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4 Running Title: EFFECTS OF LAND USE ON SOIL CARBON
5

6 **Impacts of Land Use and Salinization on Soil Inorganic and Organic**
7 **Carbon in the Middle-lower Yellow River Delta**
8

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24 **HIGHLIGHTS**

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

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

31

32 **ABSTRACT**

33 Soil inorganic carbon (SIC) is an important reservoir of carbon in arid, semi-arid and semi-
34 humid regions. However, knowledge is incomplete on the dynamics of SIC and its relationship
35 with soil organic carbon (SOC) under different land uses in the semi-humid region, particularly
36 in coastal zones impacted by soil salinization. We collected 170 soil samples from 34 profiles
37 across various land use types (maize-wheat, cotton, paddy and reed) in the middle-lower
38 Yellow River Delta (YRD), China. We measured soil pH, electrical conductivity (EC), water-
39 soluble salts, and SOC and SIC contents. Our results showed significant differences in both
40 SOC and SIC among land uses. The dry cropland (maize-wheat and cotton soils) had
41 significantly higher SOC and SIC densities (4.71 and 15.46 kg C m⁻², respectively) than the
42 paddy fields (3.28 and 14.09 kg C m⁻², respectively) in the 0-100 cm layer. Comparing with
43 paddy soils, reed soils contained significantly higher SOC (4.68 kg C m⁻²) and similar SIC
44 (15.02 kg C m⁻²). There was a significantly positive correlation between SOC and SIC densities
45 over 0-100 cm soil depth in dry cropland, but a negative relationship in the paddy field. On
46 average, SOC and SIC densities under maize-wheat cropping were 15% and 4% lower,
47 respectively, in the salt-affected soils of the middle-lower YRD than that in the upper YRD.
48 This study indicated that land use types had great influences on both SOC and SIC and the SIC-
49 SOC relationship, and salinization had adverse effects on soil carbon storage in the YRD.

50

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

53

54 **INTRODUCTION**

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

63 A number of studies have shown that land use and management can have large impacts on
64 SOC and SIC dynamics (Wu *et al.*, 2003; Mikhailova and Post, 2006; Wu *et al.*, 2009; Meng *et al.*,
65 2014). For instance, land cover with different vegetation types can significantly affect SOC
66 content because of the large differences in the root systems and associated changes in microbial
67 processes and soil chemical and physical properties (Jobbágy and Jackson, 2000; Zhao *et al.*,
68 2016; Han *et al.*, 2018). Land management or agricultural practices (i.e., cultivation,
69 fertilization and irrigation) have great influence on SIC storage (Wang *et al.*, 2014; Bughio *et al.*,
70 2016). A few studies have shown that both SOC and SIC stocks are much larger in croplands
71 than in the non-cropland of Northwest China (Su *et al.*, 2010; Wang *et al.*, 2015), and in the
72 Kursk region of Russian (Mikhailova and Post, 2006).

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

81 Over the past decade, most studies focusing on the influence of land uses on SIC dynamics

82 and its relationship with SOC have been conducted in the arid and semi-arid areas of China
83 (Chang *et al.*, 2012; Tan *et al.*, 2014; Wang *et al.*, 2014; Zhang *et al.*, 2015; Gao *et al.*, 2017).
84 There are a few recent studies on the variations of both SIC and SOC in the semi-humid
85 croplands of north China (Bugchio *et al.*, 2016; Guo *et al.*, 2016; Shi *et al.*, 2017). These limited
86 studies demonstrate that SOC and SIC in the semi-humid cropland are influenced by
87 fertilization management (Bugchio *et al.*, 2016), and SIC has a positive relationship with Ca²⁺
88 and Mg²⁺ levels (Guo *et al.*, 2016). In addition, our previous analyses indicates that there are
89 significant differences in SOC and SIC densities between salt-affected soils and those
90 containing less salts (Guo *et al.*, 2016; Shi *et al.*, 2017), implying that salinization might also
91 impact on soil carbon dynamics under other land use types in the semi-humid region.

92 The Yellow River Delta (YRD) is characterized by various degrees of salinization with
93 about 60% of land covered by salt-affected soils (Fang *et al.*, 2005; Cui *et al.*, 2011; Li *et al.*,
94 2014). Much of the land in the YRD has been exploited to cropland (i.e., cotton and paddy)
95 from natural wetland (Zhao *et al.*, 2018). Here, we hypothesize that land use types not only
96 affect SOC and SIC densities but also their relationship in the YRD. The objectives of this study
97 were to assess the impact of land use types on both SIC and SOC densities in salt-affected soils
98 of semi-humid region, and to analyze the influences of salinization on SIC and SOC
99 densities/stocks in the YRD.

