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No-tillage for flooded rice in Brazilian subtropical paddy fields: history, challenges, advances and perspectives

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ABSTRACT: No-tillage (NT) has been one of the main advances related to soil management in Brazilian agriculture in the last 30 years. However, its full adoption in lowland areas that are traditionally cultivated with flooded rice is still incipient (<5 %). The main reasons are associated with the soil hydromorphic condition and the management of highly recalcitrant residual crop biomass, demanding soil disturbance even occasionally. This review presents a historical survey about the soil management systems utilized in lowland areas in southern Brazil, emphasizing the experiences of NT adoption in areas with flooded rice. Results from studies focused on the main changes in chemical, physical, and microbiological soil properties due to NT adoption were addressed, as well as the NT effects on greenhouse gas emissions and crop yields. Finally, the main challenges and prospects for NT were discussed considering new emerging scenarios for flooded rice production in lowlands, especially soybean rotation and integrated agricultural production systems. No-tillage can increase the soil organic carbon, the cation exchangeable capacity and tends to promote the accumulation of nutrients as nitrogen in surface layers. Improvements in soil aggregation, porosity and water availability are usually observed in NT, but only if medium or long-term trials are considered. NT favors microbial activity in the shallower soil layer by promoting microbial biomass carbon (+45 %), microbial biomass nitrogen (+54 %) and basal respiration (+54 %) compared to conventional tillage (CT), while the activity of extracellular enzymes also may be stimulated. Crop yield tends to be similar among the soil managements systems over time. Seasonal CH_4 emissions might be reduced by 21 % with NT adoption without increasing N_2O. Plant breeding and geotechnology advances associated with soybean market valuation intensified the introduction of this crop in paddy fields. The main challenge for the full adoption of NT is the need for soil tillage after rice harvesting to correct soil surface irregularities or manage rice straw. In the future, advances in plant breeding and drainage techniques probably will favor the expansion of NT in southern Brazil lowlands. The traditional system of flooded rice cultivation, based on CT and monoculture associated with beef cattle under extensive grazing, is no longer viable and will not be further established.

Keywords: soil management, *Oryza sativa*, rice production, soil properties.

INTRODUCTION

Brazil is the largest rice producer outside the Asian continent, occupying the ninth position worldwide (IRRI, 2019). Brazilian rice production was equal to 11.8 million tons in the 2020/21 crop season, including both flood irrigation and rainfed systems. The southern Brazil lowlands account for 80 % of the national rice production, which occurs predominantly under flood irrigation systems (Conab, 2021). The Brazilian commercial cultivation of flooded rice began in 1903, in the municipality of Pelotas, Rio Grande do Sul State (RS). The total area of lowland areas in RS and Santa Catarina (SC) are 4.4 and 0.68 million ha, respectively (Pinto et al., 2017) (Figure 1), where are cropped annually 0.98 and 0.14 million ha in the RS and SC, respectively (Conab, 2021).

The traditional system of flooded rice cultivation in lowland soils in RS involves soil disturbance operations, which are usually carried out according to the following steps: removal of levees from the previous crop season, soil tillage through plowing, harrowing and/or land leveling; sowing and construction of levees for irrigation (Sosbai, 2018). Involving intense soil disturbance, this is considered the conventional tillage (CT) for rice cultivation and is commonly associated with beef cattle under an extensive grazing system. Traditionally, rice was cultivated once every three years, and beef cattle was carried out during two years of fallow with spontaneous vegetation.

Pre-germinated (PG) is the traditional cultivation system in the SC state. Its main characteristics are crop implantation in soil previously flooded and pre-germination of seeds before throwing them on the soil surface (Sosbai, 2018). Tillage in PG can be performed entirely in flooded soil or partially in dry with complementation in flooded soil. This system requires a high degree of soil surface regularization, generally being implemented in leveled areas (Marchesan et al., 2001). Pre-germinated has accounted for almost the total area cultivated with rice in SC until the last decade. However, its use has been progressively decreased in recent years due to its substitution for a dry-seeded production system due to environmental restrictions of PG in areas near water resources and the advent of Clearfield® technology to control the weedy rice (Sosbai, 2018).

Figure 1. Occurrence of lowland soils in southern Brazil. Adapted from Pinto et al. (2004).

Soil management in rice production systems in Southern Brazil

For both rice sowing systems in dry and flooded soil, tillage in CT is carried out to incorporate residual crop biomass, execute mechanical control of weeds, promote favorable conditions for germination and plant development (Botta et al., 2015), eliminate compacted layers, incorporate fertilizers and liming materials, and perform land leveling (adjustment of micro-topography). Although tillage provides a momentary improvement in soil physical properties, this effect can be reversed within the same cropping year, mainly because of the aboveground water level due to flood irrigation (Peña, 1993).

In the long-term, the adoption of CT can promote a decrease in soil organic matter (SOM) and physical properties degradation, especially when performed with the absence of ideal moisture conditions (Rosa et al., 2008). When tillage is carried out with high moisture, the soil structure is affected (compaction in the tractor tracks) and the soil adheres more strongly to agricultural implements, making it unfeasible (Ribeiro et al., 2021). On the other hand, when tillage is carried out with very low soil moisture, hardly breakable clods are formed, requiring more mechanical operations and increasing fuel and time consumption (Botta et al., 2015).

The introduction of modern short cultivars in the 1980's was an important fact for rice production in southern Brazil. Initially, 'BR-IRGA 409' and, then 'BR-IRGA 410', replaced American cultivars of intermediate height, mainly the 'Blue Belle', which predominated in the rice cropped areas in RS (Terres et al., 2004). Modern varieties were more productive and increased the state's mean rice yield from 3,500 Mg ha^{-1} to more than 5,000 Mg ha^{-1} (Menezes et al., 2012). On the other hand, they played a decisive role in increasing the infestation of weedy rice in rice fields (Agostinetto et al., 2001).

American cultivars had a shorter biological cycle than the above-mentioned modern cultivars, coinciding with the weedy rice ecotypes cycle, which coexisted with commercial rice in paddy fields, so they were harvested at the same time. When modern and longer-cycle ones replaced these cultivars, the weedy rice infestation in paddy fields increased exponentially because they matured and released seeds before commercial rice harvest (Marchesan et al., 2004). A few years later, the presence of weedy rice made rice cultivation unviable in many southern Brazilian paddy fields (Agostinetto et al., 2001). Weedy rice was probably the main limitation to rice cultivation in the 1980's and 1990's in RS, triggering the search for alternatives to control the infesting plant (Agostinetto et al., 2001).

Selective herbicides, which could be used for the chemical control of weedy rice, were not available at that time as weedy rice and commercial rice belong to the same species (Ulguim et al., 2019). The available alternatives to reduce infestations were based on weedy rice phenotypic characteristics, which allowed the identification and removal of weed plants from the fields because they were taller. However, this practice selected weedy rice plants with a height similar to commercial cultivars, hampering their identification (Agostinetto et al., 2018). Among the efficient and viable alternatives to reduce weedy rice infestation in paddy fields and to promote commercial rice cropping, fallow periods of at least three years, crop rotation also for at least three years and rice cultivation under other tillage systems that could hinder weedy rice germination stood out (Sosbai, 2018). Therefore, minimum tillage (MT) and no-tillage (NT) systems for flooded rice were originated from the search for alternatives to control weedy rice (Gomes et al., 2002).

