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No-tillage promotes C accumulation in soil but has only a slight effect on yield stability and profitability of rice in subtropical lowland ecosystems

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A long-term (24-years) field experiment was assessed regarding the effect of no-tillage on organic C and rice yield in a subtropical lowland ecosystem in Southern Brazil. Based on our findings, no-tillage promotes C accumulation in subtropical paddy rice soils, but its effect on yield stability and profitability of rice crop is less prominent and only occur in long-term.

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1 **No-tillage promotes C accumulation in soil but has only a slight effect on yield stability and**
2 **profitability of rice in subtropical lowland ecosystems**

3

4 Filipe Selau Carlos,^{1*} Flávio A. O. Camargo,² Elio Marcolin,³ Murilo G. Veloso,⁴ Rodrigo Schmitt
5 Fernandes,² Cimélio Bayer²

6

7 ¹ Department of Soil Science and Graduate Program on Soil and Water Conservation, Eliseu Maciel Faculty
8 of Agronomy, Federal University of Pelotas, Pelotas, RS, Brazil.

9

10 ² Department of Soil Science and Graduate Program on Soil Science, Faculty of Agronomy, Federal
11 University of Rio Grande do Sul, Porto Alegre, RS, Brazil.

12

13 ³ Rice Institute of Rio Grande do Sul State, Cachoeirinha, RS, Brazil.

14

15 ⁴ Graduate Program on Soil Science, Faculty of Agronomy of Federal University of Rio Grande do
16 Sul, Porto Alegre, RS, Brazil.

17

18 * **Corresponding author:** E-mail: cimelio.bayer@ufrgs.br

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22 **No-tillage promotes C accumulation in soil but has only a slight effect on yield stability and**
23 **profitability of rice in subtropical lowland ecosystems**

24

25 **Abstract**

26 **CONTEXT** No-tillage effect on soil organic C (SOC) and rice yield in lowland soils is poorly
27 understood in subtropical ecosystems. **AIMS** We assessed, in a long-term (24-years) field experiment,
28 the effect of no-tillage (NT) on SOC stocks in labile ($> 53 \mu\text{m}$, particulate) and stable ($< 53 \mu\text{m}$,
29 mineral associated) fractions of soil organic matter and on rice grain yield in comparison to
30 conventional tillage (CT) and pre-germinated tillage (PG) systems in a lowland Gleysol in Southern
31 Brazil. **METHOD** Soil from 8 different layers down to 40 cm under each tillage system was sampled
32 in a field experiment, and additional soil samples were obtained from an adjacent area under native
33 grassland (NG) as reference for SOC stocks. **KEY RESULTS** While PG and CT systems maintained
34 similar SOC stocks in comparison to NG soil, NT increased SOC stocks at an annual rate of 0.41 Mg
35 ha^{-1} in relation to the traditional CT soil, mainly in mineral-associated organic matter. Rice grain yield
36 increased twice in the 24-years, amounting to 12 Mg ha^{-1} in the last crop season. Despite the lower
37 rice yield in NT system than under CT and PG systems in the most crop seasons (mean of 7.7, 8.0 and
38 8.5 Mg ha^{-1} for the whole experimental period, respectively), a slight effects on yield stability and
39 profitability ($<10\%$) were observed for NT. **CONCLUSIONS AND IMPLICATIONS** Based on our
40 findings, no-tillage promotes C accumulation in subtropical paddy rice soils, but its effect on yield
41 stability and profitability of rice crop is less prominent and only occur in long-term.

42

43 **Key words:** soil organic matter, C lability, paddy rice, profitability, southern Brazil.

44 **Introduction**

45 Rice (*Oryza sativa* L.) is the staple food for more than one-half of the world's population (Seck et al.,
46 2012). Approximately 80 million ha of rice crop and 75% of the world's rice production are managed
47 by flood irrigation at present (Irri, 2019). Irrigated rice in Brazil comes mainly from the subtropical
48 region in the South. Rio Grande do Sul, which is the southernmost Brazilian state and borders on
49 Argentina and Uruguay, is a massive rice granary with a cultivated area close to 1 Mha (Conab, 2018).
50 Rice yield in this state has increased from 4.0 to 7.5 Mg ha⁻¹ over the last 20 years (Ibge, 2019) as a
51 result mainly of the use of more productive plant varieties plus improvements in soil and crop
52 management (Irga, 2018).

53 In Southern Brazil lowlands, rice is usually grown in tilled soil in order to standardize surfaces,
54 and also to facilitate sowing and irrigation while minimizing competition from weeds (Sosbai, 2018).
55 The most widely used soil tillage systems for rice cultivation in Southern Brazil are conventional
56 tillage (CT) and minimum tillage (MT), both of which involve sowing in dry soil. However, pre-
57 germinated tillage (PG) is traditionally adopted in small farms, in which soil is flooded for almost half
58 of the year (i.e., about two months more than under CT; Sosbai, 2018).

59 Long-term field studies conducted in American, African and Asian Continents have shown
60 irrigated rice cultivation in CT soils to have an adverse impact on soil organic carbon (SOC) (Buarach
61 et al., 2014; Rosa et al., 2011; Zhou et al., 2009) despite the prevailing anoxic environment, where
62 microbial activity is partially inhibited (Sarahwat, 2005). Because of the well-known impact of SOC
63 on chemical, physical and biological properties of subtropical soils, a decline in SOC stocks can
64 adversely affect soil quality and rice yield. The extended soil flooding period in PG may result in
65 decreased microbial decomposition of soil organic matter (SOM) due to less efficient anaerobic
66 metabolism (Rinklebe & Longer, 2006). These conditions may help maintain SOM status, but no
67 scientific evidence from field studies exists as to whether this is indeed the case.

68 One of the current challenges posed by irrigated rice cultivation in the subtropical lowland
69 ecosystems of Brazil arises from the adoption of no-tillage (NT), which may be an effective practical
70 strategy for soil organic matter stabilization (Sahrawat, 2005, 2012), with potential benefits on SOC
71 stocks and lability, which can provide a useful combined indicator of soil performance potential (Blair
72 et al., 1995; Zanatta et al., 2019). However, some studies in lowland soils have shown frequent

73 flooding to decrease the stability of soil aggregates, thereby reducing physical protection of labile
74 organic fractions such as particulate organic matter (Nascimento et al., 2009; Rosa et al., 2011) —it
75 should be borne in mind that C of stable organic matter associated with minerals is the most strongly
76 affected by tillage in flooded soils (Nascimento et al., 2009).

77 Despite the potential effect of soil quality on crop yields, the response of irrigated rice yield to
78 NT remains unclear (Huang et al., 2015), with some studies suggesting a favorable effect (Buarach et
79 al., 2014) and some an adverse influence (Singh et al., 2013; Alan et al., 2014). Rather than rice yield,
80 the impact of tillage systems should be assessed in terms of between-season stability (Knapp & van
81 der Heijden, 2018) and profitability (Page et al., 2019).