100

101 **MATERIALS AND METHODS**

102 ***Study region***

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

110 Yellow River from the Loess Plateau. Soil texture is similar across the study area, which on
111 average contains $6.69 \pm 1.85\%$ clay (< 0.002 mm), $33.3 \pm 13.7\%$ silt ($0.002\text{--}0.02$ mm) and 59.7
112 $\pm 13.3\%$ sand ($0.02\text{--}2$ mm) (Li *et al.*, 2016). The majority of land has been used for farming,
113 and the rest is mainly wetland that is dominated by suaeda (*Suaeda salsa*) and reed (*Phragmites*
114 *australis*). The development of the cropping system is based on soil salinity, i.e., low salinity
115 for wheat-maize and cotton and high salinity for paddy (Li *et al.*, 2016). Thus, the main crop in
116 the middle-lower YRD is cotton and wheat-maize rotation, which has a rather longer cultivation
117 history than paddy fields. For most of the paddies, farmers often use the freshwater from the
118 Yellow River for salt-leaching in order to reduce soil salinity. Mineral fertilizers are applied
119 regularly in cropland (i.e., wheat-maize, cotton and paddy soils), and straw is incorporated in
120 most of the wheat-maize fields.

121

122 ***Soil sampling and analyses***

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

138 (H₃PO₄) to remove carbonate. SIC content was obtained as the difference between total carbon
139 and SOC contents. Detailed descriptions of methodology were given by Guo *et al.* (2016).

140

141 **Data analyses**

142 For each soil profile, densities of SOC, SIC, TDS and water-soluble Ca²⁺/Mg²⁺ (X_{DENSITY} ,
143 kg C m⁻²) were counted from carbon content (X_i , g kg⁻¹), BD (E_i , g cm⁻³) and thickness (D_i ,
144 cm):

$$145 \quad X_{\text{DENSITY}} = \sum_{i=1}^n X_i \times D_i \times \frac{E_i}{100} \quad (1)$$

146 For each vegetation type in this study, the stocks of SOC and SIC (Y_{STOCK} , kg) were then
147 computed using the mean value of carbon density (X_{DENSITY} , kg C m⁻²) in the 0-100 cm soil
148 layer and corresponding area (m²). The areas of vegetation type were from the Shandong
149 Statistical Yearbook-2016, where the reed area was assumed to be the size of natural wetland,
150 and the areas of other land use types were the size of corresponding land use types, taking the
151 city areas (including Binzhou city and Dongying city) as the unit of land use type areas (Sheng
152 *et al.*, 2016):

$$153 \quad Y_{\text{STOCK}} = X_{\text{DENSITY}} \times \text{area} \quad (2)$$

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

165

166 **RESULTS**

167 *Soil chemical properties*

168 Mean soil pH in the 0-20 cm layer was significantly lower in dry cropland (i.e., 8.28 and
169 8.46 in maize-wheat and cotton soils, respectively) ($P < 0.05$) than in paddy soils (8.63) (Table
170 I). Soil pH was not significantly different between paddy soils and natural wetland (i.e., 8.41 in
171 reed soils). Similarly, soil pH was significantly higher in paddy soils (8.79-9.01) than in dry
172 cropland (i.e., 8.47-8.61 and 8.68-8.70 in maize-wheat and cotton soils, respectively) below 20
173 cm, and in natural wetland (i.e., 8.71 in reed soils) in the 80-100 cm soil layer ($P < 0.05$). In
174 general, soil pH was significantly lower above 40 cm soil layers than below 40 cm soil layers
175 of dry cropland (including maize-wheat and cotton soils) and paddy soil ($P < 0.05$).

176 There were no obvious differences in mean values of soil EC, TDS, water soluble Ca^{2+} ,
177 Na^+ and K^+ contents in the 0-20 cm layer among land use types. Soil EC below 60 cm was
178 significantly different ($P < 0.05$) among land use types, with the largest value in reed sites (479-
179 705 $\mu\text{S cm}^{-1}$), followed by dry cropland (507-513 and 412-418 $\mu\text{S cm}^{-1}$ in maize-wheat and
180 cotton soils, respectively), and the smallest in paddy soil (265-290 $\mu\text{S cm}^{-1}$). TDS and/or water-
181 soluble Ca^{2+} contents were significantly higher in dry cropland (i.e., 1293-1308/1046-1062 and
182 108-118 mg kg^{-1} , respectively) and reed sites (i.e., 1221-1798, and 84-82 mg kg^{-1} , respectively)
183 than in paddy soils (i.e., 668-733, and 81-88 g kg^{-1} , respectively) ($P < 0.05$). Overall, the mean
184 values of soil EC, TDS, water soluble Ca^{2+} , Na^+ and K^+ contents for each land use type were
185 not significantly different among different soil layers.