The experience with rice no-tillage in Brazilian lowland soils

Due to the presence of weedy in flooded rice cultivation, eventually, soil disturbance is required to stimulate germination of weed plants, so they can be controlled before sowing the commercial rice (Gomes et al., 2004). In addition, the conditions for rice cultivation in flooded soil usually do not allow dry soil harvesting, so the harvesters, tractors and grain tanks traffic deforms the soil surface in the tire trails, requiring post-harvest operations to regularize the soil surface for subsequent crops (Sosbai, 2018). Parallel to the weedy rice controlling at that time, there was concern about the increasing costs of rice farming and the low profitability of traditional lowland cultivation system for both crop and associated extensive beef cattle production (Gomes et al., 2002).

Some of the first experiments with flooded rice under NT were carried out in RS in the 1960's and 1970's (Connil, 1977). The oldest report is from 1964, in which rice with no-tilled soil and without desiccant herbicide was cultivated in the municipality of Pedro Osório, facing problems to control weeds (Abud, 1987). Other experiences were developed at this time by technicians from the Instituto Rio Grandense do Arroz (IRGA), and weed control was also the main limitation, once herbicide was not used (Connil, 1966, 1967).

The first experiment conducted in an experimental station using glyphosate to desiccate cover plants and other herbicides to control weeds occurred in the 1979/80 crop season in the so-called EMBRAPA-UEPAE Pelotas (currently Embrapa Clima Temperado). The experiment showed equivalent productivity for CT and NT, but with lower costs for NT (Andrade, 1980). Then, several experiments were carried out in the first half of the 1980s in almost all RS rice-producing regions (Andrade, 1982; Semeato, 1991).

However, the Cerro do Tigre farm, owned by Eurico Farias Dornelles, came to be recognized as the No-tillage cradle for Flooded Rice, mainly due to the perseverance of its owner. On 02/27/1985, during a field day on his farm, Mr. Eurico founded the No-tillage Club with Minimum tillage of Flooded Rice (Clube do Plantio Direto com Cultivo Mínimo de Arroz Irrigado), along with 90 other rice growers who, few years later, were more than two thousand (Dorneles, 1995). This organization promoted the exchange of experiences related to rice farming problems in RS, focusing on NT and MT, through organizing field days, technical meetings and, mainly, the event "No-tillage Seminar" (Seminário de Plantio Direto) which was held annually in Gramado, RS, and was a meeting place for farmers, agricultural extensionists and researchers related to rice cultivation during decades (Mello, 2016).

One of the technologies developed parallel to the evolution of NT and MT for rice was the large-based levees. All effort to perform early tillage in MT and for weedy control was partially hampered by the soil mobilization to construct levees after sowing rice, promoting weedy rice infestation as the levees enabled weed multiplication and dissemination. In addition, the deep borrow ditch formed due to the construction of narrow levees, to some extent, subtracted available area for farming from the field because it was not cultivated. Furthermore, the top of the levee was sown a few days later in relation to the regular field area, causing different cycles for rice sown in the field and levees. The large-based levees were built after the early soil tillage operations, presenting a larger base, lower height and a smoother slope than the conventional narrow-based levees. These shape characteristics enabled sowing on levees and borrowing ditches because they allowed both to be crossed by the seeder without causing significant damage to their structure (Gomes et al., 2004).

Over the years, NT and MT for flooded rice evolved, and several variations emerged. Minimum tillage is currently predominant and corresponds to the execution of soil tillage operations in advance of the sowing rice period, enabling the soil vegetation cover, which is totally desiccated with herbicide before sowing (Sosbai, 2018). The early tillage recommended in MT can be carried out in the summer (in fallow areas), in post-harvest (in areas cultivated during the summer), or during the winter depending on the farm organizational schedule and soil moisture conditions. The tillage operations normally comprise a plowing and two harrowing passes, if the areas are leveled, concluding with the early construction of levees. In areas that remain irregular after harrowing, land leveling is performed (Marchesan et al., 2019).

When early tillage in MT is carried out in the summer, a winter pasture can be established to feed beef cattle, and rice is sown over the desiccated plants. This system has been also called "no-tillage with summer tillage" instead of MT or NT. Considering the NT basic precepts for upland soils, which recommend minimum soil disturbance, permanent soil covering and crop rotation, it presents low adoption in lowland areas. The more similar situations between upland and lowland NT occur when flooded rice is cultivated over the desiccated crop residues after rainfed crops such as soybean, corn or sorghum, or when livestock is perfectly integrated (Marchesan et al., 2019).

Crop rotation use has increased significantly in the last ten years, mainly due to the soybean insertion, which provided numerous technical, economic and environmental benefits. Soybean cropped area in rotation with rice reached 341,000 ha in the lowland areas of southern Brazil in the 2019/20 crop season (IRGA, 2020a). Successive monoculture for a long time increases the level of weed infestation, especially weedy rice, making rice cultivation unfeasible in several places. In this scenario, soybean rotation is essential for significantly reducing weedy plants and irrigated rice cultivation (Ulguim et al., 2018).

Soil chemical, physical, and biological properties and changes promoted by no-tillage in lowland soils

Lowlands cover approximately 4.4 million ha and represent 16.5 % of the RS state total area (Pinto et al., 2017). The main soil orders which occur in RS lowlands (Table 1) are Alfisols (Planosols; *Planossolos*) (54 %) usually associated with Aquents (Gleysols; *Gleissolos*), which together account for more than 60 % of the lowland areas in RS, Molisols (Phaeozems; *Chernossolos*) with 15.1 %, Entisols including Fluvents, Orthents and Psamments (Fluvisols, Leptosols and Regosols; *Neossolos*) with 17.2 %, Vertisols (Vertisols; *Vertissolos*) with 1.3 % and Histosols (Histosols; *Organossolos*) with 0.9 % (Pinto et al., 2017). Lowland soils occupy an area equal to 685,000 ha in SC, representing 7 % of the total state area (Pinto et al., 2006). Aquents (Gleysols; *Gleissolos*) are the

Table 1. Percent distribution of lowland soil orders in RS and SC states

Lowland soils	Area distribution
	%
Rio Grande do Sul	
Alfisols (Planosols; *Planossolos*)[1], including associated Aquents (Gleysols; *Gleissolos*)	54.3
Molisols (Phaeozems; *Chernossolos*)	15.1
Entisols including Fluvents, Orthents and Psamments (Fluvisols, Leptosols and Regosols; *Neossolos*)	17.2
Aquents (Gleysols; *Gleissolos*)	7.3
Ultisols (Acrisols; *Argissolos*)	3.9
Vertisols (Vertisols; *Vertissolos*)	1.3
Histosols (Histosols; *Organossolos*)	0.9
Santa Catarina	
Aquents (Gleysols; *Gleissolos*), including associated Inceptisols (Cambisols; *Cambissolos*) and Histosols (Histosols; *Organossolos*)	61.0
Entisols including Fluvents, Orthents and Psamments (Fluvisols, Leptosols and Regosols; *Neossolos*) associated with Aquents (Gleysols; *Gleissolos*)	20.0
Histosols (Histosols; *Organossolos*) associated with Aquents (Gleysols; *Gleissolos*) and Entisols (Fluvents, Orthents and Psamments)	9.1
Spodosols (Podzols; *Espodossolos*)	7.1
Mangrove soils, including permanently flooded areas	2.8

