Running Title: EFFECTS OF LAND USE ON SOIL CARBON

# Impacts of Land Use and Salinization on Soil Inorganic and Organic Carbon in the Middle-lower Yellow River Delta

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## HIGHLIGHTS

- Land use types had large influences on both SIC and SOC densities in the Yellow River Delta.

- Both SIC and SOC densities were significantly higher in dry cropland than in paddy fields.
- There was a significant positive SIC-SOC relationship in dry cropland, but a negative relationship in paddy.
- Salinization had impacts on soil carbon storage in the Yellow River Delta.

## ABSTRACT

Soil inorganic carbon (SIC) is an important reservoir of carbon in arid, semi-arid and semi-humid regions. However, knowledge is incomplete on the dynamics of SIC and its relationship with soil organic carbon (SOC) under different land uses in the semi-humid region, particularly in coastal zones impacted by soil salinization. We collected 170 soil samples from 34 profiles across various land use types (maize-wheat, cotton, paddy and reed) in the middle-lower Yellow River Delta (YRD), China. We measured soil pH, electrical conductivity (EC), water-soluble salts, and SOC and SIC contents. Our results showed significant differences in both SOC and SIC among land uses. The dry cropland (maize-wheat and cotton soils) had significantly higher SOC and SIC densities (4.71 and 15.46 kg C $m^{-2}$, respectively) than the paddy fields (3.28 and 14.09 kg C $m^{-2}$, respectively) in the 0-100 cm layer. Comparing with paddy soils, reed soils contained significantly higher SOC (4.68 kg C $m^{-2}$) and similar SIC (15.02 kg C $m^{-2}$). There was a significantly positive correlation between SOC and SIC densities over 0-100 cm soil depth in dry cropland, but a negative relationship in the paddy field. On average, SOC and SIC densities under maize-wheat cropping were 15% and 4% lower, respectively, in the salt-affected soils of the middle-lower YRD than that in the upper YRD. This study indicated that land use types had great influences on both SOC and SIC and the SIC-SOC relationship, and salinization had adverse effects on soil carbon storage in the YRD.

***Key words*** Soil inorganic carbon; Soil organic carbon; Land use types; Salinization; Yellow River Delta

## INTRODUCTION

Soil carbon, representing both soil organic carbon (SOC) and soil inorganic carbon (SIC), plays a significant role in the global carbon cycle and climate change (Eswaran *et al.*, 1993; Lal, 2004). The global SOC pool was estimated to be 1220–1576 Pg in the 0-100 cm layer (Batjes, 1996), which is about 2-3 times the carbon pool in the biosphere (Rosenzweig and Hillel, 2000) and 2 times the carbon pool in the atmosphere (Schlesinger, 1999). At present, SOC has received a lot of attention, while fewer studies have focused on SIC. Although limited studies indicate that the global SIC pool is also large (i.e., 695–1738 Pg over 0-100 cm), there remains a large uncertainty for estimating the SIC pool (Eswaran *et al.*, 2000).

A number of studies have shown that land use and management can have large impacts on SOC and SIC dynamics (Wu *et al.*, 2003; Mikhailova and Post, 2006; Wu *et al.*, 2009; Meng *et al.*, 2014). For instance, land cover with different vegetation types can significantly affect SOC content because of the large differences in the root systems and associated changes in microbial processes and soil chemical and physical properties (Jobbágy and Jackson, 2000; Zhao *et al.*, 2016; Han *et al.*, 2018). Land management or agricultural practices (i.e., cultivation, fertilization and irrigation) have great influence on SIC storage (Wang *et al.*, 2014; Bughio *et al.*, 2016). A few studies have shown that both SOC and SIC stocks are much larger in croplands than in the non-cropland of Northwest China (Su *et al.*, 2010; Wang *et al.*, 2015), and in the Kursk region of Russian (Mikhailova and Post, 2006).

Limited studies have focused on the SIC-SOC relationship and show inconsistent findings among different land uses. Some studies have shown that there is a negative SIC-SOC relationship in various ecosystems, including cropland (Zeng *et al.*, 2008), and grassland, shrub and forest lands (Zhao *et al.*, 2016) in the Northwest China. However, other studies suggest that SIC density is positively correlated with SOC density in the cropland (Su *et al.*, 2010; Bughio *et al.*, 2016; Shi *et al.*, 2017), forest (Gao *et al.*, 2017) and desert (Zhang *et al.*, 2010) in the North China. Further investigation is necessary to elucidate the relationship of SIC with SOC across different land uses.

Over the past decade, most studies focusing on the influence of land uses on SIC dynamics and its relationship with SOC have been conducted in the arid and semi-arid areas of China (Chang *et al.*, 2012; Tan *et al.*, 2014; Wang *et al.*, 2014; Zhang *et al.*, 2015; Gao *et al.*, 2017). There are a few recent studies on the variations of both SIC and SOC in the semi-humid croplands of north China (Bughio *et al.*, 2016; Guo *et al.*, 2016; Shi *et al.*, 2017). These limited studies demonstrate that SOC and SIC in the semi-humid cropland are influenced by fertilization management (Bughio *et al.*, 2016), and SIC has a positive relationship with $Ca^{2+}$ and $Mg^{2+}$ levels (Guo *et al.*, 2016). In addition, our previous analyses indicates that there are significant differences in SOC and SIC densities between salt-affected soils and those containing less salts (Guo *et al.*, 2016; Shi *et al.*, 2017), implying that salinization might also impact on soil carbon dynamics under other land use types in the semi-humid region.

The Yellow River Delta (YRD) is characterized by various degrees of salinization with about 60% of land covered by salt-affected soils (Fang *et al.*, 2005; Cui *et al.*, 2011; Li *et al.*, 2014). Much of the land in the YRD has been exploited to cropland (i.e., cotton and paddy) from natural wetland (Zhao *et al.*, 2018). Here, we hypothesize that land use types not only affect SOC and SIC densities but also their relationship in the YRD. The objectives of this study were to assess the impact of land use types on both SIC and SOC densities in salt-affected soils of semi-humid region, and to analyze the influences of salinization on SIC and SOC densities/stocks in the YRD.

## MATERIALS AND METHODS

### *Study region*

Our study area, covering the entire middle-lower YRD, is situated in the northeast of Shandong province, China (Fig.1). The area has a typical temperate continental monsoon climate with four distinct seasons. Annual mean temperature is 11.7-12.6°C, and annual precipitation and evaporation are 530-630 mm and 1900-2400 mm, respectively. The land is flat, with low altitude (< 25 m a. s. l.) in most parts (Yu *et al.*, 2014). The soils are classified as Alluvic Primosols, Marinic Aqui-Orthic Halosols and Ochri-Aquic Cambosols (Chinese Soil Taxonomy, 2001). The alluvial soils were mainly developed on redeposited loess carried by the

Yellow River from the Loess Plateau. Soil texture is similar across the study area, which on average contains 6.69 ± 1.85% clay (< 0.002 mm), 33.3 ± 13.7% silt (0.002–0.02 mm) and 59.7 ± 13.3% sand (0.02–2 mm) (Li *et al.*, 2016). The majority of land has been used for farming, and the rest is mainly wetland that is dominated by suaeda (*Suaeda salsa*) and reed (*Phragmites australis*). The development of the cropping system is based on soil salinity, i.e., low salinity for wheat-maize and cotton and high salinity for paddy (Li *et al.*, 2016). Thus, the main crop in the middle-lower YRD is cotton and wheat-maize rotation, which has a rather longer cultivation history than paddy fields. For most of the paddies, farmers often use the freshwater from the Yellow River for salt-leaching in order to reduce soil salinity. Mineral fertilizers are applied regularly in cropland (i.e., wheat-maize, cotton and paddy soils), and straw is incorporated in most of the wheat-maize fields.

