

1 **Post-farming land restoration schemes exhibit higher soil aggregate stability and**
2 **organic carbon: evidence in the Three Gorges Reservoir Area, China**

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17 **Abstract**

18 The Three Gorges Reservoir Area was dominated by a farming landscape but has been the target of
19 restorative land management schemes over recent decades, wherein croplands have been converted
20 to forests or citrus woodlands run by commercial enterprises or, alternatively, abandoned for natural
21 vegetation succession. How these ongoing restorative land management schemes imprint soil systems
22 remains poorly understood. Accordingly, in this study, a space-for-time substitution approach was
23 applied to compare soil aggregate stability and organic carbon stocks between lands used for ongoing
24 arable production and areas subjected to restorative practices. Composite soil samples from
25 reforestation woodlands, abandoned croplands, citrus woodlands, and present-day croplands were
26 collected, and a variety of soil metrics (i.e., water-stable aggregate percentage, mean weight diameter,
27 geometric mean diameter, erosion resistance of the aggregates, bulk soil organic carbon and
28 aggregate-specific soil organic carbon) were used as a basis for comparison. Reforestation woodlands
29 and abandoned croplands exhibited a higher mass percentage of macro-aggregates, higher values of
30 mean weight diameter and geometric mean diameter, and higher organic carbon content within the
31 sampled 0-40 cm depth soil profiles. Reforestation and cropland abandonment significantly increased
32 the stability of soil aggregates and organic carbon stocks. Moreover, abandoned cropland samples
33 exhibited higher soil aggregate stability and organic carbon stocks than reforestation woodlands. In
34 contrast, soil aggregate stability for all sampled soil depths and organic carbon content except for the
35 topsoil (0-10 cm) of citrus woodlands exhibited lower values than those for present day croplands.
36 Exclusion of crop farming and reestablishment of restorative vegetation have therefore contributed to
37 changes in soil physical structure and organic carbon stocks, with reforestation and cropland
38 abandonment being more beneficial for soil aggregate stability and soil organic carbon stocks in the
39 Three Gorges Reservoir Area.

40 **Keywords:** Land use conversion; Reforestation; Cropland abandonment; Farming exclusion; Soil
41 aggregates; Soil organic carbon; Three Gorges Reservoir Area

42 **1. Introduction**

43 The long history of human exploitation of natural resources (e.g., land, biomass, water) has
44 modified natural ecosystems substantially into various artificial landscapes (Bryan et al., 2018). The
45 extent and intensity of human alteration to natural systems have accelerated over recent centuries. In
46 China, widespread political and socioeconomic development have occurred over recent decades, with
47 concomitant heavy anthropogenic disturbance to the environment. Here, for example, large-scale
48 natural forests have been harvested for domestic or industrial fuel use, while pristine lands have been
49 converted for cultivation to meet growing food demand for the growing population since the 1950s
50 (Xu et al., 2006). During the Great Leap Forward campaign (1958-1960), deforestation continued as
51 small forests were cut down for timber and fuel use (Du, 2001). Critically, the Chinese government's
52 ability to manage natural resources diminished during the Cultural Revolution Campaign (1966-1976),
53 which further exacerbated environmental degradation (Marks, 2017). As a result, national natural
54 forest declined in extent from 102.0 M ha in 1949 to 66.7 M ha in 1993 (Fang et al., 2001; Xu et al.,
55 2006). In response and since the late 1990s, multiple national vegetation restoration schemes (e.g.,
56 natural forest reservation, reforestation) have been launched to mitigate land degradation and water
57 contamination, as well as to conserve forests and biodiversity (Ouyang et al., 2016). More recently, in
58 the 21st century, rapid industrialization and urbanization has promoted the migration of rural
59 populations with a corresponding transferral of livelihood strategies from the agricultural sector to
60 other sectors. At the same time, cropland abandonment for natural vegetation succession, has
61 become an important feature of land use change (Su et al., 2022).

62 Human activities have promoted land use change both at global and regional scales, and these
63 deliver profound consequences to ecosystem composition, structure, and functionality (Chen et al.,
64 2015). Increasing attention has recently been directed to examining the efficacy of restoration efforts
65 across landscapes. Globally, reforestation plays an important role in global greening (Wang et al., 2012;
66 Sun et al., 2014). Re-vegetation increases rainfall interception, vegetation transpiration, and soil
67 infiltration, and thereby reduces surface runoff generation (Wang et al., 2011). It also plays an
68 important role in controlling elevated soil erosion by altering surface hydrological processes. Here, for
69 example, studies have shown that the intensity of soil erosion was reduced by more than 90% after
70 the conversion of cropland to grassland and woodland (Zhang et al., 2015; Gao et al., 2017).

71 Revegetation has also been identified as the most effective way to improve soil quality (Kroepfl et al.,
72 2013; Bienes et al., 2016). Increasing nutrient pools, soil organic carbon content, enzyme activity and
73 soil porosity are just a few specific examples of how revegetation can improve the physical, chemical
74 and biological properties of soils (An et al., 2010). Additionally, increased soil aggregate stability can
75 improve resistance to soil erosion and reduce the loss of dissolved organic carbon (Strassburg et al.,
76 2020). A comprehensive understanding of the effects of vegetation restoration can provide compelling
77 evidence in support of recommendations for land use change.