186

187 *Spatial distributions of SOC and SIC densities*

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

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

200

201 *SOC and SIC under different land use types*

202 SOC content decreased significantly with soil depth under all land use types (Fig. 3).
203 Overall, the decrease of SOC was mainly from the 0-20 cm layer to the 20-40 cm layer. Mean
204 values of SOC content varied greatly in the profiles of dry cropland (i.e., from 8.16-6.23 to
205 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
206 4.87 to 1.68 g kg⁻¹). We averaged SOC densities in the 0-20 and 20-100 cm layers for each land
207 use type (Table II). Mean SOC density in the 0-20 cm layer was significantly lower ($P < 0.05$)
208 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
209 and cotton soils, respectively) and natural wetland (1.81 kg C m⁻² in reed soils). SOC density
210 in the 20-100 cm layer was significantly lower ($P < 0.05$) in paddy soils (2.03 kg C m⁻²) than
211 in dry cropland (2.75 and 2.95 kg C m⁻² in maize-wheat and cotton soils, respectively) (Table
212 II).

213 SIC content showed different vertical trends across land use types (Fig. 3). There was little
214 vertical variation in SIC content in all land use types, i.e., 12.56–11.39, 10.46–10.55, 10.34–
215 10.33 and 12.82-10.55 g kg⁻¹ in maize-wheat, cotton, paddy and reed soils, respectively. On
216 average, SIC density in the 0-20 cm layer was not significantly different among paddy soils
217 (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
218 m⁻²) (Table II). There was a significant difference for SIC density in the 20-100 cm layer in
219 cropland ($P < 0.05$), with a largest value in maize-wheat soils (13.39 kg C m⁻²), followed by
220 cotton soils (11.84 kg C m⁻²), then smallest value in paddy soils (11.39 kg C m⁻²). Compared

221 with paddy soils, reed soils contained similar SIC density ($11.94 \text{ kg C m}^{-2}$).

222

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

224 There were similar spatial distributions between SIC and SOC stocks, especially in the 20-
225 40 cm and 40-100 cm soil layers (see Fig. 2). Our analyses showed that in dry cropland
226 (including maize-wheat and cotton soils), SIC density had a significant positive correlation with
227 SOC density in both the 0-20 and 0-100 cm soil layers ($P < 0.001$) (Fig. 4), with a greater slope
228 of 2.3 in the 0-100 cm layer than in the 0-20 cm layer. Despite of the overall positive SIC-SOC
229 relationship in the middle-lower YRD, higher SIC levels corresponded to lower SOC densities
230 in paddy and reed soils, particularly in the 0-100 cm soil layer.

231

232 **DISCUSSION**

233 *Influences of land uses and salinization on SOC*

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

249 indicating that soil salinization has adverse effects on SOC density in the YRD.

250 Land use types can have a great influence on SOC dynamics (Meng *et al.*, 2014; Yu *et al.*,
251 2016). Previous studies have shown that SOC density is greater in cropland than in non-
252 cropland of northwestern China, which primarily results from fertilization and irrigation (Su *et*
253 *al.*, 2010; Wang *et al.*, 2015). Our study shows a significantly higher SOC density in dry
254 cropland ($>4.44 \text{ kg C m}^{-2}$) than in paddy soil (3.28 kg C m^{-2}) in the middle-lower YRD. The
255 relatively higher level of SOC in the dry cropland may be due to longer history of cultivation
256 with straw return, which leads to more organic carbon input into soil thus SOC enhancement
257 (Zhang *et al.*, 2010; Li *et al.*, 2016). Han *et al.* (2018) also reported that large SOC increases in
258 the agriculture lands of the North China Plain from 1980 to 2010 is due to successful
259 desalinization and subsequent increases of carbon inputs, such as improved cultivation
260 managements (i.e., fertilizer application and straw return). On the other hand, the relatively
261 lower SOC in paddy fields may be due to salt washing, which could cause losses of soil carbon
262 during salt-leaching process (Jobbágy and Jackson, 2001). Interestingly, SOC density in reed
263 soils (4.68 kg C m^{-2}) is comparable with those in dry cropland in the middle-lower YRD, which
264 may be due to lower decomposition rates of soil organic matter under the anaerobic conditions
265 in natural wetland (Li *et al.*, 2014; Zhao *et al.*, 2017; Zhao *et al.*, 2018).