### *Soil sampling and analyses*

In order to study the influences of land use on the SOC and SIC's distribution in the middle-lower YRD, we selected 34 soil sites across four types of vegetation in the fall of 2015 or 2016. The main cropping system in this study area is maize-wheat rotation, followed by cotton, then rice. Accordingly, we selected 10 maize-wheat rotation sites, 12 cotton sites, 8 paddy sites, and 4 reed sites (Fig. 1). Three-four plots were randomly selected for each site, and soils samples were collected from 0–20, 20–40, 40–60, 60–80, and 80–100 cm (in 5 cm diameter), mixed for the respective layers in the field, air-dried and passed through a 2-mm sieve. Soil bulk density (BD) was determined for a few representative profiles for each land use types (i.e., wheat-maize, cotton, paddy and reed soils). Well mixed 2-mm soils with water were prepared at 1:5 ratio to measure soil pH by pH Meter, electric conductivity (EC) and total dissolved solids (TDS) by Conductivity Meter, and water-soluble $Ca^{2+}$, $Mg^{2+}$, $K^{+}$ and $Na^{+}$ by Atomic Absorption Spectrometry by ICP-MS. Here, the changes of EC value were used to infer variations of salinity (Zhang *et al.*, 2011; Wang *et al.*, 2017). Total soil carbon and SOC contents were analyzed using representative sub-samples (0.25 mm) by CNHS-O analyser (Model EuroEA3000). For SOC measurement, soil samples were preprocessed with phosphoric acid

($H_3PO_4$) to remove carbonate. SIC content was obtained as the difference between total carbon and SOC contents. Detailed descriptions of methodology were given by Guo *et al.* (2016).

### *Data analyses*

For each soil profile, densities of SOC, SIC, TDS and water-soluble $Ca^{2+}$/$Mg^{2+}$ ($X_{\mathrm{DENSITY}}$, kg C $m^{-2}$) were counted from carbon content ($X_{\mathrm{i}}$, g $kg^{-1}$), BD ($E_i$, g $cm^{-3}$) and thickness ($D_i$, cm):

$$X_{\mathrm{DENSITY}} = \sum_{i=1}^{\mathrm{n}} \mathrm{X_i} \times \mathrm{D}_i \times \frac{\mathrm{E}_i}{100} \qquad (1)$$

For each vegetation type in this study, the stocks of SOC and SIC ($Y_{\mathrm{STOCK}}$, kg) were then computed using the mean value of carbon density ($X_{\mathrm{DENSITY}}$, kg C $m^{-2}$) in the 0-100 cm soil layer and corresponding area ($m^2$). The areas of vegetation type were from the Shandong Statistical Yearbook-2016, where the reed area was assumed to be the size of natural wetland, and the areas of other land use types were the size of corresponding land use types, taking the city areas (including Binzhou city and Dongying city) as the unit of land use type areas (Sheng *et al.*, 2016):

$$Y_{\mathrm{STOCK}} = X_{\mathrm{DENSITY}} \times \mathrm{area} \qquad (2)$$

We used analysis of variance (ANOVA) or Kruskal-Wallis tests for the data with normal and non-normal distribution, respectively, to assess the differences in soil properties among different vegetation types (i.e., maize-wheat, cotton and paddy soils) and soil layers. The Duncan's post-hoc multiple comparisons (parametric test) or pairwise Wilcox test (non-parametric test) were used to compare the means at $P < 0.05$ for dry land sites. Independent-Sample T-tests (parametric test) or Mann-Whitney tests (non-parametric test) were used to compare soil properties between paddy and reed soils in the middle-lower YRD, and also used to compare them between in middle-lower YRD and in upper YRD. A $P$ value of $<0.05$ (two tail) was considered to be statistically significant. Pearson correlation and linear regression were performed using SPSS (version 24), and maps were created using SigmaPlot (version 12.5) and ArcMap (version 10.5).

## RESULTS

### *Soil chemical properties*

Mean soil pH in the 0-20 cm layer was significantly lower in dry cropland (i.e., 8.28 and 8.46 in maize-wheat and cotton soils, respectively) ($P < 0.05$) than in paddy soils (8.63) (Table I). Soil pH was not significantly different between paddy soils and natural wetland (i.e., 8.41 in reed soils). Similarly, soil pH was significantly higher in paddy soils (8.79-9.01) than in dry cropland (i.e., 8.47-8.61 and 8.68-8.70 in maize-wheat and cotton soils, respectively) below 20 cm, and in natural wetland (i.e., 8.71 in reed soils) in the 80-100 cm soil layer ($P < 0.05$). In general, soil pH was significantly lower above 40 cm soil layers than below 40 cm soil layers of dry cropland (including maize-wheat and cotton soils) and paddy soil ($P < 0.05$).

There were no obvious differences in mean values of soil EC, TDS, water soluble $Ca^{2+}$, $Na^+$ and $K^+$ contents in the 0-20 cm layer among land use types. Soil EC below 60 cm was significantly different ($P < 0.05$) among land use types, with the largest value in reed sites (479-705 µS cm$^{-1}$), followed by dry cropland (507-513 and 412-418 µS cm$^{-1}$ in maize-wheat and cotton soils, respectively), and the smallest in paddy soil (265-290 µS cm$^{-1}$). TDS and/or water-soluble $Ca^{2+}$ contents were significantly higher in dry cropland (i.e., 1293-1308/1046-1062 and 108-118 mg kg$^{-1}$, respectively) and reed sites (i.e., 1221-1798, and 84-82 mg kg$^{-1}$, respectively) than in paddy soils (i.e., 668-733, and 81-88 g kg$^{-1}$, respectively) ($P < 0.05$). Overall, the mean values of soil EC, TDS, water soluble $Ca^{2+}$, $Na^+$ and $K^+$ contents for each land use type were not significantly different among different soil layers.

### *Spatial distributions of SOC and SIC densities*

Our data revealed small spatial variability in both SOC and SIC densities in the 0-20 cm layer (Fig. 2A and B), showing a range of 0.99–2.65 and 2.04–4.30 kg C m$^{-2}$, respectively. Overall, SOC densities were higher in the west of the middle-lower YRD which was far away from the coastal zone, while relatively higher SIC densities were found in the east section close to the coastal zone.