78 Among the many soil properties, aggregate stability and organic carbon are important indicators
79 of soil structure and functionality. Aggregate stability is a fundamental component of soil physical
80 structure (Rabot et al., 2018). Soil aggregates control soil organic matter, nutrient cycling, porosity,
81 and aeration within the soil profile, thereby affecting plant and microbial populations, soil water
82 retention, and resistance to soil erosion (Chevallier et al., 2004; Bossuyt et al., 2005). Soil organic
83 carbon is the principal component of the soil carbon pool, the magnitude of which alters the balance
84 between atmospheric CO₂ concentration and the soil carbon sink, affecting the global carbon cycle
85 significantly (Schmidt et al., 2011; Balesdent et al., 2018; Xu et al., 2021). Soil organic carbon
86 breakdown and storage are influenced by several factors, including climate change and human activity
87 (Don et al., 2011; Bastin et al., 2019). Soil aggregates are also significant for organic carbon storage,
88 transformation, and stabilization. Soil aggregates improve the physical protection of organic carbon
89 and decrease microbial mineralization and breakdown, both of which are crucial mechanisms for the
90 stability of soil organic carbon (Torres-Sallan et al., 2018). Meanwhile, soil organic carbon, as an
91 essential cementing agent for aggregate production, has a significant impact on the structure of soil
92 aggregates (Torres-Sallan et al., 2018; Bucka et al., 2019). Current studies on the stability of soil
93 aggregates and their organic carbon sequestration include agricultural soils with different fertilization
94 treatments (Du et al., 2017), different tillage practices (Du et al., 2015), natural grasslands with
95 different management practices (Egan et al., 2018) and planted woodlands with different durations of
96 restoration (Liu et al., 2021). Land use change is a hot topic due to its significant impact on soil
97 aggregation and organic carbon storage (Spohn and Giani, 2011). For example, vegetation restoration
98 can improve soil organic carbon storage, soil aggregate stability, and soil and water conservation (Liu
99 et al., 2019). Returning farmland to forest can increase organic carbon storage by 20-50%, but

100 converting forest to farmland can reduce organic carbon storage by ~40% (Guo and Gifford, 2002). In
101 contrast to farmland cultivation which disrupts aggregate formation and stability, vegetation
102 restoration promotes soil aggregate formation and stability by accelerating plant community
103 development and enhancing soil organic carbon inputs (Six et al., 2002). Influenced by the type of
104 vegetation used for restoration, soil depth, and restoration time (Li et al., 2012), soil aggregate
105 stability and soil organic carbon can increase or change negligibly with the recovery of farmland
106 vegetation, or initially decrease in the early stages and then increase with the ongoing development of
107 vegetation cover (Deng et al., 2014). Despite the large body of previous work, however, the trends in
108 soil aggregate stability and organic carbon content under either artificial or natural restoration during
109 post-agricultural transformation are not clear, underscoring the need for new research to address this
110 evidence gap.

111 The Three Gorges Reservoir Area was dominated by a farming landscape where cultivation was
112 commonplace on steep hillslopes. Collectively, intensive human disturbance associated with tillage
113 and farming operations, along with intrinsic factors such as hilly and mountainous landforms, frequent
114 erosive rain storms, and soils with low resistance to water erosion, renders the land extremely
115 susceptible to water erosion. Meanwhile, this area is of utmost priority for soil conservation and
116 ecosystem restoration given its vicinity to the world's largest reservoir. During the past 30 years, a
117 variety of conservation schemes (i.e., the Yangtze River Basin Protection Forest System Construction,
118 Nature Forest Project, Grain to Green Project, and Afforestation along the Yangtze River Project) have
119 been introduced to improve forest cover to mitigate elevated soil erosion, as well as to improve the
120 sustainability of land and water resources, including the ecosystems therein (Xiao et al., 2020). Besides
121 these management interventions, over the past 20 years, a large number of rural residents migrated
122 for livelihood strategies in non-farming sectors. Extensive areas of cropland have therefore been
123 abandoned, thus promoting the continuous transformation of farmland to natural grasslands (Huang
124 et al., 2022; Quintas-Soriano et al., 2022). Additionally, citrus woodlands have been used to convert
125 traditional croplands as a means of increasing farmer incomes. To date, however, how these ongoing
126 diverse land best management practices imprint on soil systems remains poorly understood.
127 Accordingly, this study quantified differences between soil aggregate stability and organic carbon
128 stocks for different post-farming land management practices (reforestation, cropland abandonment,

129 citrus woodlands) to clarify the impacts of farming exclusion and vegetation change.

