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Conservation tillage in temperate rice cropping systems: Crop production and soil fertility

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ABSTRACT

Context: Conventional tillage (i.e. ploughing) that is applied in Italian rice fields ensures high grain yields, but may result in negative effects on physical and chemical fertility of soil. Conservation tillage can be a viable alternative to conventional allowing to reduce the environmental and economic impact of rice cultivation. However, there is limited knowledge on the effects of these alternative tillage systems on rice yield and paddy soil fertility in temperate climates.
Objective: The aim of this study was to evaluate the effects on yield and soil fertility of conservation tillage in the medium term in temperate rice continuous monoculture system.
Methods: A six-years monocrop rice experiment (2014–2019) was carried out in North-West Italy, comparing three tillage methods: conventional tillage (ploughing – *CT*), minimum tillage (*MT*), and no tillage (*NT*) combined with three N fertilization rates (*N0*, *N* – 120 kg N ha^{-1} year^{-1}, and *N+* – 160 kg N ha^{-1} year^{-1}). The study evaluated yield, yield components, plant N uptake, apparent N recovery (ANR), soil bulk density, total soil organic carbon (SOC) stock and C and N distribution between different soil organic matter (SOM) fractions.
Results: *MT* showed a similar grain yield to *CT*, while a 15 % reduction was recorded with *NT*, which was penalized by low plant density and high soil compaction in the surface layer. Although *NT* exhibited higher panicle density, spikelets per panicle, and 1000-grain weight than *CT* and *MT*, these factors were not sufficient to compensate for the grain yield gap. *NT* resulted in decreased plant N uptake and ANR, making increasing N fertilization in *NT* ineffective for recovering the yield gap with *CT*. After six years, no significant difference was found in SOC stock among the tillage treatments. However, conservation tillage influenced the vertical distribution of SOC, resulting in higher concentration in the superficial soil layer (0–15 cm) compared to *CT*. *MT* led to the highest amounts of labile and physically protected SOM in the 0–15 cm layer compared to *NT*, where lower crop residue input due to lower straw production limited the accumulation of these types of SOM fractions.
Conclusions: *MT* use production resources more efficiently compared to *CT* and sustains soil fertility by promoting organic matter and nitrogen inputs, facilitating soil aggregation and preventing soil compaction. Yield reductions and excessive soil compaction are the main obstacles to the wide adoption of *NT*.
Implications: Minimum tillage is a viable alternative to conventional tillage for improving the environmental and economic sustainability of Italian temperate rice cropping system, while no tillage may only be suitable for marginal and less productive areas.

1. Introduction

Rice is the second most important cereal crop in the world with 194 Mha cultivated globally, and Italy stands out as the main rice producer in Europe, with an area of 227.320 ha (FAOSTAT, 2020). In Italy rice is cultivated once per year from the end of April until the beginning of October. Soil preparation commonly involves three or four operations, depending on the soil characteristics: mouldboard ploughing, which is carried out in either autumn or spring, followed in spring by laser leveling and one or two harrowing (Cordero et al., 2018; Miniotti et al., 2016). These conventional tillage practices provide high grain yields, but their sustainability in rice cropping systems has often been

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questioned primarily due to their negative effects on soil organic matter (SOM) mineralization, soil physical, chemical and biological fertility (Chen et al., 2007). In addition, conventional tillage leads to high costs due to higher energy demand and longer time required for seedbed preparation (Calcante and Oberti, 2019). Therefore, alternative soil management practices that allow to reduce agronomic, environmental, and economic impact of European temperate rice cultivation, while maintaining high yields, deserve to be investigated (Miniotti et al., 2016; Moreno-García et al., 2020).

Conservation agriculture can be a viable alternative to conventional management in rice cropping systems (Huang et al., 2015). Among the three pillars of conservation agriculture (reduced mechanical soil disturbance, permanent soil cover using crop residues or cover crops, and crop rotation), reduction of soil tillage intensity, i.e. minimum tillage and no tillage, is the one which is currently being adopted by a certain extent in Italian rice cropping systems, and its application is continuously increasing (Ferrero et al., 2021). Indeed, rice in Italy is mainly cultivated as monocrop and the use of cover crops is limited, even though their cultivation has increased over the last years, particularly in organic rice cultivation (Fogliatto et al., 2021; Vitalini et al., 2020).

The benefits of conservation tillage on rice crop yield generally depends on climatic conditions, soil type, cultivar and agronomic practices adopted (Huang et al., 2015). Conservation tillage in subtropical regions was shown to increase rice yield by 3.4 % to 4.1 % when compared to conventional tillage (Denardin et al., 2019; Zheng et al., 2014), though similar (Xu et al., 2010) or even decreased yields (Huang et al., 2015) have been previously reported. Moreover, information about the effects of conservation tillage on rice grain yield in temperate continuously flooded rice is still lacking, and the few studies available have reported 10–20 % reductions in yields with no-tillage when compared to ploughing (Cordero et al., 2017; Perego et al., 2019).

The reduction of tillage in paddy soils generally results in increased soil bulk density in the surface layer and thus increased compaction (Kahlon, 2014), which is already favored by the typical flooded conditions of rice cultivation (Sacco et al., 2012). Therefore, seed germination, seedling establishment and root development can be hampered, eventually resulting in yield reduction (Busari et al., 2015; Munkholm et al., 2013; Tesfahunegn, 2015). For cereals other than flooded rice, the higher compaction under no-tillage can be mitigated after a few years of continuous adoption by the soil self-structuring capacity (Blanco-Canqui e Ruis, 2018). This can contribute to reduce yield losses compared with conventional tillage in the long term also in flooded rice cropping systems, thought depending on seeding techniques and climatic conditions (Jat et al., 2014; Zheng et al., 2014). It is well known how conservation tillage methods contributes to improve paddy soil quality and environmental sustainability, by favoring soil organic carbon (SOC) storage and reducing soil aggregate breakdown, even in the short term (Huang et al., 2012; Xue et al., 2015). However, in paddy soils managed with conservation tillage, the mulching effect of crop residues left on the soil surface results in lower soil temperatures, and together with increased soil compaction, delays N cycling (Bird et al., 2003; Li et al., 2015) and rice N uptake (Eagle et al., 2000). Indeed, SOM decomposition rates are lower under conservation than conventional tillage systems due to the physical protection of SOM within soil aggregates that reduces the exposure of labile SOM pools to degradation and mineralization by biological activity (Jin et al., 2011; Maltas et al., 2013).