There were small spatial variations in both SOC and SIC densities in the 20-40 cm layer as well (Fig. 2C and D), with a range of 0.40-1.26 and 2.35-4.93 kg C $m^{-2}$, respectively. However, there were large spatial variations in both SOC and SIC densities in the 40-100 cm layer (Fig. 2E and F), showing a range of 1.02–2.89 and 6.17–12.7 kg C $m^{-2}$, respectively. The spatial distribution was similar between SOC and SIC densities in the 20-40 and 40-100 cm layers (i.e., high values of SOC and SIC in the west). Besides, both SOC and SIC densities in the 20-40 and 40-100 cm layers revealed a decreasing trend from inland to estuary areas.

### SOC and SIC under different land use types

SOC content decreased significantly with soil depth under all land use types (Fig. 3). Overall, the decrease of SOC was mainly from the 0-20 cm layer to the 20-40 cm layer. Mean values of SOC content varied greatly in the profiles of dry cropland (i.e., from 8.16-6.23 to 2.10-2.11 g $kg^{-1}$) and reed (i.e., from 7.56 to 2.56 g $kg^{-1}$), but less in the profiles of paddy (from 4.87 to 1.68 g $kg^{-1}$). We averaged SOC densities in the 0-20 and 20-100 cm layers for each land use type (Table II). Mean SOC density in the 0-20 cm layer was significantly lower ($P < 0.05$) in paddy soils (1.26 kg C $m^{-2}$) than in dry cropland (1.69 and 2.02 kg C $m^{-2}$ in maize-wheat and cotton soils, respectively) and natural wetland (1.81 kg C $m^{-2}$ in reed soils). SOC density in the 20-100 cm layer was significantly lower ($P < 0.05$) in paddy soils (2.03 kg C $m^{-2}$) than in dry cropland (2.75 and 2.95 kg C $m^{-2}$ in maize-wheat and cotton soils, respectively) (Table II).

SIC content showed different vertical trends across land use types (Fig. 3). There was little vertical variation in SIC content in all land use types, i.e., 12.56–11.39, 10.46–10.55, 10.34–10.33 and 12.82-10.55 g $kg^{-1}$ in maize-wheat, cotton, paddy and reed soils, respectively. On average, SIC density in the 0-20 cm layer was not significantly different among paddy soils (2.70 kg C $m^{-2}$), maize-wheat and cotton soils (2.84-3.11 kg C $m^{-2}$) and reed soils (3.08 kg C $m^{-2}$) (Table II). There was a significant difference for SIC density in the 20-100 cm layer in cropland ($P < 0.05$), with a largest value in maize-wheat soils (13.39 kg C $m^{-2}$), followed by cotton soils (11.84 kg C $m^{-2}$), then smallest value in paddy soils (11.39 kg C $m^{-2}$). Compared with paddy soils, reed soils contained similar SIC density (11.94 kg C $m^{-2}$).

### *The SIC-SOC relationship under different land uses*

There were similar spatial distributions between SIC and SOC stocks, especially in the 20-40 cm and 40-100 cm soil layers (see Fig. 2). Our analyses showed that in dry cropland (including maize-wheat and cotton soils), SIC density had a significant positive correlation with SOC density in both the 0-20 and 0-100 cm soil layers ($P < 0.001$) (Fig. 4), with a greater slope of 2.3 in the 0-100 cm layer than in the 0-20 cm layer. Despite of the overall positive SIC-SOC relationship in the middle-lower YRD, higher SIC levels corresponded to lower SOC densities in paddy and reed soils, particularly in the 0-100 cm soil layer.

## DISCUSSION

### *Influences of land uses and salinization on SOC*

Mean SOC density of dry cropland in our study (4.71 kg C $m^{-2}$) is similar to the previously reported value (5.01 kg C $m^{-2}$) in dry cropland of the lower YRD (Li *et al.*, 2014), but lower than that (5.73 kg C $m^{-2}$) in the upper YRD (Guo *et al.*, 2016). The lower SOC may be attributable to the shorter cultivation history in the mid-lower YRD. In addition, our analyses also demonstrate that SOC stock has a significantly negative relationship with mean values of soil pH and EC over 0-20 or 0-100 cm soil layers in the dry cropland of middle-lower YRD (Table III), indicating that the relatively low SOC density in the middle-lower YRD may be partly caused by soil salinization that can lead to poor growth thus less inputs of organic carbon into soil profile (Li *et al.*, 2014; Yu *et al.*, 2016). Zhao *et al.* (2017) also showed that lower levels of SOC are associated with higher soil salinity in the YRD. Furthermore, we compared soil pH and EC (representing salinization level) in dry cropland (maize-wheat and cotton soils) from this study with those of maize-wheat cropland from Guo *et al.* (2016)'s (Table IV). Mean values of soil pH and EC for each soil layer were significantly higher in the middle-lower YRD than in the upper YRD above 100 cm. Clearly, the mean value of SOC content was lower in the middle-lower YRD (with higher salinization) than in the upper YRD (with lower salinization), indicating that soil salinization has adverse effects on SOC density in the YRD.

Land use types can have a great influence on SOC dynamics (Meng *et al.*, 2014; Yu *et al.*, 2016). Previous studies have shown that SOC density is greater in cropland than in non-cropland of northwestern China, which primarily results from fertilization and irrigation (Su *et al.*, 2010; Wang *et al.*, 2015). Our study shows a significantly higher SOC density in dry cropland (>4.44 kg C $m^{-2}$) than in paddy soil (3.28 kg C $m^{-2}$) in the middle-lower YRD. The relatively higher level of SOC in the dry cropland may be due to longer history of cultivation with straw return, which leads to more organic carbon input into soil thus SOC enhancement (Zhang *et al.*, 2010; Li *et al.*, 2016). Han *et al.* (2018) also reported that large SOC increases in the agriculture lands of the North China Plain from 1980 to 2010 is due to successful desalinization and subsequent increases of carbon inputs, such as improved cultivation managements (i.e., fertilizer application and straw return). On the other hand, the relatively lower SOC in paddy fields may be due to salt washing, which could cause losses of soil carbon during salt-leaching process (Jobbágy and Jackson, 2001). Interestingly, SOC density in reed soils (4.68 kg C $m^{-2}$) is comparable with those in dry cropland in the middle-lower YRD, which may be due to lower decomposition rates of soil organic matter under the anaerobic conditions in natural wetland (Li *et al.*, 2014; Zhao *et al.*, 2017; Zhao *et al.*, 2018).

The differences in SOC density among different land use types could be partly related to spatial heterogeneity in sedimentological and hydrological characters in this area (Fang *et al.*, 2005). Furthermore, the development of cropping system in the middle-lower YRD was largely based on the soil salinity, i.e., wheat-maize and cotton in low salinity soils, and paddy in high salinity soil (Li *et al.*, 2016), implying that there might be some differences in soil carbon density prior to land uses in the YRD.

