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Feasibility of mechanical rice transplanting in organic Italian rice system

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Abstract

Rice cultivation in Italy is usually performed by direct seeding in flooded or in dry fields. Mechanical rice transplanting is a technique that can help control weeds and improve rice competition. To test the feasibility of the technique for different rice varieties in Italy, a study was conducted in the Lombardy region (northwest Italy), from 2016 to 2018. The study also evaluated the efficacy of hoeing in transplanted rice fields. The experiment consisted of two studies, a 'field plot experiment' (conducted from 2017 to 2018) and an 'on-farm transplanting trial' (conducted from 2016 to 2018). The 'field plot experiment' was carried out using a split plot design to determine the optimal transplanting distances within the row (12 or 17 cm) and the most suitable rice varieties for transplanting. Hoeing was performed once in 2017 and twice in 2018. Weed infestation was assessed by counting the number of weeds within a randomly placed square frame in the interrow areas, both before and after hoeing. Rice plant density, panicle density, yield, and yield components were also assessed. The 'on-farm transplanting trial' tested transplanting in several farms over the years. Different rice varieties were transplanted using the same machines, and hoeing was performed according to a predetermined schedule. Transplanter performance was assessed as well as rice yield data in all fields, while four fields were selected each year to assess hoeing efficacy against weeds. ANOVAs were used to test the differences in weed control and rice parameters among varieties and transplanting distances. The 'field plot experiment' showed that the transplanting distance did not affect weeds or rice variety. Transplanting at 12 cm within the row resulted in a higher plant density compared to 17 cm, however tillering compensated for the difference in the number of panicles. Carnaroli consistently recorded the lowest yield, less than 2 t ha^{-1}, while Selenio, Spillo, and Laser seemed to be better suited for transplanting achieving the highest yield in 2018 (about 7 ha^{-1}). In the 'on-farm transplanting experiment' hoeing was effective in controlling weeds, although the machineries used were not always able to function properly in saturated soil. Most of the transplanted field yielded approximately 3 to 5 t ha^{-1}. Varieties with round grain exhibited the greatest yield variability among fields. The study suggests that to achieve a high yield in organic rice, the transplanting technique should be combined with an effective interrow tillage to control weeds.

Introduction

Italy is the largest European rice producer accounting for more than 50% of the total rice area, with about 218,400 hectares in 2022 (Ente Nazionale Risi, 2023a). The Italian rice area is mainly located in the northwest of the country, in particular in the Piedmont and Lombardy regions which together represent more than 90% of the total area (Ferrero et al., 2021; Ente Nazionale Risi, 2023a). In Italy, rice is mainly cultivated as monoculture and the most common cultivation techniques are broadcast seeding in flooded fields and drilling in dry fields with flooding that starts at about 30 days after seeding, followed by continuous flooding (Ferrero et al., 2021; Monaco et al., 2021). The majority of the Italian rice area is cultivated with conventional techniques, which require the implementation of integrated pest management practices in accordance with the Sustainable Use of Pesticides Directive 2009/128/EC (Bacenetti et al., 2016). In the last decades, the area of rice grown organically in Italy has increased significantly, although in the recent years a reduction has been recorded. In fact, the organic rice area in 2023 was 9057 hectares, 15% less than the area in 2022 (Ente Nazionale Risi, 2023b). This decrease is probably due to the spread of more sustainable but conventional techniques, such as practices aimed at achieving zero pesticide residues in rice grain. These conventional techniques include the appropriate and lower use of pesticides, integrated with other non-chemical pest control methods, with the aim of producing rice with the same maximum pesticide residue levels established for organic production (0.01 mg kg^{-1}) while maintaining high yields, a low price for consumers and a significant reduction in environmental impact. These characteristics can make zero residue rice more attractive to consumers than organic rice (Tabacchi M., personal communication).

The rice varieties cultivated in organic farming are often the same as those cultivated in conventional farming because there are no specific breeding programs aimed at releasing varieties best suited for organic farming (De Santis et al., 2022). According to Ente Nazionale Risi (a public Italian agency active on the rice sector), in Italy in 2023 about 3700 ha, representing 41% of the organic rice area, were cultivated with varieties with round grain size. Rice varieties with round grain belong to the round varietal group, according to the EC Regulation 1308/2013, and have a grain length of less than 5.2 mm and a length/width grain ratio of less than 2. Among these varieties, in 2023 about 2100 ha were cultivated with the variety Selenio (Ente Nazionale Risi, 2023b). The second most cultivated varietal group in organic farming in Italy was the long A grain varieties (about 3200 ha, equal to 36% of the organic area), which are mainly used in the preparation of 'risotto', the traditional Italian rice dish. The long A-grain group includes varieties with a grain longer than 6 mm and a length/width ratio between two and three. The most cultivated varieties in this group are Carnaroli and similar varieties (about 1400 ha) (Ente Nazionale Risi, 2023a). Other varieties defined as long B grain size category (grain length of more than 6 mm and a length/width grain ratio comprised between two and three) were cultivated organically in Italy on about 800 ha in 2023, while medium grain varieties (grain length ranging from 5.2 to 6.0 mm and a length/width grain ratio less than three) on about 300 ha (Ente Nazionale Risi, 2023a).

A previous study conducted in Italy (De Santis et al., 2022) showed that in organic farming the varieties constituted in the 1950s showed a similar yield to the most recently released varieties, thus suggesting that the new varieties (those released after 1980 and still cultivated today) may not have traits that can be more favorable in organic farming. Therefore, it might be appropriate to identify the most suitable rice varieties that are already available for organic cultivation with different techniques (De Santis et al., 2022).

Another issue for rice cultivation is represented by weed management, which is considered one of the main limiting factors in rice yield, especially in organic farming, where the available control means are limited and characterized by lower level of efficacy compared to herbicides (Mahajan et al., 2014). The available weed control methods in organic farming are essentially agronomic, such as crop rotation, and mechanical, such as harrowing and hoeing. Mechanical weed control poses challenges under flooding conditions; currently, in Italy, this method is exclusively employed in dry-seeded row planted rice before the fields are flooded (Ferrero et al., 2021; Fogliatto et al., 2023).

A cultivation technique that can facilitate weed control and enhance the competitive advantage of rice during its initial growth stages is rice transplanting; this technique involves utilizing tillage in the inter-row space to control weeds (Alizadeh, 2011; Dass et al., 2017). Rice transplanting currently accounts for about 50% of the world's rice area. However, the associated high labor costs and water consumption, resulting from the high-water demand for puddling, have led to a decline in the use of this technique in favor of direct seeding (Dass et al., 2017; Shekhawat et al., 2020). Mechanical rice transplanting is more efficient than manual transplanting because it requires less labor; previous studies have in fact shown that manual transplanting of one hectare necessitates about 250–300 h (Hossen et al., 2018). Moreover, mechanical transplanting offers several advantages, including timely transplanting, reduced labor requirement, lower costs, minimal plant stress and more uniform spacing between plants (Shaikh et al., 2021; Singh et al., 2023).

The first rice transplanter was designed in Japan in 1898, however the commercial development of this machine occurred only in the 1960s as a consequence of the increased labor shortage for rice transplanting (Ryu, 1986). Mechanical rice transplanting is still adopted nowadays in some Asian countries, such as Japan, India, Korea, and China, where transplanting of young seedlings in saturated fields is traditional and preferred over direct seeding (Thomas, 2002).

In Italy, manual transplanting was adopted from the beginning of 1900 to favor crop development but was abandoned in 1960 in favor of direct seeding. This occurred because of manpower shortage and increased labor costs, followed by the introduction of the first herbicides (Ferrero and Vidotto, 2010; Andres et al., 2015). Since then, rice in Italy has been direct seeded and is mainly managed using herbicides (Ferrero et al., 2021). In this context, a three-year study was conducted starting in 2016 with the aim of testing the possibility of applying the mechanical transplanting of rice in Italy. In particular, the study tested the following hypotheses and factors: (1) different rice varieties respond differently to transplanting in terms of growth, weed competition and yield, (2) transplanting distance influences crop performance, (3) mechanical weeding allows weed control but its efficacy can be variable, (4) transplanting is feasible in different organic farms and allows to obtain an acceptable rice yield. The testing of different varieties resulted from the fact that in Italy a number of different varieties are grown, which have not been improved for cultivation in organic conditions, where crop competitiveness against weeds is very important, and therefore may have different performance when transplanted. Moreover, the results obtained at different transplanting distances and the effectiveness of mechanical weeding in transplanted rice would allow adapting the technique to real field conditions and better evaluating its performance.

