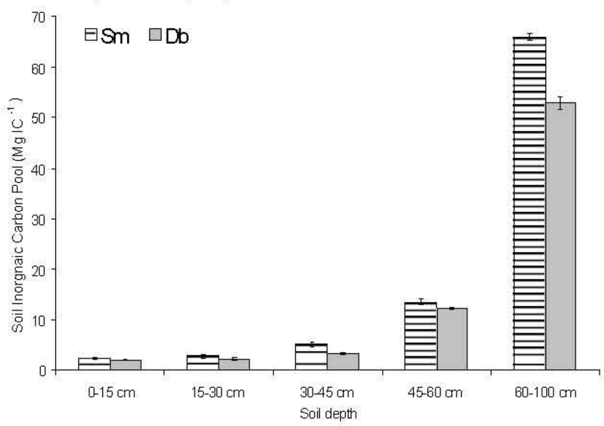

Fig. 2: Soil inorganic carbon pool (Mg IC ha^{-1}) in *Sporobolus marginatus* (Sm), *Desmostachya bipinnata* (Db) on sodic soils at Bichian

3.566-5.008 (60-100 cm soil). The carbon stock at 0-30 cm soil depth was 52-53 % of the total organic carbon stock up to 100 cm soil depth.

The protection of the grassland system over a long period of 15 years resulted in significant increase of soil carbon and biological amelioration of sodic soils. There was a marked increase in soil carbon from 0.20% in the year 1991 as reported earlier by Kaur *et al.* [4] compared to the soil organic carbon of 0.44% during this study. The carbon fixed by the plants is the primary source of organic matter input into the soil, which provides substrate for microbial processes and accumulation of soil organic matter. Thus, belowground allocation of photosynthates was found to be an important contributing factor for improving soil organic carbon.

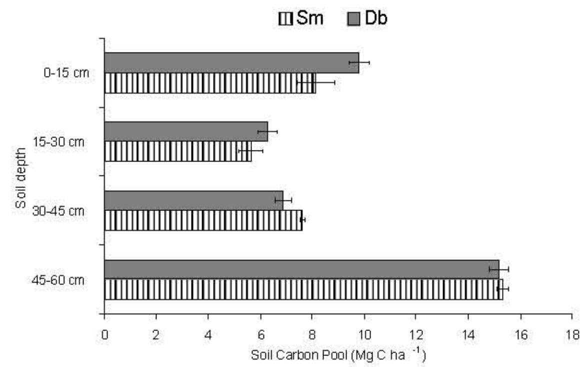

Fig. 3: Total soil carbon pool (Mg C ha^{-1}) in *Sporobolus marginatus* (Sm) and *Desmostachya bipinnata* (Db) on sodic soils at Bichian

Soil Inorganic Carbon Stock: In soil of the two grassland ecosystems, the soil inorganic carbon increased from 1.0 g kg^{-1} at 0-15 cm soil depth to 9.5 g kg^{-1} at 60-100 cm soil depth (Table 1). In the grassland systems, there was significant increase in soil inorganic carbon with increase in soil depth ($P<0.01$). In contrast to soil organic carbon distribution, most of soil inorganic carbon was found concentrated below 30 cm soil depth in the two grassland systems (Fig. 2).

The soil inorganic carbon stock in the *Sporobolus marginatus* grassland system was (Mg IC ha^{-1}): 2.325 (0-15 cm soil depth), 2.952 (15-30 cm soil depth), 5.109 (30-45 cm soil depth), 13.497 (45-60 cm soil depth), 66.012 (60-100 cm soil depth). In *Desmostachya bipinnata* grassland system the soil inorganic carbon stock (Mg IC ha^{-1}) was: 1.996(0-15 cm soil depth), 2.173 (15-30 cm soil depth), 3.299 (30-45 cm soil depth), 12.269 (45-60 cm soil depth), 52.946 (60-100 cm soil depth) (Fig. 2). The largest increase in soil inorganic carbon was observed at 60-100 cm soil depth in both the grassland systems. The inorganic carbon is found mostly in the form of $CaCO_3$ in the soils of the study area [19]. The dissolution of preexisting carbonates in the upper soil layer may get translocated vertically and its precipitation in the subsoil. Formation of soluble calcium bicarbonates helps in restoring soluble and exchangeable calcium levels in the soils as well as improving soil physical properties by decreasing exchangeable sodium percentage [7, 20].

