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Agronomic performance of a front roller multi-disk harrow prototype for legume devitalization in temporary wheat-faba bean intercropping

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ABSTRACT

The practice of cereal-legume temporary intercropping, with the legume devitalization in late winter, offers promising benefits for fall-sown organic cereal crop production, where nitrogen (N) availability is often limiting. This 3-year field experiment was focused on legume termination methods. The devitalization efficiency, operational characteristics and implications for wheat N availability, grain yield and quality of a novel non power-take-off (PTO) based front roller multi-disk harrow prototype (RMH) were compared to those of a conventional PTO-based split rotary hoeing (SRH) system. The results demonstrate that temporary intercropping significantly improves the Partial Factor Productivity of N as compared to traditional sole-crop wheat, with an average yield increase of 35 kg per kg of applied N. The RMH prototype was found to have no impact on the grain yield (3.82 vs. 3.73 Mg ha^{-1}), quality or N uptake (80.3 vs. 80.2 kg ha^{-1}) of wheat compared to SRH. Our research shows that the RMH prototype is as effective as the SRH in terms of devitalization efficacy of the legume component and N supply to wheat. Overall, the prototype appears to be a suitable tool for management of cereal-legume temporary intercropping in Mediterranean farming systems, with lower fuel consumption (-17.3 kg ha^{-1}) than PTO machines.

1. Introduction

The intercropping of cereals and legumes is an agricultural diversification practice (Liu et al., 2022) characterized by several advantages (Justes et al., 2021), most of which are related to nitrogen availability (for the cereal component) and crop protection (mainly weeds, for the legume component; Bedoussac et al., 2015). Several studies demonstrated how positive interactions (such as complementarity and facilitation) among companion species are frequent in cereal-legume intercroppings, and how these advantages can be quantified using competition indices (Zustovi et al., 2024), in order to better understand species interactions and better calibrate species choice and species proportion in crop mixtures. However, this practice has several technical disadvantages such as difficulties in the mechanization of harvesting operations and in synchronizing crop cycles. These difficulties can be overcome in the case of “temporary intercropping” (Guiducci et al., 2018; Tosti and Guiducci, 2010; Vandermeer, 1995), where the coexistence of the two species is limited to a short but significant part of their growth cycle, as the legume is devitalized at the end of the winter with the aim of transferring the N accumulated in its biomass to the cereal, which represents the cash crop species. This particular type of intercropping, where one companion species is not grown for production, but only as subsidiary species, to facilitate the growth and yield of the other, has been defined as “facilitative intercropping” (Wojtkowski, 2024).

The nitrogen nutrition of the cereal in temporary intercropping is improved by two distinct mechanisms: (i) during the co-growth period, via soil N enrichment deriving from the activity and turn-over of the legume root system (including N transfer, Thilakarathna et al., 2016), and (ii) after legume devitalization, via N released from the decomposition of the legume biomass incorporated into the soil (i.e., "green manure effect", Tosti et al., 2012; Vogeler et al., 2022). Several studies have demonstrated that the N mineralization occurring from water-rich crop biomass (such as the young tissue of a legume crop) is a fast process that takes place in a very short time span (Dhakal et al., 2020; Jahanzad et al., 2016; Tosti et al., 2012). Legume devitalization also avoids longer lasting competition with the cereal in those seasons when the legume

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might become the dominant component during the co-growth period (Zhang and Li, 2003). This is the case in rainy and mild winters, when wheat growth is limited by low soil N availability and legume growth is not depressed by frost (De Stefanis et al., 2017; Guiducci et al., 2018).

After the legume devitalization, the cereal may recover from its disadvantage (Zhang and Li, 2003), and any recovery is enhanced by the rapid increase of nutrient availability (mainly N, P and K) in the soil thanks to the quick mineralization of the fresh biomass of the legume (Vogeler et al., 2022). In addition, the improved nitrogen status of the cereal plants leads to an increase in grain protein content. The legume-derived nitrogen not only saves farmers costs, but also increases the farm N-self-sufficiency (Simon-Miquel et al., 2024) and reduces the environmental impacts associated with the production and use of fertilizers, such as greenhouse gas emissions and water pollution (Ditzler et al., 2021).

A key aspect of the temporary intercropping management is the devitalization of the legume component. The prevention of legume resprouting and the timeliness of N release in favor of cereals are of paramount importance. The subsidiary crops can be devitalized climatically (e.g., winter kill), chemically (herbicides application), or using mechanical methods such as tillage, mowing, roller-crimping or undercutting (Wortman et al., 2013). Subsidiary species termination techniques characterized by reduced soil disturbance, seem to be most effective to prevent seed weed germination and development (Wortman et al., 2013). Of course, any technique that may be suitable at the experimental plot level must also be feasible at the farm level to be adopted by farmers. In several trials, legume devitalization has been carried out using split rotary hoeing (SRH, Fig. 1), which is a highly effective way of incorporating legume biomass into the soil. However, this is time consuming, costly and involves high CO_2 emissions, as is the case with any PTO driven tillage machine (Bhattacharyya et al., 2022).