Materials and methods

Study area

The study consisted of a 'field plot experiment' and an 'on-farm transplanting trial'; the first study was carried out in the 2017 and 2018 growing seasons, while the second one started in 2016 and ended in 2018. The 'field plot experiment' was carried out in two different fields in the province of Pavia (Lombardy region, northwest Italy), while the 'on-farm transplanting trial' included transplanted fields of different organic rice farms mainly located in the Lombardy region, with a few in the Piedmont region (Fig. 1S). The sites where the study was carried out were in the main rice-growing area of Italy, considered one of the northernmost temperate rice-growing areas. The climate can be considered homogeneous across the sites, and it is defined as semi-continental Po Valley type, with hot and humid summers and cold winters, with annual precipitation of about 900 mm; the soil is alluvial (Monaco et al., 2021). Daily weather data (average, minimum, and maximum temperatures and precipitation) were recorded from the regional weather station of Lomello (PV), which is closest to the study area (Fig. 2S). During the rice growth (May to October), the average, minimum, and maximum temperatures were stable over the three years, with average values of about 21, 16, and 27°C, respectively. Precipitation was stable in 2016 and 2017, with values ranging from 163 to 166 mm in the two years during rice growth. In 2018, however, total precipitation doubled during the same period, reaching about 345 mm (Fig. 2S).

The study was conducted within the framework of a specific participatory project, funded by Regione Lombardia, with the aim of testing the rice transplanting technique in the Italian rice area. The project involved six organic rice farms, the University of Torino, and a rice mill.

In all fields belonging to both experiments, some common cropping practices were applied, namely, seedling growth in a nursery, mechanical transplanting of rice, and mechanical weed control.

Seedling growth

Rice seedlings were cultivated in a local nursery (Vivai Tassinario, Alluvioni Cambiò-AL, Italy) using the 'mat method', which consists of sowing rice seeds in trays filled with a commercial potting mix, resulting in a a dense 'mat' of rice seedlings that can be rolled up for transport. Several mats are carried by the transplanting machine, forming a reservoir of seedlings that allowed continuous transplanting with only a few stops to load other mats (Fig. 3S).

Approximately 4700 rice seeds of a single variety were sown in each individual tray (60×30 cm) filled with a commercial potting mix. Approximately 200 trays were prepared for the transplanting of one hectare. The trays were sown with the different rice varieties that were tested in the study in different years: Baldo, Balilla, Brio, Cammeo, Carnaroli, Centauro, Cerere, CRBL1, Ecco 63 (hybrid), Fenomeno, Gladio, Laser, Limperatore, Mirko, Karbor, Ronaldo, Selenio, Spillo, Vasco, Venere, Volano, 882 and, 883. The main characteristics that distinguish the varieties are reported in Table 1S. The varieties were chosen from among those most cultivated in the area to test their performance and adaptability under mechanical transplanting conditions. In the municipality where the field plot experiment was carried out (Mede, PV), almost 40 varieties were cultivated in 2017 but only about five varieties were those cultivated on at least 100 hectares (Ente Nazionale Risi, 2023a).

Seedling mats were grown until the 2–3 leaf stage (approximately 10–15 cm in height) under water-saturated conditions and maintained in a plastic greenhouse until transported to the fields for transplanting.

Rice transplanting

All the fields were transplanted using a self-propelled riding type transplanter (Yanmar model VP6D), with four-wheel drive, capable of transplanting eight rows of rice simultaneously (Fig. 3S). The transplanting distance between rows was set at 30 cm, while the spacing among plant hills within the row was adjustable between 12 and 22 cm. On average, there were three transplanted plants per hill. Transplanting was carried out on saturated soil.

Weed management

Weed control was carried out through mechanical intervention using a prototype inter-row hoe that was rear-mounted on the transplanter machine designed to work in saturated soil and capable of weeding eight rows of rice.

Field plot experiment

In 2016 a preliminary split plot experiment was conducted to test the technique and to determine the optimal transplanting distances within a row for achieving good rice establishment. These initial results indicated the need for further investigation to determine the best transplanting distance within the row; consequently, subsequent trials were conducted on all rice varieties at 12 and 17 cm transplanting distance, which were the distances that gave the best results in our previous experience.

In 2017, a split plot experiment was carried out in a rice field belonging to a farm project partner in Mede (Pavia province) with rice variety as the main plot and transplanting distance (12 and 17 cm) as the subplot with three replications. Each plot, containing a specific rice variety transplanted at a designated distance, was 4.8 m wide (16 rows of rice planted with the same variety) and had a length of 30 m in the 2017 experiment and 10.8 m in the 2018 experiment due to the smaller field size in that year. The rice varieties were selected among those having long A grain: Ronaldo, Volano, Baldo, Cammeo, Karbor, Carnaroli, Fenomeno, 882, and 883; long B grain: variety CRLB1; round grain: Selenio and Spillo and medium grain, such as Limperatore.

Transplanting was performed on May 30th and weeds were mechanically controlled through hoeing on July 4th.

In 2018, the experiment was replicated, in a different rice field located in the same municipality as the previous year, but about 600 m apart, with the same layout (same transplanting distance, same mechanical weeding). The experiment tested the adaptability of ten rice varieties to the transplanting technique. Some of the tested varieties, including Karbor, Cammeo, Carnaroli, Fenomeno, Limperatore, and Ronaldo among the long A grain varieties, and Selenio, and Spillo, among the round grain varieties, had been tested in the previous year's experiment. The varieties Laser (long B grain) and Vasco (long A grain) were tested exclusively in 2018, replacing some of the varieties used in the previous year due to unavailability of their seeds and/or seedlings from the nursery. In 2018 transplanting was carried out on May 14th and two passages of hoeing to control weeds were performed on May 25th and June 11th. At maturity, rice was harvested in all plots on the entire field using a plot combine harvester on October 4th, 2017 and on September 20th, 2018.

Weed and crop assessments

Weed infestation was monitored throughout the growing season, before and after the mechanical intervention. Data on weed species composition, weed density and weed cover over the soil surface were collected both before (at about 20 days after transplanting) and about a week after hoeing. In particular, weed density was assessed by counting weeds in a square frame measuring 0.5×0.5 m randomly placed four times in the interrow areas for each plot. Using the same areas, the weed cover on the soil surface was estimated as percentage.

Rice adaptability to transplanting was evaluated over two years by counting rice plant density 20 days after transplanting and rice panicle density just before harvest. Rice plant and panicle density was assessed twice per plot by counting the number of plants present per linear meter and multiplying the values for the number of rows present per meter to obtain the values per square meter. Rice yield and its components, including 1000 seed weight and test weight, were evaluated at harvest. Rice yield was determined by harvesting four rows of rice (combine bar width was 1.16 m) in the center of each plot for the entire length of the plot. Yield components were determined for each plot using four subsamples of approximately 70 g each.

Statistical analyses

The statistical analyses were carried out separately for each year, using the statistical program IBM SPSS Statistics 28.0. A series of ANOVA analyses ($P \leq 0.05$) were conducted on weed density and on rice parameters to test the effect of rice varieties, transplanting distances, and their interactions. The REGWF post-hoc test was used to identify differences among the compared values when the interaction was non-significant. When the ANOVA analysis found a significant interaction, the EMMeans function was used to find out difference between the interacting factors. Pairwise contrast post-hoc test was carried out for significant factors.

On-farm transplanting trial

The on-farm trials, initiated in 2016, aimed to test the effectiveness of transplanting technique in farms participating in the project and in other rice farms, involving a total of 30 farms in Pavia province. The results of these tests were recorded for extensive evaluation of transplanting methodology. Each farm had one or more field (with a size of one to three hectares per farm) in which transplanting was tested, resulting in a total transplanted area of 66 hectares.

In 2017, 33 farms were involved, with a total transplanted area of 108 hectares. In 2018, the transplanting technique was implemented in 18 farms, resulting in an average of about five hectares of transplanted area per farming location and a total transplanted area of 116 hectares. Over the three-year period, the transplanting operations were carried out by the same operators using two identical transplanting machines. In 2016, only one machine was used. The fields were transplanted every year according to a predetermined schedule, which ranged from late May to the second half of June, with a distance of 17 cm within the row. In particular, over the three years the majority of the fields were transplanted in May (28 fields), while 22 fields were transplanted in the first half of June and 19 fields in the second half of June.

Before transplanting, the fields were tilled with either one or two passes of spring tine, rotating harrow, or disc harrow, depending on the farming equipment available. In 2016, the varieties transplanted in the different fields were Selenio, Spillo, Cerere, Brio and Centauro (round grain), Ronaldo and Cammeo (long A grain), Venere (black aromatic rice), and Ecco 63 (long B hybrid). In 2017, the varieties Selenio, Venere, and Ronaldo were again tested for transplanting, along with the addition of Volano, Karnak, Opale (all long A grain), and CRLB1 (long B grain). In 2018, in addition to the varieties from 2017, the varieties Carnaroli (long A grain), Laser, Mirko, Balilla, and Gladio (long B grain) were also transplanted.