### *Effects of land uses and salinization on SIC*

Mean SIC density of dry cropland (15.5 kg C $m^{-2}$) over 0-100 cm soil layer in middle-lower YRD is close to those (16.9 kg C $m^{-2}$) in the upper YRD (Guo *et al.*, 2016), but much lower than the values in dry cropland of Northwest China, i.e., 21.6-22.1 kg C $m^{-2}$ in the Loess

Plateau (Chang *et al.*, 2012; Zhang *et al.*, 2015) and 42.0 kg C $m^{-2}$ in the Yanqi Basin (Wang *et al.*, 2015). The large differences between the (semi-) arid regions and semi-humid areas may be attributable to the climatic conditions and associated hydrological cycles (Wang *et al.*, 2018). For instance, relatively higher precipitation in the YRD could result in dissolution of soil carbonate then leaching of bicarbonate and $Ca^{2+}$/ $Mg^{2+}$ down to deeper soil or groundwater (Shi *et al.*, 2017). In addition, the lower levels of SOC density in the middle-lower YRD can cause less $CO_2$ production thus smaller carbon sources for carbonate precipitation, leading to lower levels of SIC density (Wang *et al.*, 2015).

The effects of land use on SIC are complex because carbonate precipitation and dissolution may be affected by both biotic and abiotic processes (Monger and Gallegos, 2000). Our study shows a lower SIC density in paddy (14.09 kg C $m^{-2}$) and reed soil (15.02 kg C $m^{-2}$) than in maize-wheat soils (16.24 kg C $m^{-2}$) in the middle-lower YRD. Anaerobic conditions in flooded or saturated soil often inhibit microbial activities, causing a lower decomposition rate of soil organic matter (Zhao *et al.*, 2018), thus a smaller source of carbon, which is unfavorable for carbonate precipitation (Wang *et al.*, 2015); Such impact may be greater in paddy fields because of the lower levels of SOC. On the other hand, periodic salt washing and draining in paddy fields can cause dissolution of soil carbonate and removal of bicarbonate and $Ca^{2+}$/ $Mg^{2+}$, leading to lower SIC levels in the upper part of soil profile (Sartori *et al.*, 2007; Tang *et al.*, 2016). Our analyses shows that water-soluble $Ca^{2+}$ content is significantly higher in dry cropland than in paddy soils, especially below 20 cm soil depth (Table I); there is a significant positive correlation ($P < 0.05$) between SIC and water-soluble $Ca^{2+}$ in the 0-100 cm layer of the dry cropland. Similar finding on the SIC-$Ca^{2+}$ relationship was also reported for the maize-wheat cropland of upper YRD (Guo *et al.*, 2016). Apparently, land use and management have large influences on the formation and transformation of SIC in salt-affected lands.

### *Impacts of land uses and salinization on the SIC-SOC relationship*

Our analyses demonstrate that in dry cropland, SIC density has a significant positive correlation with SOC density in both the 0-20 and 0-100 cm soil layers ($P < 0.001$) (Fig. 4).

Similar findings of positive SIC-SOC relationship were reported for the Hebei Plain (Shi *et al.*, 2017) and the Yanqi Basin of northwest China (Wang *et al.*, 2015). On the other hand, some studies showed a negative SIC-SOC relationship in the topsoil, including cropland in the Hebei Plain (Li *et al.*, 2010) and non-cropland (grass, shrub and forest lands) in the Loess Plateau (Zhang *et al.*, 2015; Zhao *et al.*, 2016; Han *et al.*, 2018).

Limited studies have reported a significant negative relationship between SIC and SOC in paddy fields, i.e., in the Hangzhou Bay (Du *et al.*, 2012) and the Songnen Plain of east China (Tang *et al.*, 2016). Despite of the non-significant negative SIC-SOC relationship in the middle-lower YRD, higher SIC levels correspond to lower SOC densities in paddy and reed soils, particularly in the 0-100 cm layer (Fig. 4).

The negative relationship between SIC and SOC stocks in paddy fields may be explained by the equilibrium of carbonate precipitation and dissolution:

$$\mathrm{Ca}^{2+} + 2\mathrm{HCO}_3^- \leftrightharpoons \mathrm{CaCO}_3 + \mathrm{CO}_2 + \mathrm{H}_2\mathrm{O} \qquad (3)$$

In general, more SOC can produce more $CO_2$ in the soil profile. The higher levels of $CO_2$, together with water in paddy fields, would drive the above equation to the left, i.e., the dissolution of carbonate, leading to lower levels of SIC. In fact, Sartori *et al.* (2007) reported that decalcification might occur during the process of water percolation, and increasing SOM inputs could cause a reduction of SIC.

To better understand the effects of salinization on the SIC-SOC relationship, we compared the correlation in the dry cropland (maize-wheat and cotton) of middle-lower YRD in this study with that in the upper YRD using data of Guo *et al.* (2016). While there was a significant positive correlation between SOC and SIC densities in both studies, the relationship differed largely (Fig. 5). Intercept was greater in the middle-lower YRD than in the upper YRD, which reflects the differences in SOC and SIC densities, i.e., significantly lower SOC in the middle-lower YRD (Table II and IV). The large SIC density in the middle-lower YRD may be due to the high levels of water soluble $Ca^{2+}/Mg^{2+}$ (Table IV). Previous studies have indicated that high levels of $Ca^{2+}$ and $Mg^{2+}$ in high pH soils can lead to enhanced carbonate precipitation (Bughio *et al.*, 2016; Shi *et al.*, 2017).

### *Implications of land uses and management for soil carbon storages*

There are numerous studies addressing the influences of land use and management on SOC dynamics, mainly focusing on topsoil (Fang *et al.*, 2012; Chen *et al.*, 2019). However, there is evidence of a great capacity for soil carbon storages in subsoil (Jobbágy and Jackson, 2000; Mikhailova and Post, 2006), and an increasing number of studies have shown that SOC/SIC stocks in the subsoil are highly variable among different land uses and managements (Chang *et al.*, 2012; Zhang *et al.*, 2015; Han *et al.*, 2018). Our analyses demonstrate that there are significant differences in both SOC and SIC densities below 20 cm among land use types, with significantly higher SOC and SIC densities and larger variations in the dry cropland (Table II).

There are 5.9 x $10^3$ $km^2$ cropland (including maize-wheat, cotton and paddy) in the YRD, so we estimate that SOC and SIC stocks are 28.4 Tg C and 91.9 Tg C, respectively (Table V). Given that low-to-middle salinity lands can have a maize-wheat rotation system, and high salinity lands can only grow cotton and rice in the YRD, any changes in land gradation would have impacts on soil carbon storage. Amelioration of saline-alkaline soil not only results in improvements of soil physical and chemical properties (Nan *et al.*, 2016; Meng *et al.*, 2019), but also leads to increased SOC and SIC densities (Lal, 2002; Amini *et al.*, 2016). If soil salinization could be abated with soil quality improved as those in the upper YRD, soil carbon storage would be increased by 8.8% (10.6 Tg C) in the cropland of the YRD. However, if soil degradation occurs, with worsened salinization (as those for cotton and paddy fields), soil carbon storage might be reduced by 12% (14.6 Tg C) in the cropland of the YRD. Therefore, land management has impacts not only on agricultural production, but also on soil carbon storage.