For this reason, researchers and technicians at the University of Pisa (Department of Agricultural, Food and Agro-environmental Sciences) have designed and built a prototype front roller multi-disk harrow (RMH, Fig. 1), which is designed to fell the legume plants, cut them just below the soil surface and bury them with rear-mounted discs inter-row cultivator. The effectiveness of this machine in devitalizing legumes and its effect on N transfer to cereal was then tested in a 3-year experimental trial carried out at the University of Perugia (Department of Agricultural, Food and Environmental Sciences) where farmers and technicians collaborated to fine-tune the prototype. In this trial, RMH and SRH were compared in terms of: (i) operational characteristics and efficacy of legume devitalization; (ii) N-effect of the legume on the N nutritional status of the wheat; (iii) wheat yield and quality. Besides these treatments, a sole crop (SCR) wheat grown following the standard technique adopted in the area was adopted as a control.

Fig. 1. Split rotary hoeing (SRH) during the devitalization of faba bean in alternate row temporary intercropping with wheat (A). Tractor with the complete roller multi-disk harrow (RMH): front-mounted machine for temporary intercrop management and rear-mounted disk inter-row cultivator (B).

2. Materials and methods

2.1. Experimental site

Field experiments were carried out over three years (2016/17, 2020/21 and 2021/22) in three adjacent fields with similar soil characteristics at the experimental station of the Department of Agricultural, Food and Environmental Sciences of the University of Perugia, Italy. The FieldLab is located in the Tiber alluvial plain at 42°57'22" N 12°22'34" E, 163 m a.s.l. The soil is a typical Fluventic Haplustept (USDA soil taxonomy, 1993) clay-loam (about 20 % sand, 46 % silt and 34 % clay, 1.4 Mg m^{-3} bulk density at 0–0.3 m depth), subalkaline (pH_{H2O} = 7.8), poor in organic matter (12 g kg^{-1}, C/N ratio = 11) and in extractable phosphorus (around 30 mg P_2O_5 kg^{-1}, Olsen method) and rich in exchangeable potassium (about 250 mg K_2O kg^{-1}, int. method). In the first year, the preceding crop was processing tomato, while in the other two experimental years, wheat was sown after grain maize.

2.2. Treatments and crop management

Durum wheat (*Triticum turgidum* subsp. *durum* Desf. (Husn.), cv Dylan) was grown as a sole crop (SCR, single rows 0.15 m apart), representing the control, and in temporary intercropping (TIC, Tosti and Guiducci, 2010; Guiducci et al., 2018) with faba bean (*Vicia faba* L. var. *minor* Beck. cv Scuro di Torrelama) in alternate rows, with the legume devitalized at the beginning of the wheat shooting phase (16/03/17, 01/03/21 and 16/03/22, respectively), using two different tools: a PTO-propelled split rotary hoe (SRH, Fig. 1) and a static roller multi-disk harrow (RMH) prototype. The three treatments (SCR, TIC-SRH, TIC-RMH) were laid down according to a randomized block design with four replicates. In the experimental plots in intercrops, wheat rows were 0.45 m apart and the faba bean row was sown in the middle of the wheat inter-row. The temporary intercropping was established according to an additive intercropping design (Malézieux et al., 2009). Sowing density was 400 viable kernels m^{-2} for wheat (in all systems) and 90 seeds m^{-2} for faba bean (in temporary intercropping). To keep the same overall seeding density of wheat in all treatments, wheat in the row of the intercrop was sown at triple seed density as compared to each row of the sole crop (Tosti and Guiducci, 2010). The experimental plots were 6 m × 45 m (270 m^2).

Wheat N fertilization in SCR was carried out with urea (N = 46 %) applied as top-dressing at tillering (25/01/17, 19/01/21, 19/01/22 at Z-scale 21; 50 % of the total rate) and shooting (22/03/17, 08/03/21, 29/03/22 at Z-scale 32; 50 % of the total rate) for a total rate of 140 kg N ha^{-1} (Zadoks et al., 1974). In 2016/17, the N fertilization of durum wheat in the temporary intercropping came entirely from the incorporated faba bean plants, so that approximately an overall amount of 40–50 kg N ha^{-1} was expected (Tosti et al., 2016; Guiducci et al., 2018), while in 2020/21 and 2021/22, an additional side-dress fertilization with 40 kg ha^{-1} of N applied as poultry manure (4–4–4) was carried out before the faba bean devitalization to better meet wheat N requirements from shoot elongation onwards. In terms of the aim of this work, the different N availability of wheat in the sole crop and in the intercrop was not relevant: the sole crop was just taken as a reference, while focusing on the comparison between the two different faba bean devitalization tools in the intercrop. A similar approach with different wheat N availability in sole crop and intercrop had been used in previous experiments (Tosti and Guiducci, 2010). Weed control was not necessary in TIC-SRH and TIC-RMH, while a post emergence treatment (Pinoxaden + Cloquintocet-mexyl) was applied to SCR wheat (21/03/17, 21/04/21 and 20/04/22, respectively).