82 The starting hypothesis for this work was that no-tillage would have a more favorable long-
83 term impact on SOC stocks and rice yield in subtropical lowland ecosystems than would tillage.
84 Carbon stabilization in lowland soil under NT occurs mainly by association with minerals and has a
85 minor effect on particulate SOM. Rather than grain yield, NT increases between-season yield stability
86 and gross margin in rice crop. The main purpose of this work was to assess the long-term effect of
87 three tillage systems on SOC stocks and lability, grain yield and its between-season stability, and gross
88 margins of irrigated rice in a subtropical sandy loam Gleysol in Southern Brazil.

90 **Materials and Methods**

91 ***Site description, experiment design and conduction***

92 The study was based on a 24-yr old experiment at the Experimental Station of the Rio Grande do Sul
93 Rice Institute in the municipality of Cachoeirinha (Rio Grande do Sul State, Southern Brazil;
94 29°57'02" S, 51°05'02" W, 7 m a.s.l.). The climate as per Köppen's classification is Cfa, and the mean
95 annual temperature and rainfall are 18.4 °C and 1412 mm, respectively. The soil was a sandy loam
96 Gleysol (WRB/FAO) and had the following properties: clay content = 170 g kg⁻¹, organic matter
97 content = 17 g kg⁻¹, p_{H2O} = 5.3, available P (Mehlich-1) = 14.3 mg dm⁻³ and available K (Mehlich-1)
98 = 41.8 mg dm⁻³. The original vegetation was native grassland, which was preserved in a small area in
99 the vicinity of the experiment site.

100 The experiment, established in 1994, involved a monoculture of irrigated rice (*Oryza sativa* L.)
101 in the spring/summer in succession to a self-growing ryegrass (*Lolium multiflorum* Lam.) as a

102 nonirrigated cover crop in the autumn/winter. The soil was subjected to three tillage systems, namely:
103 (a) conventional tillage (CT), where the soil was mobilized on a yearly basis through plowing (2
104 months after rice harvest) and harrowing (first immediately after plowing and then 2 weeks after
105 ryegrass desiccation) immediately before rice was sown in spring; (b) pre-germinated tillage (PG), by
106 which soil was disturbed similarly to CT, but smoothing and levelling with a blade were performed
107 under flooding (water layer of approximately 5 cm) prior to sowing previously germinated seeds; and
108 (c) no-tillage (NT), with which the soil was not subjected to any tillage operation and the rice was
109 sowed through the straw layer on the soil surface. The experimental design consisted of complete
110 randomized blocks with three replications. Each plot was 28 × 40 m and separated from the others by
111 levees.

112 A glyphosate-based herbicide was applied at 3 L ha⁻¹ to ryegrass at the flowering stage in early
113 spring, followed by machine chopping of standing biomass in the three tillage systems. The rice sowing
114 was performed until the first half of November. With CT and NT, rice was mechanically seeded at a
115 rate of 125 kg ha⁻¹ with a seed drill along lines spaced 17.5 cm; also, the soil was irrigated by flooding
116 when the plants were at developing stage V4 (Counce et al., 2000). With PG, the soil was flooded
117 about 60 days before seeding and pre-germinated seeds were broadcast after the plots were leveled
118 and flooded.

119 The rice varieties and rates of N, P₂O₅ and K₂O fertilization for each crop season were identical
120 for all tillage systems (see Table S1 in Supplementary data).

122 ***Biomass and carbon input by rice and ryegrass***

123 An average annual C input was estimated for the whole experimental period as the combined biomass
124 of ryegrass in winter and rice in summer. The shoot biomass of ryegrass was estimated by averaging
125 biomass production in 2001, 2002, 2014 and 2015 as evaluated in six sub-samples collected from a
126 0.5 m² area in each plot. The shoot biomass supplied by rice was estimated from rice grain yields,
127 using an apparent (without roots) harvest index of 0.5 (Fageria et al., 2007). A dry matter contribution
128 of roots equivalent to 30% of shoot biomass of rice (Holzschuh et al., 2009) and ryegrass (Assmann et
129 al., 2014) was considered. Also, a mean concentration of 0.45 kg C kg⁻¹ dry matter of both residues
130 was used to estimative of C input (Nascimento et al., 2009).

131

132 ***Soil sampling and analysis***

133 The soil profile was sampled at eight different depths (0–2.5, 2.5–5, 5–7.5, 7.5–10, 10–15, 15–20,
134 20–30 and 30–40 cm) after rice harvest in March 2015 (i.e., 21 years after the experiment was started).

135 An area under native grassland adjacent to the experimental site was also sampled at the same soil
136 depths and used as reference for natural SOC stocks. A total of 20 soil sub-samples were collected
137 with a cutting shovel and combined into a single composite sample from each plot that was air dried
138 and ground to ≤ 2 mm in a Marconi 330 grinder. Approximately 20 g of soil was further ground to \leq
139 0.025 mm in a mortar and analyzed for C by dry combustion in a Fisher Scientific Flash 2000 CN
140 analyzer.

141 SOC stocks were calculated by using the equivalent soil mass approach (Ellert & Bettany,
142 1995) with CT soil mass as reference. Soil bulk density (BD, Table S2) was determined by using the
143 volumetric ring method (Blake & Hartge, 1986) in duplicate at the same soil depths as for SOC.

144 Soil organic matter was subjected to granulometric fractionation in order to quantify the labile
145 and stable C-pools in soil organic matter. Briefly, 20 g soil samples were shaken horizontally in 80
146 mL of sodium hexametaphosphate solution (5 g L^{-1}) for 16 h (Cambardella & Elliott, 1992). The
147 resulting suspensions were sieved through $53 \mu\text{m}$ mesh and the retained fraction, which consisted of
148 particulate SOM (POM, labile fraction), were washed, oven dried at $50 \text{ }^\circ\text{C}$ and analyzed for C by dry
149 combustion. The C content of mineral-associated organic matter (min-OM, stable fraction) was
150 calculated as the difference between SOC and POM-C.

151 The carbon management index (CMI) for the 0–40 cm layer was calculated as originally
152 proposed by Blair et al. (1995), and POM-C and Min-OM-C were used as proxies for the labile and
153 stable C pools, respectively (Vieira et al., 2007). CMI was calculated from data for the native grassland
154 (NG) soil used as reference (CMI = 100) as follows:

$$155 \text{ CMI} = \text{CLI} \times \text{CPI} \times 100 \quad (1)$$

$$156 \text{ CPI} = \text{C pool index} = \frac{\text{treatment Cstock}}{\text{reference Cstock}} \quad (2)$$

$$157 \text{ CLI} = \text{C lability index} = \frac{\text{C lability (L) in treatment}}{\text{C lability in the reference NG}} \quad (3)$$

158 $L = C \text{ lability} = \frac{C \text{ stock in labile SOM fraction } 0 - 40 \text{ cm}}{C \text{ stock in stable SOM fraction } 0 - 40 \text{ cm}}$ (4)

159
160 ***Rice grain yield, between-season yield stability and gross margin***

161 Rice grain yield was determined by harvesting 6 subsamples from a 4 m² area in each plot and
162 expressed at 130 g kg⁻¹ soil moisture. No rice was harvested in the 2001/02 season because the crop
163 had been attacked by birds; also, soybean was grown from 2010/11 to 2013/14, so rice yield could
164 only be assessed in 19 seasons.