130

131 **2. Materials and methods**

132 *2.1. Study area*

133 Our investigation was undertaken in the middle reaches of the Three Gorges Reservoir Area in
134 Zhong County of the Chongqing Municipality (Fig. 1a). Regional landforms are characterized by hills
135 and low mountains, with elevations ranging from 117–1680 m above sea level (Wei et al., 2018). The
136 climate is subtropical with humid monsoons, with a mean annual precipitation of 1172 mm. Annual
137 rainfall is unevenly distributed across the year, of which a major proportion occurs in the rainy season
138 from May to September (Tang et al., 2014). Purple soil with poor structural stability dominates and is
139 prone to disaggregation and dispersal by rainfall and runoff. Mid-subtropical evergreen broad-leaved
140 forest is the local natural vegetation type.

141 This area was previously dominated by arable lands in the form of sloping lands or cultivated
142 terraces. With the implementation of the "Grain for Green" project in 2002, croplands on the slopes
143 were reforested. The main species in reforestation woodlands was *Cupressus funebris* Endl., which
144 was fertilized in the planting year. There has been no artificial disturbance post-planting. At the same
145 time, large areas of abandoned croplands emerged due to the reduction in the rural working
146 population. Abandoned croplands were allowed to restore naturally, with the dominant species
147 including *Broussonetia kazinoki* S. et Z., *Polygonum chinense* Linn., *Cuscuta chinensis* Lam., and
148 *Cyclosorus interruptus* (Willd.) H. Ito. Large-scale agricultural operations have transformed some
149 low-altitude slopes into citrus woodlands dominated by *Citrus reticulata* Blanco, with annual
150 fertilization and weeding. Vegetation coverage in reforestation woodlands, abandoned croplands, and
151 citrus woodlands are 72–90%, 65–92%, and 40–60%, respectively. Meanwhile, the remaining
152 croplands are mainly planted with *Zeamays* L., *Capsicum annuum* Linn., and *Solanum melongena* Linn.,
153 ploughed 1–2 times a year and fertilized with both inorganic fertilizers and farm manure.

154

155 *2.2. Field sampling*

156 Field sample collection was undertaken in October 2021. To ensure the spatial representativeness
157 of the samples taken, we selected three independent sub-areas with similar elevations and slopes for

158 sample collection (Fig. 1b and Fig. 2). Reforestation woodlands, abandoned croplands, and citrus
159 woodlands were sampled using 3 replicates for each, and present day croplands were sampled in pairs
160 near the other land conversion types to assist direct comparisons. In total, 15 plots (20 m × 20 m)
161 were selected. Then, three subplots (1 m × 1 m) were randomly selected within each plot. Samples
162 from the three subplots were composited to represent each plot. Under the influence of tillage, the
163 soil in the croplands was homogeneous in the tilled layer. However, there were obvious differences
164 between the tillage layer and the subsoil layer. Moreover, the vegetation type was assumed to impact
165 the topsoil. Therefore, we collected undisturbed soil samples at depths of 0–10 cm, 10–20 cm, and
166 20–40 cm in present day croplands. In the other three vegetation types, litter and moss were removed,
167 and undisturbed soil samples were collected from the same three soil layers (N.B., soils were collected
168 to bedrock when the soil thickness was <40 cm). To avoid contamination, the soil samples were kept in
169 rigid plastic containers. In total, 45 composited soil samples were retrieved from the field. Before the
170 soil sample was completely dry, undisturbed soil samples were broken into little pieces (around 1 cm
171 in diameter) along their cracks. Plant roots, organic material, and stones were removed. Finally, the
172 samples were split into two parts: one was utilized to quantify aggregate stability, and the other was
173 sieved through a 0.15 mm mesh to assess soil physicochemical properties (Table 1).

174

175 2.3. Analytical methods

176 Soil aggregate particle size and stability were determined using dry and wet sieving (Zhao et al.,
177 2017). A vibrating sieve shaker (TPF-100; Top Cloud-Agri, China) was utilized for dry sieving. A total of
178 500 g of air-dried bulk soil (with an aggregate diameter of less than 10 mm) was quartered, then
179 sieved at an amplitude of 1.5 cm for 5 minutes using stacked sieves of 0.25 and 0.053 mm,
180 respectively. The soil particles that remained on the sieves were collected and weighed. Proportionally,
181 50 g subsamples of these aggregate fractions were soaked for 5 min before being placed on stacked
182 sieves of 0.25 and 0.053 mm, and the stacked sieves were placed in a cylindrical tank containing
183 deionized water. The sieves were shaken vertically for 30 minutes at a frequency of 50 times per
184 minute and an amplitude of 3–4 cm. Three fractions of water-stable aggregates were obtained in this
185 study: 0.25–10 mm, 0.053–0.25 mm, and 0.053 mm. These aggregates were dried in an oven at 105 °C
186 and weighed. The remaining air-dried soils and dried aggregate samples from each plot were ground

187 to pass through 0.15-mm sieves for the measurement of organic carbon concentrations. The
 188 concentrations of organic carbon in both bulk soils and aggregate fractions were determined using the
 189 potassium dichromate external heating method (Nelson and Sommers, 1982).