Total Soil Carbon Stock: The largest increase in soil inorganic carbon was observed at 60-100 cm soil depth in the grassland system and was found to be reflected in a substantial carbon stock of 69.578 to 57.953Mg C ha^{-1} in soil, (Fig. 3). Total carbon stock

Table 5: Percent soil weight distribution in aggregate size classes in the grassland system across soil depths at Bichian in Saraswati Reserved Forest (± standard error)

	Percent soil weight in soil aggregates		
Soil depth (cm)	2 mm - 250 μm	250μm - 53 μm	<53μm
Sporobolus marginatus			
0 - 5	3.79±0.77	28.12±1.85	68.09±0.42
5 - 15	3.10±0.43	32.78±1.98	64.12±1.23
15 - 30	3.66±0.58	38.34±1.60	58.00±2.85
LSD (p<0.05)	1.36	5.87	3.79
CV (%)	23.76	9.91	3.40
Desmostachya bipinnata			
0 - 5	5.45±0.32	56.41±1.26	38.14±1.60
5 - 15	4.79±0.77	59.18±2.84	36.03±0.81
15 - 30	4.42±0.74	61.56±1.09	34.02±1.05
LSD (p<0.05)	1.36	4.42	4.30
CV (%)	15.89	4.25	6.83

Table 6: Organic carbon distribution in aggregate size classes in soils of grassland system at various soil depths at Bichian (± standard error)

	Organic carbon (%)			
Soil depth (cm)	Soil	2 mm - 250 μm	250μm - 53 μm	<53μm
Sporobolus marginatus				
0 - 5	0.32±0.01	0.41±0.01	0.25±0.02	0.21±0.01
5 - 15	0.19±0.01	0.31±0.02	0.18±0.01	0.16±0.01
15 - 30	0.12±0.01	0.19±0.01	0.13±0.01	0.09±0.01
LSD(p<0.05)	0.062	0.067	0.059	0.034
CV (%)	18.08	12.63	17.88	13.20
Desmostachya bipinnata				
0 - 5	0.46±0.01	0.58±0.03	0.33±0.01	0.20±0.01
5 - 15	0.23±0.01	0.33±0.02	0.22±0.01	0.16±0.01
15 - 30	0.17±0.01	0.28±0.01	0.16±0.02	0.09±0.01
LSD(p<0.05)	0.062	0.059	0.045	0.034
CV (%)	13.36	9.15	10.52	11.07

in the *Sporobolus marginatus* and the *Desmostachya bipinnata* grassland system was(Mg C ha^{-1}): 8.137 to 9.799 (0-15 cm soil depth), 5.658 to 6.279 (15-30 cm soil depth), 7.604 to 6.883 (30-45 cm soil depth), 15.320 to 15.179 (45-60 cm soil depth), 69.578 to 57.953 (60-100 cm soil depth).

Soil Aggregate Composition and Carbon Storage: In the two grassland systems, only a small amount of macroaggregates (2mm-250μm) were recovered from soils up to 0-30 cm soil depth (Table 5). The proportion of small macroaggregates (2mm-250μm) was higher in *Desmostachya bipinnata* grassland (4.42 to 5.45%) compared to that in the *Sporobolus marginatus* grassland system (3.10 to 3.79%). Microaggregates (250μm – 53μm) varied from 28.12 to 38.34% in the *Sporobolus marginatus* and from 56.41 to 61.56% in *Desmostachya bipinnata* grassland. The clay and silt associated aggregates (<53μm) formed large fraction of the soil; the values being 58.00 to 68.09% for the *Sporobolus marginatus* and 34.02 to 38.14% for the *Desmostachya bipinnata* grassland system.

