International Journal of

Soil Science

ISSN 1816-4978

Academic Journals Inc.

www.academicjournals.com

OPEN ACCESS International Journal of Soil Science

ISSN 1816-4978
DOI: 10.3923/ijss.2017.120.127

Research Article
Distribution and Stratification of Carbon in Irrigated Calcareous Soil under Rice-based Cropping Pattern in Bangladesh

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Abstract

Background and Objective: Agricultural activities release three primary greenhouse gases to atmosphere which are responsible for climate change. Soil, a natural capital is considered as a big reservoir of carbon dioxide (CO_2). Irrigation may or may not change soil carbon in a desirable direction. It is, therefore, important to evaluate soil carbon in irrigated soils. The objective of this study was to evaluate the influence of irrigation on soil carbon dynamics in a tropical calcareous soil under rice-based cropping systems. **Materials and Methods:** Soil organic and inorganic carbon stock and their stratification were evaluated from three soil series located in same catena of Ganges-Kobadak (G-K) irrigation project as well as adjoining non irrigated area of G-K soils which were calcareous in nature. Two-way analysis of variance (ANOVA) was undertaken for all factors. All statistical analyses were performed by JMP 4.0 (SAS Institute, Cary, North Carolina, USA). **Results:** Soil organic carbon (SOC) was increased due to long-term irrigation in calcareous soils irrespective of soil depth and series. The research showed the significant loss of soil inorganic carbon (SIC) under irrigated condition compared to non irrigated condition regardless of soil series. Soil organic carbon density was lower in coarse textured soils than fine textured soils while in case of SIC it was higher in coarse textured soils than fine textured soils, regardless of management practices and soils. The potential SOC stock was higher in non irrigated soils than irrigated soils and the reverse was true for the SIC. Stratification ratios of SOC under irrigated soils were significantly higher than under non irrigated soils. On the other hand, the stratification ratios of SIC was significantly lower under irrigated soils than under non irrigated soils. **Conclusion:** Results indicated that irrigation practices may slightly increase SOC but remarkable decrease SIC in calcareous soils.

Key words: Carbon stratification, carbon stock, irrigation, calcareous soils, rice cultivation

Citation: M. Hasinur Rahman, 2017. Distribution and stratification of carbon in irrigated calcareous soil under rice-based cropping pattern in Bangladesh. Int. J. Soil Sci., 12: 120-127.