## CONCLUSIONS

This study reports the spatial distributions of SIC and SOC under various land uses in the middle-lower YRD. For the upper 100 cm soil depth, both SOC and SIC densities were significantly higher ($P < 0.05$) in dry croplands (maize-wheat and cotton soils) than in paddy.

Compared with paddy soils, reed soils contained significantly higher ($P$ < 0.05) SOC and slightly higher SIC. Our analyses showed a significant positive SOC-SIC relationship in dry cropland, but a potentially negative relationship in paddy fields. On average, SOC and SIC densities were 15% and 4% lower in the middle-lower YRD than in the upper YRD for the maize-wheat cropping systems, due to the influences of cultivating history and soil salinization. This study demonstrates that soil salinization has adverse effects on soil carbon storage, and land use types can influence both SOC and SIC densities in the YRD.

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TABLE I

Mean values (standard errors) of soil pH, electric conductivity (EC), total dissolved solids (TDS), water-soluble $Ca^{2+}$ , $Mg^{2+}$, $K^+$ and $Na^+$ in the 0-20, 20-40, 40-60, 60-80 and 80-100 cm layers under different land use types in the middle-lower Yellow River Delta.

| **Depths** | **Types** | **pH** | **EC (μS cm$^{-1}$)** | **TDS(mg kg$^{-1}$)** | **$Ca^{2+}$ (mg kg$^{-1}$)** | **$Mg^{2+}$ (mg kg$^{-1}$)** | **$K^+$ (mg kg$^{-1}$)** | **$Na^+$ (mg kg$^{-1}$)** |
|---|---|---|---|---|---|---|---|---|
| 0-20 | Maize-Wheat | 8.28 (0.23) B a) | 520 (434) A | 1325 (1108) A | 131 (60) A | 41 (25) AB | 22 (12) A | 471 (431) A |
| | Cotton | 8.46 (0.23) AB | 621 (477) A | 1585 (1216) A | 178 (111) A | 62 (36) A | 28 (15) A | 438 (400) A |
| | Paddy | 8.63 (0.17) Aa | 298 (92) Aa | 753 (238) Aa | 99 (17) Aa | 26 (13) Ba | 15 (8) Aa | 171 (107) Ab |
| | Reed | 8.41 (0.29) a | 1048 (271) a | 2671 (689) a | 180 (68) a | 88 (38) a | 26 (7) a | 911 (215) a |
| 20-40 | Maize-Wheat | 8.47 (0.21) B | 369 (240) A | 938 (614) A | 99 (30) AB | 36 (19) A | 14 (10) A | 496 (385) A |
| | Cotton | 8.70 (0.30) A | 497 (268) A | 1266 (683) A | 121 (53) A | 46 (20) A | 19(22) A | 377 (227) A |
| | Paddy | 8.79 (0.15) Aa | 324 (180) Ab | 817 (455) Ab | 79 (12) Ba | 33 (9) Aa | 23 (21) Aa | 231 (162) Aa |
| | Reed | 8.59 (0.26) a | 883 (310) a | 2250 (790) a | 102 (29) a | 52 (22) a | 12 (1) a | 887 (343) a |
| 40-60 | Maize-Wheat | 8.57 (0.21) B | 459 (290) A | 1166 (742) A | 85 (28) AB | 37 (19) A | 15 (13) A | 541 (402) A |
| | Cotton | 8.73 (0.26) AB | 530 (250) A | 1352 (637) A | 107 (34) A | 52 (40) A | 33 (68) A | 455 (253) A |
| | Paddy | 8.83 (0.21) Aa | 282 (105) Aa | 712 (267) Aa | 76 (15) Ba | 37 (23) Aa | 18 (14) Aa | 281 (257) Aa |
| | Reed | 8.65 (0.18) a | 733 (86) a | 1868 (218) a | 83 (13) a | 37 (10) a | 11 (2) a | 727 (96) a |
| 60-80 | Maize-Wheat | 8.61 (0.27) A | 418 (178) AB | 1062 (454) AB | 80 (15) B | 33 (16) A | 16 (14) AB | 553 (386) A |
| | Cotton | 8.69 (0.33) A | 513 (148) A | 1308 (378) A | 108 (34) A | 52 (25) A | 7 (2) B | 492 (285) A |
| | Paddy | 8.88 (0.22) Aa | 290 (130) Bb | 733 (332) Bb | 88 (26) Ba | 35 (19) Aa | 18 (8) Aa | 300 (267) Ab |
| | Reed | 8.64 (0.10) a | 705 (54) a | 1798 (138) a | 82 (6) a | 36 (5) a | 9 (0.2) a | 683 (92) a |
| 80-100 | Maize-Wheat | 8.58 (0.29) B | 412 (136) A | 1046 (347) A | 82 (18) B | 34 (12) A | 18 (15) A | 619 (408) A |
| | Cotton | 8.68 (0.36) B | 507 (138) A | 1293 (351) A | 118 (37) A | 69 (45) A | 7 (2) B | 517 (316) A |
| | Paddy | 9.01 (0.20) Aa | 265 (90) Bb | 668 (229) Bb | 81 (25) Ba | 33 (18) Aa | 20 (8) Aa | 305 (269) Aa |
| | Reed | 8.71 (0.06) b | 479 (70) a | 1221 (179) a | 84 (6) a | 30 (2) a | 13 (5) a | 405 (69) a |

a) Values followed the same letter within a column for each layer (upper case letter for the comparisons maize-wheat, cotton and paddy soils, and low case letter for the comparisons between paddy and reed soils) are not significantly different at $P < 0.05$.

TABLE II

Soil organic carbon (SOC) and inorganic carbon (SIC) densities under different land use types and depths in the middle-lower Yellow River Delta.

| Types | SOC density (kg C m$^{-2}$) | | | | SIC density (kg C m$^{-2}$) | | | |
|---|---|---|---|---|---|---|---|---|
| | 0-20 cm | SE[a)] | 20-100 cm | SE | 0-20 cm | SE | 20-100 cm | SE |
| Maize-Wheat | 2.02A[b)] | 0.31 | 2.95A | 0.69 | 3.1A | 0.54 | 13.39 A | 1.68 |
| Cotton | 1.69B | 0.77 | 2.75A | 0.43 | 2.84A | 0.36 | 11.84AB | 2.16 |
| Paddy | 1.26Cb | 0.18 | 2.03Ba | 0.40 | 2.7Ab | 0.44 | 11.39Ba | 0.89 |
| Reed | 1.81a | 0.37 | 2.86a | 0.47 | 3.08a | 0.45 | 11.94a | 0.80 |

[a)] The standard error under different land use types.