Mechanical weeding was conducted using hoeing machines in all farms, typically at least once during the growing season following a predetermined schedule, approximately 30 days after transplanting. However, in a few cases in 2016, some fields were not hoed because they were difficult to drain and the hoeing machine could not work on saturated soil. Throughout the three-year period, all fields were managed organically, with the exception of two fields in 2016, four fields in 2017 and four fields in 2018 that were managed conventionally. In these fields, rice was also transplanted and weed control was performed using the commonly employed herbicide program for rice. In the conventional field of 2016, three areas of approximately 20 m^2, fairly rectangular in shape, were randomly selected and designated as untreated plots for weed evaluation purposes by closing the nozzles on the boom sprayer and not applying herbicides in those areas. In this field, clomazone was applied in pre-emergence at label rate and in rice post-emergence (3–4 leaf stage) a mixture of MCPA and Halosulfuron-methyl was applied at a label rate.

All rice fields were harvested using the combine harvester available on each farm for the entire transplanted area. Farmers recorded rice yield separately for each transplanted field.

Assessment of the transplanter performance

The following operational parameters of the transplanter were recorded during transplanting operation:

- field area (ha),
- forward speed (km h^{-1}),
- working width (m),
- time taken for transplanting (h),
- in-field displacement time (such as travel within the field and turning time) (h),
- loading time (time required for loading the trays on the platform of the transplanter) (h),
- time for repair, maintenance, and setting the machine (h),
- fuel and lubricant consumption (kg h^{-1}).

Collecting these data allowed the determination of field efficiency (%) and effective field capacity (ha h^{-1}), following the ASAE Standard EP496.3 guidelines (ASABE Standards, 2010). The amount of fuel was determined by filling the fuel tank, while the lubricant was determined based on ASABE Standard indications (ASABE, 2011). The energy content of fuel and lubricant were considered to be, respectively, 51.2 and 52.9 MJ kg^{-1}. The assumed energy content of the transplanter was 160 and MJ kg^{-1} (Barber, 2004), with an expected operational life of 2500 h.

Weed and crop assessments

Farmers or farm technicians collected data on rice yield, transplanting dates and weed hoeing dates. To assess the efficacy of weed control (hoeing), four fields in 2016 and 2017, and two fields 2018 were selected for evaluation. Weed density and cover were recorded before and after hoeing in these fields using the previously established methodology. Two fields in 2016 hosted the variety Selenio, one the hybrid variety Ecco 63, and the conventional field was cultivated with the variety Cammeo. In the 2016 conventional field, weed density and cover were assessed in both treated and untreated areas, excluding the edge of untreated areas where herbicide drift could have occurred. In 2017 and 2018 all the assessed fields were cultivated with the variety Selenio.

Weed density before and after hoeing for each field was compared using ANOVA and means were separated with REGWF post-hoc test ($P \leq 0.05$). The variability of rice yield between varietal groups recorded for all the transplanted fields over the three years was shown using boxplots. SPSS Statistics 28 was used to build the boxplots and to calculate the mean, median, minimum, and maximum values for each varietal group.

Results and discussion

Field plot experiment

Weed and crop assessments

Weeds: In 2017, weed density assessed before hoeing showed a different infestation in plots hosting different varieties, while no

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differences were found between the two-transplanting distances (Fig. 1a). Among the tested varieties, Baldo showed the lowest weed density and cover, while plots with Selenio exhibited the highest values of weed density, with a peak of more than 800 plants m^{-2} when rice was transplanted at a distance of 17 cm (Fig. 1a). The variation in weed infestation and rice vigor of the two varieties may have caused this difference; in fact, Baldo is a taller variety compared to Selenio (Table 1S). However, in 2018 no differences in weed density were observed between varieties due to a more uniform infestation in the field (Fig. 2a). The assessment carried out after hoeing in 2017 did not reveal differences among varieties, but rice transplanted at 12 cm within the row showed a significant lower level of infestation compared to plots with rice transplanted at 17 cm (Fig. 2b). In 2018, a significant interaction was observed between the transplanting distance and rice varieties impacting weed density. The post-hoc analysis showed a different weed density among varieties in 2018, while only Laser and Vasco exhibited distance-dependent differences, with higher infestation at 12 cm (Fig. 2b). The variety Carnaroli had on average the lowest weed density (almost 150 plants m^{-2}) and Vasco the highest (250 plants m^{-2}). Carnaroli rice is a very tall variety, with a plant height that often exceeds 115 cm (Ente Nazionale Risi, 2018); this trait could explain the lower weed presence in this variety, especially in 2018, as it has been emphasized that plant size is the main indicator of rice competitiveness against weeds as tall plants can reach light more easily and shade smaller weeds (Saito, 2010; Schreiber et al., 2018). The Vasco variety, on the contrary, is characterized by maximum average height of 80 cm, qualifying it as a short, semi-dwarf cultivar that is likely to exhibit lower levels of weed competitiveness (Ente Nazionale Risi, 2018).

The efficacy of weed control was notably high, with the ability to reduce weed density by over 80% in many plots. However, in this study, hoeing was effective in removing inter-row weeds in rice, while intra-row weeds are more difficult to control with mechanical methods and were left almost undisturbed and can continue to provide strong competition to the crop (Tillett et al., 2008; Liu et al., 2023). The study showed variable results on weed presence, depending on the year of the experiment, indicating a lower weed presence at 12 cm in 2017 but higher weed density at the same distance, albeit only for two varieties, in 2018. The variability in weed emergence between years depends on the fact that the fields were different and had a different seedbank, but also that the precipitations in 2018 were more than double compared to the previous year, requiring another hoeing operation (Fig. 2S).

Weed presence is only one aspect to take into consideration when choosing the best transplanting distance as it is strongly related to control means efficacy. Rice performance, in terms of both plant growth and yield, needs also to be evaluated at varying transplanting distances to be able to establish the most suitable spacing between plants. It has been suggested that both an intra-row and inter-row spacing comprised between 15 and 30 cm enable high weed suppression and offer sufficient space for rice growing (Adeyemi et al., 2015; Alagbo et al., 2022). Weed competition varies depending on the weed species present. In the 2017 field study, *Cyperus difformis* was highly prevalent before hoeing, representing about 36% of the total infestation, along with *Lindernia dubia*, *Heteranthera reniformis* and *Echinochloa* spp. (Fig. 4S). After hoeing, the dominant weeds found were *E. crus-galli* and *Heteranthera reniformis*, and *Cyperus esculentus*, while *Lindernia* spp. was highly controlled by hoeing; weed control of *C. difformis* was also observed to a lesser extent. Previous studies have found that monocot weeds are generally less controlled by hoeing than dicots; however, hoeing efficacy can vary widely depending on other field conditions, such as weather conditions, soil type, and driving speed (Melander et al., 2003; Naruhn et al., 2021). Higher hoeing efficacy against monocots was also observed in our study in 2017 with *Echinochloa* spp. being poorly controlled; however, in 2018, *Panicum dicothomoflorum* was quite effectively controlled, but the hoeing machine used was different (Fig. 5S).

In 2018, during the pre-hoeing assessment, *P. dichotomiflorum* was the most represented weed, accounting for about 63% of the total infestation, followed by and *Lindernia procumbens* and *Ammania coccinea* (Fig. 5S). After hoeing, the presence of *P. dichotomiflorum* was strongly reduced, resulting in *Lindernia* spp. (mainly *L. dubia*) becoming the primary weed, albeit with a lower density than the previous assessment (Fig. 5S). The probable high presence of *Echinochloa* spp. in the seedbank of the field that hosted the experiment in 2017, which was only partially controlled by mechanical weeding, resulted in intense competition with rice, leading to a high yield loss as it has been demonstrated that the species is one of the most competitive weeds in rice (Bajwa et al., 2015; Awan et al., 2021). In 2018, weed competition was less intense despite high weed density, as the infestation consisted of less competitive weeds such as *Lindernia* spp. (Fig. 5S).

Crop

Rice plant density. In 2017, rice density assessed 20 days after transplanting revealed an effect of the interaction between the rice variety and the transplanting distance (Fig. 3a). The post-hoc tests showed that there were significant differences in rice density between the varieties at both 12 and 17 cm transplanting distances. At a distance of 12 cm, the Carnaroli variety displayed the lowest rice density of about 23 plants m^{-2}, while the highest density was observed in plots hosting the Limperatore, with nearly 80 plants m^{-2}, followed by Fenomeno and Spillo, both of which had values slightly higher than 70 plants m^{-2}. All of the other rice varieties displayed an intermediate rice density. Transplanting at a distance of 17 cm showed variable results with regards to plant density; once again, Carnaroli had the lowest values, with less than 20 rice plants m^{-2}, followed by Volano, while the highest density, with about 50 plants m^{-2}, was observed with Spillo and Limperatore.

The comparison between transplanting distances within the same variety showed differences only for certain varieties, namely 882, 883, Fenomeno, Limperatore, and Spillo, which always recorded a higher number of plants when rice was transplanted at 12 cm. For all the other varieties, rice density did not change as a function of the transplanting distance.