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Competing Interest: The author has declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The Food and agriculture organization (FAO) anticipated that food demand will be increased by 70% between 2000 and 2050[1]. To meet the demand, higher yields per hectare of food crops are needed from countries where there is little scope for bringing additional land into cultivation. To produce more food, land that previously grew one crop per year should produce two or three crops by adopting intensive agricultural practices, including the use of irrigation. However, intensive agriculture releases three primary greenhouse gasses (CO_2, CH_4 and N_2O) to atmosphere which are responsible for climate change. The degree of CO_2 emission from agricultural and deforestation activities is calculated at about 1.6×10^3 million t C y^{-1} and SOC sequestration potential could be offset about 15% of global CO_2 emission[2]. Greenhouse gas emissions from agriculture within New Zealand account for 48% of all national greenhouse gas emissions. In the USA, relative contribution to greenhouse gas emission by agriculture is 6.3%[3]. Carbon capture and sequestration is one of the major tools for reducing carbon dioxide concentration in the atmosphere[4]. Soil has been considered as huge reservoir of CO_2 as organic matter (soil organic carbon), which has long been recognised as one of the indicators for soil quality. Global soil organic carbon (SOC) was estimated about 1462-1548 Pg in the upper 1 m and 2376-2456 Pg in the upper 2 m. On the other hand, soil inorganic carbon (SIC) was estimated 720 Pg to 1 m depth and 950 Pg to 2 m depth[5,6]. Therefore, the total soil C in soil may exceed 3300 Pg to 2 m depth. More than one third of global SOC was stored in Northern circumpolar permafrost soils. Perennially frozen hill toe deposits stored considerable SOC stocks because of their extent, depth and SOC density[7]. The SOC varies with agro ecological zones and large quantities of SOC stock were observed by Schuur *et al.*[8] in frozen soils (permafrost) within Arctic and sub-Arctic regions. As part of input agriculture, worldwide irrigated crop land exceeds 271 million hectares and additional land was expected to be irrigated as the world's population increasing and secondary lands are reclaimed for agriculture[9]. High input agriculture releases more greenhouse gases and therefore, deserves further research on mitigating climate change through reducing the production of those gases. Greater food security and the risk of accelerated greenhouse gas emissions are both connected to the sustainability of soil quality and its affiliation to the soil carbon pool and dynamics. Rectifying these issues requires the maintenance of current status or enhanced amounts of SOC. The SOC pool includes unrecompensed cellular residue of plants, humic compounds and living microbial biomass[10]. The loss of soil carbon has been reported under some dairy and dry stock pastoral land uses in New Zealand[11]. The conversion of crop land to pasture or forest is likely to lead to an increase in soil carbon Vesterdal *et al.*[12]. It was, therefore, predictable that agricultural management systems determine whether soils will be a net carbon sink or source. The experimental soils develop in semi-arid climate generally on Pleistocene alluvial or loess deposits. They have a fairly good structure and a fair amount of organic matter. Low soil moisture and high temperature are common in the areas where soils are calcareous in nature which is the most limiting factor for the accumulation of organic carbon of those soils. The amount of SOC may not be the best indicator of soil quality and therefore, irrespective of soil and climatic conditions the stratification ratio of carbon can be used as an indicator of soil quality[13]. Stratification of soil carbon and particle size was common after puddling. For example, the sand fraction settles first from muddy water and gradually was covered by finer silt and clay, in medium textured soils. Stratification of soil particles is well developed in Northen Thailand with a fine texture surface layer[14]. Soil plays an important role in the global carbon cycle with the third largest active carbon pool. Soil organic carbon was not likely to accumulated in non irrigated calcareous soils due to high decomposition rates induced by high temperature. Additionally the carbonate is the most common form of C in calcareous soils may leach out under irrigation and intensive cultivation. Carbonates have a remarkable influence on soil pH[15]. Wallace[16] stated that calcium was the most important cementing agent for organic matter and clay to maintaining soil structure. Therefore, loss of carbonate can reduce soil quality if they fall below a critical threshold level. In Bangladesh more than 20% soils are calcareous in nature which have been using for rice cultivation under irrigated and non irrigated management[17]. Calcareous soils developed on floodplain differ in their physico-chemical properties mainly due to mineralogy, age of sedimentation, relief, drainage and biotic activity. It is very important to monitor carbonates in calcareous soil under different management conditions. This study hypothesized that soil carbon in calcareous soil may not change in a desirable direction by irrigation and intensive cultivation. The objective of this study was to evaluate the influence of irrigation on soil carbon dynamics in a tropical calcareous soil under rice-based cropping systems.

MATERIALS AND METHODS

In order to evaluate the influence of long time irrigation with puddling on soil carbon, soils were collected in January and the analyses were done throughout the year. Soils were collected from three soil series namely, Sara (silt to silt loam), Gopalpur (silt loam to silty clay loam) and Ishurdi (silt loam to clay) located in same catena at 0-25, 25-50, 50-75 and 75-100 cm depth under irrigated rice-based cropping pattern in Ganges-Kobadak (G-K) irrigation project area (latitude 23°11'N to 24°08'N, longitude 89°03'E to 89°10'E; altitude 7-14 m) of Bangladesh. Soils were also collected from same soil series from adjoining non irrigated area which had been under rice-based cropping pattern and these soils were used as paired samples. The G-K irrigation project was established in 1962-63 with the aims of developing irrigation and road systems, improving drainage and for controlling river floods. These three soil series were selected because they cover vast area of G-K project and located in the same catena. The G-K project area has a tropical monsoon climate, as does the rest of country. The Sara series occur on level to nearly level topography with about 1-2% slope. The Sara series soils were developed on the upper part of the ridge of Young Ganges Meander Floodplain belong to the subgroup of Aquic Eutrochrepts under the order of Inceptisol. The Gopalpur series occur on very gently undulating to undulating level topography with about 3-8% slope. On the other hand, the Ishurdi series occur on very gently undulating level topography with about 3-5% slope. The Gopalpur and Ishurdi soils developed on the middle and lower part of the ridge, respectively, of the Young Ganges Meander Floodplain belong to the subgroup of Aeric Fluvaquentic Haplaquepts under the order of Inceptisol.

