



No-tillage promotes C accumulation in soil and a slight increase in yield stability and profitability of rice in subtropical lowland ecosystems

Filipe Selau Carlos, Flávio a O Camargo, Elio Marcolin, Murilo G Veloso, Rodrigo Schimitt Fernandes, Cimélio Bayer

► To cite this version:

Filipe Selau Carlos, Flávio a O Camargo, Elio Marcolin, Murilo G Veloso, Rodrigo Schimitt Fernandes, et al.. No-tillage promotes C accumulation in soil and a slight increase in yield stability and profitability of rice in subtropical lowland ecosystems. Soil Research, 2022, 60, pp.601 - 609. <10.1071/sr21185>. <hal-04259940>

HAL Id: hal-04259940

<https://normandie-univ.hal.science/hal-04259940v1>

Submitted on 30 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization



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

Journal:	<i>Soil Research</i>
Manuscript ID	SR21185
Manuscript Type:	Research paper
Date Submitted by the Author:	02-Jul-2021
Complete List of Authors:	Carlos, Filipe; Federal University of Pelotas, Camargo, Flávio; Universidade Federal do Rio Grande do Sul, Departamento de Solos Marcolin, Elio; Rice Institute of Rio Grande do Sul, Rice Experimental Station Veloso, Murilo; Universidade Federal do Rio Grande do Sul, Departamento de Solos Schmitt, Rodrigo; Federal University of Rio Grande do Sul, Soil Science Bayer, Cimelio; Universidade Federal do Rio Grande do Sul, Faculdade de Agronomia, Dept Solos
Keyword:	Soil organic carbon, Rice, Paddy soils, Tillage

SCHOLARONE™
Manuscripts

SUMMARY TEXT FOR THE TABLE OF CONTENTS

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.

Do Not Distribute

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

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

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

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

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

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

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

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

Abstract

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

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

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

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

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

Materials and Methods

Site description, experiment design and conduction

The study was based on a 24-yrs old experiment at the Experimental Station of the Rio Grande do Sul Rice Institute in the municipality of Cachoeirinha (Rio Grande do Sul State, Southern Brazil; 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 annual temperature and rainfall are 18.4 °C and 1412 mm, respectively. The soil was a sandy loam Gleysol (WRB/FAO) and had the following properties: clay content = 170 g kg⁻¹, organic matter content = 17 g kg⁻¹, p_{H2O} = 5.3, available P (Mehlich-1) = 14.3 mg dm⁻³ and available K (Mehlich-1) = 41.8 mg dm⁻³. The original vegetation was native grassland, which was preserved in a small area in the vicinity of the experiment site.

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

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

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

The rice varieties and rates of N, P_2O_5 and K_2O fertilization for each crop season were identical for all tillage systems (see Table S1 in Supplementary data).

Biomass and carbon input by rice and ryegrass

An average annual C input was estimated for the whole experimental period as the combined biomass of ryegrass in winter and rice in summer. The shoot biomass of ryegrass was estimated by averaging biomass production in 2001, 2002, 2014 and 2015 as evaluated in six sub-samples collected from a 0.5 m^2 area in each plot. The shoot biomass supplied by rice was estimated from rice grain yields, using an apparent (without roots) harvest index of 0.5 (Fageria et al., 2007). A dry matter contribution of roots equivalent to 30% of shoot biomass of rice (Holzschuh et al., 2009) and ryegrass (Assmann et al., 2014) was considered. Also, a mean concentration of $0.45 \text{ kg C kg}^{-1}$ dry matter of both residues was used to estimate 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°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:

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

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

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

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

Rice grain yield, between-season yield stability and gross margin

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

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

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

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

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

Carbon pool indices

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

Rice yield, between-season yield stability and gross margin

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

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

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

Discussion

Soil organic carbon stocks

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

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

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

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

Rice yield, between-season yield stability and gross margin

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

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

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

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

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

Conclusions

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

Conflicts of Interest

The authors declare no conflicts of interest

Data Availability Statement

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

Declaration of Funding

This research did not receive any specific funding

Acknowledgments

The authors thank the staff at IRGA, whose help and support were essential.

References

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

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

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

704. DOI: 10.1016/S1002-0160(13)60062-4.

Zanatta, J.A., Vieira, F.C.B., Briedis, C., Dieckow, J. & Bayer, C. (2019). Carbon indices to assess quality of management systems in a Subtropical Acrisol. *Scientia Agricola*, **76**, 501–509. DOI: 10.1590/1678-992x-2017-0322.

Zanatta, J. A., Bayer, C., Dieckow, J., Vieira, F.C.B. & Mielniczuk, J. (2007). Soil organic carbon accumulation and carbon costs related to tillage, cropping systems and nitrogen fertilization in a subtropical Acrisol. *Soil Tillage & Research*, **94**, 510–519. DOI: 10.1016/j.still.2006.10.003.

Zhou, P., Song, G., Pan, G., Li, L. & Zhang, X. (2009). Study on the accumulation mechanism of organic carbon in three typical paddy soils in South China under long-term experiments II. Chemical binding mechanism of organic carbon in aggregates. *Journal of Soil Science*, **46**, 263–273.

