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RESEARCH ARTICLE

Agronomic performance of disc chain harrow as a conservation agriculture tool for a one-step cover crop termination and seedbed preparation

Mattia Trevini[1], Giacomo Tosti[2] and Paolo Benincasa[2]

[1]Agroingegno, Verona, Italy and [2]Dipartimento di Scienze Agrarie, Alimentari ed Ambientali, Università di Perugia, Perugia, Italy
Corresponding author: Paolo Benincasa; Email: paolo.benincasa@unipg.it

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Summary

Cover crops and conservation soil tillage are reconsidered in cropping systems for their several agronomical and ecosystem services. In this frame, an important role is played by cover crop termination and seedbed preparation, which are crucial for a timely and successful establishment of the following cash crop. This work was aimed at testing a disc chain harrow for terminating a cover crop of hairy vetch and preparing a seedbed for soybean and defining its operational characteristics. A total of three trials were carried out to (1) compare two types of discs in two different front + rear combinations and two different working speeds (8 vs. 14 km h^{-1}) in terms of efficacy of hairy vetch termination; (2) evaluate the seedbed preparation by the disc chain in terms of soybean establishment as a following cash crop; (3) evaluate operational characteristics (working speed, fuel consumption, absorbed power, etc.) of the disc chain at the two different speeds. Results demonstrate that the disc chain is a valid tool for cover crop termination and seedbed preparation in a conservation tillage approach. The quality of work was affected by the type of disc and the working speed. The disc chain showed good operating performance, with low mechanical pulling force, low energy requirement for traction, and low fuel consumption as compared to alternative conservation practices for cover crop termination and/or shallow soil tillage.

Keywords: absorbed power; conservation tillage; fuel consumption; Green manure; traction force; working speed

Introduction

Cover crops and conservation soil tillage techniques are more and more reconsidered both in organic and conventional cropping systems for a sustainable management of soil fertility and for many other agroecosystem services (Foley *et al.*, 2011). Cover crops prevent soil compaction and erosion (Blanco-Canqui and Ruis, 2020), prevent nitrate leaching in rainy seasons (De Notaris *et al.*, 2021), and contribute to the biodiversity and stability of agroecosystems (Quintarelli *et al.*, 2022). Moreover, when used for green manuring, cover crops supply organic matter and nitrogen to the soil, the latter representing a new input to the system if legume species are included, thanks to symbiotic N fixation by legume root-associated rhizobia. Coupling cover crop and conservation tillage practices helps to maintain soil cover, reduces soil disturbance and aeration, preserves organic matter from mineralization, and reduces fuel consumption, overall contributing to the safeguard of soil carbon stock and to the mitigation of CO_2 emission into the atmosphere (Kaye and Quemada, 2017; Kumar *et al.*, 2023).

Together with species choice, seeding rate, and sowing date, the plant devitalization date and modality are crucial aspects of cover crop management (Antichi *et al.*, 2022; Benincasa *et al.*, 2010; Delgado and Gantzer, 2015; Thorup-Kristensen *et al.*, 2003), since they affect the magnitude of the above-mentioned benefits and, in addition, the nutrient availability for the next crop, the soil moisture, the timeliness of the following cash crop plantation, and the success of its establishment. Finally, the modality of cover crop termination may affect fuel consumption (per unit time and unit area), the working speed, and the traction force required, with implications on the tractor needed and on farm management and logistics. The traditional termination of cover crops is carried out by incorporating their biomass into the soil with several possible tools, such as rotavators, rotary hoes, and disc harrows. Several alternatives have been proposed, aimed at reducing tillage depth and increasing crop stubbles on soil surface, up to leaving a dead mulch covering the soil, which is considered the cornerstone of soil conservation management in organic cropping systems (Stagnari *et al.*, 2009; Vincent-Caboud *et al.*, 2019). Among these, we can mention several mechanical treatments like harrowing, hoeing, strip tillage, and roller crimping (Antichi *et al.*, 2022; Benincasa *et al.*, 2017; Creamer *et al.*, 2002; Kornecki *et al.*, 2009; Stagnari *et al.*, 2009; Trevini *et al.*, 2013). In particular, with the use of roller crimper, plants remain anchored to the ground forming a thick dead mulch which, while degrading very slowly, provides soil protection and prevents weed growth (Ashford and Reeves, 2003; Mirsky *et al.*, 2009). The roller crimper can be used either alone or in combination with chemical or thermal treatments, e.g., herbicides (such as glyphosate) or flaming (Antichi *et al.*, 2022; Ashford and Reeves, 2003; Frasconi *et al.*, 2019; Price *et al.*, 2009). Anyway, seedbed preparation after roller crimping generally needs a subsequent soil tillage, at least along the furrow where the seed will be laid.