165 Between-season stability in grain yield was assessed by calculating a relative stability ratio for
166 each tillage system according to Knapp & van der Heijden (2018). Such ratio, which represents the
167 variability per unit grain yield, was calculated by dividing the coefficient of variation (CV) for each
168 tillage system by that for the CT system (the reference). Thus, ratio values of 1, < 1 or > 1 for a tillage
169 system indicated that between-season stability in grain yield under it was identical with, lower than or
170 higher than, respectively, that for CT system.

171 An economic analysis was conducted to compare the gross margins for the three tillage
172 systems. Gross margin was calculated as the income from grain minus the operating costs involved in
173 producing the summer cash crop each year. No fixed or overhead expenses such as rates, tax,
174 insurance, interest or depreciation on machinery and buildings were considered. All costs and income
175 were calculated on the basis of present-day values with provision for no fluctuations in input costs
176 over time. The overall costs for rice under CT in the 2018/19 crop season estimated by the
177 Riograndense Rice Institute were used as reference (1372 US\$ ha⁻¹). With NT, the economy of diesel
178 resulting from less tillage operations amounted to 96 US\$ ha⁻¹ and was subtracted from the costs of
179 the CT system. With PG, the additional cost of irrigation for 2 further months (73 US\$ ha⁻¹) was added
180 to the CT costs. The gross income from the grain harvest was calculated on the assumption of a grain
181 price of 221 US\$ Mg⁻¹ (viz., the current price rice paid to farmers). No fluctuations in grain price over
182 time were considered.

183

184 ***Statistical analysis***

185 The results were checked for variance normality and homoscedasticity with the Kolmogorov–Smirnov
186 and Levene test, respectively, and appropriated data transformation were performed when assumptions
187 were violated. The analysis of the variance was performed and, when significant ($p < 0.05$), the
188 differences between treatment means were evaluated with Tukey's test at $p < 0.05$. The MIXED
189 procedure was used to compare the effects of tillage method (T) and soil layer (L) on the response of
190 the SOC and SOM pools. On the other hand, tillage methods (T) were compared in terms of their effect
191 on rice yield and SOC stocks in the 0–40 cm layer. The results for NP were excluded from the statistical
192 analysis because this tillage system did not follow the experimental design and was simply used as
193 reference for the effects of tillage. The statistical procedures used tillage method as a fixed factor, and
194 blocks and experimental errors as random variables. All analyses were performed with SAS® v. 9.4
195 (Statistical Analysis System Institute, Cary, NC, USA).

196

197 **Results**

198 ***Carbon input by crops***

199 The average addition of biomass (shoots + roots) from winter ryegrass and summer rice for the three
200 tillage systems was 15.09 Mg ha⁻¹ and rice biomass accounting for 64% of total biomass addition
201 (Table 1). The annual C input ranged from 6.7 to 7.0 Mg ha⁻¹ across tillage systems.

202

203 ***Soil carbon content and stocks, and soil organic matter fractions***

204 Twenty-one years of contrasting tillage systems resulted in large differences in SOC stocks in the 0–40
205 cm soil layer (Table 2). In fact, SOC stocks ranged from 46.5 Mg ha⁻¹ in CT soil to 55.6 Mg ha⁻¹ in
206 NT soil (Table 2), with an intermediate value (47.8 Mg ha⁻¹) in PG soil. However, the increased SOC
207 level under NT was restricted to the surface soil layer (0–2.5 cm; Figure 1). The difference in SOC
208 down to 40 cm between CT and NT (9.1 Mg ha⁻¹) resulted in an annual C accumulation rate of 0.41
209 Mg ha⁻¹. SOC stocks under NT were similar to those in the reference soil (NG; Table 2).

210 POM-C and Min-C were affected by tillage system only in the surface soil layers (Figure 1).
211 Thus, POM-C ranged from 4.9 to 24.4 g kg⁻¹ soil in the surface layer but dramatically decreased with
212 depth (to 0.3–0.4 g kg⁻¹ soil in 30–40 cm layer; Figure 1). As with SOC, tillage had a substantial impact

213 on the surface soil layer, where POM-C was 100 and 110% greater with NT than it was with CT and
214 PG, respectively. No differences in POM-C stocks in the 0–40 cm soil layer among tillage systems
215 were observed, however (Table 2). NT also resulted in increased Min-C stocks in the surface soil layers
216 (Figure 1), the increased levels reflecting in Min-C stocks down to 40 cm that were 16 and 19% greater
217 than with CT and PG, respectively (Table 2).

218

219 ***Carbon pool indices***

220 Relative to NG (CLI and CPI = 1, CMI = 100), CPI and CMI in the 0–40 cm layer were influenced by
221 tillage system, whereas CLI was not (Table 2). Thus, CLI was 20–40% lower with the three systems
222 than it was in the reference soil (NG). On the other hand, CPI was 10% lower with CT and PG, but
223 10% higher with NT (Table 2). The combination of the previous CLI values and the respective
224 quantitative changes in SOC stocks embodied in CPI led to a CMI value with CT, PG and NT
225 corresponding to 59.6%, 79.9% and 81.4% that for NG.

226

227 ***Rice yield, between-season yield stability and gross margin***

228 The average rice yield for the body of tillage systems increased from 5.0 Mg ha⁻¹ in the 1994/95 crop
229 season to around 8.0 Mg ha⁻¹ in the 2000s and almost 12.0 Mg ha⁻¹ in the last season (Figure 2).
230 Overall, rice grain yield under PG was higher than it was under CT and/or NT in 10 of the 19 crop
231 seasons (Figure 2). In contrast, NT had slight lower yields than did CT and/or PG in 11 seasons (Figure
232 2). The mean rice grain yield for the experimental period was 8.0 Mg ha⁻¹ with CT, 8.5 Mg ha⁻¹ with
233 PG and 7.7 Mg ha⁻¹ with NT.

234 Yield stability, as measured in terms of the ratio of coefficient of variation for rice yield relative
235 to the CT system, was higher with PG and NT. The yield stability ratio under NT exceeded 1.0 and
236 was 15% higher on average than under CT and PG during the first 7 years, but decreased in the long
237 term (Figure 3). In fact, the ratio was 4% and 10% lower under PG and NT, respectively, than it was
238 under CT between the 8th and 14th year, and 13 % and 23% lower, respectively, between the 15th and
239 24th year (Figure 3). These results indicate that PG and NT led to more stable yields in the long-term
240 than did CT (Figure 3).

241 The absolute gross margins of rice production under NT and PG were slightly higher than they
242 were under CT in 17 and 12 crop seasons, respectively (Figure 4a). Gross margins across seasons
243 averaged at 428 US\$ ha⁻¹ with NT and 425 US\$ ha⁻¹ with PG, both figures being slightly higher than
244 that for CT (392 US\$ ha⁻¹). While the differential gross margin between PG and CT was similar
245 throughout the experimental period, that between NT and CT increased from nearly -60 US\$ ha⁻¹ in
246 the early years to around 131 US\$ ha⁻¹ in the latest (Figure 4b).