190

191 2.4. Data analysis

192 As sampled reforestation woodlands, abandoned croplands and citrus woodlands had been
 193 converted from croplands for a relatively long period and impacts of land management practices on
 194 imprinting soil systems are assumed to be relatively stable, the strategy of space time substitution was
 195 adopted to evaluate the potential impacts of ongoing land management schemes on soil aggregate
 196 stability and organic carbon stocks, using the present day croplands as a benchmark.

197 The mean weight diameter (MWD) and geometric mean diameter (GMD) were used to
 198 characterize soil aggregate stability (Jiang et al., 2019), and 1/K was used to assess the resistance to
 199 soil erosion (Shirazi and Boersma, 1984). These were defined using the following equations:

$$199 \text{ MWD} = \sum_{i=1}^n (R_i W_i) \quad (1)$$

$$200 \text{ GMD} = \exp \left[\frac{\sum_{i=1}^n W_i \ln R_i}{\sum_{i=1}^n W_i} \right] \quad (2)$$

$$201 \frac{1}{K} = \frac{1}{7.954 \times \left\{ 0.0017 + 0.0494 \times \exp \left[-0.5 \times \left(\frac{\log \text{GMD} + 1.675}{0.6986} \right)^2 \right] \right\}} \quad (3)$$

200 where W_i is the weight fraction (%) of the aggregate fraction, R_i is the mean diameter of each size
 201 class (mm) and K is the soil erodibility.

202 The soil organic carbon stocks were calculated using the following equations (Deng et al., 2016):

$$203 \text{ SOC}_{\text{Stock}} = \frac{\text{SOC} \times \text{BD} \times \text{T}}{10} \quad (4)$$

203 where $\text{SOC}_{\text{Stock}}$ represents soil organic carbon stocks ($\text{Mg} \cdot \text{ha}^{-1}$), SOC represents the soil organic carbon
 204 content ($\text{g} \cdot \text{kg}^{-1}$), BD represents the soil bulk density ($\text{g} \cdot \text{cm}^{-3}$), and T represents the soil layer thickness
 205 (cm).

206 The SOC stock ($\text{Mg} \cdot \text{ha}^{-1}$) associated with each aggregate size fraction was calculated as follows:

$$207 \text{ SOC}_{\text{Stock in aggregate } i} = \frac{\text{SOC}_i \times \text{BD} \times W_i \times \text{T}}{10} \quad (5)$$

207 where SOC_i is the soil organic carbon concentration ($\text{g}\cdot\text{kg}^{-1}$) associated with each aggregate size
208 fraction and W_i is the proportion of each size fraction relative to the total sample (%).

209 All indices measured or calculated were tested for normality and variance homogeneity. A
210 two-way analysis of variance (ANOVA) was conducted to test for significant differences between
211 present day cropland and restorative land management schemes and soil depth on the basis of: (1)
212 the proportions of each aggregate fraction, MWD, GMD, and $1/K$, and; (2) the concentrations and
213 stocks of organic carbon in bulk soils and aggregate-specific fractions. The least significant difference
214 (LSD) test was undertaken to identify significant differences. Statistical analyses were performed using
215 SPSS 22.0 (SPSS Inc., Chicago, IL, USA) and Origin 9.0 (Origin Lab, Hampton, MA, USA). The significance
216 level was set at $P < 0.05$ for all statistical analyses unless stated otherwise. All data were presented as
217 the means and standard errors.

218

219 **3. Results**

220 *3.1. Soil aggregate composition under different post-farming land management schemes*

221 Soil aggregate measurements indicated that reforestation woodlands and abandoned croplands
222 exhibited relatively higher proportions of macro-aggregates in bulk soils at all sampled depths in
223 comparison with present day croplands and citrus woodlands (Fig. 3). The mass percentages of
224 macro-aggregates for bulk soils from reforestation woodlands and abandoned croplands ranged from
225 53% to 73%, while micro-aggregates and silt + clay particles accounted for 9–17% and 17–38%,
226 respectively. The proportions of silt + clay particles in bulk soils from citrus woodlands and present day
227 croplands ranged between 37–48%, with these proportions being slightly higher than those of
228 macro-aggregates (26–38%) and micro-aggregates (22–31%). Moving down the sampled soil profiles,
229 the mass percentages of macro-aggregates under the four land management schemes decreased, and
230 the content of silt + clay particles increased. For example, the macro-aggregates proportion in the 0–
231 10 cm layer of sampled soils from abandoned croplands was 1.08 and 1.39 times higher than those
232 from the 10–20 cm and 20–40 cm layers, respectively. Silt + clay particle content in 0-10 cm depth soil
233 was 79% and 56% of the corresponding contents in the 10–20 cm and 20–40 cm depths, respectively.

234 Different behaviors of soil aggregate composition were observed between the different land uses.
235 Based on averaging aggregate distribution across soil profiles, reforestation plots exhibited 30% higher

236 macro-aggregate content, but 15% and 16% lower micro-aggregate and silt + clay particle content,
237 respectively. Abandoned cropland exhibited 37% higher macro-aggregate content, relative to present
238 day cropping, but a reduction in micro-aggregates and silt + clay particles of 17% and 21%, respectively.
239 Present day croplands, compared with citrus woodlands, exhibited a lower (3–8%) macro-aggregate
240 content. Comparisons of these two land uses for micro-aggregates and silt + clay particles did not
241 reveal consistent differences.