An alternative is represented by the disc chain harrow (Kelly and Kelly, 2010), which was conceived to terminate the cover crop and till a very shallow soil layer in order to obtain, in one step, also a seedbed ready for the sowing of the following cash crop. It consists of catenary systems of idle discs mounted and hooked together (Kelly and Kelly, 2010), arranged in a single or double V-shape on folding wings brought by a central beam frame, which is mounted on wheels and towed by the tractor through a hitch. When in traction at high speed (around 10 km h^{-1} or higher), the discs rotate on their own axis operating within the top 5–7 cm soil layer. This would allow to break soil crust and surface capillarity, fill cracks, maintain most of the stubble on the soil surface, and create a dry vegetation layer that can cover and protect the wet underlying surface. Therefore, the disc chain harrow would have the potential to be included among the tools for the 'occasional strategic tillage' approach in no-till soil management (Blanco-Canqui and Lal, 2008; Çelik *et al.*, 2019; Dang *et al.*, 2018), since it would mitigate the negative effects arising from no-till in the long-term, such as herbicide resistance, increased stubble-borne pathogens pressure, stratification of nutrients, and organic carbon concentration on soil surface.

Despite the potential interest of the disc chain harrow, the scientific literature on this subject is very scarce. Actually, this technology has been developed and patented in the USA (Kelly and Kelly, 2010), but, to our knowledge, no scientific literature on its performance is available worldwide. It can only be assumed that it should be suitable to sandy soils and dry environments, where it should help to keep soil moisture in the top soil layer, thus ameliorating seed germination, as it has been demonstrated in general for shallow (non-inversion) tillage using tyne or disc implements (Dang *et al.*, 2018). However, the benefits of the disc chain harrow need to be tested in any kind of environment, including Northern Italy, where soils contain clay and the climate is, in most cases, rainy in early spring, which is the period when cover crops are terminated and spring summer cash crops are planted.

This work was carried out in the Po Valley plain (Northern Italy) and was aimed (i) at testing the disc chain efficacy to terminate a cover crop of hairy vetch and prepare the seedbed for a subsequent cash crop of soybean and (ii) at evaluating the disc chain operational characteristics.

Materials and methods

Three different field trials were carried out to test the disc chain harrow in terms of cover crop termination, seedbed preparation for the subsequent cash crop, and operational characteristics

Trial #1 – Cover crop termination efficacy

This trial was aimed at evaluating the quality of work, in terms of hairy vetch termination, obtained by using a disc chain harrow with two different combinations of front and rear tools and with two different working speeds.

The trial was performed at Cascina Marianna in Landriano (Province of Pavia), in a plain field with a sandy-silty soil (54% sand, 35% silt, and 11% clay), average bulk density of 1910±70 kg m^{-3} in the top 0–10 cm layer, average cone index of 0.70±0.19 MPa in the top 0–5 cm layer and 1.16±0.34 MPa in the top 0–20 cm layer (measured with a SpotOn brand digital penetrometer) (Innoquest Inc., Woodstock, IL, USA).

The cover crop of hairy vetch (*Vicia villosa* Roth.), cultivar Minnie, had been sown on September 20th 2021 (after the harvest of fodder sorghum, followed by spreading of 30 m^3 ha^{-1} of cow slurry, ploughing, and seedbed preparation), with a seed rate of 60 kg $ha^{-1,}$ and, at the date of termination, it had a soil cover of 100% and average above-ground fresh biomass of 695±58 g m^{-2} (with 11% dry matter content). The average soil moisture at the date of vetch termination was 12%.