266 The differences in SOC density among different land use types could be partly related to
267 spatial heterogeneity in sedimentological and hydrological characters in this area (Fang *et al.*,
268 2005). Furthermore, the development of cropping system in the middle-lower YRD was largely
269 based on the soil salinity, i.e., wheat-maize and cotton in low salinity soils, and paddy in high
270 salinity soil (Li *et al.*, 2016), implying that there might be some differences in soil carbon
271 density prior to land uses in the YRD.

272

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

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

277 Plateau (Chang *et al.*, 2012; Zhang *et al.*, 2015) and 42.0 kg C m⁻² in the Yanqi Basin (Wang
278 *et al.*, 2015). The large differences between the (semi-) arid regions and semi-humid areas may
279 be attributable to the climatic conditions and associated hydrological cycles (Wang *et al.*, 2018).
280 For instance, relatively higher precipitation in the YRD could result in dissolution of soil
281 carbonate then leaching of bicarbonate and Ca²⁺/Mg²⁺ down to deeper soil or groundwater (Shi
282 *et al.*, 2017). In addition, the lower levels of SOC density in the middle-lower YRD can cause
283 less CO₂ production thus smaller carbon sources for carbonate precipitation, leading to lower
284 levels of SIC density (Wang *et al.*, 2015).

285 The effects of land use on SIC are complex because carbonate precipitation and dissolution
286 may be affected by both biotic and abiotic processes (Monger and Gallegos, 2000). Our study
287 shows a lower SIC density in paddy (14.09 kg C m⁻²) and reed soil (15.02 kg C m⁻²) than in
288 maize-wheat soils (16.24 kg C m⁻²) in the middle-lower YRD. Anaerobic conditions in flooded
289 or saturated soil often inhibit microbial activities, causing a lower decomposition rate of soil
290 organic matter (Zhao *et al.*, 2018), thus a smaller source of carbon, which is unfavorable for
291 carbonate precipitation (Wang *et al.*, 2015); Such impact may be greater in paddy fields because
292 of the lower levels of SOC. On the other hand, periodic salt washing and draining in paddy
293 fields can cause dissolution of soil carbonate and removal of bicarbonate and Ca²⁺/Mg²⁺,
294 leading to lower SIC levels in the upper part of soil profile (Sartori *et al.*, 2007; Tang *et al.*,
295 2016). Our analyses shows that water-soluble Ca²⁺ content is significantly higher in dry
296 cropland than in paddy soils, especially below 20 cm soil depth (Table I); there is a significant
297 positive correlation ($P < 0.05$) between SIC and water-soluble Ca²⁺ in the 0-100 cm layer of the
298 dry cropland. Similar finding on the SIC-Ca²⁺ relationship was also reported for the maize-
299 wheat cropland of upper YRD (Guo *et al.*, 2016). Apparently, land use and management have
300 large influences on the formation and transformation of SIC in salt-affected lands.

301

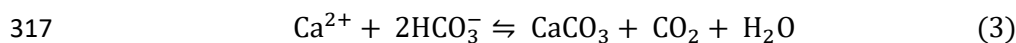
302 ***Impacts of land uses and salinization on the SIC-SOC relationship***

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

305 Similar findings of positive SIC-SOC relationship were reported for the Hebei Plain (Shi *et al.*,
306 2017) and the Yanqi Basin of northwest China (Wang *et al.*, 2015). On the other hand, some
307 studies showed a negative SIC-SOC relationship in the topsoil, including cropland in the Hebei
308 Plain (Li *et al.*, 2010) and non-cropland (grass, shrub and forest lands) in the Loess Plateau
309 (Zhang *et al.*, 2015; Zhao *et al.*, 2016; Han *et al.*, 2018).

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

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



318 In general, more SOC can produce more CO₂ in the soil profile. The higher levels of CO₂,
319 together with water in paddy fields, would drive the above equation to the left, i.e., the
320 dissolution of carbonate, leading to lower levels of SIC. In fact, Sartori *et al.* (2007) reported
321 that decalcification might occur during the process of water percolation, and increasing SOM
322 inputs could cause a reduction of SIC.

323 To better understand the effects of salinization on the SIC-SOC relationship, we compared
324 the correlation in the dry cropland (maize-wheat and cotton) of middle-lower YRD in this study
325 with that in the upper YRD using data of Guo *et al.* (2016). While there was a significant
326 positive correlation between SOC and SIC densities in both studies, the relationship differed
327 largely (Fig. 5). Intercept was greater in the middle-lower YRD than in the upper YRD, which
328 reflects the differences in SOC and SIC densities, i.e., significantly lower SOC in the middle-
329 lower YRD (Table II and IV). The large SIC density in the middle-lower YRD may be due to
330 the high levels of water soluble Ca²⁺/Mg²⁺ (Table IV). Previous studies have indicated that high
331 levels of Ca²⁺ and Mg²⁺ in high pH soils can lead to enhanced carbonate precipitation (Bughio
332 *et al.*, 2016; Shi *et al.*, 2017).