Adapted from Pinto et al. (2006) and Pinto et al. (2017). [1] The soil classification adopted in the text is presented according to the following format: Soil Survey Staff (2014) (IUSS Working Group WRB, 2015; Santos et al., 2018).

main order of lowland soils in SC (Table 1), accounting for 18 % of the total areas as simple units and for more 43 % while associated with other orders Inceptisols (Cambisols; *Cambissolos*), Ultisols (Acrisols; *Argissolos*) and Histosols (Histosols; *Organossolos*), followed by Entisols including Fluvents, Orthents and Psamments (Fluvisols, Leptosols and Regosols; *Neossolos*) (17 %), Histosols (Histosols; *Organossolos*) (8.3 %) and Spodosols (Podzols; *Espodossolos*) (7.1 %) (Pinto et al., 2006). The soil classification adopted in the text is presented according to the following format: Soil Survey Staff (2014) (IUSS Working Group WRB, 2015; Santos et al., 2018).

Soil chemical properties

Despite the high heterogeneity of lowland soil types, some characteristics are frequently observed: shallow A horizon, almost impermeable subsurface horizons, high soil bulk density, low total porosity, high micro/macropores ratio, presence of compacted layers, unfavorable consistency, and poor natural drainage (Streck et al., 2008). From a chemical perspective, lowland soils are commonly acidic, with low cation exchangeable capacity (CEC) and base saturation, and low levels of available P and SOM (Boeni et al., 2010). They show low to medium natural fertility and require liming and fertilization to improve chemical properties. Some soils, especially those with 2:1 minerals, such as Vertisols (Vertisols; *Vertissolos*) and Molisols (Phaeozems; *Chernossolos*), are relatively more fertile and do not present such chemical limitations (Marchesan et al., 2019).

A survey based on 17,665 lowland soil samples from RS (Anghinoni et al., 2004) evidenced low levels of SOM, showing values lower than or equal to 25 g dm^{-3}, which corresponded to 77.5 % of the evaluated samples. In comparison to upland soils from RS evaluated at the same period (Rheinheimer et al., 2001), only 29.7 % of the samples presented values within the same range, indicating lowland soils cultivated with flooded rice have proportionally lower SOM than upland soils. The low SOM values in lowlands probably occurs due to soil disturbance and alternated redox conditions, with aerobic and anaerobic decomposition cycles between the flooded cultivations (Carlos et al., 2021). In addition, the same survey of soil samples showed that, in rice-producing regions, sandy soils (with less than 25 % of clay) predominated, reaching 96.5 % of the total evaluated samples (Rheinheimer et al., 2001). Considering the role of soil mineral particles in protecting C against microbial decomposition, it is evident that lowland soils provide weak protection to C, explaining the predominance of samples with low SOM content (Rosa et al., 2008; Carlos et al., 2021).

Currently, a significant part of the area sown with flooded rice in RS is cultivated under MT (60.6 %), but only a small proportion is cropped under NT (2.5 %) (Sosbai, 2018). The NT enables the reduction or elimination of operations that generate soil disturbance, the reduction of the SOM decomposition rate and the introduction of cover plants which increase the supply of plant residual biomass to the soil (Martins et al., 2017). This scenario contributes to an increase in soil carbon stocks (Rosa et al., 2008; Denardin et al., 2019). Higher levels of SOM were verified on the soil surface in rice over ryegrass under NT compared to the continuous rice in CT in a long-term experiment (Table 2), showing values similar to those observed in non-cultivated soil (Santos, 2006). The residual plant biomass from the rice harvest and ryegrass dry matter production, associated with the absence of soil disturbance, explain the superficial accumulation of SOM in NT. The increase of SOM content in NT was more expressive in the soil superficial layer (0.00-0.025 m), reflecting a significant increase in total N and $CEC_{pH\ 7}$ and showing positive relation between SOM content and CEC (Figure 2). Recently, studies have focused on short or long-term effects of NT adoption in lowland areas in southern Brazil (Martins et al., 2017; Carlos et al., 2020), also indicating NT generated an increase in the total and particulate organic carbon content in the surface layer (0 to 0.05 m) (Denardin et al., 2019; Carlos et al., 2021).

Table 2. Soil organic matter content (SOM), total nitrogen (N) and cation exchangeable capacity ($CEC_{pH\ 7}$) in two soil layers of an Alfisol (Planosol; *Planossolo*) after 19 years under different tillage systems

Tillage	SOM		Total N		$CEC_{pH\ 7}$	
	0.00-0.025 m	0.025-0.05 m	0.00-0.025 m	0.025-0.05 m	0.00-0.025 m	0.025-0.05 m
	g kg^{-1}		g kg^{-1}		cmol$_c$ kg^{-1}	
Conventional	22 b	20 b	1.1 b	1.1 a	8 b	8 a
No-tillage	67 a	27 a	3.5 a	1.3 a	12 a	9 a
Natural soil	73 a	25 a	3.4 a	1.2 a	14 a	8 a

Mean values followed by the same letter in columns within the same layer are not significantly different according to the Duncan test ($p<0.05$). Conventional: rice conventional cultivation (all years); No-tillage: rice continuously cultivated under no-tillage with ryegrass in winter (all years); Natural soil: Natural and non-cultivated soil. Adapted from Santos (2006).

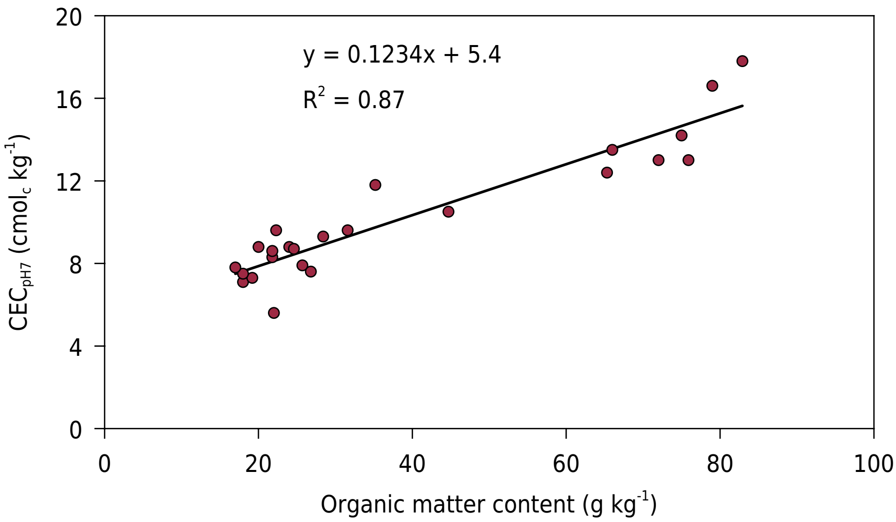

Figure 2. Relation between soil organic matter and cation exchangeable capacity at pH 7 ($CEC_{pH\ 7}$) in an Alfisol (Planosol; *Planossolo*) after 19 years under different tillage systems. Adapted from Santos (2006).