242

243 *3.2. Soil aggregate stability under different post-farming land management schemes*

244 In general, the values of MWD, GMD, and 1/K of soils from reforestation woodlands and
245 abandoned croplands were clearly higher than those of present day croplands and citrus woodlands
246 (Fig. 4). Higher values of MWD, GMD, and 1/K indicate better soil aggregate stability. As a result,
247 reforestation woodlands and abandoned croplands have significantly higher aggregate stability than
248 present-day croplands and citrus woodlands. Specifically, averaged across the sampled soil depths,
249 previous croplands converted to reforestation woodlands exhibited 96%, 290%, and 259% higher
250 values of MWD, GMD, and 1/K, respectively compared with present day croplands. Abandoned
251 croplands exhibited 130%, 472%, and 393% higher values for these three indicators compared with
252 present day croplands. In addition, the estimates of these three indicators for abandoned cropland
253 soils were significantly higher than those for the sampled reforestation woodland soils in the 0–10 cm
254 soil layer. However, there were no statistically significant differences in GMD and 1/K between present
255 day cropland soils and citrus woodland soils, and MWD was only significantly different within the 0–10
256 cm soil layer.

257 The values of MWD, GMD, and 1/K were higher in the upper layer of the four land management
258 schemes compared to the lower layer of the sampled soil profiles. The values of MWD, GMD, and 1/K
259 were significantly higher in the 0–10 cm depth soil samples for present day croplands and citrus
260 woodlands than in the 10–40 cm soil layers. The values of MWD, GMD, and 1/K were significantly
261 higher in 0–20 cm depth soil samples compared with those collected at 20–40 cm depth in
262 reforestation woodlands and abandoned croplands.

263

264 *3.3. Organic carbon stocks of bulk soils under different post-farming land management schemes*

265 Compared to present day cropland soils, reforestation woodland and abandoned cropland soils
266 exhibited significantly higher soil organic carbon content and stocks in bulk samples at all depths.
267 Values for citrus woodland soils were also higher than those for present day croplands at depths of 0–
268 10 cm, but, conversely, lower at depths of 10–20 and 20–40 cm (Fig. 5). More specifically, the soil
269 organic carbon stocks of citrus woodlands, reforestation woodlands, and abandoned croplands at 0-10
270 cm depth were 15.72, 26.53, and 29.34 Mg·ha⁻¹, respectively, which were 1.25, 2.11, and 2.34 times
271 higher than the corresponding estimate (12.56 Mg·ha⁻¹) for present day croplands, respectively. In the
272 10–40 cm depth soil layer, the soil organic carbon stocks in reforestation woodland, abandoned
273 cropland, and citrus woodland were 1.58, 1.92, and 0.89 times higher than those in present day
274 cropland soils, respectively. Notably, in the 0–40 cm depth soil layer, the difference between total soil
275 organic carbon stocks in citrus woodlands and present day croplands was small, with the former being
276 only 1.04 times higher than the latter. In addition, the content of soil organic carbon decreased
277 downwards in the sampled soil profiles under the four land management schemes. For example, in
278 the case of the abandoned croplands, the soil organic carbon content in the 0-10 cm depth soil layer
279 was 1.74 and 1.53 times higher than that in the 10-20 cm and 20-40 cm depth layers, respectively.

280

281 *3.4. Aggregate-specific organic carbon stocks under different post-farming land management schemes*

282 In the four land management schemes and three soil layers, macro-aggregates of >0.25 mm
283 exhibited the highest soil organic carbon content (4.86–23.99 g·kg⁻¹) (Fig.6). The lowest
284 aggregate-specific soil organic carbon content was measured in 0.053-0.25 mm micro-aggregates in
285 present day croplands and citrus woodlands, but the overall lowest soil organic carbon content was
286 measured in <0.053 mm silt + clay particles in reforestation woodlands and abandoned croplands. On
287 the basis of averaging the soil organic carbon stocks within the sampled soil profiles for the four land
288 management schemes, macro-aggregates, micro-aggregates, and silt + clay particles accounted for
289 58%, 14%, and 28%, respectively.

290 When compared to present day cropland soils, citrus woodland soils, reforestation woodland
291 soils, and abandoned cropland soils exhibited soil organic carbon contents in >0.25 mm aggregates
292 that were 31%, 95% and 136 % higher, compared with 36%, 204% and 260% higher in 0.053–0.25 mm
293 aggregates and 26%, 89% and 126 % higher in 0.053 mm aggregates forming the 0-10 cm depth soil

294 layer.