The soils of the G-K project area are plowed and harrowed in water saturated condition (puddled by disc harrowing type tractor with 10 cm depth) and standing water was maintained during the production of wetland rice (transplanted: T-Aman, T-Aus) species and after draining winter brassica and/or wheat crops (rabi crops) are grown and the fields were kept fallow and dry after harvest. On the other hand, non irrigated area adjoining the G-K project soils are plowed in unsaturated condition (mouldboard ploughing by 10-15 cm depth) and broadcasted aman rice (B-Aman) and robi crops are grown under rainfed condition and fields were kept fallow and dry after harvest. Alternate wetting and drying is common in calcareous G-K project soils to eliminate the S and Zn deficiency. The irrigated land produced twice the yield of the non irrigated land, partly due to the irrigation and partly due to substantially increased application of NPK based fertilizers. At each of the selected sites, undisturbed core samples (Daiki Rika Kogyo Co., Ltd., Japan) and disturbed soil samples with 5 replications were collected from each of the genetic horizon's up to a depth of 100 cm. The core samples were placed in core sampler bags and disturbed samples were placed into polythene bags for transportation to the laboratory. Soil bulk density was measured[18]. Soil organic carbon (SOC) was measured by wet chemistry[19] and soil inorganic carbon as $CaCO_3$ (SIC) was measured[15] from sieved (<2 mm) soils. Soil carbon storage is a function of soil carbon concentration and the bulk density of the soil, i.e., the carbon storage per soil layer at 0-25, 25-50, 50-75 and 75-100 cm was calculated[20].

The surface layer of soil is the vital interface where most of the agricultural activities concentrated. Therefore, surface soil layer quality was evaluated compared to other soil layers using stratification ratio the indicator of soil quality established by Franzluebbers[13]. The stratification ratios were calculated based on concentration of SOC, SIC and TSC (total soil carbon) at a depth of 0-25 cm divided by the concentration of those properties at a depth of 25-50 cm (SR1: Surface soil quality), 50-75 cm (SR2: Subsurface soil quality) and 75-100 cm (SR3: Below subsurface soil quality).

Statistical analysis: Two-way analysis of variance (ANOVA) was undertaken for all factors. The ANOVA model was employed depth, soil series and irrigation as the main source of variation and the three pairwise viz., depth×irrigation, depth×soil series and soil series×irrigation and one three-way viz., depth×soil series×irrigation interaction. Principal component analysis (PCA) scores based on soil carbon density were also established. The relative proportions of sum of square due to management practices soil types and depths were calculated to find potential effects of those factors on soil carbon density. All statistical analyses were performed by JMP 4.0 (SAS Institute, Cary, North Carolina, USA) at a 5% level of significance.

RESULTS AND DISCUSSION

Soil organic carbon and SIC were significantly affected by irrigation, soil type, depth and their interactions. Among three factors, soil depth had a predominant effect on SOC account for 72.93% of the total variation. On the other hand, SIC and TSC had the greatest influence by soil type, accounting for 52.37 and 71.66% of the total variance in the data, respectively. At all soil series, SOC was higher in irrigated condition and the reverse was true for SIC (Table 1). In irrigated soils humification rather than mineralization might be responsible for higher SOC. Irrigation may reduce soil microbial stress and improve microbial C metabolism by lowering soil microbial quotient[21] turn to C neutral status to C sink. Increased water use and intensive crop management within the irrigated area increased plant production and

Table 1: Carbon concentration (%) in calcareous soils of G-K project area of Bangladesh

Soil series	Management	Depth (cm)	SOC	SIC	TSC
Sara	Irrigated	0-25	0.88	9.78	10.66
		25-50	0.25	13.58	13.83
		50-75	0.20	14.20	14.40
		75-100	0.15	14.50	14.65
	Non irrigated	0-25	0.30	13.31	13.61
		25-50	0.17	14.50	14.67
		50-75	0.14	14.46	14.60
		75-100	0.14	14.54	14.68
Gopalpur	Irrigated	0-25	0.90	5.00	5.90
		25-50	0.42	8.76	9.17
		50-75	0.39	9.40	9.79
		75-100	0.29	11.40	11.68
	Non irrigated	0-25	0.42	11.50	11.92
		25-50	0.26	12.84	13.10
		50-75	0.17	12.89	13.06
		75-100	0.15	13.32	13.48
Ishurdi	Irrigated	0-25	1.10	3.40	4.51
		25-50	0.45	5.98	6.43
		50-75	0.39	11.00	11.39
		75-100	0.37	12.90	13.28
	Non irrigated	0-25	0.78	6.16	6.94
		25-50	0.46	7.07	7.53
		50-75	0.39	11.24	11.63
		75-100	0.33	13.04	13.37