333

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

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

343 There are 5.9×10^3 km² cropland (including maize-wheat, cotton and paddy) in the YRD,
344 so we estimate that SOC and SIC stocks are 28.4 Tg C and 91.9 Tg C, respectively (Table V).
345 Given that low-to-middle salinity lands can have a maize-wheat rotation system, and high
346 salinity lands can only grow cotton and rice in the YRD, any changes in land gradation would
347 have impacts on soil carbon storage. Amelioration of saline-alkaline soil not only results in
348 improvements of soil physical and chemical properties (Nan *et al.*, 2016; Meng *et al.*, 2019),
349 but also leads to increased SOC and SIC densities (Lal, 2002; Amini *et al.*, 2016). If soil
350 salinization could be abated with soil quality improved as those in the upper YRD, soil carbon
351 storage would be increased by 8.8% (10.6 Tg C) in the cropland of the YRD. However, if soil
352 degradation occurs, with worsened salinization (as those for cotton and paddy fields), soil
353 carbon storage might be reduced by 12% (14.6 Tg C) in the cropland of the YRD. Therefore,
354 land management has impacts not only on agricultural production, but also on soil carbon
355 storage.

356

357 **CONCLUSIONS**

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

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

368

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374

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524 TABLE I

525 Mean values (standard errors) of soil pH, electric conductivity (EC), total dissolved solids (TDS), water-soluble Ca²⁺, Mg²⁺, K⁺ and Na⁺ in the 0-20, 20-40, 40-60, 60-80 and
526 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

527 ^{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
528 comparisons between paddy and reed soils) are not significantly different at $P < 0.05$.

529 TABLE II

530 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

531 ^{a)}The standard error under different land use types.

532 ^{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
533 letter for the comparisons between paddy and reed soils) are not significantly different at $P < 0.05$.

534
535 TABLE III

536 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 (Maize-wheat and cotton)	SOC density	0-20	-0.557* ^{b)}	-0.543*	0.072	-0.367
		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

537 ^{a)}EC, electric conductivity.

538 ^{b)}*Significant correlation at the 0.05 probability level (2 tailed).

539

540 TABLE IV

541 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 ($\mu\text{S}/\text{cm}$)		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

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

543

544

545 TABLE V

546 Means (\pm 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 \pm 1.05	16.89 \pm 3.18	1023	23.1	23.1	18.7
Maize-Wheat (lower)	4.97 \pm 0.87	16.24 \pm 2.07	2967	62.9	67.1	54.1
Cotton	4.44 \pm 0.52	14.67 \pm 2.48	1733	33.1	39.1	31.6
Paddy	3.28 \pm 0.57	14.09 \pm 1.34	73	1.2	1.6	1.3
Total	-	-	5796	120.3	130.9	105.7

547 ^{a)} The area sizes are from the Shandong Statistical Yearbook-2016.

548 ^{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}

549 ^{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.