295

296 *3.5. Correlation between soil organic carbon content and aggregate stability*

297 Pearson correlation analysis indicated that soil organic carbon content was significantly and
298 positively correlated with the proportions of macro-aggregates, MWD, GMD, 1/K, soil organic carbon
299 stock, soil aggregate-specific organic carbon content, and soil macro-aggregate organic carbon stock
300 (Fig. 7, $p < 0.01$). Soil organic carbon content was negatively correlated with micro-aggregate
301 proportions, silt + clay particle proportions, soil micro-aggregate organic carbon stock, and soil silt +
302 clay particle organic carbon stock. Soil organic carbon content exhibited the strongest correlation with
303 GMD ($r = 0.83$), and the lowest with micro-aggregates ($r = -0.65$) among the soil aggregate indicators.
304 Soil organic carbon content showed the strongest association with soil organic carbon stock ($r = 0.99$),
305 followed by soil macro-aggregate organic carbon content ($r = 0.95$), and soil micro-aggregate organic
306 carbon stock ($r = -0.04$), among the organic carbon indicators (Fig. 7).

307

308 **4. Discussion**

309 *4.1. The effect of different post-farming land management practices on soil aggregates*

310 Soil aggregate composition and stability were significantly influenced by the different
311 post-farming land management practices. Our study indicates that soils under reforestation and
312 cropland abandonment exhibit more large soil aggregates (> 0.25 mm) and increased soil aggregate
313 stability across a soil depth range of 0–40 cm, compared with present day croplands. Large soil
314 aggregates are disintegrated by the mechanical damage associated with tillage operations on the
315 present day croplands, but reforestation woodland soils and abandoned cropland soils accumulate
316 large soil aggregates due to the exclusion of tillage (Xiao et al., 2019; Ye et al., 2020). Tillage can also
317 bring subsoil to the surface, exposing it to drying and wetting cycles and speeding up aggregate
318 fragmentation (Denef et al., 2001). Fresh organic matter, moreover, accumulates as a result of
319 vegetation cover and then serves as the primary binding agent in the aggregate formation process,
320 increasing the stability of soil aggregates in soils converted to reforestation woodlands and abandoned
321 croplands (Wiesmeier et al., 2012). Fresh organic matter derives primarily from litter and roots after
322 farmland restoration, which could act as direct binding agents and help in the formation of aggregates

323 (Fahey et al., 2011; Rillig et al., 2015). In addition, we observed that the soil macro-aggregate content
324 and aggregate stability in abandoned croplands were higher than in reforestation woodlands. This may
325 be caused by the higher organic carbon content of the abandoned cropland soils, which generated
326 more binding capacity.

327 Citrus woodland soils exhibited reduced macro-aggregate content and aggregate stability at a
328 depth of 0–40 cm, compared to present day cropland soils. Citrus woodlands have low canopy density,
329 and the splash of raindrops results in the dispersion and destruction of large soil aggregates on the
330 surface layer. Moreover, in addition to seasonal tillage and fertilization, trampling and poaching of the
331 soil surface is associated with activities such as pruning, fertilizing, weeding, and picking in mountain
332 orchards, resulting in increased soil compaction, destruction of soil aggregates, and reduced aggregate
333 stability.

334 In addition to the differences introduced by different land management schemes, soil depth also
335 significantly affected the stability of soil aggregates. Stability decreased with increasing soil depth (Liu
336 et al., 2020). The high content of organic matter near the surface supports the formation of large
337 aggregates, thus increasing the content of water-stable aggregates and ultimately improving soil
338 quality.

339

340 *4.2. The effect of post-farming land management schemes on soil organic carbon stocks*

341 Soil organic carbon stocks were significantly influenced by the different post-farming land
342 management practices. Our study found that reforestation and cropland abandonment soils exhibited
343 higher soil organic carbon content and stocks across a depth range of 0–40 cm, compared with
344 present day croplands. Cropland soils accumulate less organic matter on the surface due to tillage
345 operations (Liu et al., 2020). In contrast, because reforestation woodland soils and abandoned
346 cropland soils were largely uncultivated, a large number of animal and plant residues and humic
347 substances return to the soil, and consequently, carbon content and stock is higher (Wang et al., 2016;
348 Liu et al., 2021; Zheng et al., 2021). Higher vegetation cover in reforestation woodlands and
349 abandoned croplands can also reduce soil erosion and concomitant organic carbon loss by decreasing
350 surface runoff and sediment redistribution (Dong et al., 2022). Abandoned cropland soils exhibited
351 higher soil organic carbon than reforestation woodland soils. The biomass of surface herbs and shrubs

352 on abandoned land is much more than that of the artificial forest, and the annual litter fall is likewise
353 higher than that of the artificial forest. Therefore, more organic carbon enters the soils of the
354 abandoned cropland.

355 In contrast, soil organic carbon content and stocks in citrus woodlands increased only in the 0–10
356 cm depth soil layer compared to present day arable soils. This most likely reflects the fact that the root
357 systems of most fruit trees are shallow, meaning that the degradation of the root system and litter
358 mostly affects the surface soil. As a result, the deeper soils of citrus woodlands were not recharged
359 with organic carbon, and there was no substantial difference between the carbon content of these
360 soils and those beneath present day cropland at deeper soil depths.