SOC: Soil organic carbon, SIC: Soil inorganic carbon, TSC: Total soil carbon

therefore, increased plant litter and root growth provided organic carbon inputs to those soils. This study results for SOC were consistent with those of De Clerk and Singer[22], who observed increases in SOC over 60 years of irrigation. Silveira *et al*.[23] observed that crop intensification increased SOC stock. Remarkable differences in concentration of SOC among the soil series were observed with the highest value in Ishurdi and the lowest in Sara soil series. In this study, SIC of top soil layers was lower than that of the three subsoil layers with the lower values present in irrigated soils than non irrigated soil. This may be due to the formation of carbonates at lower depth and/or dissolution of carbonates from the top soil layer. Pedogenic carbonates generally accumulate in the subsoil near the depth of average maximum annual percolation of soil water[24]. Soil inorganic carbonate ($CaCO_3$) remarkably reduced in irrigated soils than non irrigated soil. Calcium carbonate has impact on soil chemical properties[15], i.e., loss of calcium carbonate can reduce soil quality. Wallace[16] stated that calcium was the most important cementing agent for organic matter and clay particle which maintained soil structure. Therefore, loss of $CaCO_3$ could decrease the stability of soil. Irrespective of irrigation, SIC ($CaCO_3$) was varied in Sara, Gopalpur and Ishurdi series, respectively. Research indicated that the maize growth is hampered when calcareous soil contains more than 35% of $CaCO_3$. Calcareous soils in Indus basin with weak structure contains 6-10% of $CaCO_3$ from 90-120 cm depth while stratified alluvial soils are moderate in calcareous nature contains 8-10% of $CaCO_3$. Irrespective of irrigation and soil, a linear decrease in soil organic carbon was observed (r = -0.665), while linear increases were observed for soil inorganic carbon (r = 0.579) and total soil carbon (r = 0.453) with increasing depth.

The density of SOC was significantly affected by the management (irrigation), soil series and soil depth accounting for 15.99, 19.95 and 64.06%, respectively. Soil inorganic carbon was also affected by the management (irrigation), soil series and soil depth and their interactions, indicating that there were depth-soil series specific differences in SIC density to management practice (Table 2). The higher SOC stock was recorded in surface and the reverse was true for SIC. Franzluebbers and Stuedemann[25] stated that greater SOC stock can be expected in surface layer. Total soil carbon was strongly influenced by management practice, soil series and soil depth. The effect of soil depth on SOC, SIC and TSC were more pronounced than management and soil series accounted for 64.06, 56.57 and 77.84%, respectively. The PCA scores showed that there was a fairly large irrigation and soil effect on soil carbon (Fig. 1). The SOC density (stock) calculated by taking the differences in antecedent bulk density showed a similar pattern or slightly different pattern as SOC concentration. The highest SOC density throughout the 100 cm profile was stored in Ishurdi fine textured soils) series, intermediate in Gopalpur and the lowest was in Sara series (coarse textured soils), irrespective of management.

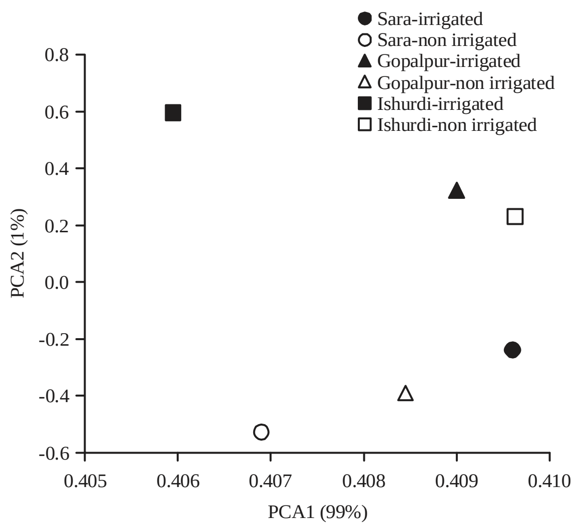

Fig. 1: Irrigation effects on the first and second principal components based on soil carbon density

Symbols represent the principal component scores of individual soil type and management, percentages described on each axis mean the eigen value of the scores

Table 2: Carbon density (t ha^{-1}) in calcareous soils of G-K project area of Bangladesh