Therefore, to compensate for the lower N availability due to the slower SOM mineralization and the consequent negative effects on rice yield under conservation tillage, these alternative techniques may require increased rates or a different splitting strategy in N fertilization compared to conventional tillage (Huang et al., 2018; Lundy at al, 2015).

Several authors demonstrated that in subtropical and tropical areas conservation tillage promotes SOC accumulation in paddy soils, particularly when these alternative tillage methods are applied in the medium to long term, i.e. more than 6 years (Carlos et al., 2022; Huang et al., 2012; Wang et al., 2019). The SOM stratification induced by the non-inversion of the soil layers with reduced tillage, results in higher SOM contents in the superficial soil layers that decrease progressively with soil depth (Varvel and Wilhelm, 2011). On the contrary, conventional systems determine a homogeneous SOM distribution in the topsoil because crop residues are incorporated to greater depths, that also favor SOM decomposition as a result of the breakdown of soil aggregates (Qi et al., 2021; Xue et al., 2015). This induces the formation of smaller aggregates, with low C content, and free particulate organic matter, characterized by less stability and faster turnover (Zhu et al., 2014).

Long and medium-term adoption of conservation tillage and its effects on rice yield and on SOC dynamics have already been studied in tropical and subtropical areas (Carlos et al., 2022; Huang et al., 2015; Wang et al., 2021). In temperate climates the effects of these techniques have been investigated in many cropping systems (Fiorini et al., 2020; Krauss et al., 2017; Van den Putte et al., 2010), however there is a lack of knowledge concerning the effects on paddy soils in medium-term applications.

Building upon these considerations, this work aims to evaluate the adoption of conservation tillage in the medium term for rice cultivation in temperate climate areas as an alternative to conventional tillage, and particularly evaluate whether conservation tillage can provide high grain yields by increasing soil fertility. We hypothesized that: (1) conservation tillage decreases grain yield, but in the medium-term stabilization of yield at levels comparable to conventional tillage can occur due to improved soil fertility; (2) increasing mineral fertilization with N allows to fill the yield gap in conservation tillage compared with conventional tillage; (3) conservation tillage increases SOC stocks even in temperate rice cropping systems, where the only OM input to the soil is crop residues, thus increasing the environmental sustainability of these cropping systems; (4) conservation tillage accumulates labile and physically protected OM in the superficial layers of paddy soils, increasing N availability for the rice plant. To test these hypotheses, we compared conventional and conservation tillage in a medium-term field experiment evaluating their effects on rice yield and yield components, on soil bulk density and SOM fractions distribution in the soil profile.

2. Material and methods

2.1. Experimental site and pedoclimatic characteristics

A rice field experiment was carried out from 2014 to 2019 within a medium-term continuous rice monocrop experimental field. The site was located in the western part of the Po River valley (Pieve Albignola, NW Italy; 45°06’41.2" N, 8°57’06.2" E), representing the main Italian paddy area.

According to Köppen-Geiger (Köppen, 1936), climate in the area is defined as *Cfa*, with hot summers, cold winters and two main rainy periods in spring and autumn. Total yearly rainfall was highly variable during the experimental period (Fig. 1), ranging from 916 to 371 mm, but nevertheless lower than the mean total annual precipitation over the last 10 years (952 mm). Mean annual minimum and maximum temperatures were close to 0 and + 25 °C, respectively, while the mean annual temperature (+13.6 °C) was slightly higher than the last decade (+12.9 °C).

According to the USDA soil taxonomy (Soil Survey Staff, 2010), the soil of the experimental field was an Ultic Haplustalf, sandy loam, mixed, mesic. The content of sand (2–0.05 mm), silt (0.05–0.002 mm) and clay (< 0.002 mm) was corresponding to 63 %, 30 % and 7 %, respectively. The topsoil (0–30 cm) was chemically characterized as follows: acidic pH (in H_2O), 5.7; medium soil total N content (Kjeldahl), 1.3 g kg^{-1}; high organic matter content (Walkley and Black), 19.0 g kg^{-1}; medium-high cation exchange capacity (ammonium acetate method, pH 7), CEC: 9.7 $cmol_+ kg^{-1}$, where exchangeable Ca^{2+}, Mg^{2+} and K^+ were 510.5, 63.9 and 72.7 mg kg^{-1}, respectively.

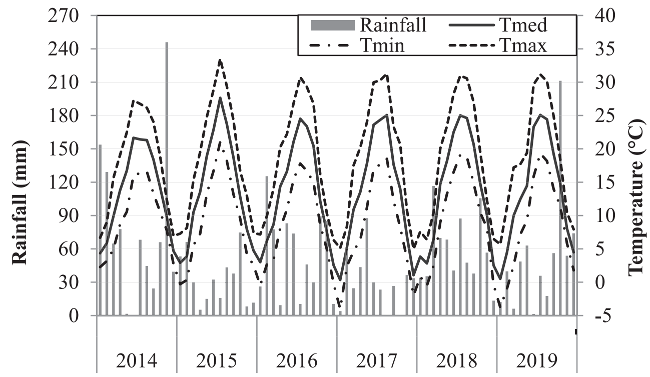

Fig. 1. Maximum, minimum and average monthly temperature and precipitation from 2014 to 2019.

2.2. Experimental setup and agronomic management

The experimental design was a split plot with two experimental factors: tillage practices in the main plots and N fertilization rates in the subplots. Three different tillage practices were compared for seedbed preparation: (1) conventional tillage (*CT*), managed with reversible mouldboard plough with 30 cm working depth, followed by one disc harrowing and dry seeding; (2) minimum tillage (*MT*) managed with one passage of a combined cultivator (chisels and discs) with 10 cm working depth, followed by one disc harrowing and dry seeding; (3) no-tillage (*NT*) that implied a sod-seeding management performed with a sod-seeder with planter unit consisting of a single disk. The three tillage treatments were conducted in plots of about 600 m^2 and were set up in a randomized complete block design with three replicates. In both *CT* and *MT*, tillage was performed in spring and dry seeding was carried out using a pneumatic seed drill to uniform with *NT* management. After harvest, crop residues were always left in the field.