Considering parameters such as soil pH, base saturation and available P and K, studies have reported divergent results due to the high variability of types and intensities of tillage operations, of utilized crop rotations, and of lime and fertilizer rates supplied to the crops (Santos, 2006). Based on this context, although nutrient accumulation in surface layers is expected in NT, the impacts of the conservation systems and crop rotation adoption in flooded rice are still less prominent in lowlands than those detected in uplands soils.

Soil physical properties

Monitoring soil physical properties under flooded rice cultivation is not always considered because rice crop does not depend directly on the physical structure to obtain air, water, and nutrients. However, the soil physical quality is fundamental for rainfed crops in rotation with rice, as the plants demand aeration, drainage, water availability and non-restrictive resistance to root penetration to deal with both water excess and deficit periods. Thus, the physical quality of lowland soils has been estimated by using structural indicators related to water and gas transport, such as porosity, saturated hydraulic conductivity, soil bulk density, and mechanical resistance to penetration (Table 3). Additionally, aggregates size and stability in water have also been used (Tuchtenhagen et al., 2018; Ribeiro et al., 2021).

Soil tillage operations in MT, although less frequent and intense than in CT, may cause aggregate breakdown and compaction (Goulart et al., 2020). In addition,

Table 3. No-tillage impacts on the physical quality of lowland soils and crop yield in southern Brazil

Soil type[(1)]	NT age	Crop rotation	Main outputs	Crop yield	Reference
	year				
Alfisol (Planosol; *Planossolo*)	8	Ryegrass and rice succession under NT[(2)]	NT decreased soil bulk density	na[(3)]	Pedrotti et al. (2001, 2005)
Alfisol (Planosol; *Planossolo*)	5	Ryegrass, bird's foot trefoil, soybean, corn, and sorghum	NT and CT[(4)] resulted in similar physical quality	na	Lima et al. (2008)
Alfisol (Planosol; *Planossolo*)	19	Ryegrass and rice succession system under NT	NT did not generate compacted layers	na	Bamberg et al. (2009)
Psamment (Regosol; *Neossolo*)	na	Rice (additional information about crop rotation not available)	NT and CT resulted in similar physical quality	No effect on rice yield.	Munareto et al. (2010)
Psamment (Regosol; *Neossolo*)	na	Rice (additional information about crop rotation not available)	Effects of NT and CT varied according to the previous historic of areas under CT	No effect on rice yield.	Beutler et al. (2012)
Alfisol (Planosol; *Planossolo*)	7	Corn, ryegrass and soybean	NT promoted microporosity and water holding along crop cycle	NT increased soybean yield.	Ribeiro et al. (2016)
Alfisol (Planosol; *Planossolo*)	7	Soybean, wheat, corn, sunflower, ryegrass, and sorghum	NT increased soil organic matter which leaded to lower soil bulk density, resistance to penetration, micro/macropores ratio, pre-consolidation pressure and higher total porosity, aggregates size and stability	na	Reis et al. (2016, 2018)
Alfisol (Planosol; *Planossolo*)	3	a) Crop-livestock integration including corn, ryegrass, soybean, and wheat under NT and b) NT including corn, ryegrass, soybean and wheat	NT promoted soil organic carbon and aggregation	na	Tuchtenhagen et al. (2018)
Alfisol (Planosol; *Planossolo*)	na	Soybean and ryegrass	Deep tillage promoted lower resistance to penetration than NT, which presented subsurface compaction. This effect was detected in two cropping seasons	Deep tillage increased soybean yield by 24 %.	Marchesan et al. (2017)
Alfisol (Planosol; *Planossolo*)	up to 2	Soybean, ryegrass, and corn	Soil chiseling improved soil physical quality by decreasing resistance to penetration and increasing macropores while NT and conventional tillage presented similar results	Soil chiseling increased corn yield in comparison to NT and CT, however, NT presented higher yield than CT.	Giacomeli et al. (2017)
Alfisol (Planosol; *Planossolo*)	1	Soybean	Soil chiseling increased macroporosity, saturated hydraulic conductivity, and decreased soil bulk density and the frequency of oxygen deficiency estimated by the transpiration reduction factor	Soil chiseling promoted higher soybean yield (4,610 kg ha^{-1}) than NT on ridges (3,565 kg ha^{-1}) and NT without ridges (2,842 kg ha^{-1}).	Gubiani et al. (2018)
Aquent (Gleysol; *Gleissolo*)	17	Monocropping succession of flooded rice in the summer and spontaneous ryegrass in the winter	Long-term NT increased organic matter by 67 % and decreased soil bulk density	NT increased rice yield by 3.4 %.	Denardin et al. (2019)
Alfisol (Planosol; *Planossolo*)	12	Soybean and corn in the summer and ryegrass, black oats, vetch and turnip with the introduction of beef cattle	NT and minimum tillage presented similar results	na	Ribeiro et al. (2021)

[(1)] The soil classification adopted in the tablet is presented according to the following format: Soil Survey Staff (2014) (IUSS Working Group WRB, 2015; Santos et al., 2018). [(2)] NT: No-tillage. [(3)] na: data not available. [(4)] CT: conventional tillage.

soil disturbance and intensive machinery traffic generate aggregate disruption, reducing porosity and forming compacted subsurface layers (Bamberg et al., 2009). The effectiveness of NT in improving physical quality, when compared to systems that promote soil disturbance, has generated controversial results considering crop yield (Table 3). Denardin et al. (2019) indicated that long-term NT increased SOM, decreased soil bulk density and resulted in higher mean productivity of flooded rice. No-tillage also increased the yield of rainfed crops such as soybeans due to greater water availability (Ribeiro et al., 2016).

Deceleration of SOM decomposition in soils under NT favors aggregation over time, resulting in greater pores amount, mainly macropores, and soil bulk density reduction (Reis et al., 2016; Denardin et al., 2019). The absence of soil disturbance also preserves biopores originated from root expansion of previous crops or edaphic fauna activity. These biopores contribute more to aeration and drainage than the pores formed by soil disturbance, which have limited connectivity among each other (Zhang et al., 2019). However, some studies which indicate beneficial effects promoted by NT in properties such as soil bulk density, mechanical resistance to penetration and porosity did not report the impacts of this system on crop yields, generating uncertainties regarding the economic feasibility of NT in lowlands (Bamberg et al., 2009; Reis et al., 2018; Tuchtenhagen et al., 2018; Ribeiro et al., 2021).