550 **FIGURE CAPTIONS**

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

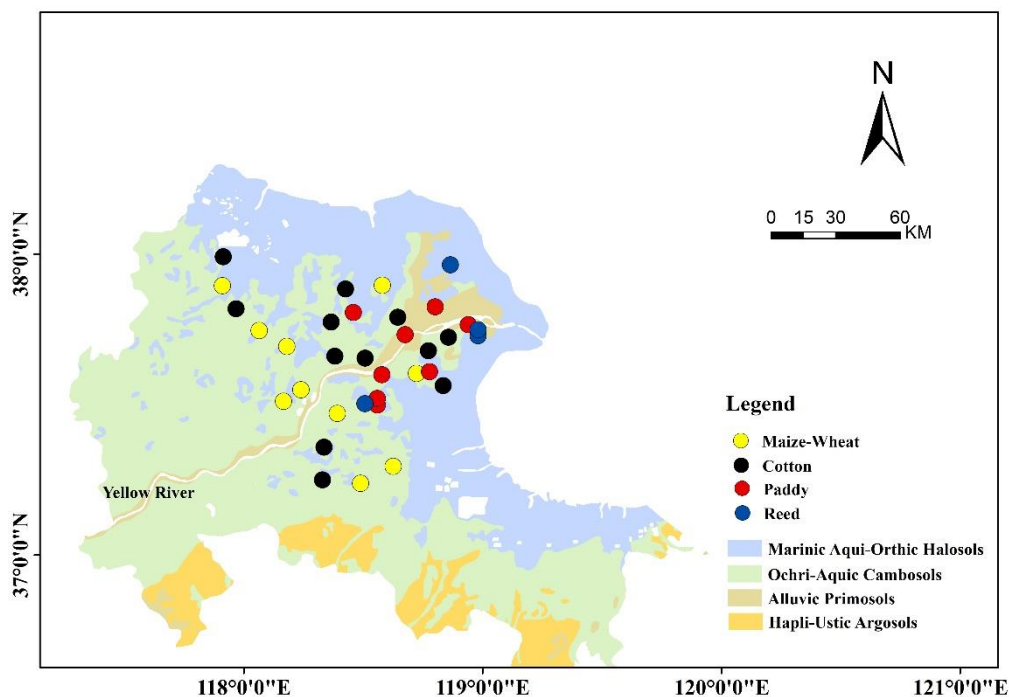
553 **Figure 2** Spatial distributions of soil organic carbon (SOC) and inorganic carbon (SIC) densities (kg C
554 m⁻²) in the 0–20 (A, B), 20–40 (C, D) and 40–100 cm (E, F) layers under four land use types: maize-
555 wheat (yellow circles), cotton (black circles), paddy (red circles), and reed (blue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

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

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

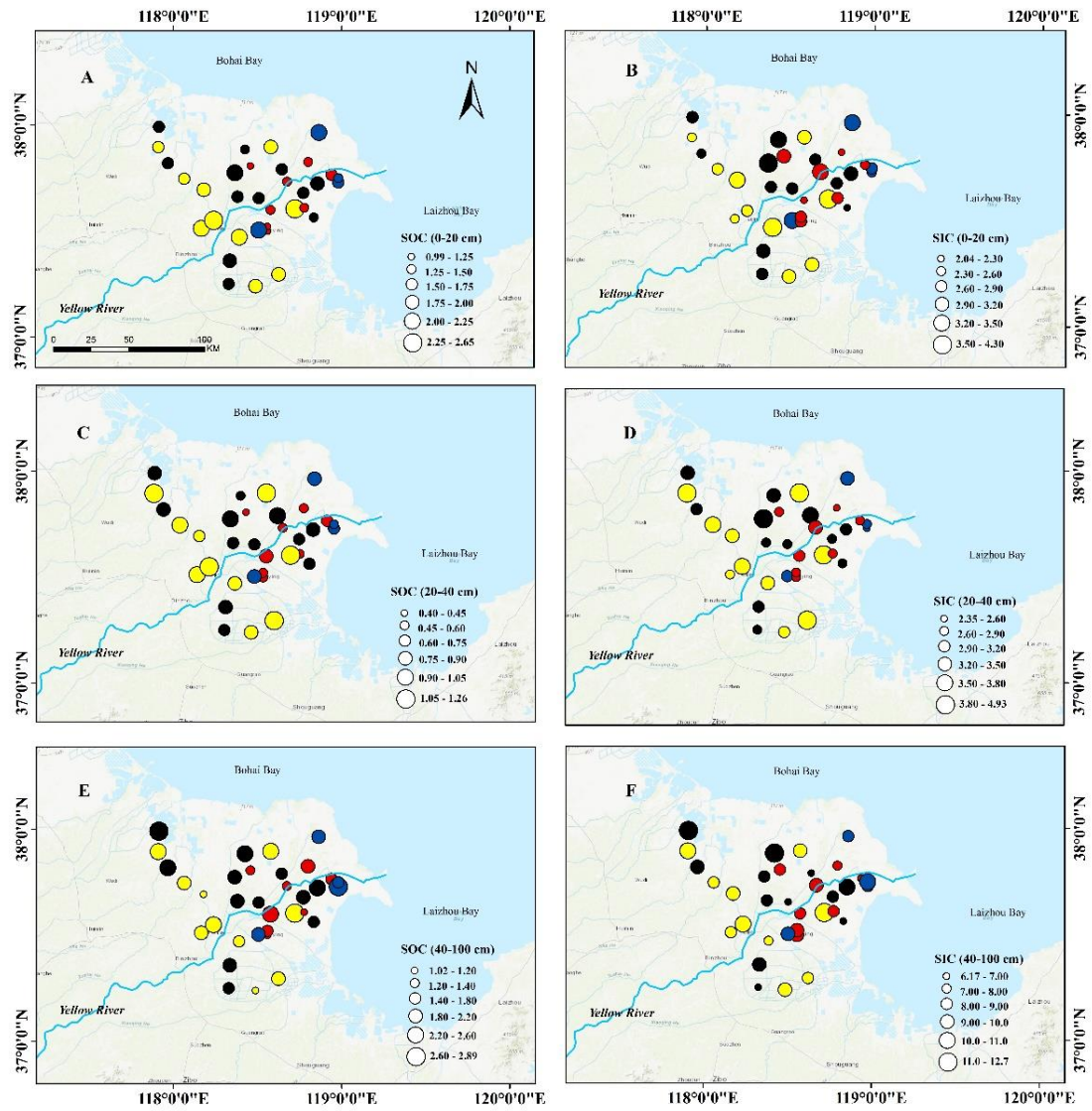
562 **Figure 5** Relationship between soil inorganic carbon (SIC) and organic carbon (SOC) stocks in the 0–20
563 and 0–100 cm layers in dry cropland of the middle-lower Yellow River Delta (orange circles) (maize-
564 wheat and cotton sites) and upper Yellow River Delta (green circles) (maize-wheat soils).