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.

Do Not Distribute

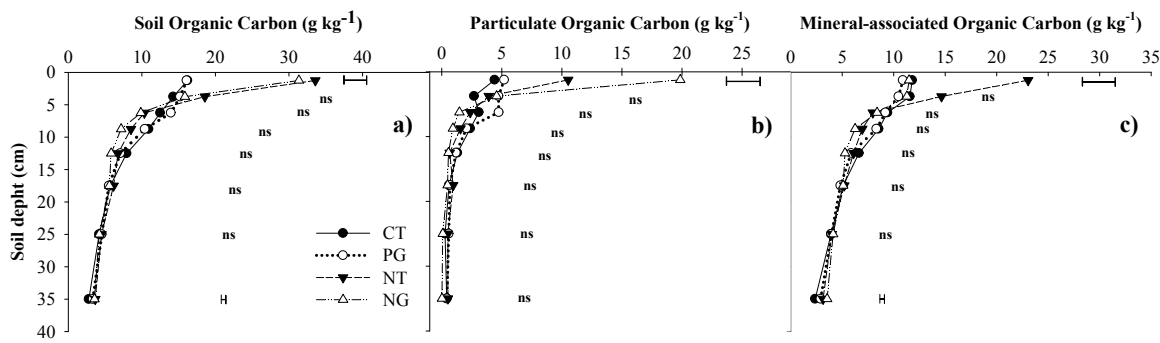


Fig. 1.

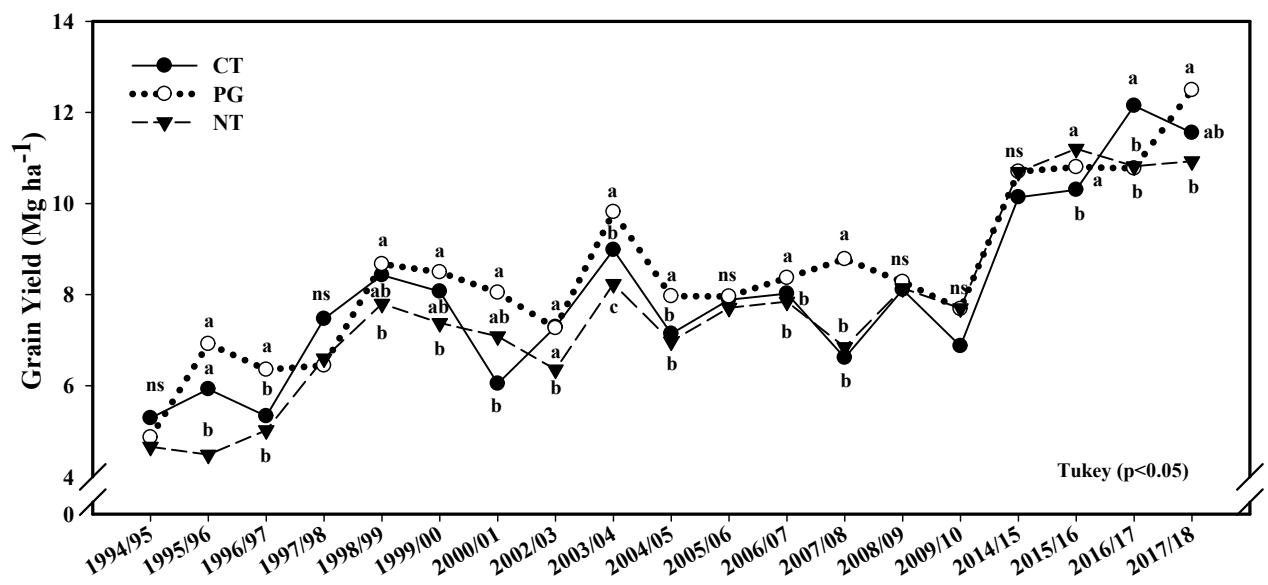


Fig. 2.