In 2018, the ANOVA analysis revealed that both the varieties considered and the transplanting distances chosen had an effect, while their interaction was not significant (Fig. 3b). In terms of the varieties, Carnaroli confirmed to be the one with the lowest density, with values slightly above 10 plants m^{-2}, whereas Selenio reached the highest values with more than 80 rice plants m^{-2}, followed by Laser and Limperatore. With respect to transplanting distance, rice density had higher values at 12 cm than at 17 cm.

Rice plant density is determined by the selected transplanting distance, hence a higher density should have been observed in the plots where rice was transplanted at a distance of 12 cm, as the average number of transplanted rice plants in each plot was similar for each transplanting distance. However, this was only observed in 2018, when the plots transplanted at 12 cm had the highest rice density for all the varieties. In 2017, only a few varieties displayed differences in transplanting distance, indicating

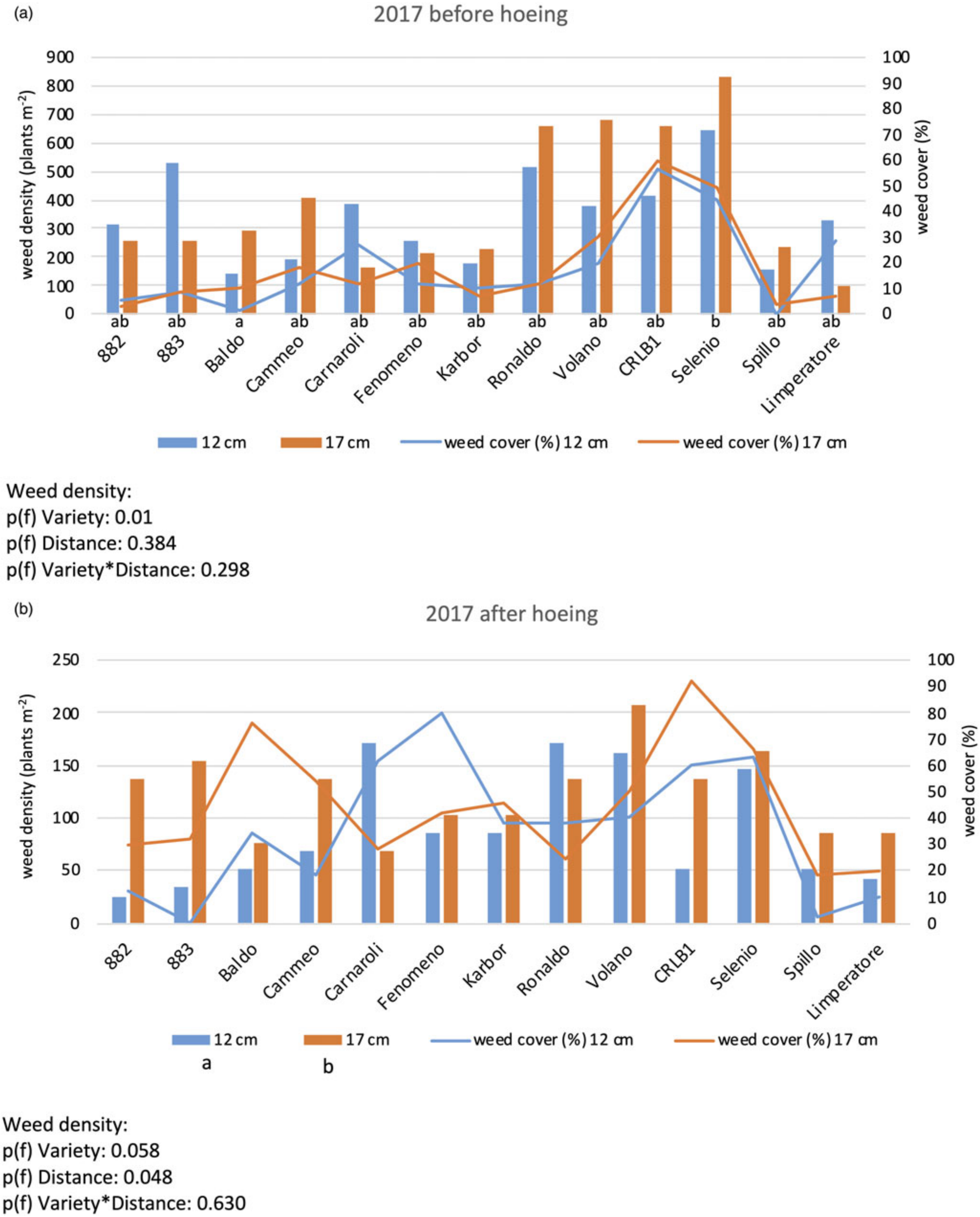

Figure 1. Weed density and weed cover recorded before hoeing in 2017 (a) and after hoeing (b) in the field plot experiment. Values sharing the same letter among varieties (a) and between transplanting distance (b) are not statistically significant according to the REGWF post-hoc test ($P \leq 0.05$).

that not all the plants were able to survive after transplanting; this phenomenon was also dependent on the rice variety chosen. Specifically, the varieties Fenomeno, Limperatore, and Spillo showed a significant higher number of plants during both years when transplanted at 12 cm, while Carnaroli consistently showed the lowest number.

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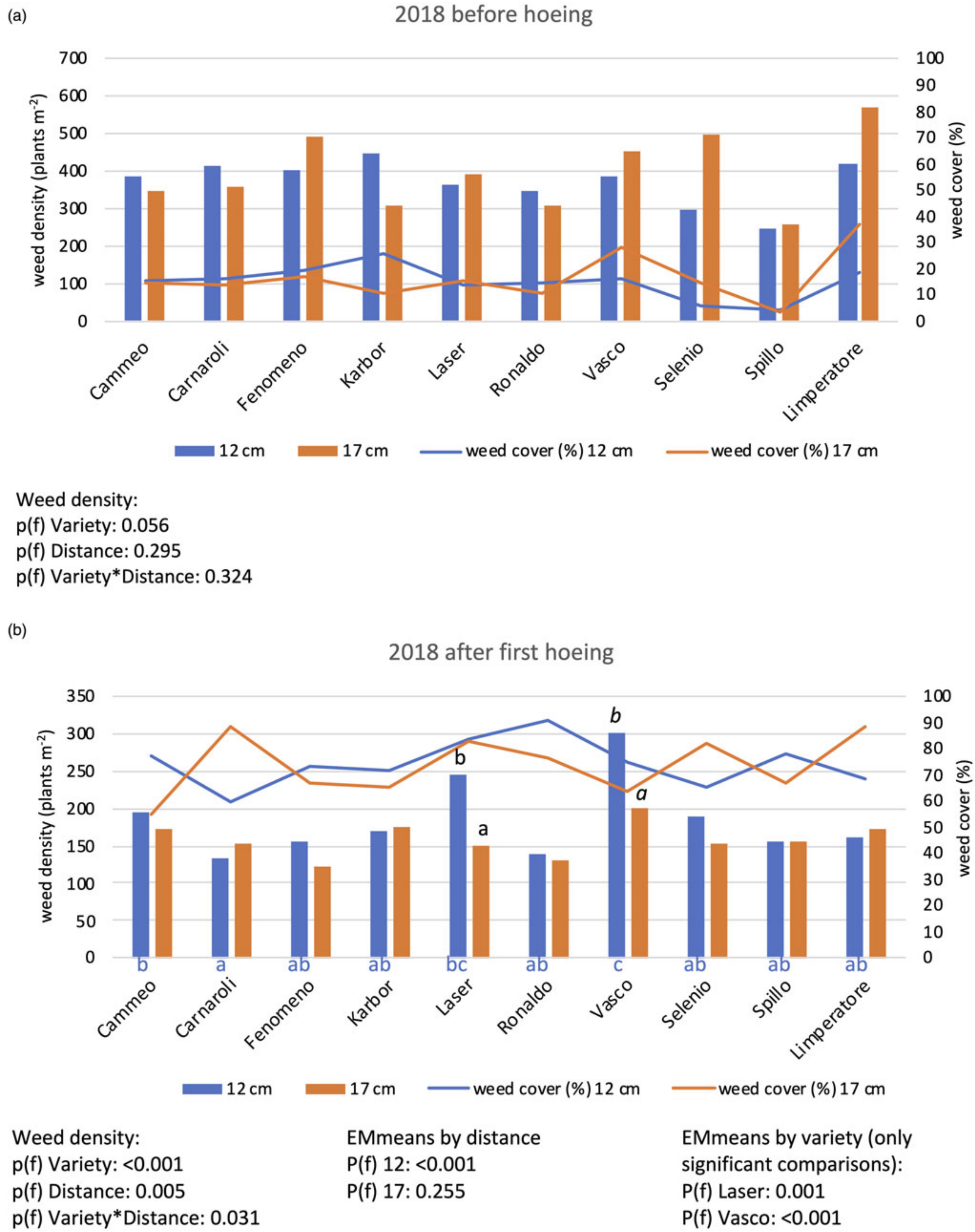

Figure 2. Weed density and cover recorded before hoeing in 2018 (a) and after hoeing (b) in the field plot experiment. Values sharing the same letter between varieties (in blue) and between transplanting distance within variety (in black) are not statistically significant according to the REGWF post-hoc test ($P \leq 0.05$) (B).