247

248 Discussion

249 *Soil organic carbon stocks*

250 Twenty-one years of contrasting tillage systems resulted in large differences (up to 9.1 Mg ha⁻¹) in
251 SOC stocks in the soil profile (0–40 cm; Table 2). Conversion from NG to irrigated rice in tilled soil
252 decreased SOC stocks, with little difference between CT (2.8 Mg C ha⁻¹) and PG (1.5 Mg C ha⁻¹).
253 This similarity in SOC down to 40 cm between NG, CT and PG was possibly a result of the combined
254 effect of a high biomass input by summer rice (presumably higher than 9 Mg DM ha⁻¹) and the slow
255 decomposition of organic matter in flooded soil relative to NP even though the soil was annually
256 perturbed by plowing and disking. Anaerobic organisms in flooded soil are less efficient in obtaining
257 energy from organic matter than are aerobic organisms (Pett-Ridge et al., 2006)—and hence also less
258 efficient in mineralizing plant residues incorporated into soil (Bellinger et al., 2012). The increased
259 SOC levels of PG relative to CT may have resulted from the former system involving flooding for a
260 longer time (approximately 2 months), thereby reducing the rate of mineralization of organic
261 compounds in the soil.

262 On the other hand, increase of SOC stocks in NT relative to CT is consistent with previous
263 reports (Liping and Erda, 2001; Nascimento et al., 2009; Rosa et al., 2011; Xu et al., 2013). The
264 increased SOC stocks under NT resulted from enrichment with C of the soil surface layer by effect of
265 the absence of perturbations and the presence of a high annual C input. Thus, NT increased SOC down
266 to 40 cm at a rate of 0.41 Mg C ha⁻¹ yr⁻¹ relative to CT. These annual soil C accumulation rates in NT
267 soil under irrigated rice are similar to those found by Zanatta et al. (2007) in uplands (0.44–0.60 Mg
268 ha⁻¹) under similar climatic conditions.

269 If annual C inputs are assumed to be similar among tillage systems, then the increase in SOC
270 stocks was a result of more marked SOC stabilization in NT soil than in no-tilled soils. The SOC
271 differences of NT with CT and PG can be ascribed to differences in Min-C stocks, which correspond
272 to organomineral associations. The association of organic C with minerals has been deemed one of the
273 main mechanisms for stabilizing organic C in soil, mainly in lowland rice soils where frequent flooding
274 causes rupture of soil aggregates and low efficiency of physical protection to organic matter
275 stabilization (Nascimento et al., 2009; Conceição et al., 2013).

276 Despite the marked residue input by rice, the increased C/N ratio and Si content (Devêvre &
277 Horwáth, 2000; Pereira et al., 2004) relative to NG also probably diminished turnover of residual C
278 and hindered its incorporation into the POM-C pool (or CLI). This was also probably why, even under
279 NT, POM-C and CLI (0.7 in 0–40 cm soil layer) tended to decline and were never restored to the
280 starting level in NG soil (Table 2). As a result, CMI was lower under CT and PG than it was under
281 NG. On the other hand, NT allowed CMI in 0–40 cm soil layer to be partially recovered and CMI
282 levels under this system to be similar to those in NG soil. Based on these results, NT provides an
283 effective method for increasing SOC stocks in soil bearing irrigated rice in the long term, albeit with
284 potentially adverse effects on the role played by labile carbon (POM-C) in soil.

285

286 ***Rice yield, between-season yield stability and gross margin***

287 A marked increase in rice yield (5–12 Mg ha⁻¹) was observed over the 19 crop seasons irrespective of
288 tillage system. This was mainly the result of improved soil and crop management, and of using shorter,
289 soluble Fe-tolerant, resistant to diseases and, thus, more productive rice varieties. Especially prominent
290 among soil and crop management conditions were the preferential time to sowing; better seed quality
291 and treatment; a reduced sowing density; higher, more balanced fertilizer rates; earlier irrigation; and
292 more efficient control of weeds, insect pests and diseases (Menezes et al., 2012).

293 The increased rice yield observed under PG in 11 of the 19 years can be ascribed to the fact
294 that flooding was advanced by approximately 30 days before rice sowing. Earlier flooding led to also
295 earlier electrochemical changes in the soil solution, and raised pH, reduced Al³⁺ concentrations and
296 increased nutrient availability in the soil solution as a result, thus boosting rice development

297 (Ponnamperuma, 1972). In addition, earlier flooding facilitated physical control of weeds (red rice
298 mainly), thus reducing disease and damage to the crop (Sosbai, 2018).

299 On the other hand, NT exhibited lower rice yields in 11 of the 19 growing seasons.
300 Interestingly, this system led to limited crop yield during the first ten seasons, possibly as a result of
301 N being immobilized by soil microorganisms (Beri et al., 1992). This was probably not the case with
302 CT and PG, which led to increased rice yields relative to NT. However, yields were similar with NT
303 and PG in the last 5 crop seasons (except in penultimate season), and also with NT and CT in the last
304 10 crop seasons (except in last season). The gradual increase in rice grain yield under NT in the long
305 term may be associated to the increase in soil organic matter increasing the availability of N, which is
306 the individual nutrient most markedly influencing rice development (Nadelhoffer et al., 1983).

307 NT and PG led to greater temporal yield stability than did CT (Page et al., 2019). Interestingly,
308 relative yield stability ratio was negatively related to rice yield. Thus, as previously found by Knapp
309 & Van Heijden (2018) and Page et al. (2019), such stability ratio decreased with increasing yield in
310 long term. In relation to profitability, the reduced production costs of NT, and the yield advantage of
311 NT and PG, resulted in higher gross margins with these two tillage systems than with CT. Although
312 rice yield was substantially higher under PG than it was under NT, the former system was not more
313 profitable than the latter owing to the increased cost derived from irrigation for 2 further months. Our
314 results suggest that profits from conventional rice production systems in Southern Brazil could be
315 increased by 33 US\$ ha⁻¹ by switching from CT to PG, and by 36 US\$ ha⁻¹ by replacing CT with NT.
316

317 **Conclusions**

318 Tillage system is a key factor influencing soil organic matter and gross margins in irrigated rice. No-
319 tillage appears to be a C-friendly system for lowland soils, mainly because it increases their contents
320 in mineral associated organic matter. Despite lower rice yield than pre-germinated and conventional
321 tillage systems, no-tillage determined a slight increase on yield stability and profitability, which effects
322 are less obvious and only occur in the long term.