In contrast, other reports indicated that NT was inefficient in improving both soil physical quality and crop yields (Beutler et al., 2012; Giacomeli et al., 2017). Beutler et al. (2012) and Munareto et al. (2010) compared NT and CT, demonstrating that both resulted in similar effects on physical properties and did not interfere in rice yield. These studies were probably carried out in short-term NT and the areas under CT were previously native fields, fallow areas for a long period (around seven years), or recently converted to flooded rice cultivation, without considerable previous historic of mechanization, which is the main responsible for soil physical degradation. The positive effects of NT on physical properties have been reported in long-term experiments, requiring at least five years for the detection of improvements (Reis et al., 2016, 2018) and up to 14 years to convert these benefits into yield increase in comparison to the CT for flooded rice cultivation (Denardin et al., 2019).

Thus, NT may promote soil physical quality and productivity of both flooded rice and rainfed crops such as soybean (Goulart et al., 2020). Crop rotation and drainage techniques adoption, such as ridge construction, are alternatives to improve soil structural quality (Theisen et al., 2017). No-tillage positive effects are verified mainly in the medium and long-term, and reports showing superior results in systems that promote soil disturbance usually are found only if compared to NT under short-term, without adoption of drainage techniques and without introduction of cropping rotations with diversified plant species (Martins et al., 2017). Additionally, there is a demand for long-term studies integrating the productivity of commercial crops such as rice, corn and soybean, and associating more diversified crop rotations and/or crop-livestock integration with impacts on the soil physical quality under NT.

Soil biological properties

Microorganisms have important functions in soils such as residual crop biomass decomposition (Bastida et al., 2012), phosphorus solubilization (Alori et al., 2017), phytohormones production (Bamisile et al., 2018), and soil aggregation by the action of hyphae and polysaccharides releasing (Six et al., 2000). The relation of microbial attributes with soil fertility and crop response has been progressively investigated. Basal soil respiration (Balota et al., 2004), microbial biomass (Dong et al., 2017), the activity of extracellular enzymes (Burns et al., 2013) and, more recently, the use of next-generation molecular sequencing technologies (Pylro et al., 2014) have been the most widely studied microbial attributes.

In flooded environments, the changes caused by the establishment of aboveground water result in reduction of O_2 rate and lead to the predominance of anaerobic microorganisms, which in general have lower metabolic activity in the soil microbial profile (Liesack, 2000). In this sense, the effects of management practices on soil microbial attributes and parameters have been increasingly studied. The residual plant biomass deposition on lowlands surface under NT contributes to greater microbial activity in the shallower soil layer. Hence, NT allowed an increase (+45 %) in microbial biomass carbon, (+54 %) in microbial biomass nitrogen and (+54 %) in basal respiration compared to CT (Carlos et al., 2021).

Extracellular enzymes play a key role in the biogeochemical cycle of soil elements. For example, the β-glucosidase enzyme is related to the mineralization of carbon-rich compounds such as cellulose; urease acts in the breakdown of nitrogenous organic compounds; acid phosphatase acts in the mineralization of compounds that contain organic phosphorus; and fluorescein diacetate (FDA) is related to the activity of lipases, esterases and proteases (Burns et al., 2013). These enzymes are generally responsible for the simple and more labile organic compounds mineralization, such as sugars, amino acids, proteins, and lipids (Xiao et al., 2018).

No-tillage increased the activity of β-glucosidase (+43 %), acid phosphatase (+68 %), FDA (+34 %) and urease (+96 %) in an experiment with rice monoculture under different tillage systems in southern Brazil (Carlos et al., 2021). The acid phosphatase activity is generally associated with low soil availability of phosphorus (Mndzebele et al., 2020). However, the increase in acid phosphatase under NT in lowlands can be attributed to the increase in organic and microbial phosphorus fractions (Ali et al., 2019). The impacts of NT adoption on the increase of microbial activity in Alfisols (Planosols; *Planossolos*) from southern Brazil may occur in the short-term (<2 years) (Martins et al., 2017) because these soils are mostly subjected to annual soil tillage for long periods (Botta et al., 2015).

Soil microbial species are also influenced by soil use and management (Suleiman et al., 2017). Recently, advances related to next-generation molecular sequencing technologies enabled the profile identification of microorganism species and genera influenced by the adoption of NT, crop rotation, use of cover crops, and other management practices (Suleiman et al., 2013). Reduction in species richness ($p=0.11$) and in diversity index ($p=0.19$) of microbial species was caused by NT compared to CT in a long-term experiment (20 years) under flooded rice cultivation in southern Brazil (Carlos et al., 2021). The authors attributed such impacts to alterations in some soil properties under NT like higher macroporosity and greater amount of C and N labile fractions, which may favor a more limited group of microbial species that has greater capacity of dominance over other microbial groups (Carlos et al., 2021).

Some authors reported CT induces greater oxidation of soil organic carbon and increases soil microbial diversity (Pastorelli et al., 2013). Carlos et al. (2021) demonstrated higher concentration of microorganisms in the phylum Proteobacteria under NT (45.4 %) than under CT (32.3 %). Thus, the higher proportion of this phylum in NT demonstrates a trend towards dominance of some taxonomic units in relation to the CT.

In general, long-term adoption of NT in lowlands allows soil microbial activity to increase, even higher than in Oxisols (Balota et al., 2011). This effect is possibly due to the low carbon levels in total and labile fractions because of frequent soil tillage in Alfisols (Planosols; *Planossolos*) (Denardin et al., 2019). On the other hand, Oxisols, soils traditionally cultivated with uplands crops, naturally present higher organic carbon levels, mainly because they have higher iron oxide contents, which promotes greater soil organic carbon stability regardless of the adopted management.

Crop yield in different rice systems

Flooded rice yield is supposed to be similar in CT, MT and NT under the same soil and climate conditions since factors that can restrict plant growth are absent in each system. A long-term experiment carried out by IRGA showed that rice yield was equivalent in CT and NT in most evaluation periods (Figure 3) (Carlos, 2017). The differences varied according to the crop season mainly due to the different annual climate conditions, affecting the advantages provided by each system to overcome the limiting factors, allowing the rice crop to express its potential productivity under the presented conditions.

Similarly, Munareto et al. (2010) carried out three field experiments with flooded rice and, in two of them, no yield differences between NT and CT were observed. No-tillage generated lower rice yield in one of these trials and this effect was attributed to the straw accumulation on the soil surface, which may have caused toxic levels of organic acids. Furthermore, Beutler et al. (2012, 2014) did not detect statistical differences between CT and NT for grain yield even at plant residue additions of 24,588 kg ha^{-1} and 11,178 kg ha^{-1} to the soil surface in NT, showing that other factors may influence crop productivity.

Fermentation of residual plant biomass in flooded soils promotes organic acids production, which is toxic to rice. However, the produced amount is smaller when the residual crop biomass remains on the soil surface, as in NT, and are not incorporated, as in CT (Sousa et al., 2002). Additionally, the occurrence of organic acids at toxic levels is related to the residual plant biomass origin and the time in which vegetation cover desiccation occurs. Desiccation few weeks before flooding may be enough to stimulate oxidation of significative amounts of carbon from the biomass residuals under aerobic metabolism, not forming toxic organic acids and resulting in lower carbon availability to fermentation during the flooded soil period.