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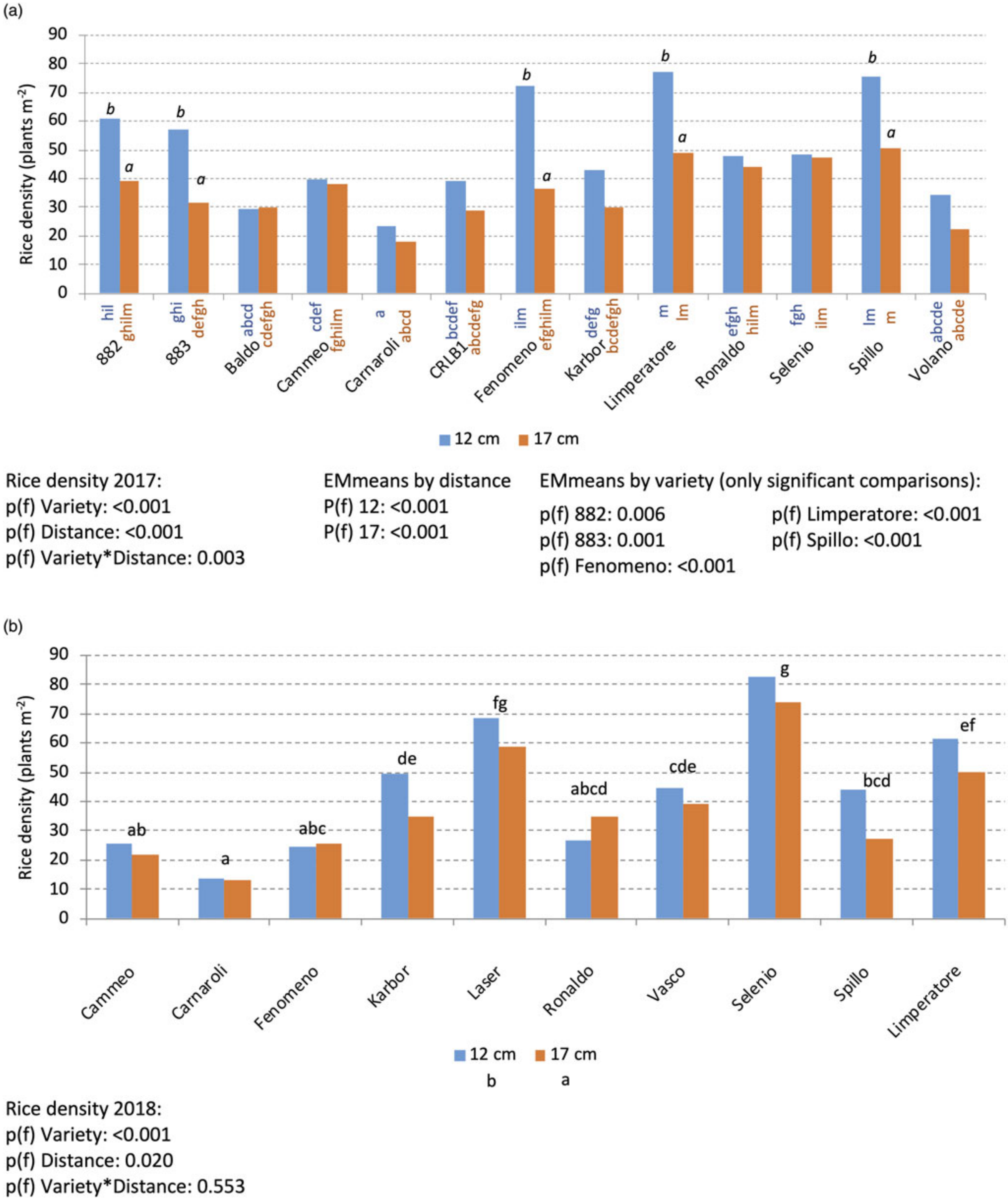

Figure 3. Rice density at 20 days after transplanting in 2017 (a) and 2018 (b). Values sharing the same letter are not statistically significant according to the REGWF post-hoc test ($P \leq 0.05$). In a: values were compared between varieties within transplanting distance (in blue within 12 cm and in orange within 17 cm) and within variety between transplanting distance (in black, in italics); In b: values were compared between varieties, averaging between transplanting distance (above bars in black), and between transplanting distance averaging among varieties.

Variation in plant density likely resulted from different rice seedling survival to transplanting shock among varieties as machine problems causing missed hills during transplanting (e.g. finger picking and placing failures, floating hills, buried seedlings) were minimal and homogeneous in all plots. Additionally, different rice varieties can exhibit different abilities to rapidly

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produce roots and to withstand uprooting after field re-flooding, leading to a variable seedling establishment (Hossen et al., 2018). Appropriate plant density is hence important as it can impact rice yield by influencing competition for light, water, and nutrients among plants (Yun, 2023).

Panicle density. In both years, the panicle density was only affected by the rice variety, while no differences were found between the distances of transplanting; moreover, the interaction between variety and distance was not found to be significant (Fig. 4a and 4b). Carnaroli exhibited the lowest number of panicles in both years due to the low plant density observed in this study and the low tillering ability known for the variety (Ente Nazionale Risi, 2018). In 2017, the varieties 883 and Limperatore showed the highest number of panicles, with average values exceeding 120panicles m^{-2}. Additionally, this variety showed the highest plant density in this study. Most of the varieties exhibited an intermediate panicle density, typically around 100 panicles m^{-2}. In 2018, Laser had the highest panicle density, followed by Selenio, which also recorded the highest plant density that year. The varieties showed a higher average panicle density in 2018 than in 2017, with values often exceeding 200 plants m^{-2}; this variability can most likely be attributed to the lower weed infestation in 2018, which exerted less competition and enabled higher rice tillering. The difference in rice plant density between the two transplanting distances observed in 2018 (with higher values at 12 cm) was not maintained in terms of panicle density, for which no differences were found. Since it has been previously established that the transplanting density has an effect on tillering and panicle number (Zhang and Yamagishi, 2010), it is probable that a wider spacing of 17 cm between plants permitted a higher tillering, enabling to produce the same level of panicles as that recorded with a spacing of 12 cm. A previous study already demonstrated the increased tillering ability of rice at high seeding space, although the tested variety was a hybrid with a higher tillering ability compared to traditional varieties (Wang et al., 2014). It was also reported that planting rice at wider distance allowed for a better growth of individual plants that were taller, with a more favorable tillering and leaf angle for better light interception (Wang et al., 2014).

Rice yield and yield components. In 2017, rice yield was significantly lower on average than in 2018 mainly due to the high weed infestation. In fact, that year, the average yield ranged from about 0.6 t ha^{-1} for CRLB1 variety to 3.9 t ha^{-1} for Limperatore variety (Table 1). No effect of transplanting distance and the interaction with variety on yield was detected. The variety CLRB1 and Selenio displayed the lowest 1000 seed weight, with values of about 23 g, while Volano recorded the highest, exceeding 40 g. Test weight was lowest in Carnaroli at approximately 46 kg hl^{-1}, while Ronaldo and Limperatore had the highest test weight values that exceeded 53 kg hl^{-1}. In 2018, Fenomeno recorded the lowest yield of approximately 2 t ha^{-1}, whereas Spillo, Selenio, and Laser reached the highest values exceeding 6.5 t ha^{-1} (Table 2). In terms of 1000 seed weight, Laser and Selenio yielded the lowest values, about 25 g, while the highest values were obtained by Cammeo, Carnaroli, and Karbor. Apart from Selenio, which displayed both low 1000 seed weight and test weight, the varieties that recorded the highest 1000 seed weight exhibited the lowest test weight. The inverse correlation between 1000 seed weight and test weight was however significant only in 2017, with a Pearson r value of 0.5 (Table 3). The reason for Laser and Selenio having the highest yield but the lowest 1000 seed weight, and CRLB1 having the lowest yield and 1000 seed weight in 2017, is because 1000 seed weight is more related to the shape of the grain, such as grain length and width, which are characters that varies with varieties, rather than yield (Wu et al., 2018). In our study, in fact, the correlation between 1000 seed weight and yield was found to be inversely correlated only in 2018. Test weight is an indicator of the grain quality, as higher values indicate higher proportion of endosperm relative to bran and hulls. However, test weight is not always correlated with yield as it is affected by wetting and drying cycles, and hence indirectly by precipitation (Whitney, 2017). In this study, only the test weight in 2017 was highly correlated with yield (Table 3). Furthermore, in both years, the trend of rice yield followed that of the panicle density as it has been demonstrated that the two variables are positively correlated (Wang et al., 2014); this was also proven in our study in which panicle density was highly correlated with rice yield, showing r value of about 0.7 (Table 3).