2.3. Plant sampling and N analysis

Above ground biomass and N accumulation of wheat and faba bean were determined at the legume devitalization stage (16/03/2017, 01/03/2021 and 16/03/2022), and wheat biomass accumulation and grain production were determined at wheat maturity (01/07/2017, 01/07/2021 and 23/06/2022). At each sampling date, the plant height was recorded and the above ground biomass of the species was hand harvested at ground level from two areas of 1.8 m^2 per plot.

Immediately after devitalization, the soil incorporation efficiency of faba bean in both TIC-SRH and TIC-RMH was estimated by sampling the legume biomass remaining on the soil surface from 4 areas (0.5 m^2 each) per plot. The non-incorporated N was then calculated by multiplying the non-incorporated biomass and the N concentration of the faba bean; and, following the indications found by Piccoli et al. (2020), we hypothesize that the amount of N in the biomass non-incorporated into the soil (i.e. not available for the wheat) would be an indicator of the lack of efficiency of the considered termination tool. At wheat maturity, vegetative parts and grains of wheat were kept separate to determine dry matter accumulation in straw and grain. Before threshing, the number of unfertile spikes (spike with no grains) in the sample was determined. Kernel specific weight and 1000-kernel weight were determined on grain yield at maturity.

All samples were oven dried at 80°C until constant weight and then ground to a fine powder for the analysis of N content. The N content was measured on Kjeldahl digests using an auto-analyzer (Flowsys Systea, Italy). Partial Factor Productivity (PFP) of applied N, expressed as the ratio of grain dry matter (Gw) to applied N (via fertilizers and/or faba bean incorporated biomass) was calculated (Dobermann, 2007).

2.4. Prototype description

The machine for temporary intercrop management was built to be connected to the front three-point linkage of the tractor. Five working unit each consisting of a front roller and a rear long wing half sweep with rigid stem cultivator are connected to the main horizontal frame by means of an articulated parallelogram. The overall width is 2.5 m, the working width is 2.15 m and the weight is 600 kg (Fig. 2).

The roller is 20 cm wide and has 9 blades 6.5 cm high (Fig. 2A). The diameter is 36 cm without the blades (49 cm with the blades). The long wing half sweep with rigid stem cultivator (Fig. 2C and D) is height adjustable (stem and tool height is 37 cm), and has a working width of 20 cm (the length of the wing is 34 cm).

The function of the roller is to knock down the legume species and that of the rear static sweep tool is to undercut its stem at the height of the root system. A machine connected to the rear three-point linkage of the tractor was designed to bury the legume (Fig. 2B). Five articulated parallelograms with one (lateral working units) or two pairs of discs are connected to a horizontal frame. Each disk has a diameter of 35 cm and is equipped with a scraper system. The distance between the discs is

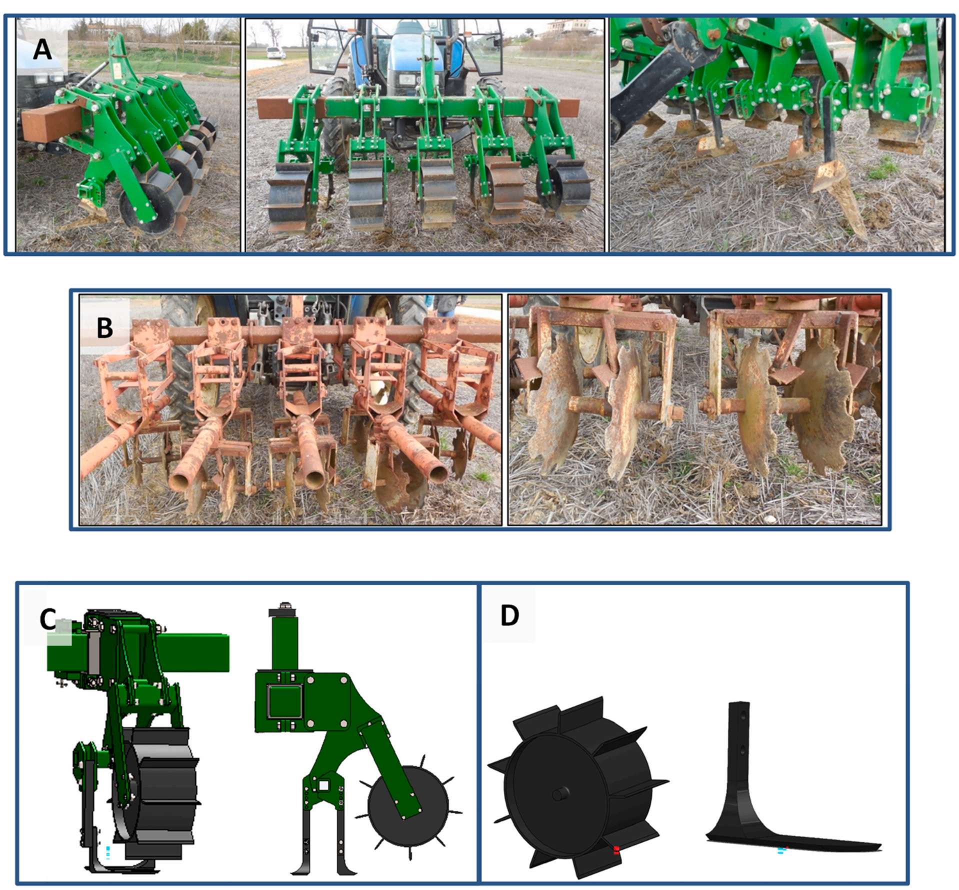

Fig. 2. The machine for temporary intercrop management: (A) front roller details and static sweep tool and (B) rear disk machine. (C) Scheme of the working unit of the front mounted prototype, side view (on the right) and frontal view (on the left). (D) Working tools of the prototype, front roller (on the left) and static sweep tool (on the right).