Soil series	Management	Depth (cm)	SOC	SIC	TSC
Sara	Irrigated	0-25	28.74	320.50	349.24
		25-50	8.62	461.36	469.99
		50-75	6.80	477.72	484.52
		75-100	5.15	491.67	496.82
	Non irrigated	0-25	9.62	420.95	430.57
		25-50	5.71	493.56	499.27
		50-75	4.61	470.48	475.09
		75-100	4.36	466.11	470.47
Gopalpur	Irrigated	0-25	29.89	165.70	195.59
		25-50	14.33	301.59	315.92
		50-75	12.83	311.66	324.50
		75-100	10.08	402.16	412.24
	Non irrigated	0-25	13.60	376.69	390.29
		25-50	9.17	452.57	461.75
		50-75	5.83	451.96	457.79
		75-100	5.67	490.47	496.14
Ishurdi	Irrigated	0-25	35.14	108.40	143.54
		25-50	15.53	206.51	222.04
		50-75	13.31	376.64	389.95
		75-100	12.74	439.34	452.08
	Non irrigated	0-25	22.95	181.96	204.92
		25-50	15.32	235.64	250.95
		50-75	12.40	358.46	370.86
		75-100	11.78	466.12	477.90
Sara	Irrigated	0-100	49.32	1751.25	1800.56
	Non irrigated	0-100	24.30	1851.10	1875.40
Gopalpur	Irrigated	0-100	67.13	1181.11	1248.25
	Non irrigated	0-100	34.28	1771.69	1805.97
Ishurdi	Irrigated	0-100	76.71	1130.89	1207.60
	Non irrigated	0-100	62.45	1242.18	1304.63

Wu *et al*.[26] observed that SOC stocks were related to the content of clay, silt and moisture of soils. Twenty five years irrigation has increased SOC density but decreased SIC density and total soil carbon density across the top 100 cm layer in calcareous soils. The increased rate of SOC was 58.17% and the decreased rates of SIC and TSC were 17.19 and 9.01%, respectively, across soil profile. Therefore, SOC can be sequestered in calcareous (G-K project) soils under irrigated rice production systems but the amounts may be very unstable as climatic conditions (high temperature) and soil properties (coarse textured soils, low soil moisture) are limiting factors for the accumulation of SOC. Australian research has shown that SOC declines after the conversion of land to cultivation and the rate of decline was between 19 and 45% in major soils of cereal belt of southern Queensland after 20-70 years of cropping[27,28]. On the other hand, conversion of crop land to pasture or forest increases soil carbon[12]. It was, therefore, predictable that agricultural management systems determine whether soils will be a net carbon sink or source in relation to soil characteristics. It is clear from this study that in calcareous soils there is a risk of soil acidification and subsequent volatilisation of carbonates if high levels of ammonia-based fertilizers have been used to grow high yields with irrigation resulting in the conversion of carbonates into CO_2 which is released into the atmosphere and/or to deposit a significant amount of free carbonates in ground water. The content of carbonate in calcareous soils can be preserve by keeping crop residues on the soil surface and by reducing irrigation.

The stratification ratio of SOC has been considered as indicator of soil quality as surface organic matter is one of the key factors influencing soil stability. The stratification ratios of SOC were established and SIC in calcareous soils under rice based cultivation systems in 0-100 cm depth with an increment of 25 cm as surface (0-25 cm), subsurface (25-50 cm) and bottom layer (50-75 cm) and results were shown in Table 3. Regardless of soil series the stratification ratios of SOC irrigated soils were higher than non irrigated soils in surface, subsurface and bottom layer, respectively (Table 3). The stratification ratios of SOC is proportionate to soil depth while for SIC it was inversely proportionate to the soil depth. The stratification of SOC varied among soils depending upon management practices. The stratification ratios of SOC were higher in irrigated soil among all soil series and while lowest values were recorded for SIC among the soil series. The stratification ratios of SOC were highest in Sara followed by Gopalpur and then Ishrudi series in irrigated soils, however, there were no definite trends in non irrigated soils. With a few exception, the stratification ratios of SOC were always higher than 2, irrespective of soils and management practices indication that the calcareous soils of G-K project are fertile for plant growth according to Franzluebber[13].

The carbon stock potentiality (%) was calculated in a soil layer of a profile for series-specific soil under irrigated and non irrigated rice management systems and results were furnished in Table 4. It is logical that soil stored more carbon in subsurface to bottom layers than surface layer of those profiles are more capable or potential in carbon sequester as there are more risk to emit carbon easily from surface layer than subsurface layers. Non irrigated soils exhibited a significantly higher capacity of SOC at lower soil depths (25-100 cm and onwards) than irrigated soils, regardless of soil series. The proportion of SIC in soil profiles was more uniform in non irrigated soils than irrigated management and more SIC was stored in surface soil layer of non irrigated soils than irrigated soils.