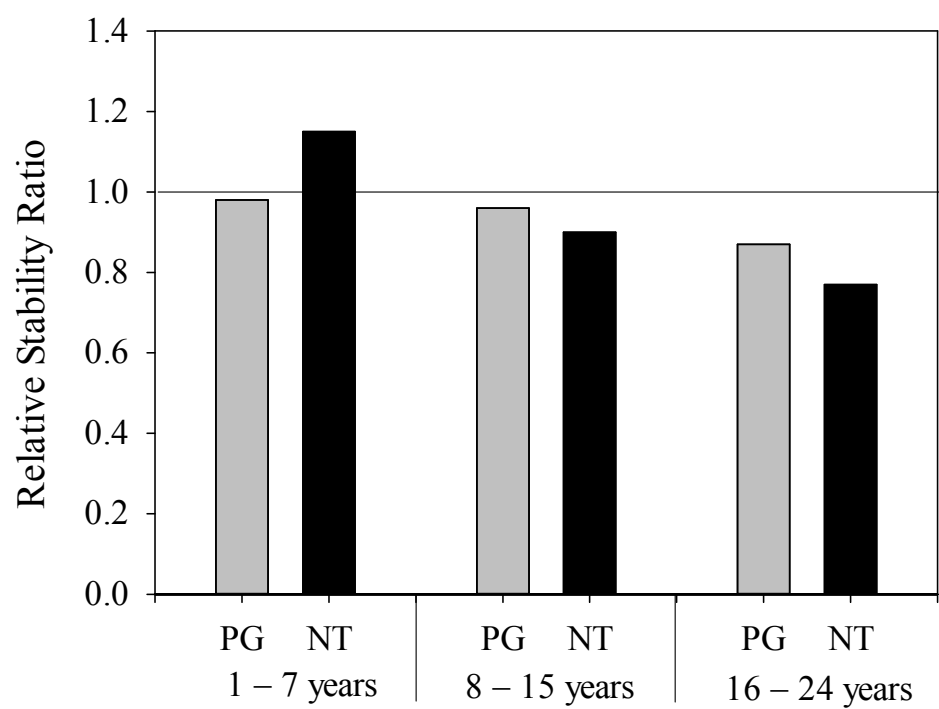


Fig. 3.

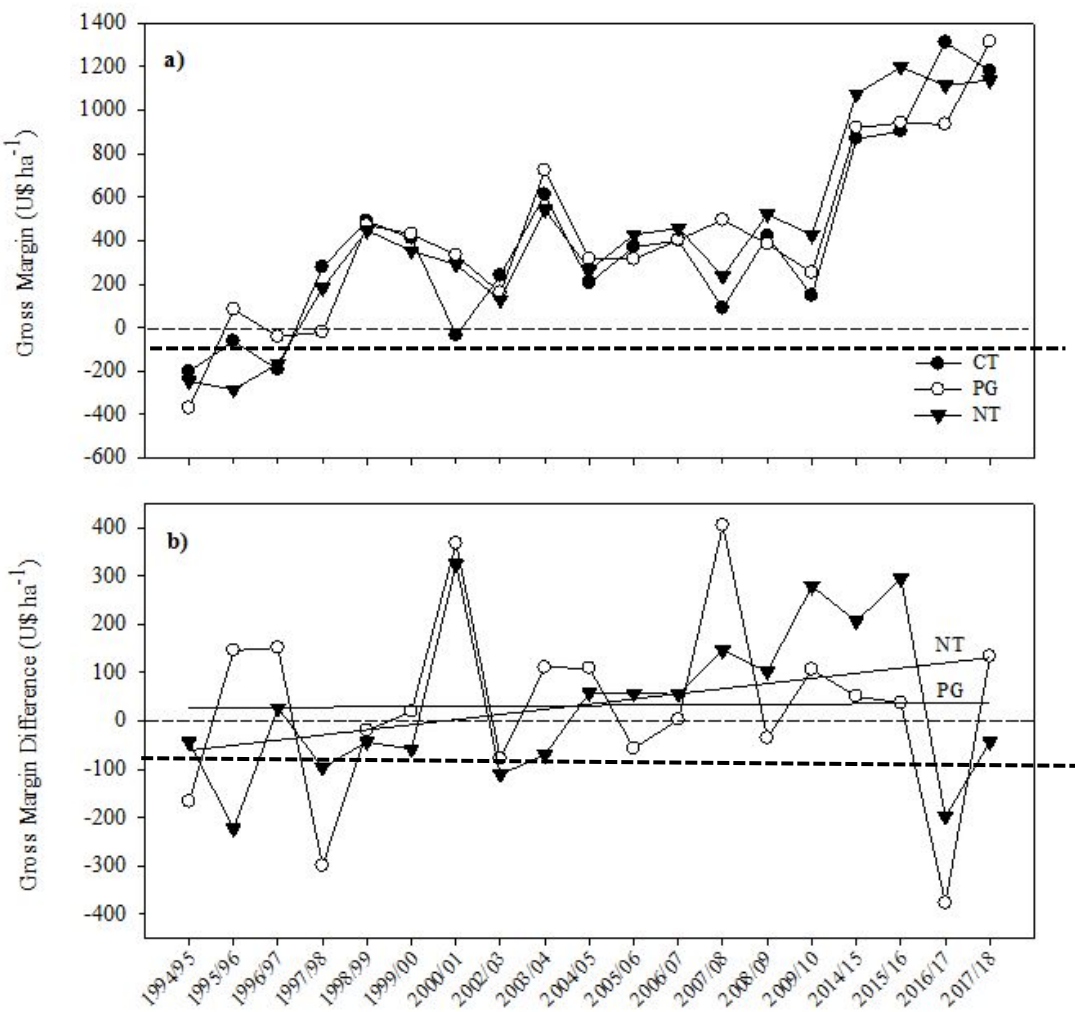


Fig. 4.

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 -----		
<i>Dry matter</i>	CT	5.43	9.55	15.0
	PG	5.30	10.28	15.6
	NT	5.49	9.22	14.7
<i>C input</i>	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,