15.5 cm. The inclination of the discs with respect to the driving direction can be easily adjusted. The weight of this machine is 450 kg, the working width was adjusted at 2.15 m.

The two machines can be mounted by a tractor forming a manageable and easy to use working chain even without automatic guidance systems (Fig. 1B).

2.5. Data analysis

Before faba bean incorporation into the soil, TIC-SRH and TIC-MRH represented the same treatment (dummy plots), therefore the analysis of variance (ANOVA) was performed according to a randomized block design with 8 and 4 replicates for temporary intercropping and wheat sole crop, respectively (unbalanced design), thus the ANOVA was conducted adopting marginal F-tests (Lenth, 2016). After the faba bean incorporation, ANOVA was performed according to a randomized block (balanced) design with 4 replicates. In both cases, "Year" was considered as a fixed factor because the purpose of the study was to evaluate the efficacy of the devitalization method, which is expected to be greatly affected by weather. Therefore, the primary interest was in the "Tr x Year" interaction (i.e., focus on narrow space inference). The standard error of the difference (SED) was used as a variability index; when F test was significant, post-hoc multiple comparison test (Tukey method) was adopted to compare the means (significance level used: $\alpha = 0.05$). The statistical analysis was performed using the software R (R Core Team, 2023).

Working parameters of the different implements used for the devitalization of the intercrop were assessed adopting the standards ASAE EP496.3 and D497.7 (ASABE, 2016). Regarding RMH, the draft force was measured at the experimental station of the Department of Agricultural, Food and Environmental Sciences of the University of Perugia, using a TLP-100KNB dynamometer (Tokyo Sokky Kenkyuio Ltd. Japan) connected to a laptop computer functioning as data logger. Data sampling rate was adjusted at 1 Hz. The dynamometer was connected between two tractors according to the standard test procedure (RNAM, 1983).

3. Results and discussion

3.1. Weather conditions

During the experiment, the average temperature from November to June was 11.7 °C, and the average cumulated precipitation was 714.5 mm. Most precipitation events were observed from November to March, but with differences between years: 2016/17 being quite dry (213 mm), 2021/22 normally wet (311 mm), and 2020/21 very wet (443 mm) compared to the long-term average. A very late frost event, with temperature of −1.44 °C, was recorded the final ten days of April 2017 (Fig. 3); other severe late frost events were observed in the first ten days of April 2021 (−5.01 °C) and in the central ten days of April 2022 (−1.17 °C).

3.2. Working parameters of the machines

Draft force values (comprehensive of tractor's motion resistance) of the RMH prototype were measured separately for the front and the rear implement and when they work together (Tab. S1). For this reason, the total draft force data are not equal to the sum of the draft data of the single implements: in fact, when the machines work together, the rear implement operates on shallow previously tilled soil by the front mounted machine. Regarding working speed data (Tab. S1) the value of SRH appear to be quite low, this should not be surprising, in fact, most PTO-driven soil tillage machines are characterized by fairly slow working speeds, as the powered rotary working tools require time to properly till soil and break up clods. However, PTO-driven soil tillage machines with working tools presenting a rotary motion in accordance