361

362 *4.3. The effect of post-farming land management schemes on soil aggregate-specific organic carbon* 363 *stocks*

364 Soil aggregate-specific organic carbon stocks were significantly influenced by the different
365 post-farming land management practices. Our study found that soils beneath reforestation and
366 cropland abandonment exhibited higher soil organic carbon content and stocks in each aggregate
367 fraction across a depth range of 0–40 cm when taking present day croplands as a comparative
368 benchmark. This increase might be attributed to the buildup of organic components from litter, dead
369 roots, and root exudates, which release organic carbon during decomposition and bind to soil particles
370 (Ayoubi et al., 2012; Zheng et al., 2021). Soil aggregate-associated organic carbon content first
371 decreased and then increased with the aggregate size in citrus woodlands and present day croplands
372 in this study. The same finding has been reported by previous work (Liu et al., 2020). Large
373 macro-aggregates are mainly associated with decomposing plant residue and hyphae (Tisdall and
374 Oades, 1980; Wang et al., 2016), whereas smaller-sized aggregates are mainly associated with clay
375 particles (Fernandez-Ugalde et al., 2011). As the surface biomass and organic residue inputs to the soil
376 vary considerably between management scenarios, this affects the binding of aggregates of different
377 particle sizes to organic carbon. The accumulation of organic matter in the macro-aggregates (Wei et
378 al., 2013; Qiu et al., 2015) also protects the organic matter from microbes and oxygen, reducing soil
379 organic carbon loss due to decomposition (Zimmermann et al., 2012; O'Brien and Jastrow, 2013).

380

381 *4.4 Implications of the relationship between soil organic carbon and aggregates*

382 In this study, a significant positive correlation between soil aggregate stability and soil organic
383 carbon content was confirmed, in line with previous studies (Plaza-Bonilla et al., 2013; Deng et al.,
384 2018; Yao et al., 2019; Ferreira et al., 2020; Liu et al., 2020; Okolo et al., 2020). Less anthropogenic
385 interference in reforestation woodlands and abandoned croplands permits more plant residues to
386 remain on the surface, which, in turn, increases soil organic carbon inputs, and supports the formation
387 of particulate organic matter in the larger aggregates, reducing damage to the larger aggregates,
388 increasing their structural stability, and promoting the formation of soil aggregates in general (Ferreira
389 et al., 2020). At the same time, aggregate formation provides physical protection mechanisms for soil
390 organic carbon and reduces its loss (Torres-Sallan et al., 2018).

391 We found that soil organic carbon content was significantly and positively correlated with
392 macro-aggregate content and significantly and negatively correlated with micro-aggregates and silt +
393 clay particles. This indicates that elevated organic carbon content can provide more cementing
394 substances for the formation of large aggregates by cementing micro-aggregates and silt + clay
395 particles to form macro-aggregates, reducing the content of aggregates with smaller particle sizes and
396 thus promoting the formation and stabilization of large aggregates. Conversely, a reduction in organic
397 carbon content promotes the conversion of larger aggregates to smaller aggregates (Zou et al., 2018).

398 Moreover, in our study, soil organic carbon was mainly stored in macro-aggregates and its
399 content was also mainly influenced by the soil organic carbon content in macro-aggregates (Fig.7). The
400 correlation coefficient between soil organic carbon content and soil macro-aggregate organic carbon
401 content was $r = 0.95$, which was greater than the corresponding correlations with soil micro-aggregate
402 organic carbon and soil silt + clay particles organic carbon, which is consistent with the findings of Qiu
403 et al. (2015). However, large aggregates can provide less protection for soil organic carbon than
404 micro-aggregates and powdered mucilage (Six et al., 2002; Saha et al., 2010). Here for example, Xu et
405 al. (2021) reported that there is a significant positive correlation between large aggregates and the
406 active carbon fraction, which is unstable (e.g., aromatic carbon and carbonyl carbon). The active
407 carbon fraction encourages the formation of large aggregates, while the micro-aggregates are
408 protected by the more stable carbon fraction. The soil organic carbon content of large aggregates in
409 this study exhibited higher values in reforestation woodland and abandoned cropland soils than citrus

410 woodland and present day cropland soils, and higher values in surface soils compared with subsurface
411 soils. This indicates that the stability of soil organic carbon in reforestation woodland and abandoned
412 cropland soils and surface soil is low, meaning that the protection of reforestation woodland and
413 abandoned cropland soils and surface soil should be strengthened to avoid the fragmentation of
414 aggregates which could result in the soil organic carbon in them being decomposed and utilized,
415 which is unfavorable to sustained carbon sequestration.

416

417 *4.5. Implications for sustainable land and ecosystem management*

418 Soil aggregates are the basic building blocks and functional units of soil (An et al., 2010; Tang et
419 al., 2013). Soil aggregate stability is influenced by a combination of factors, and in this study, the
420 entanglement of plant roots and the cementation of litter and root secretions after vegetation
421 restoration are all likely to have contributed to the formation of macro-aggregates. Soil organic carbon
422 depends on the dynamic balance between the input and output of soil organic matter (An et al., 2010),
423 and the direct result of different land management schemes is the difference in vegetation cover.
424 After vegetation restoration, the input of organic matter such as litter and roots increases, and the
425 surface cover blocks the decomposition of organic carbon, meaning that the soil organic carbon
426 content increases. Meanwhile, soil aggregates and soil organic carbon can promote each other and
427 together influence the soil ecosystem (Fig. 8).