Table 3: Carbon stratification ratio in calcareous irrigated soils of Bangladesh

Soil series	Management	Indicator	Depth ratio	SOC	SIC	TSC
Sara	Irrigated	SR1	(0-25)/(25-50)	3.47	0.72	0.77
		SR2	(0-25)/(50-75)	4.36	0.69	0.74
		SR3	(0-25)/(75-100)	5.91	0.68	0.73
	Non irrigated	SR1	(0-25)/(25-50)	1.82	0.92	0.93
		SR2	(0-25)/(50-75)	2.20	0.92	0.93
		SR3	(0-25)/(75-100)	2.30	0.92	0.93
Gopalpur	Irrigated	SR1	(0-25)/(25-50)	2.26	0.57	0.64
		SR2	(0-25)/(50-75)	2.35	0.53	0.61
		SR3	(0-25)/(75-100)	3.26	0.44	0.51
	Non irrigated	SR1	(0-25)/(25-50)	1.61	0.91	0.92
		SR2	(0-25)/(50-75)	2.54	0.90	0.92
		SR3	(0-25)/(75-100)	2.71	0.87	0.89
Ishurdi	Irrigated	SR1	(0-25)/(25-50)	2.45	0.57	0.70
		SR2	(0-25)/(50-75)	2.86	0.31	0.40
		SR3	(0-25)/(75-100)	2.96	0.27	0.35
	Non Irrigated	SR1	(0-25)/(25-50)	1.70	0.89	0.94
		SR2	(0-25)/(50-75)	2.01	0.56	0.60
		SR3	(0-25)/(75-100)	2.36	0.47	0.52

SOC: Soil organic carbon, SIC: Soil inorganic carbon, TSC: Total soil carbon

Table 4: Carbon stock potentiality (%) in calcareous soil profile under rice based cropping pattern

Soil series	Management	Depth (cm)	SOC	SIC	TSC
Sara	Irrigated	0-25	58.29	18.30	19.40
		25-50	17.49	26.34	26.10
		50-75	13.79	27.28	26.91
		75-100	10.44	28.08	27.59
	Non Irrigated	0-25	39.58	22.74	22.96
		25-50	23.50	26.66	26.62
		50-75	18.97	25.42	25.33
		75-100	17.95	25.18	25.09
Gopalpur	Irrigated	0-25	44.52	14.03	15.67
		25-50	21.35	25.53	25.31
		50-75	19.12	26.39	26.00
		75-100	15.01	34.05	33.03
	Non irrigated	0-25	39.69	21.26	21.61
		25-50	26.76	25.54	25.57
		50-75	17.02	25.51	25.35
		75-100	16.53	27.68	27.47
Ishurdi	Irrigated	0-25	45.80	09.59	11.89
		25-50	20.24	18.26	18.39
		50-75	17.35	33.30	32.29
		75-100	16.61	38.85	37.44
	Non irrigated	0-25	36.75	14.65	15.71
		25-50	24.53	18.97	19.24
		50-75	19.86	28.86	28.43
		75-100	18.86	37.52	36.63

SOC: Soil organic carbon, SIC: Soil inorganic carbon, TSC: Total soil carbon

CONCLUSION

Results show that the adoption of irrigation slightly increased SOC but remarkably decreased SIC in calcareous soils irrespective of soil depth and texture. As a result irrigation may have a negative impact on total soil carbon stock in calcareous soils. The substantially higher use of N based fertilizers resulted more production under irrigated agriculture caused a little increase in SOC. On the other hand, the reason for decreasing SIC is irrigation either washed out and/or converted huge amount of $CaCO_3$ from soil profiles. The potential SOC stock was higher in non irrigated soils (more SOC stock in deeper soil layer) than irrigated soils (less SOC stock in deeper soil layer) and the reverse was true for the SIC.

SIGNIFICANCE STATEMENT

In calcareous soils it seems likely that total soil carbon will continue to decrease with intensive cultivation and continuous irrigation under rice-based cropping systems. Results reveal that irrigation and increased input of NPK based fertilizers led to around 10% loss of soil carbon over 25 years. Therefore, it is indispensable to monitor $CaCO_3$ leaching as well CO_2 gas emission in calcareous irrigated soils under rice production system. Hence, without reducing the loss of SOC and substantially increasing SOC levels to act as a buffer to mitigate the effects of ammonium-based fertilizers there is the potential to lose of carbonates in calcareous soils and may be in other soils as well under intensive irrigated agriculture.

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