565



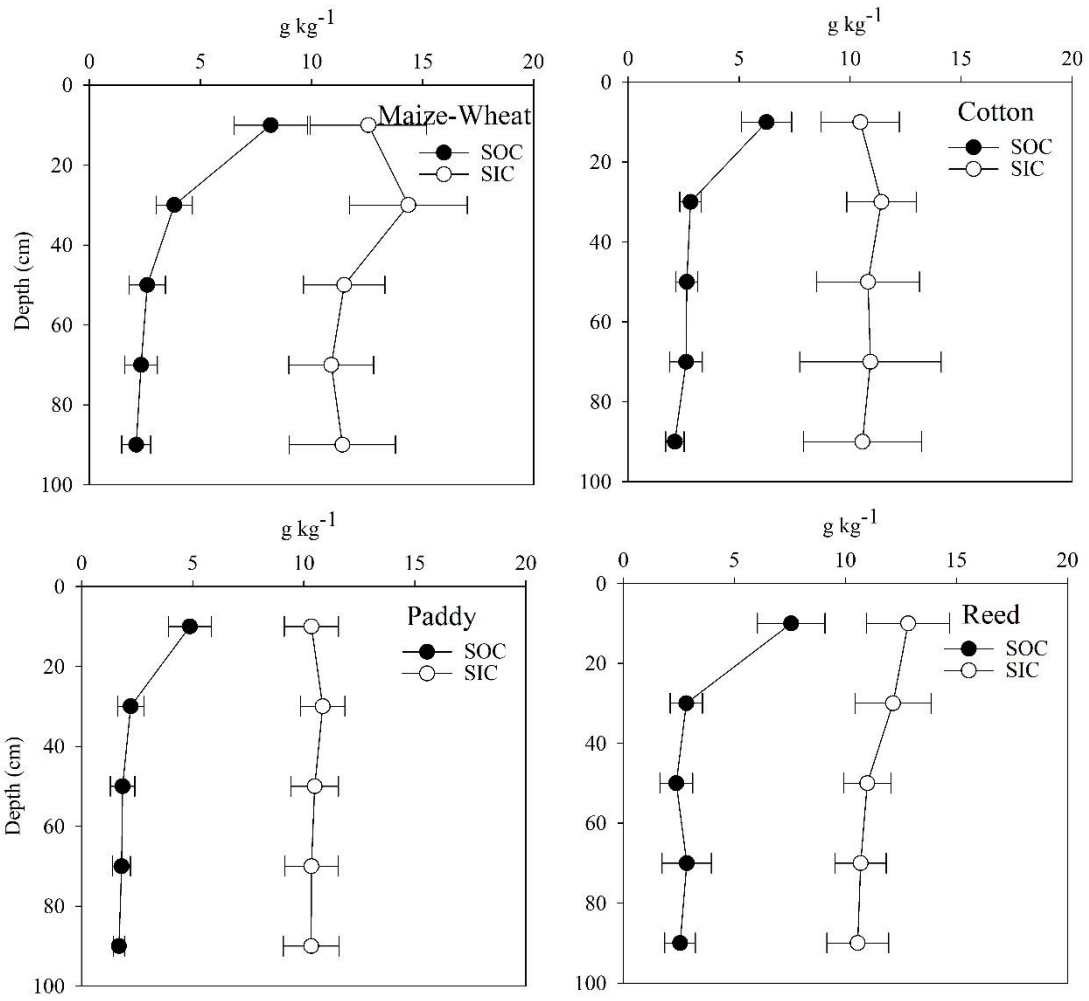
566

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



569

570 **Figure 2** Spatial distributions of soil organic carbon (SOC) and inorganic carbon (SIC) densities (kg C
 571 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-
 572 wheat (yellow circles), cotton (black circles), paddy (red circles), and reed (blue circles). The figure
 573 was generated using ArcMap 10.5 (<http://www.esri.com/>).