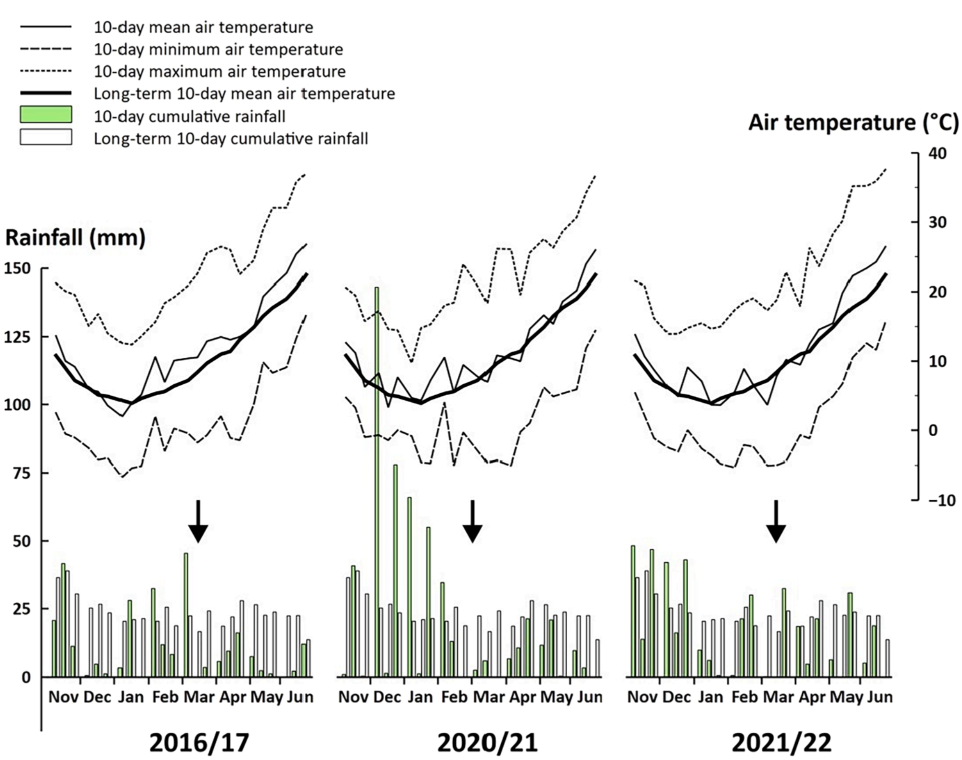

Fig. 3. Ten-day cumulative rainfall (green bars) and ten-day mean, max and min air temperature (lines) during the cropping cycle in the three experimental years. Long-term (since 1950) ten-day cumulative rainfall (white bars) and ten-day mean air temperature (bold line) are also shown. The arrows indicate the time when the faba bean was devitalized. Weather data were obtained from an automatic meteorological station at the experimental site (FieldLab, University of Perugia, Italy; 42°57'22" N 12°22'34" E).

with the tractor wheels do not require draft force. Nevertheless, the power requirement of the PTO-driven soil tillage implement (like SRH) is not low, because the rotation regime of the tractor's internal combustion engine should be at quite high values (i.e., about 2000 rpm) to guarantee rotation speed values of 540 rpm (in our case) at the PTO. The low value of the working speed of the SRH machine for the temporary management intercrops, determines a low value of the theoretical field capacity, which associated with the high power requirement, causes high fuel consumption (Tab. S1)

3.3. Biomass and N accumulation of faba bean and wheat at legume termination

In all years, wheat biomass accumulation at faba bean devitalization in TIC was rather constant across years and always significantly lower than in SCR (Table 1). The wheat N uptake at the time of faba bean devitalization in temporary intercropping was rather constant across years (15.4 ± 0.960 kg N ha^{-1}) and significantly lower than in SCR (Table 1). At the time of faba bean devitalization, the plant height of wheat in temporary intercropping was taller than in SCR in 2017, similar to SCR in 2021 and shorter in 2022 (Table 1).

As observed in previous studies (MacLaren et al., 2023; Salinas-Roco et al., 2024), cereal-legume intercropping usually provides a stabilization of biomass accumulation of the cereal component, but in our study, in all years, the competitive effect of faba bean reduced the biomass and N accumulation of wheat in temporary intercropping. As expected, wheat grown in temporary intercropping always showed a lower N uptake than in SCR. In particular, this was observed in the first year which was quite dry, while in the other two years, characterized by higher rainfall, also wheat in SCR showed a low N uptake, implying a low recovery of the N input and loss from the system.

Faba bean was devitalized at the beginning of March, and it accumulated, on average, 1.01 ± 0.021 Mg ha^{-1} of dry biomass and 38.9 ± 0.098 kg of N ha^{-1} with an average plant height of 27 ± 1.3 cm with no significant differences across years (Table 2).

3.4. Faba bean devitalization and incorporation efficiency

The efficiencies of the two systems in incorporating the faba bean biomass into the soil were similar in two out of three years (2017 and 2022) (Table 2). On the contrary, in 2021, the efficiency of the RMH prototype was more than halved as compared to the split rotary hoeing for both biomass and N. In detail, the non-incorporated biomass into the soil vs. total biomass averaged over the two systems was 38.2 % in 2017, and 11.4 % in 2022, while in 2021 it was much lower in TIC-SRH than in TIC-RMH (16.7 % vs. 40.7 %). Similar trends were observed for the proportion of non-incorporated vs. total N (Table 2).

The devitalization efficiency of the front roller multi-disk harrow was similar to that of the split rotary in two out of three experimental years, thus the prototype is confirmed to be an interesting energy-saving system (Tab. S1) for temporary intercropping management when compared to PTO-based techniques. Soil humidity was the main factor affecting the devitalization efficiency of both tools. In detail, the time interval from a significant rain event played a key-role in the proportion of faba bean biomass that was successfully incorporated into the soil (Fig. 3 and Table 2). It has to be pointed out that the soil hosting the experiment is rather clayey, so that the resistance to penetration of the tools employed in this study is found to be strongly associated with the soil's water content. In dry and difficult-to-penetrate soil conditions, the efficacy of the tools decreased, while in overly moist soil, particularly in the upper layers, the issue was more pronounced due to the increased adhesiveness rather than the reduced penetration depth of the tools. Even though the first year had the driest fall-winter season, it showed the worst soil incorporation efficiency of faba bean biomass, as the devitalization took place 9 days after a 40-mm rain event. On the other hand, the third year showed a very wet Autumn, but the devitalization was carried out 18 days after the last 30-mm rain event, and the observed efficiency was the highest with no significant difference between the split rotary hoeing and the prototype. It is worth noting that, based on the results observed in 2021 (16 days after 42 mm rain event, Fig. 3), the prototype appears to be more susceptible to soil moisture conditions than traditional split rotary hoeing.