The 'field plot experiment' indicated that the transplanting distance did not have a strong impact on weed infestation, and the same outcome was found for the effect of the rice variety. The variable levels of infestation observed over the two-year period were likely more influenced by the field soil seed bank, the precipitations, and the efficacy of weed control means. It was generally noted that transplanting rice at 12 cm within the row resulted in a higher rice plant density than when transplanted at 17 cm, in line with expectations. However, the difference in transplanting distance did not impact rice panicle density. The similar panicle density recorded at the two transplanting distances was probably due to tillering, which allowed for standardization of the panicle density. The selected varieties showed an effect on both plant and panicle density, with Carnaroli consistently performing poorly. Regarding yield, there was no effect from the transplanting distance, while the variety had a significant impact. The varieties Selenio, Spillo, and Laser seemed to be better suited for transplanting, or at least had better performance in our experimental conditions over the two years, achieving high yield, especially in 2018, and good grain quality as measured by test weight. Carnaroli, CRLB1, and Fenomeno showed the lowest yield values and probably due to their low competitive ability against weeds especially in the first year of the study.

On-farm transplanting trial

Transplanter performance

Under the specific operating conditions, the rice transplanting machine operated at an average speed of 5.9 km h^{-1}. The recorded field capacity was 1.0 ha h^{-1}, resulting in a field efficiency of 70.7%. The loading of trays emerged as a critical factor, accounting for 16.9% of the total operational time. Less than 10% of the work time was instead devoted to the turning time of the transplanting machine and to the infield movement. The overall energy demands averaged 182.9 MJ ha^{-1}. These findings align with the trends observed by Yang et al. (2023) and Singh et al. (2006), which documented field efficiency ranging from 60.0 to 72.5%, and energy consumption ranging from 90.6 to 230.0 MJ ha^{-1}. This variation can be attributed to a combination of factors related to the type of machinery used and the different operational conditions in rice transplanting, including soil characteristics and management practices.

Weeds

In 2016 and 2017, the weed density assessed before mechanical intervention was quite high and varied between about 100 plants m^{-2} in the conventional field (2016) and almost 700 plants m^{-2} in

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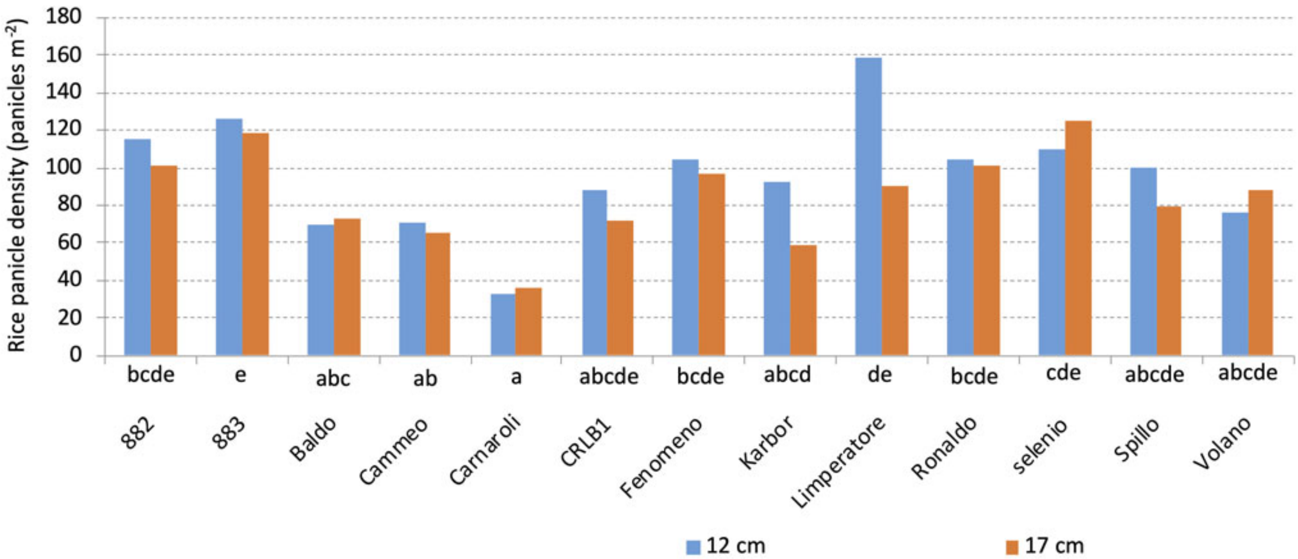
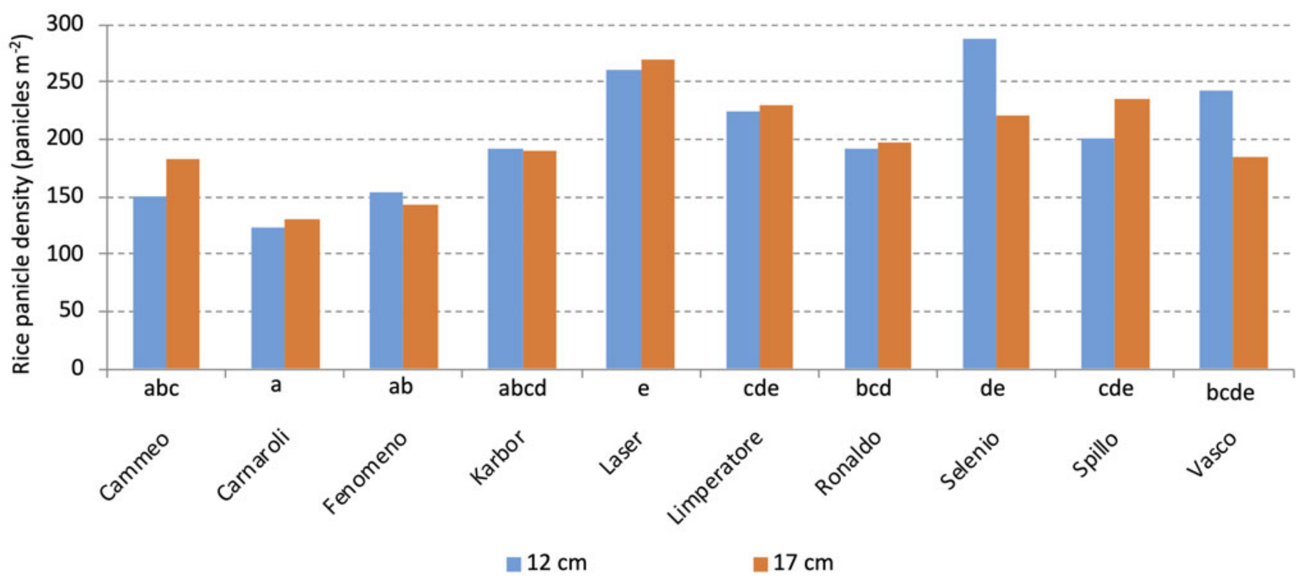
(a)



Rice panicle density 2017:
p(f) Variety: <0.001
p(f) Distance: 0.121
p(f) Variety*Distance: 0.682

(b)



Rice panicle density 2018:
p(f) Variety: <0.001
p(f) Distance: 0.653
p(f) Variety*Distance: 0.332

Figure 4. Rice panicle density at harvesting in 2017 (a) and 2018 (b). Panicle density values between varieties, averaging between transplanting distance (a and b), sharing the same letter are not statistically significant according to the REGWF post-hoc test ($P \leq 0.05$).

one of the organic fields (2017) (Table 4). However, the infestation consisted of weeds being at early growth stage, demonstrated by the low values of weed cover over the soil surface, except for the field with 700 plants m^{-2}, which recorded a weed cover above 70%. The assessment carried out after hoeing recorded the lowest weed density in the field cultivated with the hybrid Ecco 63 (65.4 plants m^{-2}) in 2016 and the highest in the Field 2 cultivated with Selenio in 2017 (251.4 plants m^{-2}). The

Table 1. Rice yield and yield components at 14% RH in the field plot experiment in 2017

2017	Rice yield (t ha^{-1})		1000 seed weight (g)		Test weight (kg hl^{-1})	
882	2.19	cde	27.09	b	49.00	de
883	2.84	e	29.32	c	49.97	e
Baldo	1.32	abc	36.54	ef	47.21	abc
Cammeo	2.05	cde	33.08	d	47.94	bcd
Carnaroli	0.93	ab	37.8	f	45.98	a
Fenomeno	1.52	abcd	26.40	b	46.57	ab
Karbor	1.37	abc	35.75	e	48.63	cde
Ronaldo	2.57	de	30.86	c	53.73	g
Volano	1.72	bcd	40.19	g	46.74	ab
CRLB1	0.62	a	23.27	a	48.78	de
Selenio	1.95	bcde	23.17	a	49.91	e
Spillo	2.51	de	25.59	b	52.17	f
Limperatore	3.92	f	25.74	b	54.52	g
ANOVA	*P*(f) Variety: <0.001 *P*(f) Distance: 0.150 *P*(f) Variety*Distance: 0.615		*P*(f) Variety: <0.001 *P*(f) Distance: 0.517 *P*(f) Variety*Distance: 0.587		*P*(f) Variety: <0.001 *P*(f) Distance: 0.743 *P*(f) Variety*Distance: 0.230	

Values sharing the same letter are not statistically significant according to the REGWF post-hoc test ($P \leq 0.05$).