The three different tillage practices were then combined with three N fertilization doses applied in sub-plots of 40 m^2: (1) *N0* fertilization, with no N fertilizer supply; (2) *N* fertilization, with a N dose traditionally supplied in the area (120 kg N ha^{-1} y^{-1}), and (3) *N+* fertilization, involving a N application dose that was 25 % higher than *N* (160 kg N ha^{-1} y^{-1}). The N fertilizer (Urea, 46 %) was always split in two applications: 60 % of total N amount at tillering stage (BBCH code 21) and 40 % at panicle differentiation stage (BBCH code 34). In addition, 30 kg P_2O_5 ha^{-1} y^{-1} (13.2 kg P ha^{-1} y^{-1}) and 100 kg K_2O ha^{-1} y^{-1} (83 kg K ha^{-1} y^{-1}) were applied at tillering stage across all treatments.

Sole CL variety (imidazolinone-tolerant) was dry seeded at the seeding rate of 170 kg ha^{-1} between the second and the third decade of May in each year. For all treatments, the fields were flooded with a 5 cm water level at tillering stage, approximately one month after seeding, after the herbicide treatments and the first top-dressing fertilization. Afterwards, field flooding was maintained throughout the cropping season, except for one drainage period at panicle initiation stage to allow for second top-dressing fertilization. After drainage period, water level was raised and kept around 10–15 cm, until the field was drained approximately one month prior to harvest.

Weed control differed between tillage practices. In *NT* glyphosate (1080 g ha^{-1}) was applied before seeding. In all tillage treatments, pendimethalin and oxadiazon were applied together in pre-emergence (770 and 380 g ha^{-1}, respectively) and imazamox and halosulfuron-methyl (34 g ha^{-1} and 30 g ha^{-1} respectively) were applied twice in post-emergence.

2.3. Crop yield, yield components and efficiency indices

Grain and straw yields were measured every year with a combine harvester at the end of the growing season (first decade of October) when grains reached a moisture content of about 20 %. No data were measured for 2017 due to a strong hailstorm that compromised crop yield.

Grain and straw samples were dried to reach a moisture content of 14 %, and subsequently ground and analyzed for total N by dry combustion (UNICUBE Elemental Analyzer, Elementar, Germany). Moreover, yield components (i.e. panicle density, number of spikelets per panicle, 1000-grain weight and panicle sterility) were measured using a sample of rice plants collected in three 0.25 m^2 areas in each sub-plot before harvesting. Plant density was estimated at seedling emergence stage in three sampling areas (0.25 m^2) for each sub-plot. Tillering capacity index was calculated as ratio between panicle density (at harvest) and plant density (at seedling emergence stage). Apparent Nitrogen recovery (ANR) was calculated for *N* and *N+* treatments according to Zavattaro et al. (2012):

$$ANR = \frac{(N \quad uptake_N) - (N \quad uptake_0)}{F_N} \times 100\%$$

where *N uptake*$_N$ is plant (grain + straw) uptake expressed as kg N ha^{-1} for *N* and *N+* rate fertilization, *N uptake*$_0$ is plant uptake expressed as kg N ha^{-1} in the *N0* treatment, F_N is the amount nitrogen applied with mineral fertilizer (as kg N ha^{-1}). N uptake was obtained by multiplying grain and straw dry weight by respective N content.

2.4. Soil measurements

Soil measurements were performed at the end of experimental period (after harvesting in 2019). These measurements were carried out for the three tillage methods and only for one level of nitrogen fertilization (*N* treatment). Soil samples were obtained from subplots where a dose of 120 kg N ha^{-1} was applied, because this is the usual rate applied by local farmers. Two sampling depths were considered: 0–15 and 15–30 cm. The samples were air dried, ground and sieved at 2 mm. SOM characterization was determined by the density fractionation method (Golchin et al., 1994; Sohi et al., 2001), modified to obtain an additional coarse particulate OM fraction (POM) with size > 200 μm. This fraction was obtained by wet sieving 24 g of ground soil (<2 mm) together with 6 stainless steel balls with a diameter of 6 mm, in a rotating sieve (200 μm mesh) immersed in 0.8 L of water for 60 min to facilitate the breakdown of soil macroaggregates and release of coarse free POM. On the fraction obtained after this process (< 200 μm) the density-based separation scheme (density cutoff = 1.6 g cm^{-3}; microaggregate breakdown energy = 440 J ml^{-1}) was applied (Golchin et al., 1994). Four fractions were thus separated: (i) free particulate organic matter with dimensions > 200 μm (*coarse fPOM*), (ii) free particulate organic matter with dimensions < 200 μm (*fine fPOM*), (iii) physically protected intra-micro-aggregate particulate organic matter (*iPOM*); (iv) mineral-associated and chemically protected organic matter (*MOM*). Total soil organic C (SOC), total N (SN) and their distribution between different SOM fractions were determined by dry combustion (UNICUBE Elemental Analyzer, Elementar, Germany).

Soil bulk density was measured in 2019 in *N* treatments sub-plots at a soil depth of 7.5 cm (representative of first layer 0–15 cm) and 22.5 cm (representative of second layer 15–30 cm) using cylinders of volume equal to 100 cm^3, replicated three times for each layer. Dry weight was determined at 105 °C until a constant weight was reached.

The stocks of total SOC, TN and each SOM fractions were calculated as follows according to (Morgan and Ackerson, 2022):

$$STOCK = X \times BD \times H \times 0.1$$

where, X is organic C or N concentration (mg g_{soil}^{-1}), BD is bulk density (g cm^{-3}); H is soil depth (cm), 0.1 is the conversion factor to obtain value expressed as Mg ha^{-1}.

2.5. Data analysis

Yield and yield components data were analyzed by a linear mixed effect (lme) model including tillage practices, fertilization treatments and year as fixed factors and block as random effect. The effects of tillage practices, depth and their interactions on soil bulk density, SOC and SN stocks, C and N stocks in all soil organic matter fractions were tested by two-way ANOVA. Treatment averages were separated through Bonferroni post hoc test at $P<0.05$. Analyses were performed using *nlme*, *emmeans* and *multcomp* R packages.

For multivariate analysis, the PCA was applied by means of the R software library *FactoMinerR*. PCA was performed only on the different tillage methods considering the *N* fertilization level, because previous statistical analysis did not identify significant differences in grain yield between nitrogen levels, except for *N0*. Statistical analysis was performed using R software, version 3.6.2.

3. Results

3.1. Grain and straw yield

Both tillage and N fertilization significantly influenced rice grain yield, separately and in interaction with year, but the interaction between the two factors was never significant (Table 1). *CT* and *MT* never showed differences between them. Conversely, *NT* resulted in a significantly lower grain yield than *CT* and *MT* except for 2014. Looking at the entire period, *NT* average yield was 15 % lower than *CT* and *MT*. However, tillage × year interaction in grain yield highlighted a different behavior over time among the three tillage techniques, as *NT* performed not dissimilarly to *CT* and *MT* in 2014 only.