The disc chain harrow adopted for the trial was a Kelly Diamond 1204 (Kelly Engineering, Booleroo, SA, Australia), a wheeled trailed type machine, consisting of a central beam frame bringing two hydraulically locking side wings equipped with discs and having a catenary tensioning system and a hydraulic body lifting system to allow the discs to work properly and at the correct working depth (Kelly and Kelly, 2010) (Fig. 1a).

Two typologies of disc were implemented to the disc chain (Fig. 1b): Cl1 and K4 (Kelly Engineering, Booleroo, SA, Australia). CL1 are concave discs of 328 mm diameter and 11.2 kg each (70 kg m^{-1}), 163 mm apart, conceived to till the soil in the upper 5–7 cm layer, slightly incorporate crop straw, flatten the soil, and prepare the seedbed; K4 are sharp edge discs of 330 mm and 11 kg each (68.5 kg m^{-1}), 160 mm apart, conceived to kill and rip off weeds while tilling the soil at a greater depth (>7 cm).

In a split-plot design with three replicates (randomized blocks), a total of four treatments were compared, consisting of two different front + rear combinations of discs (K4 front + CL1 rear vs. CL1 front + CL1 rear) and two different working speeds (8 vs. 14 km h^{-1}), with the working speed in the subplot. Each subplot was 5 m wide (machine width 4 m) and 50 m long. The machine entered the individual plots always from the same side. The working width was 4 m. The tillage depth was set at around 5–6 cm. The tractor used was a Massey Ferguson S 6718, four-wheel drive, with 129 kW.

In each subplot, the average amount of hairy vetch above-ground biomass present before the disc chain passage had been measured by sampling plants on five 0.25 m^2 per subplot. Similarly, the average amount of hairy vetch biomass that remained undetached after the disc chain passage was measured in five 0.25 m^2 sampling areas per subplot, collected by random throws of a frame. The vetch biomass was immediately weighed and then oven dried at 105 °C for 48 hours to determine fresh and dry weights. The performance of each treatment (front + rear tool combinations and working speed) was expressed as the ratio between the biomass of the hairy vetch undetached and the biomass of the vetch present before the chain passage. The lower the ratio, the more efficient the hairy vetch termination. Devitalization efficiency ratios were subjected to arcsin-of-square-root transformation and subjected to two-factor ANOVA with three replicates (sub-plots), using the statistical software R (R Core Team, 2023).

Figure 1. (a) The disc chain harrow Kelly Diamond 1204. (b) Detail of the CL1 discs (left) and K4 discs (right). In Figure 1A, the disc chain harrow is equipped with K4 front and CL1 rear.

Trial #2 – Seedbed preparation quality

This trial was carried out to evaluate the use of disc chain for seedbed preparation for soybean planting by comparison with the use of the disc chain plus an additional passage with a subsoiler combined with multitiller.

The trial was performed on a field contiguous to the field used for trial #1, having similar soil characteristics and a same hairy vetch cover crop (same cultivar, same growth stage).

In a randomized block design with three replicates, two treatments were compared: (1) three passages of disc chain (K4 front + Cl1 rear) at the working speed of 14 km h^{-1}, as described for trial #1; (2) three passages of disc chains (K4 front + Cl1 rear) at the working speed of 14 km h^{-1}, plus a minimum tillage performed with one passage of subsoiler with shanks working at the depth of 45 cm and one passage of multitiller (shanks + discs) working at the depth of 15 cm. The tractor used was a John Deere 6150 M, four-wheel drive, with 110 kW.

Soybean (cultivar LG Avril) was sown on May 10th, 2022 at the density of 50 seeds m^{-2} with rows 0.35 m apart. No fertilization and irrigation were performed, while weeds were controlled by one pre-emergence herbicide application.

The following determinations were performed: soil moisture in the upper 10 cm soil layer, measured gravimetrically (oven drying samples at 105 °C for 48 h), by three samplings per plot; number of plants on three 2-m long segments of furrow per plot; fresh and dry weights of soybean plants by sampling plants on three 1-m long furrows per plot. Average data of each plot were subjected to one-factor ANOVA, using the statistical software R (R Core Team, 2023).