Table 2. Rice yield and yield components at 14% RH in the field plot experiment in 2018

2018	Rice yield (t ha^{-1})		1000 seed weight (g)		Test weight (kg hl^{-1})	
Cammeo	3.59	ab	38.17	d	48.45	a
Carnaroli	2.84	ab	38.07	d	48.70	a
Fenomeno	2.21	a	30.58	bc	49.65	ab
Karbor	5.28	bc	38.38	d	47.58	a
Laser	6.48	c	25.18	a	49.70	ab
Limperatore	4.47	abc	25.65	ab	53.58	c
Ronaldo	4.72	abc	30.43	bc	52.48	bc
Selenio	7.36	c	24.94	a	47.95	a
Spillo	7.05	c	26.50	ab	50.17	ab
Vasco	3.04	ab	34.04	cd	52.25	bc
ANOVA	*P*(f) Variety: <0.001 *P*(f) Distance: 0.934 *P*(f) Variety*Distance: 0.758		*P*(f) Variety: <0.001 *P*(f) Distance: 0.514 *P*(f) Variety*Distance: 0.490		*P*(f) Variety: <0.001 *P*(f) Distance: 0.099 *P*(f) Variety*Distance: 0.691	

Values sharing the same letter are not statistically significant according to the REGWF post-hoc test ($P \leq 0.05$).

conventional field, as expected, showed the lowest weed density in the treated areas and also a high yield (7.0 t ha^{-1}). At this assessment, the organic fields had a greater weed cover over the soil surface, as uncontrolled weeds were able to grow and reach late growth stages. The two fields assessed in 2018 had a lower weed density before hoeing than those surveyed in previous years. In 2018, in Field 1 the weeds were in a more advanced growth stage, as shown by the high weed cover (63%), and thus the mechanical weeding was ineffective in controlling the vegetation; in Field 2 the weeds were at an earlier growth stage and after hoeing the weed infestation was reduced to approximately 5 plants m^{-2} (Table 4). Although the mechanical weeding only partially controlled the weeds, the rice yield was not so low, ranging from 4.4 to 5.0 t ha^{-1}.

The efficacy of inter-row hoeing in controlling weeds was often over 70%, with the exception of two fields in 2017, where no efficacy or low efficacy (34%) was observed, and one field in 2018 where weed density was not reduced by hoeing. This was also confirmed by the lower yields (< 3 t ha^{-1}) recorded in the fields with the highest infestation in 2017. Nonetheless, even when the weed control was high, a considerable number of weeds were still recorded within the rice row due to the greater available space compared to the conventionally seeded rice. In addition, weed control weed performed according to a predetermined

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Table 3. Pearson correlation coefficients of the correlation analyses between panicle density, rice yield, and yield components in 2017 and 2018

	Rice panicle density	Rice yield	1000 seed weight	Test weight
2017				
Rice panicle density	1	0.66**	−0.59**	0.55**
Rice yield	0.66**	1	−0.30	0.74**
1000 seed weight	−0.59**	−0.30	1	−0.50**
Test weight	0.55**	0.74**	−0.50**	1
2018				
Rice panicle density	1	0.74**	−0.71**	0.18
Rice yield	0.74**	1	−0.60**	−0.21
1000 seed weight	−0.71**	−0.60**	1	−0.35
Test weight	0.18	−0.21	−0.35	1

**Correlation significant for $P \leq 0.01$ (2-tails); *correlation significant for $P \leq 0.05$.

Table 4. On farm trial. Weed density, weed control efficacy before and after hoeing and rice yield of selected transplanted fields in 2016, 2017, and 2018

			Weed density (plants m^{-2})				Weed cover (%)		
Field	Management	Rice variety	Before hoeing		After hoeing		Before hoeing	After hoeing	Rice yield (t ha^{-1})
2016									
1	Organic	Ecco 63	645.3	b	65.4	a	9.5	63.0	6.2
2	Organic	Selenio	535.5	b	83.0	a	9.3	53.0	4.5
3	Organic	Selenio	464.0	b	131.2	a	34.0	45.5	7.5
4	Conventional	Cammeo	102.7	b	5.3	a	14.6	0.1	7.0
2017									
1	Organic	Selenio	468.8	b	124.8	a	15.5	10.0	6.2
2	Organic	Selenio	384.0	ab	251.4	b	4.0	46.0	4.3
3	Organic	Selenio	148.3	a	235.4	b	20.0	46.7	1.4
4	Organic	Selenio	691.2	b	144.0	a	77	90	2.8
2018									
1	Organic	Selenio	42.8		43.2		41.8	92.2	4.4
2	Organic	Selenio	54.8		9.8		5.0	3	5.0

Ecco 63: Hybrid. Weed density values within a same field sharing the same letter are not significantly different according to REGWF test ($P \leq 0.05$).
'Before hoeing' in the conventional field refers to herbicide untreated areas and 'after hoeing' refers to herbicide treated areas.

schedule, due to the need to use the same hoeing machine in all fields, rather than at the appropriate time for each field, could have resulted in lower weed control efficacy of hoeing, which could also have affected rice yield. Rice yield was highly variable among organic fields and related to the presence of weeds. The experience acquired with the on-farm experiment permitted to highlight that weed control is the main critical issue of the mechanical transplanting. Although transplanting offers advantages for rice over weeds due to differences in plant size, the transplanting shock of rice partially reduces this advantage. Additionally, the larger space between plant rows allows for a higher weed development, which necessitates appropriate control techniques (Farooq et al., 2011; Chauhan, 2012). Inter-row hoeing showed a quite high efficacy in weed control, although this was dependent on machinery type and moisture conditions of the field as some hoeing machines were ineffective in saturated conditions, as observed in certain fields; hence, repeated passages throughout the season are necessary to maintain low weed pressure.

Crop

Most of the fields (41 out of 68), were transplanted with round varieties, consisting mainly of Selenio (which accounted for about 80% of the fields), and to a lesser extent Balilla, Brio, Centauro, Cerere, and Spillo (Table 5). The other varietal groups ranged from four fields (medium varieties) to nine fields (long B hybrid variety managed conventionally). Four fields were not harvested in 2017, and five fields were not harvested in 2018 due to excessive weed infestation as the hoeing operation occurred too late to effectively control the weeds.

Rice yield varied both by year by rice variety, with the lowest yield recorded in a field cultivated with Selenio in 2018 and the highest yield in a field cultivated conventionally with a long B hybrid

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Table 5. Number of fields, mean, median, and minimum and maximum values of rice yield per varietal group and per transplanting time of all the transplanted fields in 2016, 2017, and 2018

	Rice yield (t ha^{-1}) by varietal groups (2016–2018)				
	Round	Medium	Long A	Long B	Long B Hybrid[a]
Number of fields	41	4	8	7	9
Mean	4.06	3.50	2.90	5.72	7.01
Median	4.02	3.25	2.85	6.30	7.33
Minimum	0.70	1.50	1.50	1.02	5.6
Maximum	7.51	6.00	5.00	7.30	8.00

	Rice yield (t ha^{-1}) by transplanting time (2016–2018)		
	May	June first half	June second half
Number of fields	28	22	19
Mean	5.56	3.49	3.92
Median	5.98	3.20	4.50
Minimum	1.50	1.30	0.70
Maximum	8.00	6.90	6.60

All fields were managed organically, except those in which Long B Hybrid varieties were cultivated.
[a]Managed conventionally; one field in Long A group was managed conventionally.

variety in 2017 (data not shown). The high yield obtained from the long B hybrid variety managed conventionally was achieved through effective weed control with herbicides, indicating that transplanting can lead to high yields if weeds are properly managed.

The box plot indicated that 25% of the fields in the round group recorded a yield below 2.9 t ha^{-1}, while 50% of the fields yielded between approximately 3 and 5 t ha^{-1} (Fig. 5). Round varieties exhibited the highest variability in yield, but this is likely attributable to the fact that most fields belonged to this category. Median and mean of round varieties both showed values of about 4 t ha^{-1}. Medium varieties, even though were transplanted in only four fields, showed a highly variable yield, going to a minimum of 1.5 t ha^{-1} to a maximum of 6 t ha^{-1} (Table 5). The other three groups displayed less yield variability, with long A varieties recording the lowest median and average yield and the hybrid long B variety resulting in the highest yield.