Fertilization did not show any grain yield differences between *N* and *N+* treatments and no significant interaction between tillage and fertilization was evidenced. Straw and grain yield showed a similar behavior. *CT* and *MT* demonstrated higher straw production than *NT*, except in the first year.

3.2. Yield components

Similar to grain and straw yield, for all yield components investigated, the interaction between tillage and fertilization was never found significant (Table 2). *NT* showed lower plant density than *CT* in all years, while *MT* was characterized by a variable trend over the years. Panicle density in *NT* management was lower than *CT* except for 2019, in which the three tillage methods resulted in similar values, while *MT* was always similar to *CT*. *NT* management resulted in a higher number of tillers per plant compared to *CT* in 2014 and 2016, in 2015 and 2018 tillering capacity was similar for three tillage methods tested. *NT* resulted in more spikelets per panicle than *MT* and *CT* in three years (2014, 2015 and 2018), while in 2016 and 2019 the three tillage methods provided similar results. *NT* and, in 2016, also *MT* determined a higher 1000-grain weight than *CT*, except for 2014, when no differences among managements were found. *NT* and in 2014 and 2019 also *MT* showed less sterility than *CT*, while in 2015 and 2018 no differences among tillage managements were found. As expected, a N fertilization effect was not recorded on plant density, although panicle density was significantly lower in *N0* with respect to fertilized plots except for 2015, with *N* and *N+* not showing any differences between them. Fertilization × year interaction was not significant for tillering capacity and spikelets per panicle, but the average of five years showed significantly lower values in *N0* with respect to fertilized treatments for both parameters. In contrast, plots not fertilized with nitrogen showed higher values of 1000-grain weight than the fertilized ones. Fertilization with N at both levels resulted in higher sterility than *N0*.

The Principal Component Analysis (PCA) of grain yield components allowed to obtain a set of uncorrelated PCs (see Supplemental Table A). According to Kaiser's rule (Kaiser, 1960), the first two PCs were retained, as they recorded eigenvalues higher than 1 and explained 68.2 % of the total variance (36.7 % and 31.5 % of the total variability explained by PC1 and PC2, respectively). The PC1 had the largest positive correlation with plant density and panicle density and was negatively correlated with tillering capacity. The PC2 showed positive correlation with spikelet number per panicle and sterility and negative correlation with 1000 grain weight. The datapoints referred to *NT* and *CT* management led to two distinct groups that differed mainly along PC1 axis and for higher PC2 values (Fig. 2). On the contrary, data referred to *MT* management grouped on an intermediate area of the graph, suggesting that the effect of yield components was weaker than in *NT* and *CT*.

3.3. N plant uptake and apparent N recovery (ANR)

Total N uptake in *CT* plots was always the highest, while that in *NT* plots the lowest among the tillage managements, except for the first year (Tables 3 and 4). *MT* did not reduce total N uptake with respect to *CT*, except for 2019. Regarding fertilization management, total N uptake was found to decrease in the order *N+* > *N* > *N0*. As expected, tillage × fertilization interaction recorded the lowest values for *N0* in *NT* and the highest for *N+* and *N* in *CT* and *MT* management. Moreover, in *N0*

Table 1
Grain and straw yield (Mg ha^{-1} at 14 % moisture) from 2014 to 2019. Values followed by different letters denote differences between treatments (tillage or fertilization) within year (P(f)< 0.05).

			2014	2015	2016	2018	2019	Average
Grain yield (Mg ha^{-1})	Tillage	CT	8.4 a	10.0 a	10.2 a	8.8 a	10.0 a	9.5 a
		MT	8.6 a	9.9 a	9.7 a	8.6 a	9.5 a	9.3 a
		NT	8.2 a	8.8 b	7.5 b	7.1 b	8.5 b	8.0 b
	Fertilization	N +	9.6	10.4	10.1	9.0	10.1	9.8 a
		N	9.3	10.2	9.7	8.5	10.0	9.5 a
		N0	6.4	8.2	7.7	6.9	8.0	7.4 b
P(f)	Tillage: 0.000; Fert: 0.000; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.000; Fert*Year: ns							
Straw yield (Mg ha^{-1})	Tillage	CT	9.0 a	10.1 a	8.5 a	9.4 a	9.7 a	9.3 a
		MT	8.8 a	9.8 a	7.8 a	9.2 a	9.1 ab	8.9 a
		NT	7.5 a	7.3 b	5.5 b	7.3 b	8.2 b	7.1 b
	Fertilization	N +	9.7	10.2	8.0	9.4	9.7	9.4 a
		N	9.1	9.5	7.9	9.1	9.7	9.0 a
		N0	6.5	7.6	5.9	7.3	7.5	7.0 b
P(f)	Tillage: 0.000; Fert: 0.000; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.046; Fert*Year: ns							

CT: conventional tillage with ploughing, MT: minimum tillage with non-inversion surface, NT: no tillage with sod seeding. N0: no nitrogen applied; N: 120 kg N ha^{-1} year^{-1}; N + : 160 kg N ha^{-1} year^{-1}. Fert: Fertilization

Table 2
Yield components (plant density, panicle density, tillering capacity, spikelets per panicle, 1000 grain weight, sterility) from 2014 to 2019. Means followed by different letters denote differences between treatment for each variable (tillage or fertilization effect) within year (P(f)< 0.05).