[b)] Values followed the same letter within a column in 0-20 and 20-100 cm soil layers (upper case letter for the comparisons maize-wheat, cotton and paddy soils, and low case letter for the comparisons between paddy and reed soils) are not significantly different at $P < 0.05$.

TABLE III

Correlation between SOC/SIC densities and soil properties in the 0-20 and 0-100 cm layers of middle-lower Yellow River Delta.

| Land uses | Variable | Depth (cm) | pH | EC[a)] | Ca$^{2+}$ | Mg$^{2+}$ |
|---|---|---|---|---|---|---|
| Dry cropland | SOC density | 0-20 | -0.557*[b)] | -0.543* | 0.072 | -0.367 |
| (Maize-wheat and cotton) | | 0-100 | -0.499* | -0.54* | -0.229 | 0.108 |
| | SIC density | 0-20 | 0.38 | -0.306 | 0.55* | -0.252 |
| | | 0-100 | 0.07 | -0.56* | 0.076 | 0.08 |
| Paddy | SOC density | 0-20 | -0.330 | -0.309 | 0.57 | -0.111 |
| | | 0-100 | 0.018 | -0.291 | 0.014 | -0.291 |
| | SIC density | 0-20 | 0.580 | -0.376 | 0.643* | 0.00007 |
| | | 0-100 | 0.193 | -0.047 | -0.366 | -0.0666 |

[a)]EC, electric conductivity.

[b)]*Significant correlation at the 0.05 probability level (2 tailed).

TABLE IV

Mean values of soil basic properties in dry cropland of middle-lower (maize-wheat and cotton soils, n=22) and upper (maize-wheat soils, n=31) Yellow River Delta

| Layer (cm) | pH | | EC (µS/cm) | | $Ca^{2+}$ (mg/kg) | | $Mg^{2+}$ (mg/kg) | | SOC (g/kg) | | SIC (g/kg) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper |
| 0-20 | 8.4Aa a) | 8.1Bb | 576Aa | 239Bd | 157Aa | 90Ba | 52Aa | 26Ba | 7.1Ba | 9.3Aa | 11.4Aab | 10.5Ab |
| 20-40 | 8.6Ab | 8.3Ba | 495Aa | 264Bcd | 111Ab | 85Aa | 41Aa | 27Aa | 3.3Bb | 4.3Ab | 12.8Aa | 11.7Aab |
| 40-60 | 8.7Ab | 8.2Bab | 529Aa | 334Bbc | 97Ab | 85Aa | 45Aa | 28Ba | 2.6Bc | 3.5Ab | 11.1Ab | 11.6Aab |
| 60-80 | 8.7Ab | 8.2Bb | 565Aa | 409Bab | 95Ab | 89Aa | 43Aa | 29Ba | 2.5Ac | 2.9Abc | 10.9Bb | 12.6Aa |
| 80-100 | 8.6Ab | 8.2Bb | 606Aa | 444Ba | 102Ab | 91Aa | 53Aa | 31Ba | 2.1Ac | 2.4Ac | 10.9Bb | 12.7Aa |

a)The same letter (upper case between two regions or lower case among five soil layers) indicate no significant difference at $P < 0.05$

TABLE V

Means (± standard deviation) of SOC and SIC densities and estimated total soil carbon stocks over 0-100 cm soil layer in the cropland of YRD

| **Vegetation types** | **SOC density ($kg\ C\ m^{-2}$)** | **SIC density ($kg\ C\ m^{-2}$)** | **Area a) ($km^2$)** | **Total C (Tg C)** | **Total $C_{inc}$ b) (Tg C)** | **Total $C_{dec}$ c) (Tg C)** |
|---|---|---|---|---|---|---|
| Maize-Wheat (upper) | 5.73 ± 1.05 | 16.89 ± 3.18 | 1023 | 23.1 | 23.1 | 18.7 |
| Maize-Wheat (lower) | 4.97 ± 0.87 | 16.24 ± 2.07 | 2967 | 62.9 | 67.1 | 54.1 |
| Cotton | 4.44 ± 0.52 | 14.67 ± 2.48 | 1733 | 33.1 | 39.1 | 31.6 |
| Paddy | 3.28 ± 0.57 | 14.09 ± 1.34 | 73 | 1.2 | 1.6 | 1.3 |
| Total | - | - | 5796 | 120.3 | 130.9 | 105.7 |

a) The area sizes are from the Shandong Statistical Yearbook-2016.

b) Total $C_{inc}$ was calculated by assuming SOC density =5.73 kg C $m^{-2}$, and SIC density = 16.89 kg C $m^{-2}$

c) Total $C_{dec}$ was calculated by assuming SOC density =3.86 kg C $m^{-2}$, and SIC density = 14.38 kg C $m^{-2}$, which were averages for cotton and paddy.

## FIGURE CAPTIONS

**Figure 1** Map of sampling sites under various land use types in the middle-lower Yellow River Delta, China. The figure was generated using ArcMap 10.5 (http://www.esri.com/).

**Figure 2** Spatial distributions of soil organic carbon (SOC) and inorganic carbon (SIC) densities (kg C $m^{-2}$) in the 0–20 (A, B), 20–40 (C, D) and 40–100 cm (E, F) layers under four land use types: maize-wheat (yellow circles), cotton (black circles), paddy (red circles), and reed (blue circles). The figure was generated using ArcMap 10.5 (http://www.esri.com/).

**Figure 3** Vertical distributions of soil organic carbon content (SOC) and inorganic carbon (SIC) in different land use types.

**Figure 4** Relationship between soil inorganic carbon (SIC) and organic carbon (SOC) stocks in the 0−20 and 0−100 cm layers in dry cropland (including maize-wheat and cotton sites) (grey dotted line), paddy (red dotted line) and reed soils (blue dotted line) of the middle-lower Yellow River Delta.

**Figure 5** Relationship between soil inorganic carbon (SIC) and organic carbon (SOC) stocks in the 0−20 and 0−100 cm layers in dry cropland of the middle-lower Yellow River Delta (orange circles) (maize-wheat and cotton sites) and upper Yellow River Delta (green circles) (maize-wheat soils).