The long B group, despite being managed organically, showed an unexpected high yield, with both median and mean values of about

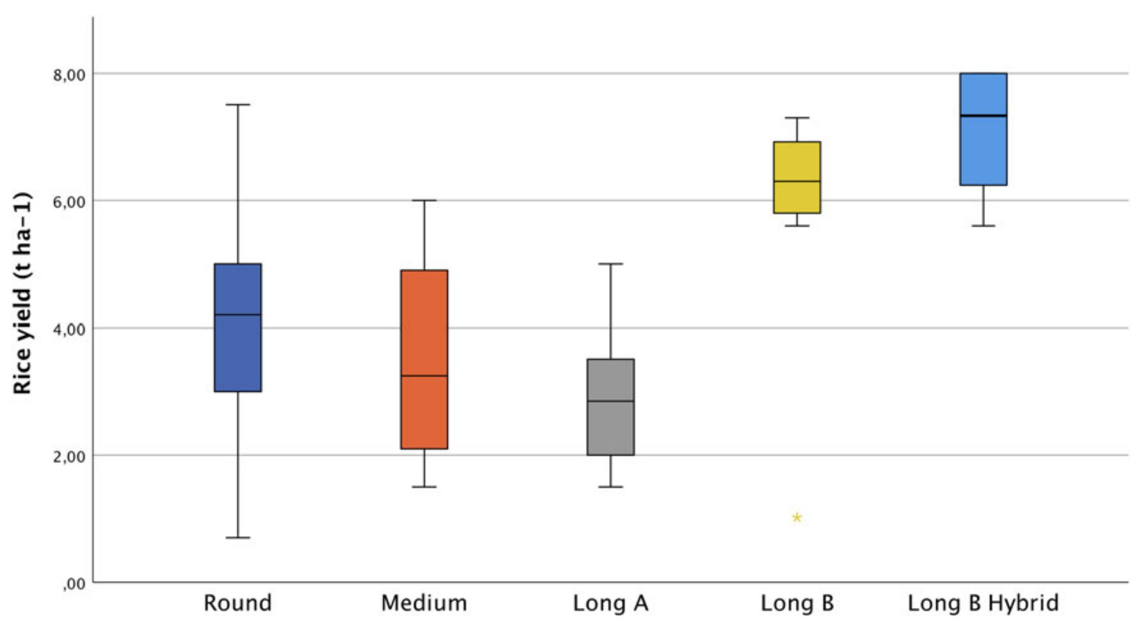

Figure 5. Box plot of rice yield of all the transplanted fields in 2016, 2017, and 2018 subdivided by varietal group. All fields were managed organically, except those in which Long B Hybrid varieties were cultivated.

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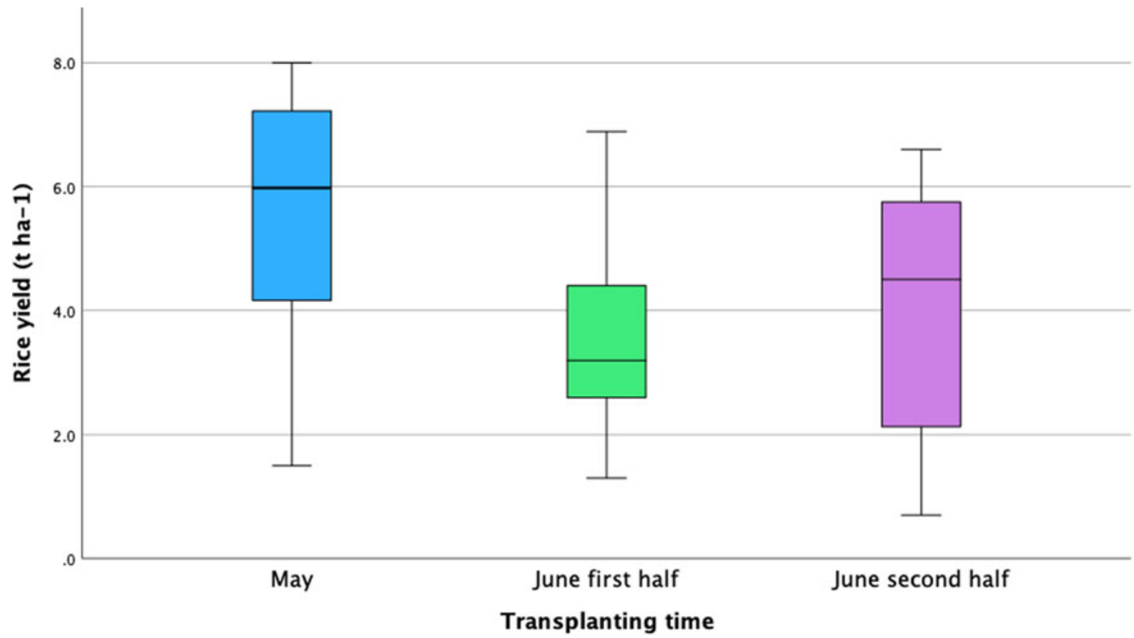

Figure 6. Box plot of rice yield of all the transplanted fields in 2016, 2017, and 2018 subdivided by transplanting time (May, first half of June, second half of June).

6 t ha^{-1}. All fields within this group were hoed at least once; however, the inclusion of only a few fields makes it difficult to conclude that the long B varieties are the most suitable for transplanting.

Rice yield also varied between transplanting periods, with the highest average yield recorded by fields transplanted in May being 5.5 t ha^{-1}, followed by those transplanted in the second half of June with3.9 t ha^{-1} and those transplanted in the first half of June with 3.5 t ha^{-1} (Fig. 6) (Table 5). However, it should be noted that all the conventional fields with Long B hybrids and the majority of organic Long B varieties were all transplanted in May. Long A varieties, the least productive one, were in fact mainly transplanted in the first half of June.

The variability in rice yield was observed in the field plot experiment both within and between varieties but even between fields cultivated with a same variety. Transplanting date also played a role in the variability of yield, although further studies are needed to confirm whether yield is more affected by rice variety or transplanting time. However, weed competition is believed to be the main cause of such variability, related to the variable weed seed bank of each field, the weather conditions, and the efficacy of weed control techniques. Weed competition was identified as the key factor of rice yield variability in Europe, especially in the organic farming sector (Delmotte et al., 2011). Other factors that affect the yield variation of transplanted rice include rice varieties, soil type, water management, fertilization, rice diseases, rice seedling age, transplanting issues, and weather conditions (Singh et al., 2019; Sujariya et al., 2020). Previous studies have identified significant variation in rice productivity among transplanted fields, as demonstrated in a trial conducted in the Philippines in which yield changed depending upon the level of fertilization and varied from about 2 to 6 t ha^{-1} in unfertilized fields. Furthermore, the authors suggested that transplanting errors contribute to the variable number of rice hills, which affects yield in transplanted fields (Dobermann et al., 1995).

The study permitted to verify the suitability of the mechanical rice transplanting technique for current Italian rice farming conditions. The results suggest that to achieve a high yield in organic rice, the transplanting technique should be combined with an effective interrow tillage to control weeds. Moreover, rice varieties with high tillering are those more suitable for mechanical transplanting, while traditional rice varieties such as Carnaroli did not perform well in this study, confirming the initial hypothesis that rice varieties respond differently to the technique. The hypothesis that rice growth is influenced by transplanting distance was rejected because in this study no differences were found at the two selected within-row distances, probably because tillering compensated for the initial lower plant density. Further research on mechanical transplanting is needed to determine the optimal field conditions and crop management practices to achieve a satisfactorily yield. Additionally, the study confirmed the hypothesis that mechanical weed control can limit weed growth but that the efficacy can be variable depending on different soil and weather conditions. The results of this study underscore the need to develop machines capable of controlling weeds in the interrow under different soil conditions, including saturated and drained soils, and to apply a timely tillage to achieve high yields. The 'on-farm trial experiment' confirmed the hypothesis that the technique can be adopted satisfactorily in Italian organic rice farms and that it is probably also potentially applicable to conventional rice farming, in where weeds are controlled with herbicides. However, a proper study needs to be performed to confirm this preliminary result as we only included few conventionally managed fields. These results further confirm that yield limitation with transplanting is mainly due to weed control.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S1742170524000188

Data availability statement. Data available on request from the author.

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Authors' contributions. All authors contributed to the study design. Field trial activity coordination was done by Giuseppe Zafferoni. Project coordination was done by Mario Zefelippo. Data collection was carried out by Silvia Fogliatto, Fernando De Palo, Gianfranco Airoldi, Elio Dinuccio and Francesco Vidotto. The first draft of the manuscript was written by Silvia Fogliatto and implemented, modified and commented by Francesco Vidotto and Elio Dinuccio. All authors read and approved the final version of the manuscript.

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