3.5. Wheat yield, grain quality and N use efficiency

Wheat spike density in temporary intercropping was not affected by the devitalization system. Both treatments showed similar values (311 ± 12.6 spikes m^{-2}), that were significantly lower when compared to SCR (Table 3). In the first year, spike fertility was compromised due to the late frost event, thus an unfertile spike rate of 24 ± 2.8 % was observed in all treatments and the "grains per spike" parameter was also negatively affected (data not shown).

The lower spike density recorded in intercrops can be ascribed to a lower and delayed N availability compared to SCR. In fact, the amount of N supplied with poultry manure (only in the second and third year) and faba bean incorporation was lower compared to that supplied in SCR and, moreover, the N release from legume biomass was certainly slower compared to urea. For this reason, N availability in intercrops was likely not adequate to support the tillering phase. In addition, we cannot exclude that some tillers might have been damaged by the devitalization tools. In this regard, the two devitalization methods appeared not to differ, because spike density in TIC-RMH and TIC-SRH was similar.

During the three experimental years, the average grain yield was in line with the regional value (ISTAT 2023 http://dati.istat.it/Index.aspx). The very low yield of the first year in all treatments was mainly due to the April frost event, which compromised floral fertility in all treatments (overall mean of 89 ± 12.7 unfertile spikes m^{-2}). The two devitalization methods did not differ substantially for grain yield, which was not much lower than that of the SCR, except for a trend observed in the first year when yields of the TIC treatments was just a bit over a half compared to the SCR yield. Similarly, the N allocation in grains of intercropped wheat was not affected by the faba bean devitalization

Table 1

Biomass accumulation (Mg ha^{-1} dry weight, DW), N uptake (kg N ha^{-1}) and plant height (cm) of durum wheat grown in temporary intercropping (TIC) and as sole crop (SCR) at the date of faba bean devitalization in 2017, 2021 and 2022. Standard error of the difference (SED) and significance of F tests are reported. Means followed by the same letter are not statistically different (Tukey's HSD, p = 0.05). ns: not significant.

		Wheat biomass (Mg ha^{-1})				Wheat N uptake (kg ha^{-1})				Wheat height (cm)			
	Year	TIC		SCR		TIC		SCR		TIC		SCR	
	2016/17	0.54	c	2.09	a	14.7	d	62.1	a	29.1	a	22.9	b
	2020/21	0.52	c	0.79	b	14.2	d	23.0	bc	20.8	b	19.7	b
	2021/22	0.54	c	0.88	b	17.3	cd	29.0	b	22.6	b	31.3	a
	Mean	*0.53*		*1.25*		*15.4*		*38.0*		*24.2*		*24.6*	
F test	Treatment (Tr)	***				***				ns			
	Year (Yr)	***				***				***			
	Tr x Yr	***				***				***			
SED		0.072				2.723				1.652			

Table 2
Faba bean biomass and N accumulation and proportions that were not incorporated into the soil (% on total amount) in the wheat-faba bean temporary intercropping (TIC) by PTO-propelled split rotary hoeing (TIC-SRH) and by the front roller multi-disk harrow prototype (TIC-RMH) in 2017, 2021 and 2022. Standard error of the difference (SED) and significance of F tests are reported. Means followed by the same letter are not statistically different (Tukey's HSD, p = 0.05). ns: not significant.

		Faba bean biomass accumulation (Mg ha^{-1})	Faba bean N accumulation (kg ha^{-1})	Biomass not incorporated into the soil (%)				N not incorporated into the soil (%)			
	Year			TIC-SRH		TIC-RMH		TIC-SRH		TIC-RMH	
	2016/17	0.99	36.5	40.2	a	36.2	a	40.5	a	35.6	ab
	2020/21	1.49	58.3	16.7	b	40.7	a	16.8	bc	40.8	a
	2021/22	0.57	22.1	8.70	b	14.2	b	4.47	c	4.28	c
	Mean	*1.01*	*38.9*	*21.9*		*30.4*		*20.6*		*26.9*	
F test	Treatment (Tr)	-	-	*				ns			
	Year (Yr)	ns	ns	***				***			
	Tr x Yr	-	-	**				*			
SED		0.126	5.97	2.55				5.50			

Table 3
Spike density (n m^{-2}), grain yield (Mg ha^{-1}), grain N accumulation (kg ha^{-1}) and Harvest Index (HI, %) recorded in durum wheat at maturity in sole crop (SCR) and in temporary intercropping (TIC) with traditional (split rotary hoeing, TIC-SRH) or static (roller multi-disk harrow, TIC-RMH) devitalization of faba bean in 2017, 2021 and 2022. Standard error of the difference (SED) and significance of F tests are reported. Means followed by the same letter are not statistically different (Tukey's HSD, p = 0.05). ns: not significant.