428 In this investigation, we used a space-time substitution approach to compare different
429 post-farming land management schemes (reforestation, cropland abandonment, and citrus woodlands)
430 with present-day croplands in the Three Gorges Reservoir Area of China in terms of soil aggregate
431 stability and organic carbon stocks. This study suggests that relative to present day cropland soils,
432 both reforestation woodland soils and abandoned cropland soils exhibit increased soil aggregate
433 stability and carbon storage, but after 20 years of recovery, soil aggregate stability and carbon
434 sequestration were higher in abandoned cropland soils than in reforestation woodland soils.
435 Conversely, aggregate stability and soil carbon were not higher in previous arable land converted to
436 citrus woodlands compared with present day croplands. Compared to present day cropland,
437 reforestation woodland soils and abandoned cropland soils are not cultivated and have much higher
438 vegetation cover. Therefore, more organic matter is imported into the soil, thus increasing the soil

439 organic carbon content and promoting the formation of macro-aggregates. Whilst citrus woodlands
440 are not tilled, due to artificial management measures, the surface biomass is low, which is not
441 conducive to the accumulation of soil organic carbon and improvements in soil aggregate stability.
442 Therefore, while planting citrus orchards is beneficial to economic development in the Three Gorges
443 Reservoir Area, it is not conducive to sustainable soil management.

444

445 **5. Conclusion**

446 Using a space-time substitution approach, and compared with present day cropland farming, this
447 investigation suggests improvements in soil aggregate stability and organic carbon content and stocks
448 in different post-farming land management schemes in the Three Gorges Reservoir Area in China. This
449 is the outcome of farming exclusion and vegetation restoration. Soil organic carbon contents were
450 higher in those areas converted to abandoned croplands than in reforestation woodlands. However,
451 compared with present-day croplands, citrus woodlands exhibited lower soil aggregate stability and
452 soil organic carbon contents in the 10–40 cm depth soil layer due to reduced surface biomass brought
453 on by artificial management measures. Artificial restoration (reforestation) and natural grassland
454 succession (i.e., cropland abandonment) are therefore more beneficial for soil aggregate stability and
455 soil organic carbon content and stocks in the study area. Further work is needed to verify the findings
456 of this study and such work could usefully adopt an alternative experimental design based on before
457 and after land use conversion sampling.

458

459 **Declaration of competing interest**

460 The authors declare that there are no competing interests.

461

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468

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674 **Figure captions**

675 **Figure 1.** (a) Location of the study area in China (inset), showing the topographic map of the Three
676 Gorges Reservoir Area; (b) Distribution of sampling plots with different land management schemes.

677

678 **Figure 2.** Photos of sampling sites representing the different land management schemes.

679

680 **Figure 3.** Proportions of different soil aggregate sizes by depth under different land management
681 schemes. Values are presented as the means and corresponding standard errors. Different lowercase
682 letters indicate statistically significant differences ($p < 0.05$).

683

684 **Figure 4.** Values of MWD, GMD, and $1/k$ of soil aggregates under different land management schemes.
685 MWD: mean weight diameter, GMD: geometric mean diameter, $1/k$: soil resistance to erosion; Capital
686 letters indicate a statistically significant difference between soil depths, and lowercase letters indicate
687 statistically significant differences among land management schemes ($p < 0.05$).

688

689 **Figure 5.** The soil organic carbon content (g kg^{-1}) and stocks (Mg ha^{-1}) under different land
690 management schemes. CL: croplands; GW: citrus woodlands; RW: reforestation woodlands; AC:
691 abandoned croplands. Different capital letters indicate statistically significant differences between
692 different soil depths, and different lowercase letters indicate statistically significant differences among
693 the four land management schemes ($p < 0.05$).

694

695 **Figure 6.** Aggregate-specific soil organic carbon content (g kg^{-1}) and stocks (Mg ha^{-1}) under different
696 land management schemes. CL: croplands; GW: Citrus woodlands; RW: reforestation woodlands; AC:
697 abandoned croplands; Different lowercase letters indicate statistically significant differences ($p < 0.05$)
698 among land management schemes.

699

700 **Figure 7.** Correlation analysis of soil organic carbon with properties of aggregates. Red indicates a
701 positive correlation, blue indicates a negative correlation, and the color shading indicates Pearson
702 coefficients * $p < 0.05$ and ** $p < 0.01$. SOC: soil organic carbon, Macro: macro-aggregate, Micro:

703 micro-aggregate, Silt + Clay: Silt + Clay particles, MWD: mean weight diameter, GMD: geometric mean
704 diameter, 1/K: represents the resistance to soil erosion, SOC t: soil organic carbon content (g kg^{-1}),
705 SOCs: soil organic carbon stock (Mg ha^{-1}).

706

707 **Figure 8.** A sythesis of the key processes resulting from the exclusion of farming and vegetation
708 conversion associated with reforestation and cropland abandonment impacting on soil aggregates and
709 organic carbon.