323

324

325 **Conflicts of Interest**

326 The authors declare no conflicts of interest

327

328 **Data Availability Statement**

329 The data that support this study will be shared upon reasonable request to the corresponding author.

330

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336

337 **References**

- 338 Alam, M.K., Islam, M.M., Salahin, N. & hasanuzzaman, M. (2014). Effect of Tillage Practices on Soil
339 Properties and Crop Productivity in Wheat-Mungbean-Rice Cropping System under Subtropical
340 Climatic Conditions. *The scientific World Journal*, **2014**, 1–15. DOI: 10.1155/2014/437283.
- 341 Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.V.G.D.A., Cecagno, D., Carlos, F.S. &
342 Carvalho, P.C.D.F. (2014). Soil carbon and nitrogen stocks and fractions in a long-term integrated
343 crop–livestock system under no-tillage in southern Brazil. *Agriculture Ecosystem &*
344 *Environment*, **190**, 52–59. DOI:10.1016/j.agee.2013.12.003.
- 345 Bellinger, B.J., Hagerthey, S.E., Newman, S. & Cook, M.I. (2012). Detrital floc and surface soil
346 microbial biomarker responses to active management of the nutrient impacted Florida
347 *Everglades*. *Microbial Ecology*, **64**, 893–908. DOI:10.1007/s00248-012-0090-2.
- 348 Beri, V., Sidhu, B.S. & Bhat, A.K. (1992). Nitrogen and phosphorus transformations as affected by
349 crop residue management practices and their influence on crop yield. *Soil Use and Management*,
350 **11**, 51–54.
- 351 Blair, G., Lefroy, R. & Lisle, L. (1995). Soil carbon fractions based on their degree of oxidation, and
352 the development of a carbon management index for agricultural systems. *Australian Journal of*

- 353 *Agricultural Research*, **46**, 1459–1466. DOI:10.1071/AR9951459.
- 354 Blake, G.R. & Hartge, K.H. (1986). Bulk density. In: Klute, A. (Ed.), *Methods of Soil Analysis, Part*
355 *1. Physical and Mineralogical Methods*. ASA/SSSA, Madison, pp. 363–382.
- 356 Buarach, K., Thongjoo, C., Udomprasert, N. & Amkha, S. (2014). Effects of tillage system and soil
357 organic matter amendment on growth, yield of Pathumthani 80 rice and carbon sequestration in
358 paddy soil. *Modern Applied Science*, **8**, 1–7. DOI: 10.5539/mas.v8n4p1.
- 359 Cambardella, C. & Elliott, E.T. (1992). Particulate Soil Organic-Matter Changes across a Grassland
360 Cultivation Sequence. *Soil Science Society of American Journal*, **56**, 777–783.
361 DOI:10.2136/sssaj1992.03615995005600030017x.
- 362 Conab. Companhia Nacional de Abastecimento. <http://www.conab.gov.br/conteudos.php>. Last
363 accessed 22/04/2020.
- 364 Conceição P.C., Dieckow J. & Bayer C. (2013). Combined role of no-tillage and cropping systems in
365 soil carbon stocks and stabilization. *Soil Tillage & Research*, **129**, 40–47, DOI:
366 10.1016/j.still.2013.01.006.
- 367 Counce, P.A., Keisling, T.C. & Mitchell, A.J. (2000). A uniform, objective, and adaptive system for
368 expressing rice development. *Crop Science*. **40**, 436–443. DOI: 10.2135/cropsci2000.402436x.
- 369 Devêvre, O.C. & Horwáth, W.R. (2000). Decomposition of rice straw and microbial carbon use
370 efficiency under different soil temperatures and moistures. *Soil Biology and Biochemistry*, **32**,
371 1773–2000.
- 372 Ellert, B.H. & Bettany, J.R. (1995). Calculation of organic matter and nutrients stored in soils under
373 contrasting management regimes. *Canadian Journal of Soil Science*, **75**, 529–538. DOI:
374 10.4141/cjss95-075
- 375 Fageria, N.K., Santos, A.B. & Cutrim, V.A. (2007). Yield and nitrogen use efficiency of lowland rice
376 genotypes as influenced by nitrogen fertilization. *Pesquisa Agropecuária Brasileira*, **42**, 1029–
377 1034. DOI: 10.1590/S0100-204X2007000700016.
- 378 Holzschuh, M.J., Bohnen, H., Anghinoni, I., Meurer, E.J., Carmona, F. de C. DOI Costa, S.E.V.G. de
379 A. (2009). Resposta do arroz irrigado ao suprimento de amônio e nitrato. *Revista Brasileira de*
380 *Ciência do Solo*, **33**, 1323–1331. DOI:10.1590/S0100-06832009000500025.
- 381 Huang, M., Zhou, X., Cao, F., Xia, B. & Zou, Y. (2015). No-tillage effect on rice yield in China: A

- 382 meta-analysis. *Field Crops Research*, **183**, 126–137. DOI: 10.1016/j.fcr.2015.07.022
- 383 Ibge (Brazilian Institute of Geography and Statistics). (2019). Systematic survey of agricultural
384 production. Rio de Janeiro-RJ, Brazil. (in Portuguese).
- 385 Irga. Bulletin of rice crop results season 2017/18. (2018). Cachoeirinha-RS, Brazil. [https://irga-](https://irga-admin.rs.gov.br/upload/arquivos/201807/30100758-boletim-final-da-safra-201-18-final.pdf)
386 [admin.rs.gov.br/upload/arquivos/201807/30100758-boletim-final-da-safra-201-18-final.pdf](https://irga-admin.rs.gov.br/upload/arquivos/201807/30100758-boletim-final-da-safra-201-18-final.pdf).
387 Last accessed 22/04/2020. (in Portuguese).
- 388 Irri, 2019. Rice facts [WWW Document]. <http://irri.org>. Last accessed 22/04/2020.
- 389 Knapp, S. & van der Heijden, M.G.A. (2018). A global meta-analysis of yield stability in organic and
390 conservation agriculture. *Nature Communications*, **9**, 1–9. DOI: 10.1038/s41467-018-05956-1.
- 391 Liping, G. & Erda, L. (2001). Carbon sink in cropland soils and the emission of greenhouse gases from
392 paddy soils: A review of work in China. *Chemosphere - Global Change Science*, **3**, 413–418.
393 DOI:10.1016/S1465-9972(01)00019-8.
- 394 Menezes, V., Anghinoni, I., Silva, P.R.F. da, Macedo, V.R.M., Petry, C., Grohs, D.S., Freitas, T.F.S.
395 & Valente., L.A.L. (2012). Project 10 – Management strategies to increase yield and
396 sustainability of irrigated rice crops in Rio Grande do Sul State: advances and new challenges.
397 Cachoeirinha-RS, Brazil. *IRGA, Estação Experimental do Arroz*. (in Portuguese).
- 398 Nascimento, P.C., Bayer, C., Netto, L. de F. da S., Vian, A.C., Vieiro, F., Macedo, V.R.M. & Macedo,
399 E. (2009). Management system and organic matter in lowlands with rice cultivation. *Revista*
400 *Brasileira de Ciência do Solo*, **33**, 1821–1827. DOI: 10.1590/S0100-06832009000600030 (in
401 Portuguese).
- 402 Nadelhoffer, K.J., Aber, J.D. & Melillo, J.M. (1983). Leaf-litter production and soil organic matter
403 dynamics along a nitrogen-availability gradient in Southern. *Canadian Journal of Forest*
404 *Research*, **13**, 12–21. DOI: 10.1139/x83-003.
- 405 Page, K.L., Dang, Y.P., Dalal, R.C., Reeves, S., Thomas, G., Wang, W. & Thompson, J.P. (2019).
406 Changes in soil water storage with no-tillage and crop residue retention on a Vertisol: impact on
407 productivity and profitability over a 50 year period. *Soil Tillage & Research*, **194**, 104319.
408 DOI:10.1016/j.still.2019.104319
- 409 Pereira, H.S., Korndörfer, G.H., Vidal, A.A. & Camargo, M.S. (2004) Silicon sources for rice crop.
410 *Scientia Agricola*, **61**, 522–528. DOI: 10.1590/S0103-90162004000500010.