		Spikes (n. m^{-2})			Yield (Mg ha^{-1})			Grain N accumulation (kg ha^{-1})			HI (%)		
		SCR	TIC		SCR	TIC		SCR	TIC		SCR	TIC	
	Year		SRH	RMH		SRH	RMH		SRH	RMH		SRH	RMH
	2016/17	382	222	221	3.02	1.84	1.72	64.4	38.5	36.1	22.0	30.7	25.0
	2020/21	324	278	274	4.71	4.14	4.17	101.1	87.2	88.2	42.5	43.5	43.1
	2021/22	568	470	399	5.46	5.21	5.56	128.2	114.8	122.7	36.4	39.5	39.9
	Mean	*425 a*	*323 b*	*298 b*	*4.40 a*	*3.73 b*	*3.82 ab*	*97.9 a*	*80.2 b*	*82.3 b*	*33.6*	*37.9*	*36.0*
F test	Treatment (Tr)	***			*			*			ns		
	Year (Yr)	***			***			***			ns		
	Tr x Yr	ns			ns			ns			ns		
SED		19.1			0.427			5.89			2.02		

method, and was generally lower than in the SCR, but the difference, even if not statistically significant, appeared to be important only in the first year (Table 3). The HI was on average rather low (35.8 ± 2.70 %), and was not affected by treatments (Table 3).

Differently from other studies (Emery et al., 2021), frost protection or other facilitative interaction during the coexistence of wheat and faba bean in temporary intercropping were not observed. As reported by Justes et al. (2021), when asymmetric rather than symmetric competitive interaction between companion species is observed in intercropping, then the overall performance could be reduced compared to pure stands due to a depowering of facilitation. In our case, wheat outcompeted faba bean in 2017 when wheat plant height was very high, thus a severe frost damage was observed in temporary intercropped wheat in comparison to the sole crop control treatment.

The treatments showed a different behavior in terms of PFP across years (Fig. 4) with a significant interaction (P = 0.0006) being observed. Wheat in intercrops showed values generally greater than SCR, although differences were significant only in the first and the third year. No significant differences were observed between TIC-RMH and TIC-SRH The low PFP of N observed in SCR compared to both temporary intercropping treatments was expected, given the much higher N rate of SCR, since increasing N rate is generally associated to decreasing PFP (Lopez-Bellido et al., 2005; Wang et al., 2016).

As a consequence of the grain yield, the kernel specific weight (KSW, kg hL^{-1}) was high and similar amongst treatments in 2017 and 2021, while it was lower in 2022. In general, treatments did not differ within each year, except for TIC-RMH in 2021, which showed a lower specific weight value compared to both TIC-SRH and SCR; however, the difference (84.1 vs. 83.0) appeared not to be significant (Table 4). A significant Treatment × Year interaction was also observed for mean kernel weight, that was similar amongst treatments within each year except for the very lower value recorded for SCR in 2022. The only plausible reason for this low value appears the very high rainfall, which might have leached the N supplied with urea, whereas the N supplied with faba bean biomass might have been released more slowly, with consequently lower exposure to leaching. However, data on kernel N concentration would not support this hypothesis, since in all years wheat in SCR showed higher values than in the two temporary intercropping treatments, which did not differ from each other (Table 4).

Overall, the RMH prototype did not differ substantially from the SRH for efficacy of faba bean devitalization, wheat N uptake, PFP of N, wheat growth, grain yield and grain quality (Tables 3 and 4). Whatever the devitalization method, the intercrop proved to be highly effective in providing N during the wheat spike development and grain filling. This N, represented by organic, but quickly available N, is of paramount importance to improve assimilate availability to grain filling, so guaranteeing considerable grain yield and quality in wheat (Kubota et al., 2018; Benincasa et al., 2022; Rosati and Benincasa, 2023).

4. Conclusions

In this study, a newly designed front roller multi-disk harrow prototype was proved to be comparable to the conventional split rotary hoeing method in terms of devitalization efficacy, reaching comparable values in two out of three years of the trial. Moreover, the two devitalization methods did not differ substantially in terms of wheat PFP of N, grain yield and protein concentration. On the other hand, measured or derived data on the operational characteristics of the two devitalization machines indicates that the new front roller multi-disk harrow prototype would save time and fuel. Further research should be conducted to transfer this technique from the experimental field to the farm level. In fact, the multi-disk harrow could be realized with a higher working width ensuring higher working capacity. Moreover, to avoid crop damages and facilitate the tractor driver tasks, these operative machines could be also provided with automatic guidance systems assisted by vision-based devices for row crop detection and real time kinematic global navigation satellite system (RTK-GNSS). This research further confirms that the tested prototype represents a viable alternative