Greenhouse gas emissions in lowland soils with different soil management systems

Lowland areas are an important source of greenhouse gases (GHG) to the atmosphere once they are potentially floodable for at least a period of time during the year (IPCC, 1997). Decomposition of organic carbon sources in an anaerobic environment produces

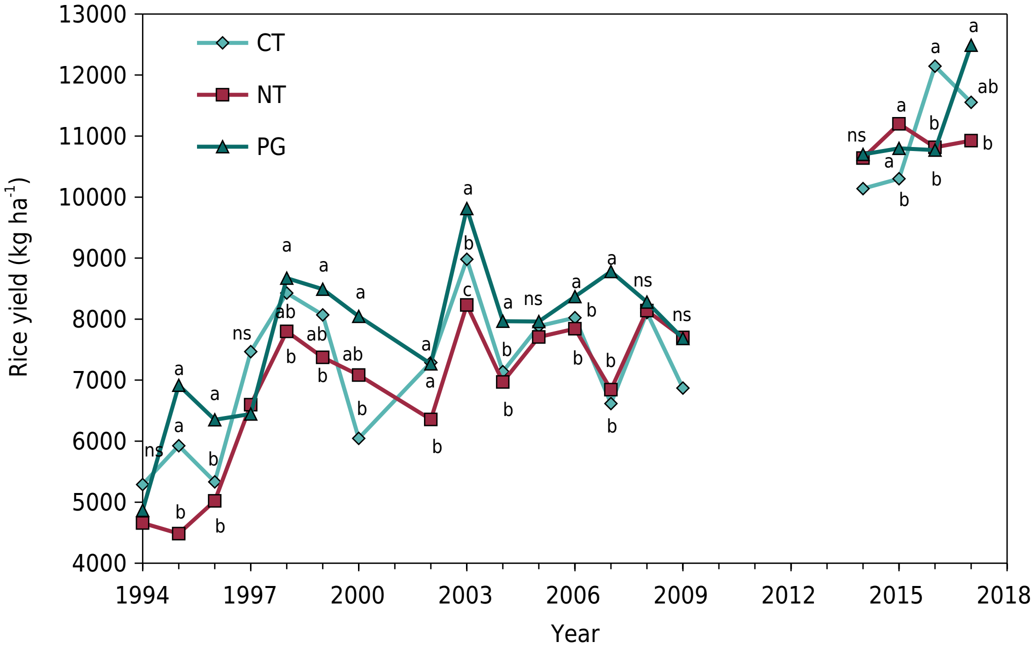

Figure 3. Rice yield under no-tillage (NT), pre-germinated (PG) and conventional tillage (CT) in Aquent (Gleysol; *Gleissolo*) with flooded rice long-term cultivation in southern Brazil. The range without data corresponds to the period with soybean cropping. Adapted from Carlos (2017). Experiment carried out in the EEA-IRGA, Cachoeirinha, Rio Grande do Sul State.

methane (CH_4), a potent GHG whose main natural source to the atmosphere is the lowlands (Watson et al., 2000). A similar process occurs in flooded rice fields, which favor CH_4 formation due to anaerobic conditions during the cultivation period. The flooded rice crop represents one of the main anthropogenic sources for CH_4 emissions and, globally, the activity accounts for more than 10 % of CH_4 emissions from agriculture (FAO, 2018). In Brazil, 89.4 % of CH_4 emissions associated with rice cultivation are originated from lowland areas in RS and SC (Brasil, 2020), as these states represent 65 % of the area cultivated with the crop (Conab, 2021).

In addition to CH_4, which is considered a critical GHG for paddy fields, nitrous oxide (N_2O) and carbon dioxide (CO_2) are also associated with rice cultivation, contributing to global warming (Arunrat and Pumijumnong, 2017). Nitrous oxide is a GHG which the emission to the atmosphere is strongly associated with the use of synthetic nitrogen fertilizers, as they increase the mineral nitrogen (N) content in the soil. However, N_2O direct emissions are also originated from the organic fertilizers use, cultivation of N_2 fixing plants, soil incorporation of residual crop biomass and N mineralization in cultivated organic soils (IPCC, 1997). Significant N_2O emissions are reported in flooded rice crops, particularly in those in which soil drainage or intermittent irrigation during cultivation are promoted (Gaihre et al., 2014), or when the soil is under fallow periods (Cai et al., 1997). Carbon dioxide emissions are mainly associated with soil tillage operations, including sowing, application of fertilizers and pesticides, pumping water for irrigation and harvesting (Lal, 2004a). On the other hand, soils present the potential to mitigate the increase in the atmospheric concentration of CO_2 through carbon sequestration (Lal, 2004b).

Several factors regulate CH_4 emissions from flooded rice, especially the input of organic matter and the water management (Yan et al., 2005), which act integrated to climate (Van Hulzen et al., 1999), soil properties (Mitra et al., 2002) and other management practices (Lu et al., 2000), varying widely among locations. In addition, GHG emissions show significant seasonality (Gaihre et al., 2011).

In summary, lowlands can be an important GHG source during both the growing and fallow periods of flooded rice and other crops in rotation, depending on the soil moisture condition. While CH_4 emissions are favored by excess water, N_2O emissions are associated with alternating soil moisture (Bronson et al., 1997), impacting the nitrification and denitrification processes. Although N_2O emissions from flooded rice are significantly lower than those from rainfed crops (Linquist et al., 2012), both gases, CH_4 and N_2O, are relevant and must be considered for the identification of strategies able to mitigate GHG emissions, once approaches that reduce CH_4 typically tend to increase N_2O emissions (Bayer et al., 2014).

Understanding the influence of different management systems and practices on GHG emissions and soil carbon dynamics is crucial to identifying opportunities for mitigating emissions in the lowlands environment. Considering the influence of tillage systems on GHG emissions in flooded rice cultivation, the research results demonstrate, in general, that higher CH_4 emissions are found in CT, in comparison to NT (Ma et al., 2012) and MT (Bayer et al., 2015). It indicates that the adoption of conservation soil management systems is a viable alternative to mitigate GHG emissions from paddy fields (Costa et al., 2004; Zschornack et al., 2011; Bayer et al., 2013, 2014).

A long-term study demonstrated the potential for reducing GHG emissions provided by NT in flooded rice fields in southern Brazil (Bayer et al., 2014). In the average of five harvests, NT provided a 21 % reduction in seasonal CH_4 emissions in relation to the CT, corresponding, respectively, to 408 and 517 kg ha^{-1}, with no difference between the systems for N_2O emissions and rice yield. This NT benefit on CH_4 emissions was reflected in the yield-scaled partial Global Warming Potential (yield-scale *p*GWP), since CH_4 was responsible for 96.5 % of *partia*l Global Warming Potential (GWPp) of the crop, evidencing the importance of this GHG for the selection of emission mitigation strategies in rice cultivation. The lower CH_4 emission under NT may be associated with lower methanogenic activity, higher methanotrophic activity or combination of both. Conventional tillage may present greater methanogenesis due to the incorporation of vegetation cover present in anaerobic subsurface layers, increasing the availability of labile carbon in deeper soil layers (Costa et al., 2004). In contrast, in NT, vegetation cover remains on soil surface, where conversion to CO_2 predominates over CH_4.