575

576 **Figure 3** Vertical distributions of soil organic carbon content (SOC) and inorganic carbon (SIC) in

577 different land use types.

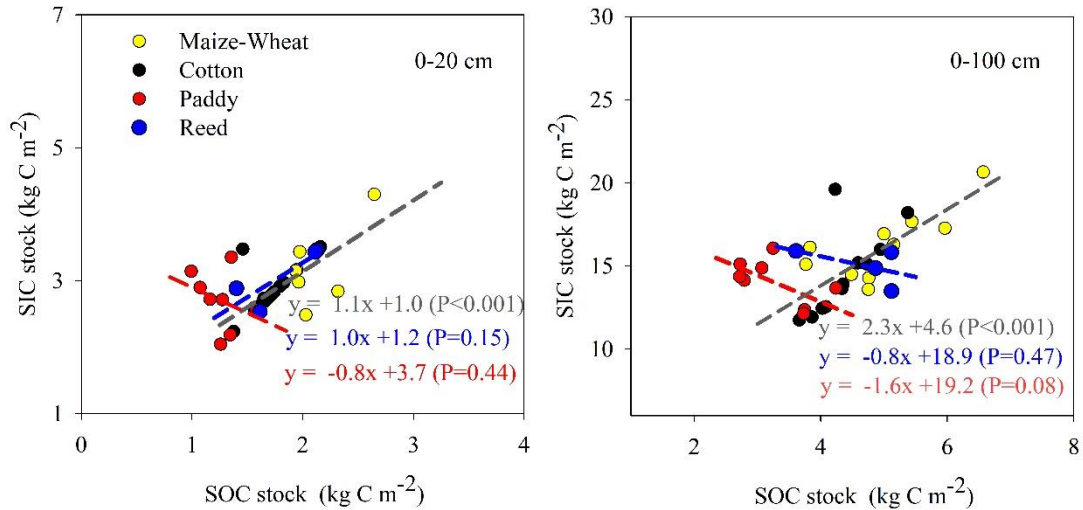
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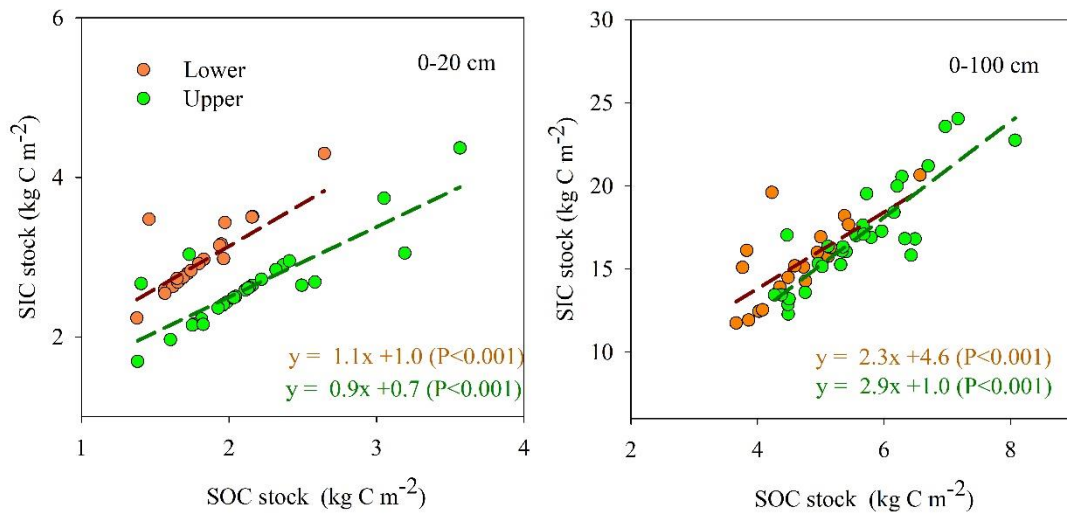
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584 **Figure 4** Relationship between soil inorganic carbon (SIC) and organic carbon (SOC) stocks in the 0–20
 585 and 0–100 cm layers in dry cropland (including maize-wheat and cotton sites) (grey dotted line), paddy
 586 (red dotted line) and reed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

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