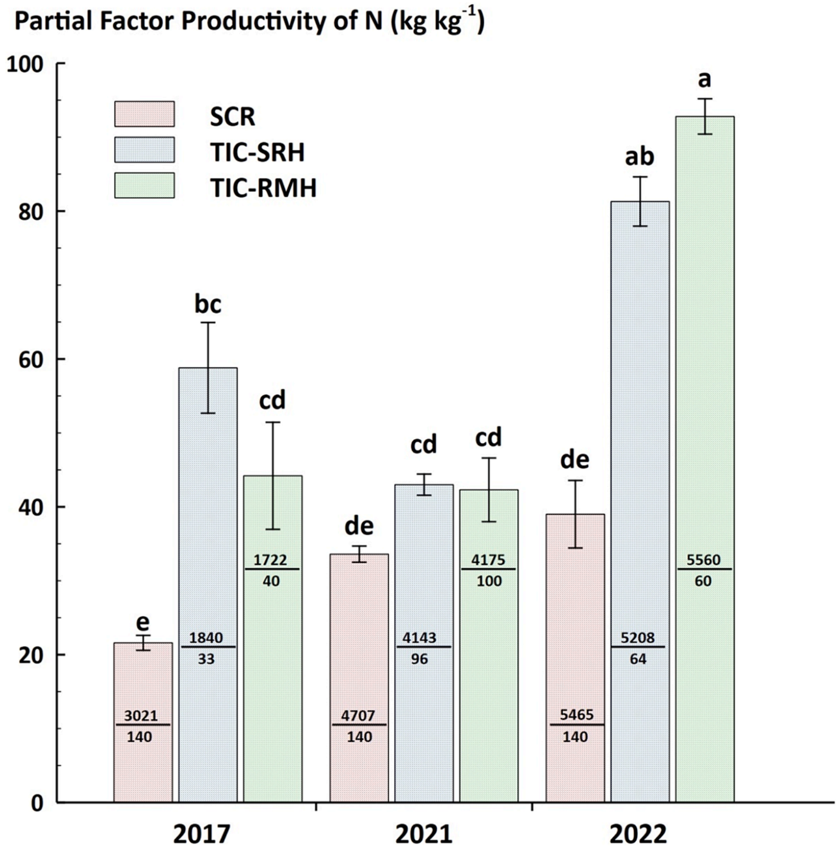

Fig. 4. Partial Factor Productivity of N (PFP, (kg harvested product per kg N applied)) of durum wheat at maturity in sole crop (SCR) and in temporary intercropping (TIC) with traditional (split rotary hoeing, TIC-SRH) or static (roller multi-disk harrow, TIC-RMH) devitalization of faba bean in 2017, 2021 and 2022. Inside the columns the ratio between yield (kg ha^{-1}) and applied N (kg ha^{-1}) are reported. Columns with the same letter are not statistically different (Tukey's HSD, p = 0.05).

Table 4
Kernel specific weight (kg hL^{-1}), 1000-kernel dry weight (g), kernel nitrogen content (%) recorded in durum wheat at maturity in sole crop (SCR) and in temporary intercropping (TIC) with traditional (split rotary hoeing, TIC-SRH) or static (roller multi-disk harrow, TIC-RMH) devitalization of faba bean in 2017, 2021 and 2022. Standard error of the difference (SED) and significance of F tests are reported. Means followed by the same letter are not statistically different (Tukey's HSD, p = 0.05). ns: not significant.

		Kernel specific weight (kg hL^{-1})			1000-kernel weight (g)			Kernel N content (%)		
		SCR	TIC		SCR	TIC		SCR	TIC	
	Year		SRH	RMH		SRH	RMH		SRH	RMH
	2016/17	84.6 a	84.0 ab	84.3 a	53.6 a	52.2 ab	53.6 a	2.13	2.09	2.09
	2020/21	84.1 a	84.1 a	83.0 b	47.8 abc	47.9 abc	47.3 bc	2.15	2.10	2.11
	2021/22	81.5c	81.4c	81.9c	43.2c	51.1 ab	52.8 ab	2.35	2.21	2.21
	Mean	*83.4*	*83.2*	*83.0*	*48.2*	*50.4*	*51.2*	*2.21 a*	*2.13 b*	*2.14 b*
F test	Treatment (Tr)	ns			*			***		
	Year (Yr)	***			***			***		
	Tr x Yr	**			**			ns		
SED		0.30			1.74			0.030		

to PTO propelled tools; thus, it represents a fundamental step towards the potential diffusion of the temporary intercropping technique among farmers. If well-conceived and managed with appropriate tools, temporary intercropping may represent a sustainable and efficient approach for enhancing nitrogen availability, reducing the reliance on synthetic fertilizers, and improving the environmental sustainability of wheat production in Mediterranean regions.

Plain language summary

Temporary cereal-legume intercropping offers promising benefits for fall-sown organic cereal crops. However, the costs of legume devitalization reduce the adoption of this technique among farmers. A three-year study was conducted to evaluate the effectiveness of static (non-PTO-based) prototype machinery for legume devitalization in terms of cereal yield and nitrogen availability. Our prototype exhibited comparable agronomic performance to the traditional tool (i.e., split rotary hoeing), while allowing for significant fuel savings.

CRediT authorship contribution statement

Giacomo Tosti: Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniele Antichi:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Falcinellii Beatrice:** Writing – review & editing, Investigation. **Christian Frasconi:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Michele Raffaelli:** Writing – review & editing, Investigation, Conceptualization. **Paolo Benincasa:** 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.

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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.ijagro.2026.100085.

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