Minimal tillage also has demonstrated to be a promising alternative to reduce GHG emissions from rice cultivation in southern Brazil. Currently, this is the predominant cultivation system in RS, accounting for more than 60 % of the cultivated area in the 2016/17 crop season (IRGA, 2020b). In MT, rice straw and residual biomass from winter cover crops are incorporated into the soil early, in autumn or winter; therefore, under drained soil conditions. Consequently, part of the labile C is converted into CO_2, decreasing CH_4 emission potential for the next rice crop (Bayer et al., 2013). Conversely, soil tillage operations are carried out in the spring in CT, immediately before rice sowing. As a result, rice straw and winter cover residual biomass incorporated into the soil act as a labile carbon source for CH_4 production during rice cultivation. The MT keeps weed residual biomass and winter coverings on the soil surface, reducing the potential for CH_4 emissions, while these materials are incorporated into 0 to 0.20 m the soil layer in CT, where the O_2 availability is even lower than in the shallower layer, reflecting in greater CH_4 production by methanogens (Costa et al., 2004; Zschornack et al., 2011; Bayer et al., 2013).

Long-term studies carried out over seven years in flooded rice fields established in three locations in southern Brazil have confirmed the benefits of MT with early tillage in autumn on mitigating GHG emissions in comparison to CT with tillage in spring. The results show a reduction of 24, 21 and 25 %, respectively, in seasonal emissions of CH_4, *p*GWP and yield-scaled *p*GWP due to earlier soil tillage in MT related to CT. As for NT, N_2O emissions and rice yield associated with CT and MT were similar (Bayer et al., 2015). The MT representativeness and the robustness of CH_4 emission data allowed its incorporation into the last two versions of the National Inventory of GHG emissions in the subsector CH_4 Emissions from Rice Cultivation (Brasil, 2020).

Main advances of rice no-tillage in lowland soils driven by crop rotation and Integrated Crop-livestock System (ICLS)'s adoption

Greater crop diversification and changes in the lowland production profile in southern Brazil have been occurred in the last ten years. Continuous rice cultivation has become unfeasible in some situations, mainly due to the high infestation of weeds (Ulguim et al., 2018) and, as an alternative, the rotation with soybean was intensified (Mundstock et al., 2017). This was possible due to the genetic evolution of soybean cultivars with indeterminate growth habits, which made them less sensitive to extreme soil moisture conditions. Additionally, the high crop valuation in the market making its production economically attractive, and the recent advances in geotechnologies, particularly, land levelling with variable slope (Parfitt et al., 2020), which corrects soil surface irregularities, enables surface drainage and facilitates irrigation management also contributed to the soybean insertion in the southern Brazilian lowlands.

Rice rotation with soybean is one of the most promising tools to control weedy rice and other weed species, which are the main limitations for rice cultivation in RS (Agostinetto et al., 2010). It also minimizes the occurrence and the negative impacts of main rice diseases, particularly rice blast, and pest insects, favors nutrient cycling, provides N to the system via biological nitrogen fixation, and reduces the crop demand for fertilizer by improving soil fertility over time. Benefits such as optimization of machinery and labor utilization also are evidenced (Emygdio et al., 2017).

Such benefits increased the flooded rice productivity by 10 to 15 % (Mundstock et al., 2017). In addition to the increase in rice yield, the soybean insertion has enabled the expansion of NT adoption in lowlands. In general, soil tillage is carried out before sowing soybean and, after harvesting, levees are built to cultivate rice in the following year. Thus, in two agricultural years, there is only one soil disturbance in comparison to the two tillage operations carried out in rice monoculture under MT. The longer is the time interval for returning flooded rice to the crop rotation in more diversified systems, the lower is the frequency and intensity of soil tillage operation.

Concomitantly with the expansion of soybean cultivation in lowlands in southern Brazil, the adoption of pastures with higher technological level increased, unlike the traditional extensive beef cattle production system. The adoption of ICLS has increased in lowland areas, principally due to crop rotation. With the implementation of rainfed crops, mainly soybeans, there is a change in the drainage structure that enables the more successful establishment of winter pastures. In this sense, several studies have pointed out that the ICLS associated with the use of NT in Alfisol (Planosol; *Planossolo*) contributed to the increase in labile carbon fractions in the soil (Martins et al., 2017), soil biological activity, and increased nutrient availability for rice established in succession (Carlos et al., 2020). Due to improvements in soil quality, it was observed that, in different rice-growing regions of southern Brazil, the rice grain yield increases and the response to fertilization decreases with the increment in the ICLS period (Carmona et al., 2016). Recently, corn cultivation has also expanded and, like soybeans, is drainage demanding. The rotation with rainfed crops is tremendously relevant for NT adoption in lowlands, as it keeps the soil drained and reduces the tillage demand for flooded rice cultivation.

Challenges of no-till farming for the rice in lowland soils

Lowland areas generally occur at low landscape elevations and are situated in altitudes below 150 m (Streck et al., 2008). Water accumulation is favored as they present flat relief and occur at low elevations. In addition, Alfisols (Planosols; *Planossolos*), which are the main order of lowland soils, have an argillic B horizon that results in very low hydraulic conductivity. This condition is one of the most important factors for the agricultural suitability of lowland soils, as it provides low water infiltration and allows the maintenance of irrigation water for prolonged periods in rice cultivation (Borin et al., 2016).

Soil flooding can control weeds, however, it leads to several changes in soil redox conditions that, in general, are chemically favorable to the development of rice plants due to soil acidity correction and increase in nutrient availability (Ponnamperuma, 1972; Schmidt et al., 2009; Carlos et al., 2020). Irrigation is suppressed for mechanized crop harvesting; however, it often occurs with saturated soil because of the soil physical characteristics as low water infiltration. Thus, the flat relief that accumulates water and presents reduced runoff associated with low permeability of the Bt horizon contributes to the water storage in paddy fields. In this condition of soils with high moisture content, the harvest is performed with large harvesting machines due to the irrigation water. This mechanized operation causes many surface irregularities, representing one of the main challenges for no-tillage adoption in lowland areas, as it requires new land leveling operations. This context explains the difficulty of adopting NT in flooded rice production in lowlands.

Recently, the previous suppression of irrigation to rice crops has been encouraged to provide soil moisture lower than the one at the field capacity at the harvesting time, promoting less soil disturbance. Under adequate moisture conditions to machinery traffic, the harvest operations consume less fuel and present greater operational efficiency. Thus, it is necessary to determine the optimal time for suppressing rice irrigation, integrating adequate soil moisture conditions for mechanized harvesting, and maintaining crop yield and/or grain quality. However, the rice harvest in some years coincides with rainy periods, so it is executed with saturated soil. Then, despite opposing the conservation perspective for soil management, harvest is carried out under inadequate moisture conditions.

The need to incorporate rice straw into the soil is another factor which may demand soil tillage operations. At the end of the crop cycle, the crop residue has high C/N ratio and high lignin and silicon levels, which biochemically are not attractive to the soil microbiota (Tsujimoto et al., 2014). Thus, the highly recalcitrant rice plant residual biomass, associated with a low O_2 availability environment, result in a very low rice straw mineralization rate (Devêvre and Horwáth, 2000). Consequently, even if the harvest is performed on dry soil, soil tillage is usually required to mitigate deleterious effects on sowing the following crop through rice straw incorporation and stimulation of its decomposition and mineralization (Botta et al., 2015).