- 411 Pett-Ridge, J., Silver, W.L. & Firestone, M.K. (2006). Redox fluctuations frame microbial community
412 impacts on N-cycling rates in a humid tropical forest soil. *Biogeochemistry*, **81**, 95–110.
413 DOI:10.1007/s10533-006-9032-8
- 414 Ponnampetuma, F.N. (1972). The chemistry of submerged soils. *Advances in Agronomy*, **24**, 29–96.
415 DOI:10.1016/S0065-2113(08)60633-1
- 416 Rinklebe, J. & Longer, U. (2006). Microbial diversity in three floodplain soils at the Elbe River
417 (Germany). *Soil Biology and Biochemistry*, **38**, 2144–2151. DOI:10.1016/j.soilbio.2006.01.018.
- 418 Rosa, C.M. da, Castilhos, R.M.V., Pauletto, E.A., Pillon, C.N. & Leal, O. dos A. (2011). Organic
419 carbon content in Planossol under irrigated rice management systems. *Revista Brasileira de*
420 *Ciência do Solo*, **35**, 1769–1776. DOI:10.1590/S0100-06832011000500031. (in Portuguese).
- 421 Sahrawat, K.L. (2005). Fertility and organic matter in submerged rice soils. *Current Science*, **88**, 735–
422 739.
- 423 Sahrawat, K.L. (2012). Soil fertility in flooded and non-flooded irrigated rice systems. *Archives of*
424 *Agronomy and Soil Science*, **58**, 432–436. DOI: 10.1080/03650340.2010.522993.
- 425 Seck, P.A., Diagne, A., Mohanty, S. & Wopereis, M.C. (2012). Crops that feed the world: Rice. *Food*
426 *Security*, **4**, 7–24. DOI: 10.1007/s12571-012-0168-1.
- 427 Singh, K., Mishra, A.K., Singh, B., Singh, R.P. & Patra, D.D. (2013). Tillage effects on crop yield and
428 physicochemical properties of sodic soils. *Land Degradation & Development*, **27**, 223–230. DOI:
429 10.1002/ldr.2266
- 430 Soil Survey Staff. (2014). Keys to soil taxonomy. *Washington: United States Department of*
431 *Agriculture, Natural Resources Conservation Service*. 12th ed. 372 pp.
- 432 Sosbai, Brazilian Society of Irrigated Rice (2018). Technical research recommendations for Southern
433 Brazil. Neiva Knaak e Fernando Fumagalli Miranda (Eds). Cachoeirinha. 205 pp. (in Portuguese).
- 434 Vieira, F.C.B., Bayer, C., Zanatta, J.A., Dieckow, J., Mielniczuk, J. & He, Z.L. (2007). Carbon
435 management index based on physical fractionation of soil organic matter in an Acrisol under
436 long-term no-till cropping systems. *Soil Tillage & Research*, **96**, 195–204. DOI:
437 10.1016/j.still.2007.06.007.
- 438 Xu, S.Q., Zhang, M.Y., Zhang, H.L., Chen, F., Yang, G.L. & Xiao, X.P. (2013). Soil Organic Carbon
439 Stocks as Affected by Tillage Systems in a Double-Cropped Rice Field. *Pedosphere*, **23**, 696–

- 440 704. DOI: 10.1016/S1002-0160(13)60062-4.
- 441 Zanatta, J.A., Vieira, F.C.B., Briedis, C., Dieckow, J. & Bayer, C. (2019). Carbon indices to assess
442 quality of management systems in a Subtropical Acrisol. *Scientia Agricola*, **76**, 501–509. DOI:
443 10.1590/1678-992x-2017-0322.
- 444 Zanatta, J. A., Bayer, C., Dieckow, J., Vieira, F.C.B. & Mielniczuk, J. (2007). Soil organic carbon
445 accumulation and carbon costs related to tillage, cropping systems and nitrogen fertilization in a
446 subtropical Acrisol. *Soil Tillage & Research*, **94**, 510–519. DOI: 10.1016/j.still.2006.10.003.
- 447 Zhou, P., Song, G., Pan, G., Li, L. & Zhang, X. (2009). Study on the accumulation mechanism of
448 organic carbon in three typical paddy soils in South China under long-term experiments II.
449 Chemical binding mechanism of organic carbon in aggregates. *Journal of Soil Science*, **46**, 263–
450 273.

Figures Caption

Figure 1. Soil organic carbon (a), particulate organic C (b) and mineral associated organic C (c) in the 0–40 cm layer of a sandy loam Gleysol subjected to three different tillage systems for 21 years, or native grassland (NG), in Southern Brazil. Horizontal bars denote least significant differences as per Tukey's test at $p < 0.05$. ns not significant. CT conventional tillage, NT no-tillage, PG pre-germinated tillage.

Figure 2. Time course of irrigated rice grain yield from 1994/95 to 2017/18 in a sandy loam Gleysol subjected to three different tillage systems in Southern Brazil. Tillage means followed by same letter for each crop season were not significantly different as per Tukey's test at $p < 0.05$. In 2001/02, rice was attacked by birds, so it was not harvested. Also, in the growing seasons from 2010/11 to 2013/14, soybean was cultivated to control red rice. CT conventional tillage, NT no-tillage, PG pre-germinated tillage.

Figure 3. Between-season relative stability ratio of rice grain yield under pre-germinated tillage (PG) and no-tillage (NT) relative to the conventional tillage (CT) in the short (1–7 seasons), medium (8–15 seasons) and long-term (16–24 seasons) in a subtropical Gleysol in Southern Brazil. A ratio < 1 or > 1 for a tillage system indicate that between-season stability in grain yield under it was higher than or lower than, respectively, that for CT.

Figure 4. Gross margin of irrigated rice (US\$ ha⁻¹) under three different tillage systems (CT, NT and PG) (a), and differential gross margin under NT and PG in relation to CT (reference) (b), on a sandy loam Gleysol in southern Brazil. The continuous line in the figure (b) represents the mean trend in differential gross margins across crop seasons in

differential gross margins between NT or PG in relation to CT system. No rice was harvested in 2001/02 because the crop was attacked by birds. Also, soybean was cultivated to control red rice in the growing seasons from 2010/11 to 2013/14. CT conventional tillage, NT no-tillage, PG pre-germinated tillage.