The organic carbon concentration was higher in macroaggregates (2mm-250μm) as compared to microaggregates (250μm–53μm) (Table 6). The carbon concentration in macroaggregates (2mm-250μm) varied from 0.19 to 0.41% in the *Sporobolus marginatus* and from 0.28 to 0.58% in the *Desmostachya bipinnata.* The concentration of carbon in microaggregates (250μm–53μm) ranged from 0.13 to 0.25% in the *Sporobolus marginatus* grassland and from 0.16 to 0.33% in the *Desmostachya bipinnata* grassland system. In the silt and clay fractions (<53μm) carbon concentration was: 0.09 to 0.21% the *Sporobolus marginatus* and

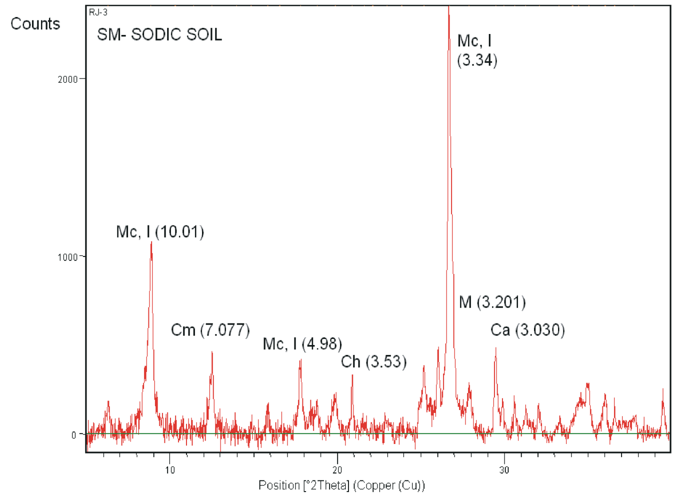

Fig. 4: X-ray diffraction pattern of untreated clay from highly sodic soil of the *Sporobolus marginatus* grassland at Bichian (I = Illite; Mc = Mica; Ch = Chlorite; M = Montmorillonite; Ca = Calcite; Cm = Chasmosite)

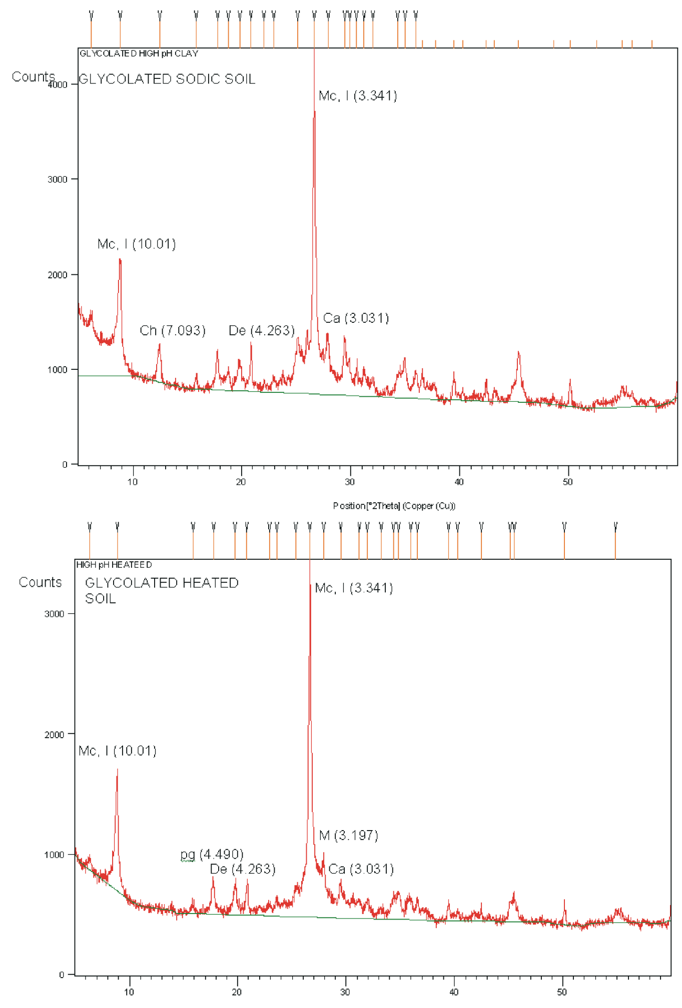

Fig. 5: X-ray diffraction pattern of clay fraction (a) Glycolated (I = Illite; Mc = Mica; Ch = Chlorite; De = Dickite; Ca = Calcite). (b) Glycolated Heated Clay (I = Illite; M = Montmorillonite; Mc = Mica; Ca = Calcite; De = Dickite)