Trial #3 – Operational characteristics of the disc chain

This was a mechanical test aimed at evaluating some operational characteristics of the disc chain used at two different working speeds. The test was carried out at the Gibelli farm of Canedole (Province of Mantova) on a plain soil with 37.7 % sand, 42.5 % silt, and 19.8 % clay. The soil, at the time of the test, had an average moisture of 10% in the upper 10 cm layer and an average penetration resistance (measured in 15 sampling positions by SpotOn) of 2.2±0.55 MPa.

The soil, before the disc chain passage, was partially covered by residues of a sugar beet crop and some weeds, mainly *Abutilon theophrasti*. The disc chain setup was with K4 front and CL1 rear discs as described for trial #1, with the drawbar pulled by hitch with an eye hook. An electronic load cell was implemented in between the tractor and the disc chain to measure the traction force and split it into vertical and horizontal components (Supplementary Material Fig. S1). The electronic load cell was the S2TECH DT100 (S2TECH SRL, Milano, Italy), 25,000 kg capacity traction, with electronic inclinometer with Modbus standard and Gizero Agritech data transmission system (Gizero Energie S.r.l., Verona, Italy). The tractor was a Deutz Fahr Agrotron 6185, four-wheel drive, with 132 kW, having powershift transmission and GPS guidance, weight 7760 kg (3280 kg front, 4530 kg rear) with a full tank of diesel, without ballast weights, and with Mitas Ac65 540/65R30 front and 650/65 R42 rear tyres.

In a randomized block design with 10 replicates, two working speeds were compared: 8 km h^{-1} and 14 km h^{-1}. The following operating data were recorded simultaneously with tractor telemetry: average working speed, total working time, average fuel consumption, operating field rate (ha h^{-1});

Results

The effect of front + rear disc combination in the disc chain and of the working speed on the termination of the vetch cover crop can be evaluated from data in Fig. 2.

Data clearly indicate that using CL1 as both front and rear tool does not allow to rip off vetch plants, the biomass of undetached vetch being over 70% of the total, independent of the working speed. On the other hand, using the K4 front + CL1 rear combination allowed to rip off most of vetch plants, so that the undetached biomass accounted for 23% of total biomass at the working speed of 8 km h^{-1} and just 10% at the speed of 14 km h^{-1}.

The effect of disc chain (in the combination K4 front + CL1 rear) on soil moisture and soybean crop establishment can be evaluated from data reported in Table 1, which reports, besides the soil moisture at sowing in the top 10 cm layer, the number of soybean plants and their mean individual fresh and dry weights on May 24th and July 25th, 2022, by comparison with data obtained preparing the soil with the same disc chain plus an additional minimum tillage.

The use of the sole disc chain harrow allowed to keep a greater soil moisture in the upper 10 cm soil layer; however, no significant differences were observed in the density of emerged soybean plants and in individual plant weight, both in May and July.

Figure 3 shows the average values of traction force in the horizontal component measured for each of the ten passages of the disc chain harrow operating at 8 and 14 km h^{-1}. Based on these data, the force required to work at 14 km h^{-1} was significantly higher than that required to work at 8 km h^{-1}, but the increase was smaller than expected, just 1.86 kN, i.e., +17.5% in front of a +75% increase of speed.

Table 2 shows the operational characteristics of the disc chain at the two working speeds. Among the data, it seems worth to highlight that fuel consumption per unit area comes out substantially the same independent of the working speed. Based on this evidence, it appears advisable to work at high speed, at least up to 14 km h^{-1}.