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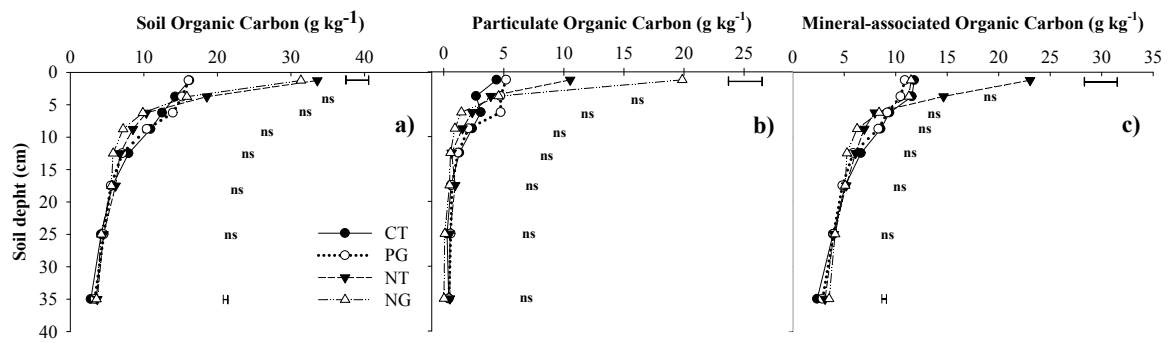


Fig. 1.

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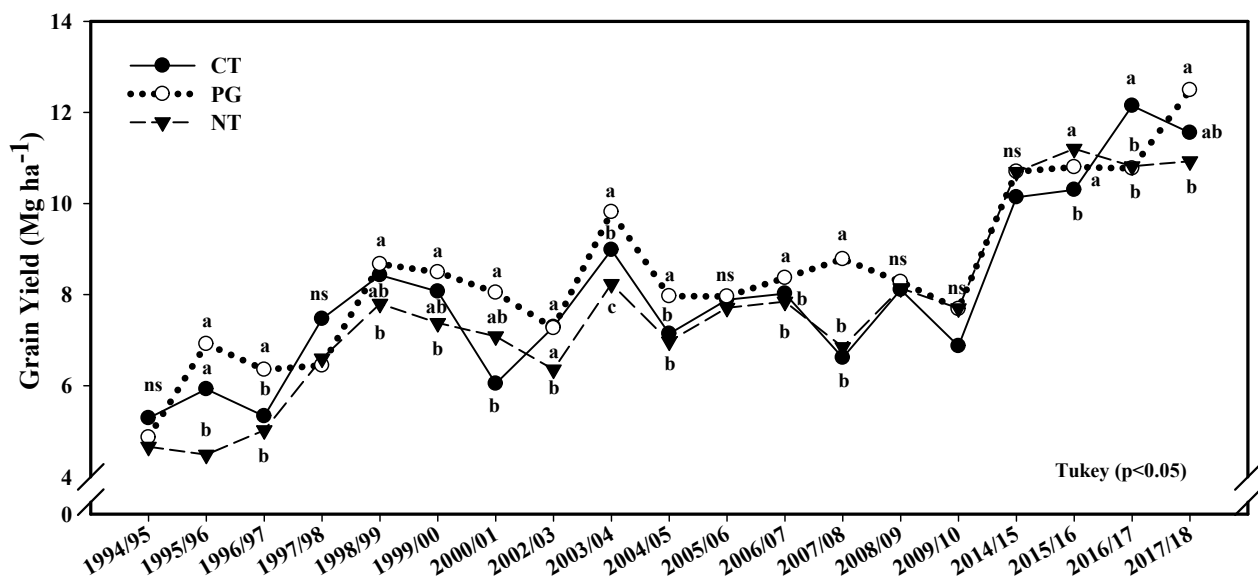


Fig. 2.

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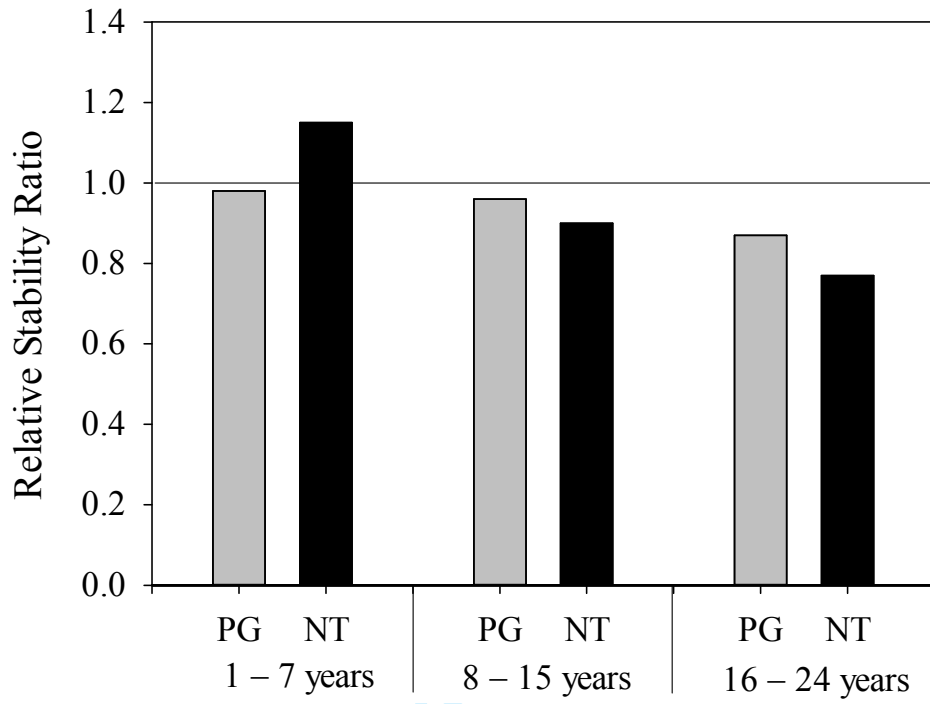


Fig. 3.