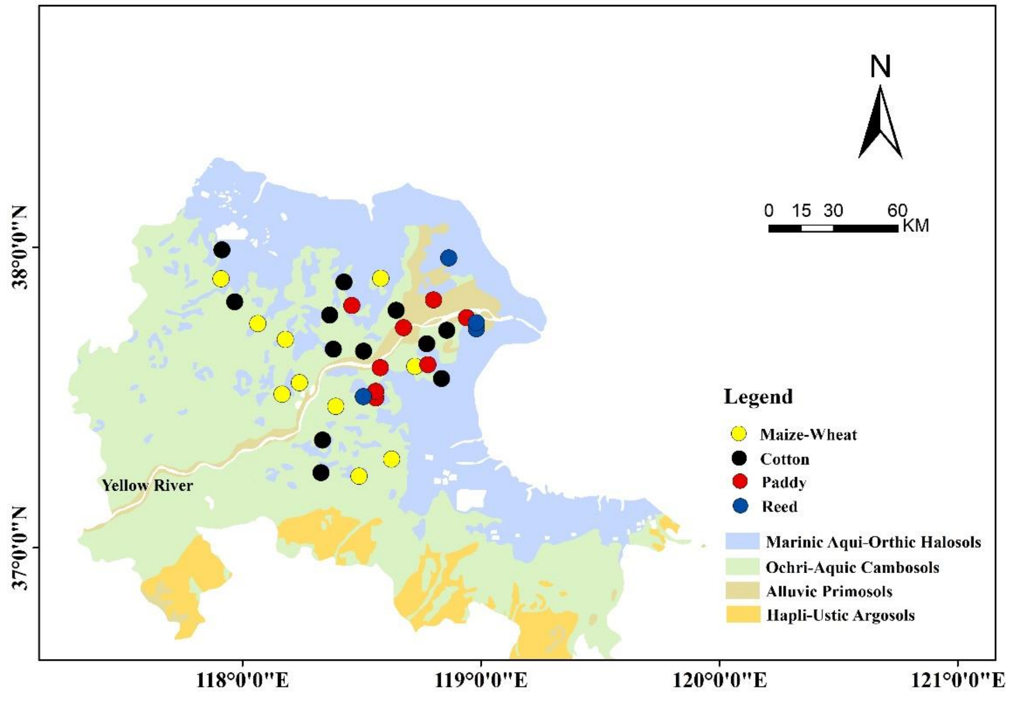

**Figure 1** Map of sampling sites under various land use types in the middle-lower Yellow River Delta, China. The figure was generated using ArcMap 10.5 (http://www.esri.com/).

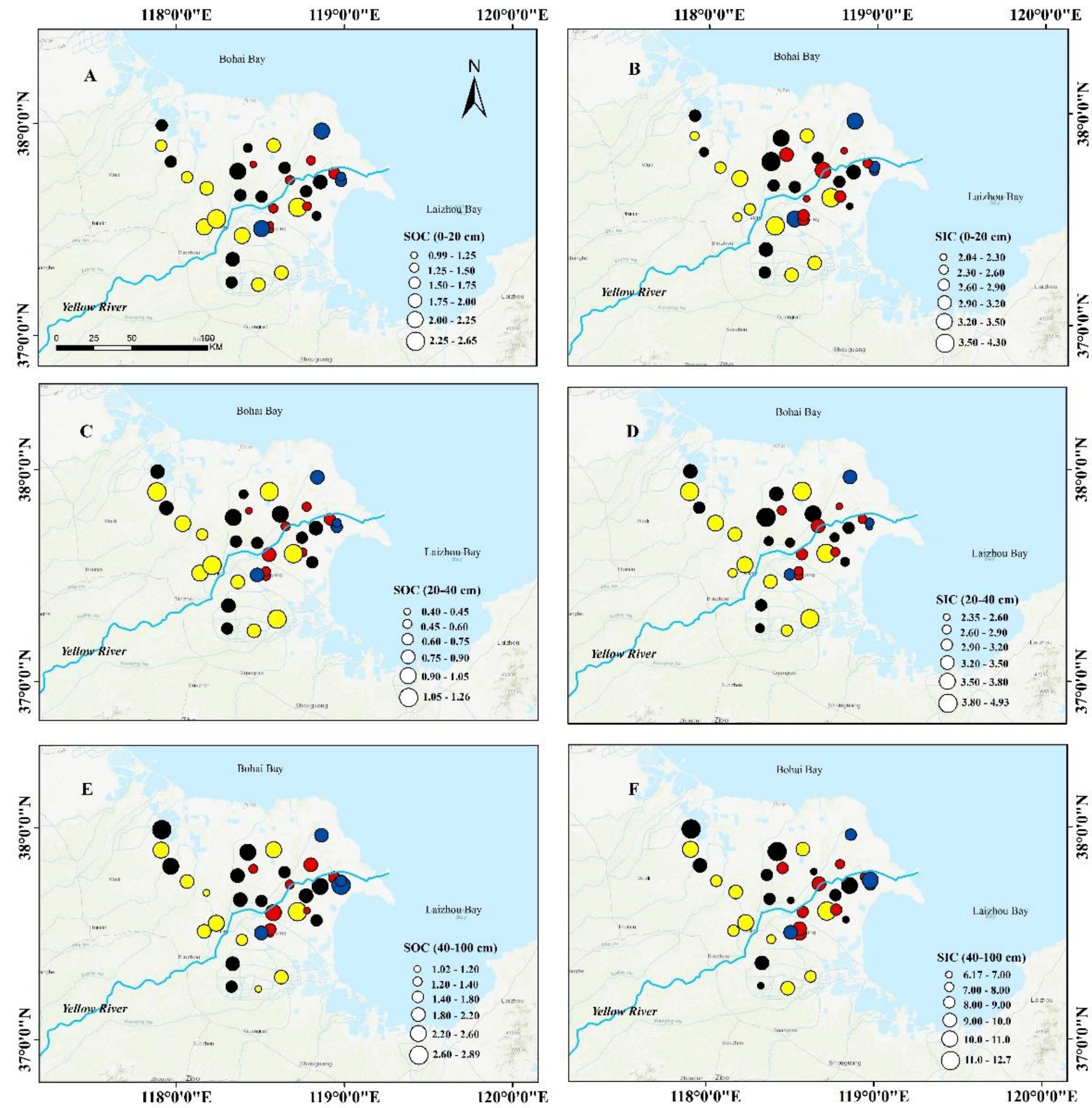

**Figure 2** Spatial distributions of soil organic carbon (SOC) and inorganic carbon (SIC) densities (kg C m$^{-2}$) in the 0–20 (A, B), 20–40 (C, D) and 40–100 cm (E, F) layers under four land use types: maize-wheat (yellow circles), cotton (black circles), paddy (red circles), and reed (blue circles). The figure was generated using ArcMap 10.5 (http://www.esri.com/).