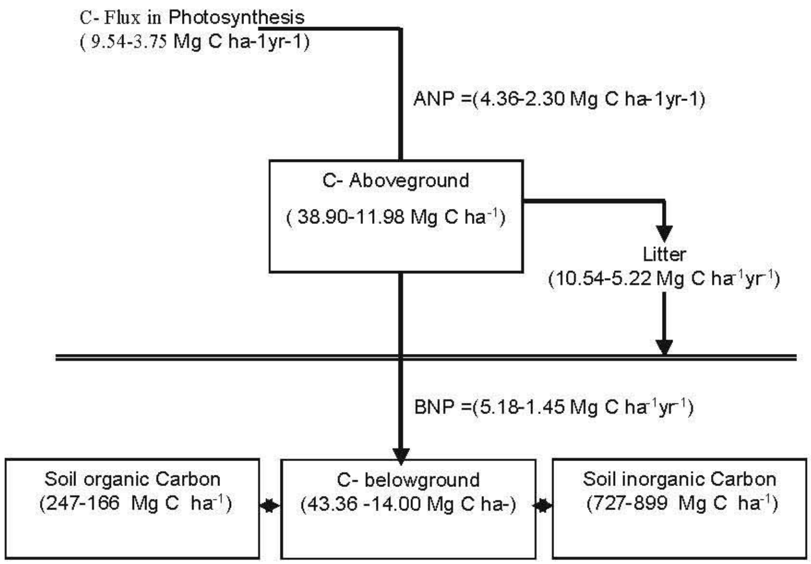

Fig. 6: Carbon budget of *Sporobolus marginatus* (Sm), *Desmostachya bipinnata* (Db) on sodic soils at Bichian. The values in compartments represent the carbon stock (Mg C $ha^{-1}yr^{-1}$). The values on the arrows represent the flows (Mg C $ha^{-1}yr^{-1}$)

0.09 to 0.20% the *Desmostachya bipinnata*. The silt plus clay fractions contained 1.202 to 4.646 g C kg^{-1} aggregate fraction, whereas microaggregates (0.443 to 1.533 g C kg^{-1} aggregate fraction) and macroaggregates (0.062 to 0.537 g C kg^{-1} aggregate fraction) stored relatively less carbon. The soil organic carbon in microaggregates is believed to be protected from degradation and is relevant for soil carbon sequestration. The silt plus clay fraction in soil of the studied grasslands could play a key role in the protection of soil organic matter as reported by Six *et al.* [21].

Clay Mineralogy: The stabilization of organic material by soil matrix is a function of chemical nature of mineral fraction and its surfaces capable of adsorbing the organic material [22]. Illite is the main precursor mineral for the formation of smectite in salt –affected soils. In this study, the illite and montmorillonite (a member of the smectite family, 2:1 clay) were predominant in the soil (Figs 4, 5). In the surface layer of salt affected soils in Alberta, Canada, Kohut and Dudas [23] reported highly diffuse smectite diffraction maxima because of mineralogical interactions with organic matter. The distribution of newly formed humic materials into minerologically distinct clay size fractions on a silt loam soil showed that new humic materials are preferentially accumulated on smectite surfaces [24]. In this study, the predominance of illite and montmorillonite in the clay could be related to soil carbon stability. The association of organic matter in soil with minerals is a controlling factor of organic carbon storage in soil [22]. The soil organic matter protection through intimate association with clay particles can provide long term stability for carbon sequestration [25, 26].

CONCLUSIONS

The native grassland vegetation on salt-affected soils has the potential for carbon sequestration by increasing plant biomass production, improving soil organic matter and improving carbon stability soil aggregates. The total carbon sequestration in soils of the natural grassland ecosystems was 247.13 to 166.49 Mg C ha^{-1} over a period of 15-years. There was stabilization of carbon within soil microaggregates and the predominance of illite and montmorillonite in the clay could be related to soil organic carbon stability.

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