			2014	2015	2016	2018	2019	Average
Plant density (Plant m^{-2})	Tillage	CT	179 a	359 a	251 a	225 a	257 a	254 a
		MT	126 b	285 b	214 a	219 a	190 b	201 b
		NT	100 b	240 c	118 b	144 b	160 b	158 c
	Fertilization	N +	139	302	197	201	213	211
		N	132	304	191	192	198	204
		N0	134	276	192	192	195	198
P(f)	Tillage: 0.000; Fert: ns; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.000; Fert*Year: ns							
Panicle density (Panicle m^{-2})	Tillage	CT	446 a	547 a	464 a	488 a	473 a	484 a
		MT	449 a	575 a	424 a	549 a	418 a	483 a
		NT	382 b	467 b	347 b	406 b	434 a	407 b
	Fertilization	N +	477 a	560 a	427 a	517 a	480 a	492 a
		N	432 a	530 ab	425 a	499 a	483 a	474 a
		N0	368 b	499 b	383 b	427 b	362 b	408 b
P(f)	Tillage: 0.000; Fert: 0.000; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.000; Fert*Year: 0.047							
Tillering capacity (Tillers plants^{-1})	Tillage	CT	2.5 b	1.5 a	1.8 b	2.2 a	1.8 b	2.0 b
		MT	3.5 a	2.0 a	1.9 b	2.5 a	2.7 a	2.6 a
		NT	3.9 a	1.9 a	3.0 a	3.0 a	2.3 ab	2.9 a
	Fertilization	N +	3.6	1.9	2.3	2.7	2.4	2.6 a
		N	3.6	1.8	2.4	2.8	2.6	2.6 a
		N0	2.9	1.9	2.2	2.3	1.9	2.2 b
P(f)	Tillage: 0.000; Fert: 0.009; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.001; Fert*Year: ns							
Spikelets per panicle (n°)	Tillage	CT	135 b	149 ab	151 a	107 b	136 a	135 b
		MT	139 b	138 b	149 a	109 b	149 a	137 b
		NT	168 a	160 a	159 a	127 a	135 a	150 a
	Fertilization	N +	155	159	160	120	145	148 a
		N	151	154	161	118	141	145 a
		N0	135	133	138	104	134	129 b
P(f)	Tillage: 0.005; Fert: 0.000; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.000; Fert*Year: ns							
1000 grain weight (g)	Tillage	CT	24.8 a	24.9 b	23.7 b	24.8 b	24.3 b	24.5 b
		MT	24.9 a	25.2 ab	24.5 a	24.9 b	24.4 b	24.8 b
		NT	24.6 a	25.5 a	25.0 a	25.7 a	25.3 a	25.2 a
	Fertilization	N +	24.3 b	24.7 b	24.1 b	24.5 b	24.1 b	24.3 b
		N	24.6 b	25.0 b	24.0 b	24.8 b	24.3 b	24.5 b
		N0	25.5 a	25.9 a	25.0 a	26.1 a	25.7 a	25.6 a
P(f)	Tillage: 0.001; Fert: 0.000; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.000; Fert*Year: 0.038							
Sterility (%)	Tillage	CT	20.9 a	12.4 a	14.9 a	9.7 a	13.0 a	14.2 a
		MT	16.0 b	12.0 a	13.2 a	9.4 a	9.8 b	12.1 b
		NT	13.3 b	10.0 a	7.6 b	9.7 a	8.4 b	9.8 c
	Fertilization	N +	18.5	14.0	13.2	10.2	12.2	13.6 a
		N	18.3	11.8	13.0	11.4	10.9	13.0 a
		N0	13.5	8.7	9.3	7.2	8.2	9.4 b
P(f)	Tillage: 0.000; Fert: 0.000; Year: 0.000; Tillage*Fert: ns; Tillage*Year: 0.000; Fert*Year: ns							

CT: conventional tillage with ploughing, MT: minimum tillage with non-inversion surface, NT: no tillage with sod seeding. N0 no nitrogen applied; N 120 kg N ha^{-1} year^{-1}; N + 160 kg N ha^{-1} year^{-1}. Fert: Fertilization

plots total N uptake was lower in *NT* respect to *CT* and *MT*. Straw N uptake also indicated a lower N availability in *NT* and *N0*. ANR showed lower values in *NT* in all years, but in 2014 and 2018, it did not exhibit significant differences compared to *CT*. In 2015, 2016, and 2019, it also did not display significant differences compared to *MT*. Considering the five-year average, ANR was the lowest in *NT* (28.7 %) and the highest in *CT* and *MT* (51.4 % and 51.1 %, respectively). Fertilization did not show a significant effect on ANR.

3.4. Soil measurements

Bulk density in the 0–15 cm layer was higher in *NT* than in *CT* and *MT* (Table 4). Differences were smaller and non-significant in the 15–30 cm layer, with an average value of 1.56 Mg m^{-3}. Moreover, bulk density increased with depth in *CT* and *MT*, but decreased in *NT*.

At the end of the 6-yr experimental period (in 2019), both *MT* and *NT* did not increase total SOC stock in the 0–15 cm soil layer compared with *CT* (Table 4). In the 15–30 cm layer, SOC stock was higher in *CT* than in *MT* and *NT*. Observing the differences between depths in each tillage practice, total SOC stock in *CT* management was similar in both layers, while both *NT* and *MT* determined a different distribution of SOC in the soil profile, resulting in its accumulation near the soil surface. A significant tillage × depth interaction was observed in the organic C stocks of SOM fractions, except in the *MOM* fraction (Fig. 3). In contrast to *CT* and *NT*, *MT* showed a higher content of *coarse fPOM* in surface layer than in deeper one. Looking at the 0–15 cm layer, *coarse fPOM* C stock was lower in *NT* respect to *CT* and *MT*. In *CT* management, organic C in *fine fPOM* was more abundant in the deeper layer, while it was homogenous between layers both in *MT* and *NT*. Both *MT* and *NT* showed a higher *iPOM* organic C content in topsoil than in the subsoil, while in *CT* there were no significant differences in *iPOM* across different depths.

Evaluation of soil TN and N stocks in the different SOM fractions mirrored organic C behavior. In the 0–15 cm layer *CT* showed a lower N content compared to *MT* and *CT*, while in 15–30 cm the opposite occurred (Table 4). The tillage × depth interaction for N stocks of SOM fraction is significant (Fig. 3). In contrast to *CT*, *MT* and *NT* showed a decrease in N stocks in the *coarse fPOM* in the deeper layer, while in *CT* there were no significant differences across different depths. In *MT* and