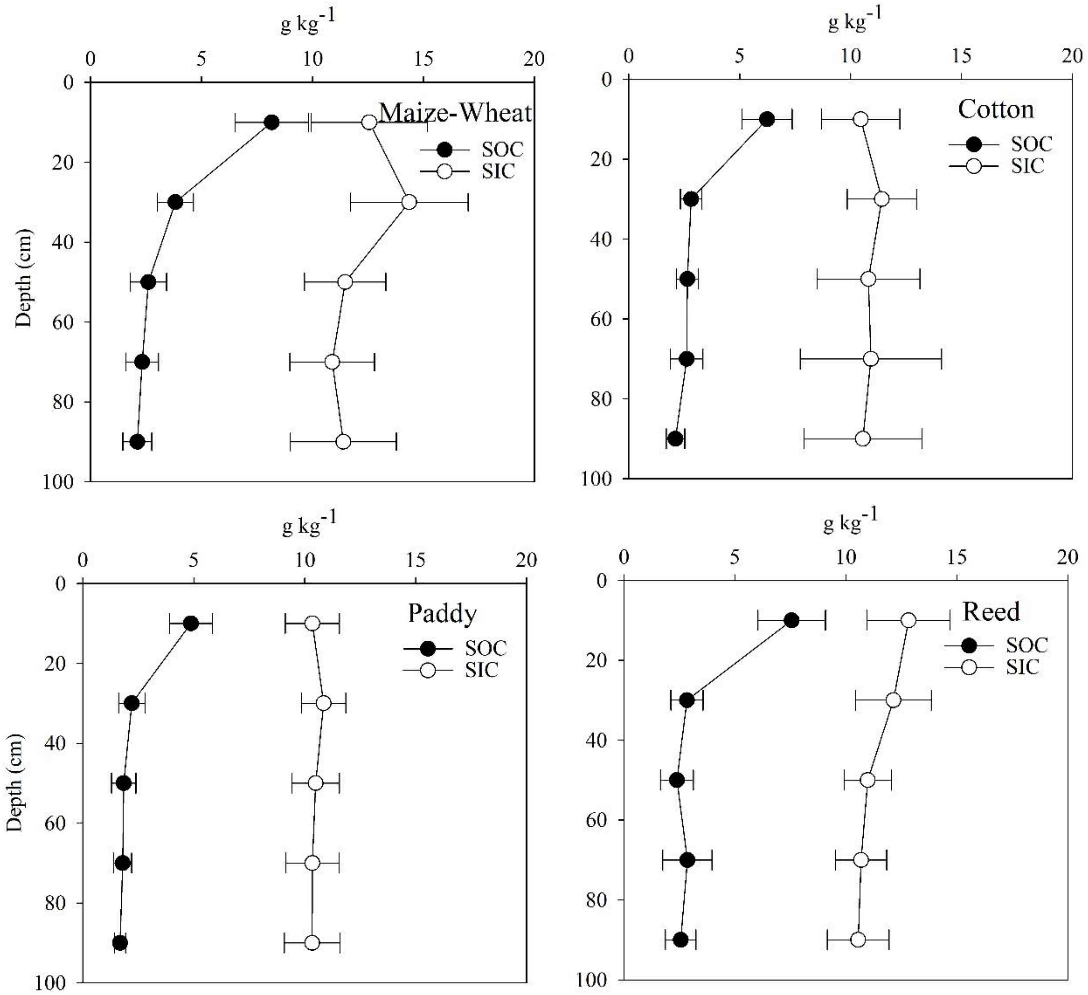

**Figure 3** Vertical distributions of soil organic carbon content (SOC) and inorganic carbon (SIC) in different land use types.

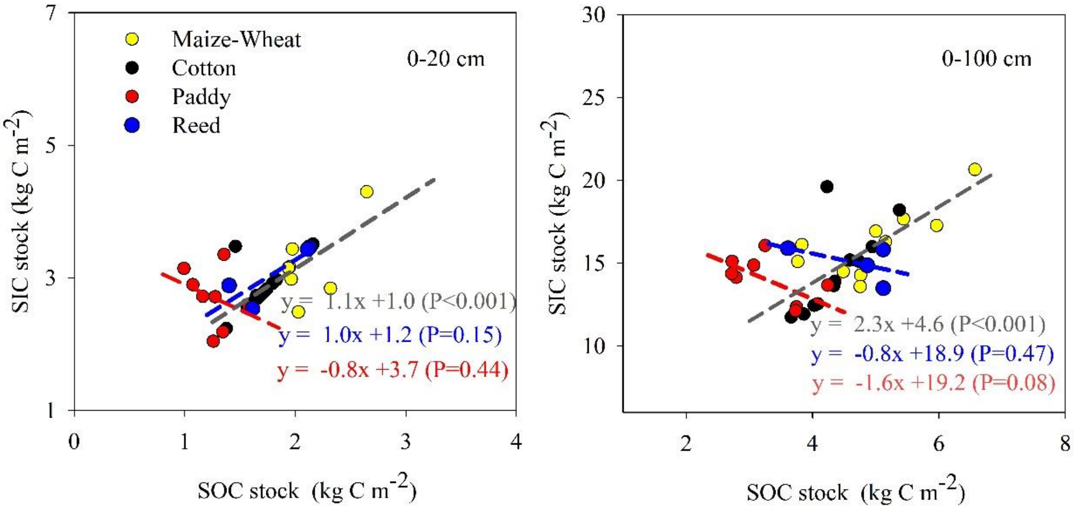

**Figure 4** Relationship between soil inorganic carbon (SIC) and organic carbon (SOC) stocks in the 0−20 and 0−100 cm layers in dry cropland (including maize-wheat and cotton sites) (grey dotted line), paddy (red dotted line) and reed soils (blue dotted line) of the middle-lower Yellow River Delta.

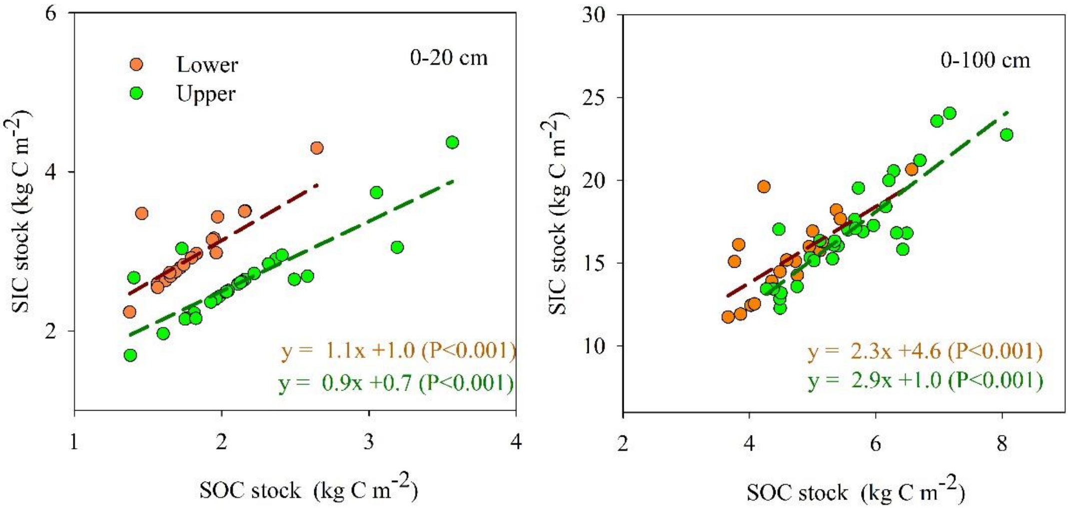

**Figure 5** Relationship between soil inorganic carbon (SIC) and organic carbon (SOC) stocks in the 0−20 and 0−100 cm layers in dry cropland of the middle-lower Yellow River Delta (orange circles) (maize-wheat and cotton sites) and upper Yellow River Delta (green circles) (maize-wheat sites).