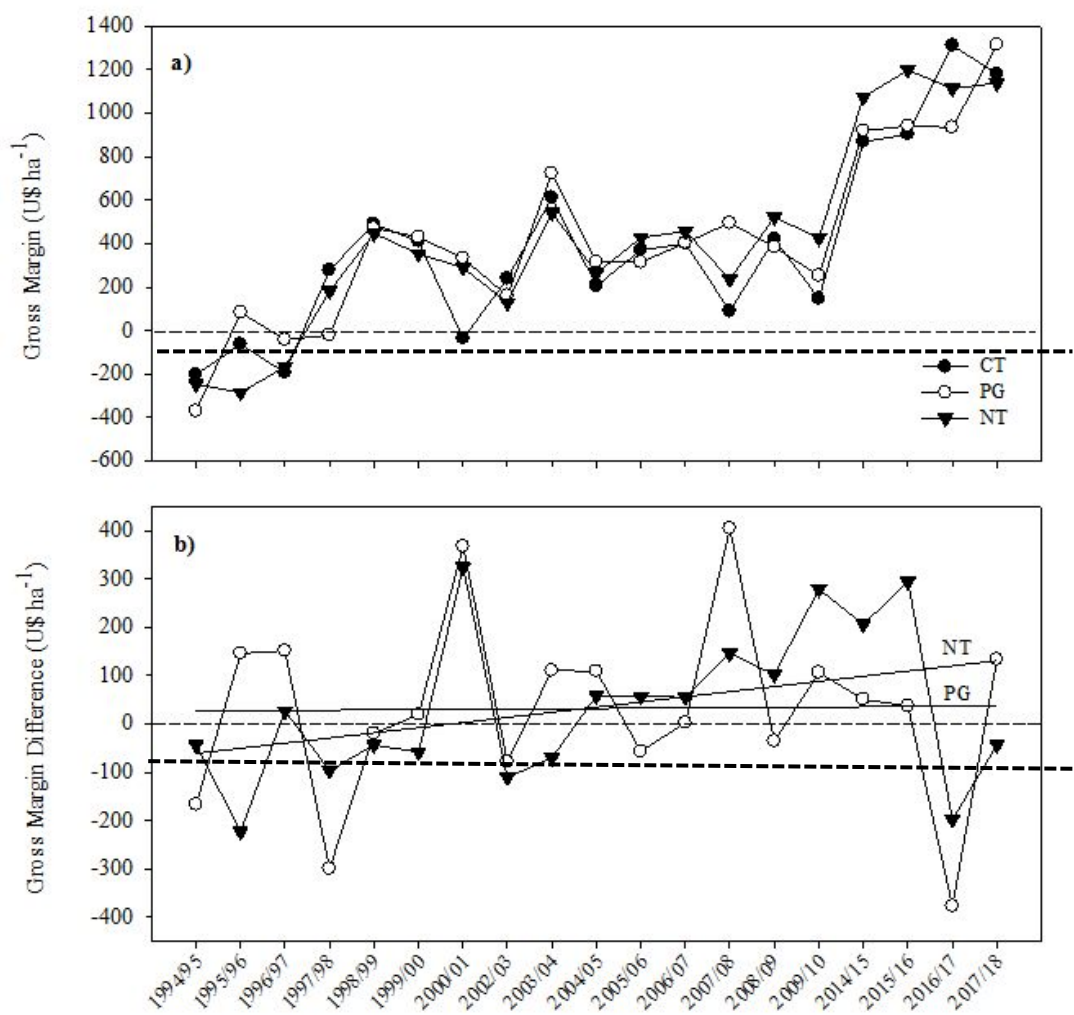
**Fig. 4.**

Table 1

Dry matter and C input (shoot + root) by ryegrass in winter and rice in summer in a subtropical Gleysol subjected to three different tillage systems in Southern Brazil.

Tillage system	Winter ryegrass	Summer rice	Annual
	----- Mg há ⁻¹ -----		
Dry matter			
CT	5.43	9.55	15.0
PG	5.30	10.28	15.6
NT	5.49	9.22	14.7
C input			
CT	2.44	4.30	6.7
PG	2.39	4.63	7.0
NT	2.47	4.15	7.0

CT conventional tillage, PG pre-germinated tillage, NT no-tillage.

Rice root biomass was assumed to be 30% of shoot biomass of ryegrass (Assmann et al., 2014) and rice (Holzschuh et al., 2009).

Root shoot biomass for the whole experimental period (1994/95 to 2017/18) was estimated by using an apparent harvest index [grain/(grain + shoot)] of 0.5 (Fageria et al., 2007).

Table 2

Soil organic carbon (SOC) stock, particulate organic carbon (POM-C), mineral-associated carbon (Min-C), and C management index (CMI) components for the 0–40 cm layer of a subtropical Gleysol under native grassland and three tillage systems in Southern Brazil.

Soil attribute	Soil use and management system ¹			
	NG	CT	PG	NT
SOC stock, Mg C ha ⁻¹	49.3	46.5 b ²	47.8 ab	55.6 a
POM-C stock, Mg C ha ⁻¹	12.0	8.1 b	10.3 a	10.8 a
Min-C stock, Mg C ha ⁻¹	37.3	38.5 b	37.5 b	44.8 a
<i>Carbon indices</i> ³				
CPI	1.0	0.9 b	0.9 b	1.1 a
CLI	1.0	0.6 a	0.8 a	0.7 a
CMI	100.0	60 b	80 ab	81 a

CMI components: C pool index (CPI), C lability index (CLI).

¹ NG native grassland, CT conventional tillage, PG pre-germinated tillage, NT no-tillage.

² Means followed by the same letter in each row were not significantly different as per Tukey's test at $p < 0.05$. NG was not included in the statistical analysis because it do not follow any experimental design.

³ C indices were calculated from eqs 1–3.

SUPPLEMENTARY DATA

Table S1. Rice varieties and rates of N, P₂O₅ and K₂O used to establish rice each crop season from 1994/95 to 2017/18.

Season	Rice variety	Tillage system								
		CT			NT			PG		
		N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
----- kg há ⁻¹ -----										
1994/95	BR IRGA 410	95	80	80	95	80	80	95	80	80
1995/96	BR IRGA 410	95	80	80	95	80	80	95	80	80
1996/97	BR IRGA 410	64	40	40	64	40	40	64	40	40
1997/98	BR IRGA 410	100	70	105	100	70	105	100	70	105
1998/99	BR IRGA 410	106	60	60	106	60	60	106	60	60
1999/00	BR IRGA 410	60	66	66	60	66	66	60	66	66
2000/01	BR IRGA 410	160	0	60	160	0	60	160	0	60
2001/02	IRGA 422 CL	140	60	90	140	60	90	140	60	90
2002/03	IRGA 422 CL	130	40	60	130	40	60	130	40	60
2003/04	IRGA 422 CL	145	60	90	145	60	90	120	60	90
2004/05	IRGA 417	135	60	90	135	60	90	135	60	90
2005/06	IRGA 417	135	60	90	135	60	90	135	60	90
2006/07	IRGA 422 CL	140	90	135	140	90	135	140	90	135
2007/08	IRGA 422 CL	120	40	90	120	40	90	120	40	90
2008/09	Puitá Inta CL	135	70	105	135	70	105	135	70	105
2009/10	Puitá Inta CL	150	50	75	150	50	75	150	50	75
2014/15	IRGA 424	166	68	108	166	68	108	166	68	108
2015/16	IRGA 424	166	68	108	166	68	108	166	68	108
2016/17	IRGA 424 RI	166	68	108	166	68	108	166	68	108
2017/18	IRGA 424 RI	166	68	108	166	68	108	166	68	108
Average		129	60	87	129	60	87	127	60	87

No rice was harvested in the 2001/02 season because the crop was attacked by birds. Also, soybean was cultivated to control red rice in the growing seasons from 2010/11 to 2013/14.

Table S2. Soil bulk density in different layers of an Entisol under three different tillage systems (CT, PG and NT) and native grassland in an adjacent reference area in a subtropical lowland ecosystem in Southern Brazil.

Soil layer (cm)	NT	PG	CT	NG
	-----Mg m ⁻³ -----			
0.0–2.5	1.37	1.38	1.62	1.32
2.5–5.0	1.37	1.38	1.62	1.32
5.0–7.5	1.71	1.55	1.64	1.46
7.5–10	1.71	1.55	1.64	1.46
10–15	1.80	1.65	1.80	1.62
15–20	1.79	1.73	1.84	1.68
20–30	1.79	1.73	1.84	1.68
30–40	1.79	1.73	1.84	1.68

NT no tillage, PG pre-germinated tillage,