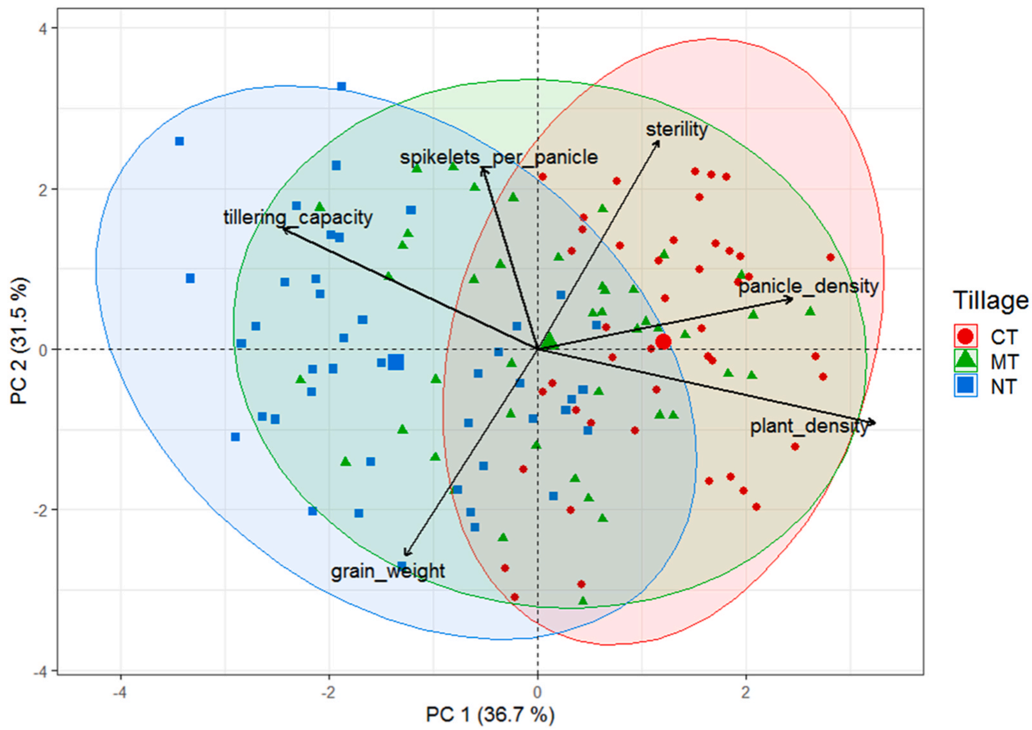

Fig. 2. PCA Biplot graph based on log-transformed data of grain yield components. CT: conventional tillage with ploughing, MT: minimum tillage with non-inversion surface, NT: no tillage with sod seeding.

Table 3
Total N uptake and straw N uptake (kg N ha^{-1}) and ANR (Apparent Nitrogen Recovery) from 2014 to 2019. Means followed by different letters denote differences between treatment for each variable (tillage or fertilization effect) within year (P(f) < 0.05). Total N uptake means followed by different letters in Tillage × Fertilization effect denote differences between all treatments.

			2014	2015	2016	2018	2019	Average	Average for Tillage*Fertilization		
									N +	N	N0
Total N uptake (kg N ha^{-1})	Tillage	CT	185.2 a	192.9 a	170.5 a	174.2 a	209.9 a	186.6 a	221.2 a	202.9 ab	135.6 d
		MT	183.5 a	186.6 a	152.5 a	178.3 a	178.0 b	175.8 a	207.5 a	193.3 ab	126.6 d
		NT	164.5 a	138.9 b	108.1 b	126.1 b	160.3 b	139.6 b	158.7 bc	148.4 cd	111.6 e
	Fertilization	N +	201.4	206.6	167.9	190.8	212.3	195.8 a			
		N	194.2	180.8	157.0	170.6	205.1	181.5 b			
		N0	201.4	131.1	106.3	117.2	130.7	124.6 c			
P(f)	Tillage: 0.000; Fert: 0.000; Year: 0.000; Tillage*Fert: 0.023; Tillage*Year: 0.000; Fert*Year: ns										
Straw N uptake (kg N ha^{-1})	Tillage	CT	82.7	80.5	55.5	71.7	81.0	74.3 a			
		MT	81.7	81.2	50.2	74.1	66.5	70.7 a			
		NT	67.0	51.1	33.9	52.0	62.0	53.2 b			
	Fertilization	N +	81.0 a	89.4 a	54.9 a	79.1 a	83.4 a	77.6 a			
		N	81.7 a	69.1 a	50.9 a	69.5 a	79.5 a	70.1 a			
		N0	68.7 b	54.4 b	33.8 b	49.2 b	46.6 b	50.5 b			
P(f)	Tillage: 0.001; Fert: 0.000; Year: 0.000; Tillage*Fert: ns; Tillage*Year: ns; Fert*Year: 0.022										
ANR (%)	Tillage	CT	38.4 ab	52.6 a	50.2 a	42.0 ab	73.6 a	51.4 a			
		MT	48.8 a	39.4 ab	46.4 ab	63.3 a	57.5 ab	51.1 a			
		NT	29.7 b	27.8 b	17.3 b	30.5 b	38.4 b	28.7 b			
	Fertilization	N +	37.5	44.4	36.3	46.0	51.0	43.0			
		N	40.4	35.5	36.2	44.5	62.0	43.7			
P(f)	Tillage: 0.007; Fert: ns; Year: 0.002; Tillage*Fert: ns; Tillage*Year: 0.046; Fert*Year: ns										

NT management, N stock in *fine fPOM* was more abundant in the upper layer, while the opposite was true in *CT*. Both *MT* and *NT* showed a higher N stock in *iPOM* in topsoil than in the subsoil, while in *CT* there were no significant differences.

4. Discussion

4.1. Effects of conservation tillage on grain yields and yield components

The application of conservative tillage in temperate Italian paddy fields determined different productive results depending on the tillage intensity adopted. This study confirmed that similar rice yields compared to conventional ploughing can be obtained with the adoption of minimum tillage in temperate rice paddies, mainly attributable to a

Table 4
Total Soil Organic Carbon (SOC) and Total Nitrogen (TN) stocks and soil bulk density measured at 0–15 and 15–30 cm layers at the end of experimental period. Lowercase letters denote different means ($P < 0.05$) between depths for each tillage management, while means followed by capital letters denote different means ($P < 0.05$) between tillage managements within each depth.

Tillage	SOC stock (Mg C ha^{-1})		TN stock (Mg C ha^{-1})		Bulk density Mg m^{-3}	
	Depth (cm)					
	0-15	15-30	0-15	15-30	0-15	15-30
CT	27.26 A a	27.68 A a	2.94 A a	3.35 A a	1.51 B	1.55 A
MT	30.77 A a	21.23 B b	3.37 A a	1.21 B b	1.53 B	1.55 A
NT	29.15 A a	21.96 B b	2.02 B a	1.39 B a	1.60 A	1.57 A
P(f)						
Tillage	ns		ns		ns	
Depth	0.008		0.007		ns	
Tillage*Depth	0.045		0.041		0.039	

CT: conventional tillage with ploughing, MT: minimum tillage with non-inversion surface, NT: no tillage with sod seeding.