Research reports show that the remaining amounts of rice straw over 600 to 800 kg ha^{-1} can harm the establishment of rice plants in subsequent cultivation (Botta et al., 2015). For this reason, alternative strategies have been investigated to increase the mineralization rate and reduce the amount of rice straw in the following season. The most promising one is characterized by the use of a rice straw chopper and distributor during harvesting. These implements improve straw distribution on the soil surface as well as increase the contact between soil and residual crop biomass. This strategy improves rice straw distribution in winter and favors the establishment of pastures such as ryegrass after flooded rice cultivation (Carvalho et al., 2011).

The chemical management of rice straw can also be utilized. Rice sprouting can occur after harvesting under favorable temperature conditions in autumn, promoting the accumulation of greater vegetation mass amounts, so chemical desiccation has been used to extinguish plant sprouting (Grohs et al., 2020). In addition, mechanized strategies like mowing can be used to increase the contact surface between straw and soil, making residual crop biomass distribution uniform and increasing the mineralization rate (Grohs et al., 2020). Other management systems that can be used for rice straw management are the application of nitrogen fertilizer in the pasture after rice and the use of livestock soon after harvest. Nitrogen fertilization reduces the rice straw C:N ratio and accelerates mineralization (Dobermann and Fairhurst, 2002). The use of rice straw for cattle grazing can be a strategy to reduce the biomass amount on the soil surface, besides being a food option for animals and providing a more suitable condition for establishing winter pastures (Dobermann and Fairhurst, 2002).

Perspectives to the future

Convential tillage for rice cultivation has been gradually replaced by other cultivation systems in RS although it has been provided relatively high crop productivity and has been widely used since the beginning of flooded rice cultivation in Brazil in the beginning of the 20th century (Figure 4) (Sosbai, 2018). The consolidation of conservation tillage, whether MT or NT, for flooded rice cultivation occurred mainly because they enable rice sowing at the correct time and optimize crop productivity (Menezes et al., 2012). Thus, it seems inevitable to affirm that the traditional system of flooded rice cultivation in southern Brazil, based on CT and monoculture associated with beef cattle under extensive grazing, is no longer viable and will not be further established.

Although NT is less expressive than MT, its adoption is becoming viable due to the introduction of production systems with rainfed crops. Crop rotation is a key factor for the success of NT in lowlands. The insertion of crops that promote significant dry mass inputs, including species diversification, is essential for NT in these areas (Theisen et al., 2017). Martins et al. (2017) found no differences between CT and NT in a short-term experiment, except when NT included species diversification in crop rotation. This fact highlights the importance of this practice for the system effectiveness as it stimulates nutrient cycling, organic carbon accumulation, and microbiological activity (Martins et al.,

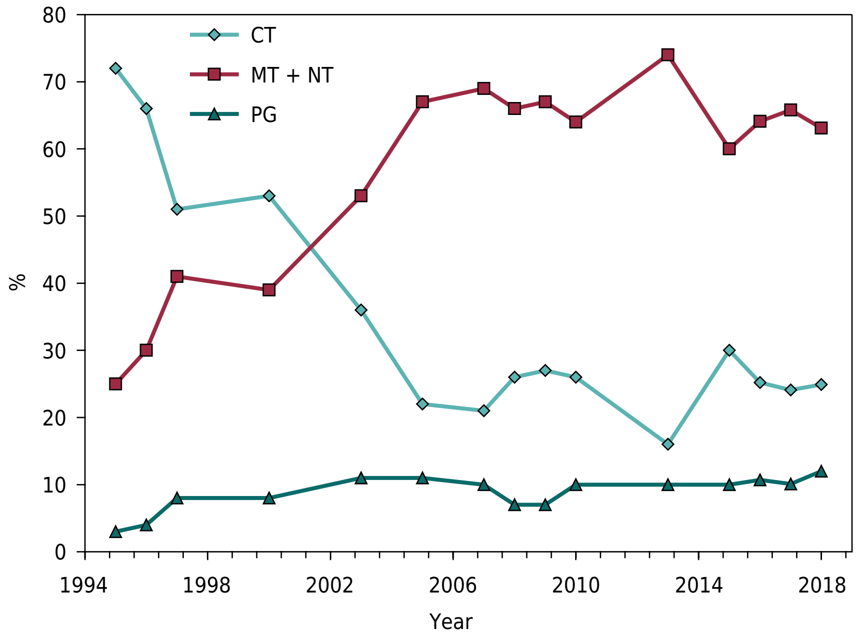

Figure 4. Distribution of tillage systems utilized for rice cultivation in RS state. CT: conventional Tillage; MT + NT: minimum tillage + no-tillage; and PG: pre-germinated.

2017; Carlos et al., 2020). In relation to the soil microbial community profile under NT adoption in southern Brazil lowlands, few studies have been developed; therefore, information about this topic is lacking (Carlos et al., 2021). Research advances are expected for the upcoming years and, mainly, a better understanding about microbial activity and impacts on nutrient availability and development of agricultural crops (Carlos et al., 2021).

Increase in the cultivation of rainfed crops such as soybean, corn and pastures in rotation with rice has promoted an increase in soil flattening, land levelling with variable slope, and advances in macro and micro drainage systems in lowlands (Parfitt et al., 2020). These improvements are predominantly performed through RTK (Real Time Kinematic) technology, which allows the precise allocation of drains and correction of soil surface irregularities (Parfitt et al., 2020). Using these technologies has progressively increased the flooded rice area, which is harvested on dry soil, promoted straw management, and enabled the establishment of soybean or rice in the following year without soil tillage. This technology is used predominantly in big and automatized farms; however, as its adoption increases, it will be more affordable for small and medium-sized farms and may contribute to greater adoption of NT in lowlands (Parfitt et al., 2020).

Crop cultivation in large ridges expands the range of crops introduced in rotation systems, providing greater plant species diversity and increasing the quantity and quality of biomass deposited on soil. This practice promotes the increase and stabilization of SOM, resulting in better soil fertility and physical conditions (Theisen et al., 2017). The construction of ridges in lowlands favors the NT adoption with rainfed crops in rotation with flooded rice. This practice aims to improve drainage by increasing the original soil level and can decrease soil bulk density and increase porosity (Giacomeli et al., 2017; Goulart et al., 2021). Gubiani et al. (2018) reported mean soybean yield 700 kg ha^{-1} higher in NT with ridges than in NT without ridges. Goulart et al. (2021) verified higher soybean and corn yields due to better soil aeration occasioned by soil chiseling associated with ridges.

Data about emissions and rice production performance in southern Brazil show both systems, NT and CT, represent promising strategies to mitigate GHG emissions and yield-scaled *p*GWP from flooded rice production systems (Bayer et al., 2014). Furthermore, these management options are affordable and interesting for the agricultural sector, not penalizing the yield and quality of rice grains and incorporating important technical and economic benefits into farming activity (Bayer et al., 2015).

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