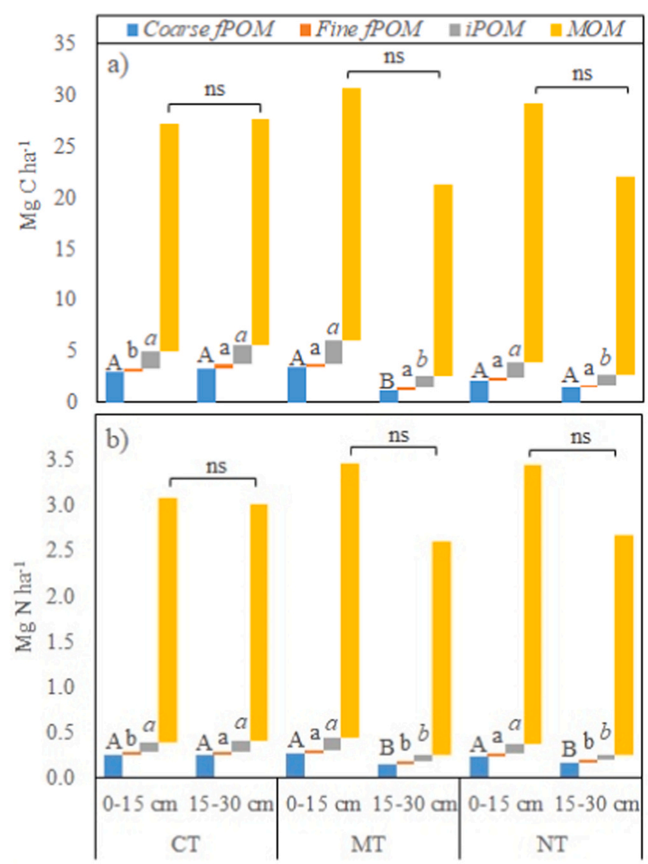

Fig. 3. Distribution of C (a) and N (b) stocks between soil organic matter fractions. Capital, lowercase and italic letters denote different means ($P < 0.05$) between depths for each tillage management for *coarse fPOM*, *Fine fPOM* and *iPOM*, respectively.

partial straw incorporation and the maintenance of an optimal soil porosity for seed germination (Linquist et al., 2008). In contrast, no tillage led to notable yield reductions of about 15 % compared to conventional tillage, similar to what has been already observed in Italy in a silty-loam paddy soil (Cordero et al., 2017; Perego et al., 2019), with significant inter-annual variability in the yield gap over the 6-yr experimental period. In particular, the yield lowered with respect to conventional tillage over the first years of no tillage adoption, but then stabilized after a few years of continuous application. This phenomenon related to the long-term adoption of no tillage is well known in scientific literature (Carlos et al., 2022; Pittelkow et al., 2015).

As highlighted by the PCA, the yield components that determined the highest grain production with ploughing are plant density and consequently panicle density. Indeed, conventional tillage represents the soil management which is able to ensure the presence of better conditions for germination and seedling establishment (Huang et al., 2012). PCA showed also that plant density is the main factor that penalized no tillage.

Low plant density and the consequent yield losses under no tillage are due to increased soil compaction according to Naresh et al. (2016). Our results revealed that the greater soil compaction in the surface layer (bulk density = 1.6 Mg m^{-3} equivalent to a 6 % increase) with respect to conventional tillage persisted even after six years of no tillage adoption in paddy soils, suggesting that this soil did not show the self-structuring capacity previously observed by Blanco-Canqui and Ruis (2018). This, together with the alteration of soil physical structure due to flooding conditions (Sacco et al., 2012), is probably due to the high sand (63 %) and low clay content (7 %) of the soil in the study site. On the other hand, minimum tillage did not determine an increase in soil compaction compared to conventional tillage in line with previous findings (Hu et al., 2007).

Moreover, the uneven seeding depth due to the impossibility of soil levelling and the deep tracks left by harvesting equipment in rice paddies, can also cause uneven germination and poor seedling establishment under no tillage, as has already been previously reported by Kumar and Ladha (2011). In this experiment, the low germination and crop seedling density may also have been due to reduced seed/soil contact, related to the high amount of crop residues on the soil surface. The choice of appropriate seeders, especially if equipped with double disc elements, can limit this problem (Crusciol et al., 2010). In addition, when practicing conservation tillage, it is advisable to consider using rice cultivars with high early vigor (Heinemann et al., 2009).

In conservation tillage plant reacts to the low plant density by producing more tillers per plant, and although the panicle density was lower, the plants produced more spikelets per panicle and larger seeds, as observed by Huang et al. (2015). On the other hand, in conventional tillage the greatest panicle density resulted in the production of smaller panicles and seeds. Our results evidenced that the compensation between yield components, which is common in rice (Huang et al., 2011b), was not sufficient to compensate for the lower plant density observed with conservation tillage, especially if the number of seedlings was too low. The lower production of no tillage can therefore be the result of a series of effects, in particular the poor seedling establishment due to low uniformity of seed germination, which eventually leads to a low plant density, as also found by Mohanty and Painuli, (2004).

The absence of an interaction between tillage and fertilization for all parameters indicates that the yield deficit obtained with no tillage cannot be recovered by increasing N fertilization even though this still determined a response from the plant as evidenced by the greater plant N uptake. Other studies pointed out that an increase in N fertilizer is not sufficient to compensate for a lower production due to a low plant density (Huang et al., 2013).

4.2. Effects of conservation tillage on N cycling and apparent N recovery

Conservation tillage practices are known to influence both the availability and plant uptake of N, by affecting the input and turnover of crop residue N, the fate of fertilizer N, as well as seedling establishment, root development and temporal changes in crop N requirements during plant growth (Huang et al., 2012).

Rice straw residues generally contain about 70 kg N ha^{-1} thus acting as an important source contributing to soil N pools, and possibly serving as a potential source of available N for the subsequent crop (Zavattaro et al., 2008). Although tillage practices did not significantly affect straw N contents, straw yields and consequently residue N inputs were significantly affected by conservation practices, in particular by no tillage. In fact, straw N uptake at harvest was around 20 kg N ha^{-1} less under no tillage practices with respect to minimum or conventional tillage (71 and 74 kg N ha^{-1}, respectively), despite the higher TN stock in *NT* in the 0–15 cm layer Moreover, unlike inorganic N fertilizer, the release of N from crop residues is closely linked to their decomposition, which, in turn, is influenced by their chemical composition, placement in the soil (e.g. incorporated into the soil or let on surface); additionally, overall environmental conditions play an important role (Cucu et al., 2014). We hypothesized that the lower straw N inputs together with the reduced mineralization of crop residues (and release of plant available N) that are left on the soil surface under no tillage with respect to conventional or minimum tillage where the residues are incorporated into the soil, are responsible for the lower *coarse* and *fine fPOM* N contents observed in the subsoil after 6 years, and could explain the decreasing trend in plant N uptake over time in the unfertilized plots under no tillage. Instead, the higher N stocks in the iPOM in both conservative tillage methods may be related to the improved stability of soil aggregates that typically occurs with these tillage practices (Topa et al., 2021).

Notwithstanding the variability in ANR over the years in the different tillage managements, probably triggered by the inter-annual variability in climatic conditions (Ando et al., 2000), the adoption of no tillage practices generally resulted in the lowest ANR values. The ANR decrease in NT with respect to the other tillage practices corresponded to a lower N uptake. The low N uptake was probably related to lower straw and grain production and to lower root development in compact soil in the early vegetative stages under no tillage (Huang et al., 2012). Moreover, sod seeded rice is known to be characterized by a higher N absorption after heading (Huang et al., 2016), and this could influence the synchrony between fertilizer N supply and plant N uptake. In fact, Huang et al. (2015) reported that the negative effects of sod seeding on N absorption could be partially mitigated by postponing N fertilization. Due to the excessively low plant density with no tillage, increasing N fertilization did not result in a positive effect on ANR, but it probably increased N immobilization and losses. In fact, with the presence of crop residues with a high C:N ratio in the superficial soil layer, microbially-mediated processes could be responsible for the immobilization of 27–50 % of applied N (Said-Pullicino et al., 2014), as confirmed by the higher TN stock in *MT* and *NT* in the superficial layer compared with *CT*.

4.3. Effects of conservation tillage on SOM pools and SOC stocks

Adoption of conservation tillage practices for 6 years in rice paddies determined a significant stratification of SOC rather than a difference in the total SOC stocks, in line with several other findings reported for other cropping systems (Abdollahi at al, 2017; Rounak et al., 2022). Most of this depth differentiation was due to management induced changes in particulate SOM fractions, as the most stable mineral-associated OM fraction that comprised about 84 % of total SOC, did not show significant tillage-induced differences in C stratification. There are conflicting results in the literature regarding the capability of conservation agriculture to increase soil C stocks and soil fertility.

Fangueiro et al. (2017) reported an increase in SOC after 7 years of no tillage adoption compared to conventional tillage in a loam paddy soil, but according to these authors, the SOC increase is more relevant in semi-arid environmental conditions and in soils with low organic matter content. Probably in this experimental site, characterized by a temperate climate and sandy soil with a high organic matter content, six consecutive years of application were not sufficient to determine an increase in C.

The stratification of soil properties, particularly the distribution of organic C resulting from conservation tillage, could be attributable to two main factors, as noted by Blanco-Canqui and Lal (2008) and Shang et al. (2021): the accumulation of crop residues on the soil surface and the reduction of soil disturbance. However, paddy management itself may compromise aggregate stability with flooding due to the disruptive energy occurring upon slaking (Six et al., 2000), and reductive dissolution of Fe-mineral binding agents holding aggregates together (Giannetta et al., 2022), therefore partially counteracting the benefits on conservation practices on soil structure. Our results nonetheless evidenced that the adoption of minimum tillage in rice paddies led to the highest amounts of labile coarse and physically protected POM in the superficial soil layer and induced significant stratification with respect to both conventional and no tillage practices. The accumulation of labile OM in the topsoil can represent an important source of nutrients for the crop in the rooting zone through decomposition, and is known to contribute to aggregate stability and soil structure favoring the physical stabilization of OM (Wang et al., 2012). In fact, it can be hypothesized that the presence of high amounts of POM in the surface horizons under minimum tillage could promote microbial activity that contributes to the formation and stabilization of water-stable aggregates, that can in turn serve to further SOM stabilization processes within micro-aggregates having a high mechanical stability (Bucka et al., 2021). In contrast, the lower OM inputs under no tillage confirmed by the lower straw yields were probably responsible for the lowest amounts of labile and physically protected OM with respect to the other tillage practices. Although in the long term the accumulation of OM in the superficial soil layer is known to contribute to limiting soil compaction in no tillage (Blanco-Canqui and Benjamin, 2013), the negative effects of this tillage practice on crop yields actually limits the topsoil OM contents in these paddy soils where crop residues represent the only OM inputs. In this light, in order to enhance the positive effects of no tillage on paddy soil properties, this practice should be combined with complementary techniques, such as the use of cover crops, to further increase the OM inputs and promote soil aggregate stability (Blanco-Canqui and Ruis, 2018).

5. Conclusions

Conservation tillage in Italian rice cropping system has shown varying effects on rice yield and soil fertility in the medium term. Among the different conservation soil management practices, minimum tillage emerges as the most suitable alternative to conventional tillage. It maintains high yields by using production resources more efficiently and sustains soil fertility by promoting OM and N inputs, while also facilitating soil aggregation and preventing soil compaction. However, the adoption of no tillage in our climatic conditions and cropping system reduces rice yields (−15 %). This reduction is primarily caused by reduced plant density due to the presence of crop residues and greater soil surface compaction, which makes the planting operation challenging. This, in turn, leads to inadequate seed-to-soil contact, compromising crop germination and seedling emergence.

Rice plants react with a greater tillering and a higher number of spikelets per panicle, however this is still insufficient to bridge the yield gap compared to conventional tillage. Additionally, no tillage tends to reduce ANR, and increasing the amount of mineral N supplied is not enough to compensate for the yield gap due to the low plant density. In fact, this practice may even lead to increase N losses.

Considering these factors, no tillage is not suitable for rice cultivation in Italian temperate rice fields. In paddy soils with under temperate climate, conservation tillage did not lead to an evident improvement in the soil physical-chemical fertility in the medium term. However, some effects were observed, primarily limited to the surface soil layer.

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CRediT authorship contribution statement

Francesco Vidotto: Data curation, Supervision, Writing – review & editing. **Silvia Fogliatto:** Data curation, Writing – review & editing. **Marco Romani:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Luisella Celi:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Daniel Said-Pullicino:** Conceptualization, Data curation, Methodology, Writing – review & editing. **Cristina Lerda:** Data curation, Formal analysis, Writing – review & editing. **Barbara Moretti:** Conceptualization, Data curation, Methodology, Writing – review & editing. **Andrea Vitali:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109276.

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