Based on the mean absorbed force and mean speed, the average power absorbed at the hitch under our experimental conditions were 23.6 and 48.5 kW at 8 and 14 km h^{-1}, respectively, i.e., 5.9 and 12.1 kW m^{-1} of disc chain, respectively. Considering that a four-wheel-drive tractor is capable

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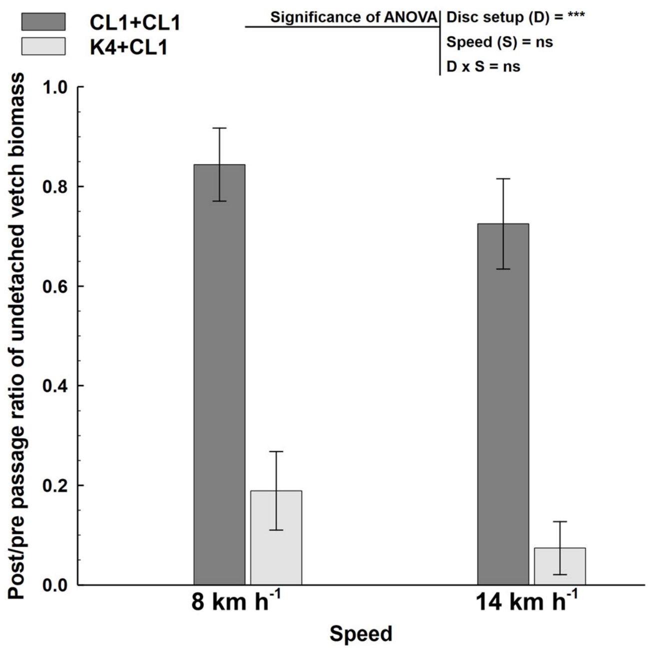

Figure 2. Ratio between the biomass of vetch remained undetached after the disc chain passage and the vetch biomass present before as affected by the front + rear disc setup (see text for K4 and CL1 disc description) and the working speed. Ratio data were subjected to arcsin-of-square-root transformation for ANOVA and then back-transformed and reported in the figure with corresponding standard errors (SE).

of transmitting power to the hitch on agricultural land with an average efficiency of 0.7 in the worst grip conditions and 0.8 in the best (ASAE D497.4 FEB03), the average tractor power required under these conditions is at least 69.2 kW (or 94.2 hp).

Discussion

The cover crop devitalization efficacy achieved with the disc chain harrow was greatly affected by the combination of discs (Fig. 1). Using CL1 discs as both front and rear tools resulted in a low devitalization efficacy but this does not necessarily represent a limit since laying plants down and crushing them on the ground can create a soil mulching similar to that obtained by a roller crimper, which is widely adopted for its recognized positive effects in a conservation tillage approach (Ashford and Reeves, 2003; Kornecki *et al.*, 2009). On the other hand, the work of the combination K4 front + CL1 rear was much more effective than that obtainable with a roller crimper, except for roller crimpers equipped with undercutting blades (Sportelli *et al.*, 2023) or associated with flaming or herbicides (Frasconi *et al.*, 2019), which guarantee a high devitalization efficacy. Interestingly, with the K4+CL1 setup, the soil surface remained slightly cusped, which is to be considered as beneficial for preventing soil crusting and enhancing water infiltration (Astafyev *et al.*, 2021; Dang *et al.*, 2018; Mwiti *et al.*, 2023). Moreover, this disc chain setup resulted in a partial mixing of cover crop biomass with soil particles, which may be considered beneficial, since it allows a certain biomass degradation (and release of nutrients for the next cash crop), while avoiding its dilution into a too deep soil layer (Marshall and Lynch, 2018). Various studies on disc tools have focused on the relationship between the quality of the work and the working depth, all of which are directly dependent on several factors, including the vertical load, the geometry of the disc section, the diameter and the interaction with the type of surface

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Table 1. Soil moisture at sowing in the top 10 cm layer, number of soybean plants and their mean individual fresh and dry weights as recorded on May 24th and July 25th, 2022 in the two soil tillage treatments: disc chain harrow (DCH) and disc chain harrow + minimum tillage (i.e., subsoiler at 45 cm depth + multitiller at 15 cm depth) (DCH+MT)

Date	Tillage treatment	Soil moisture (g $100g^{-1}$)	Plant density (plant m^{-1})	Individual soybean plant fresh weight (g)	Plant dry matter (%, w/w)
May 24th	DCH	12.5[a]	11.7	1.8	13.6
May 24th	DCH + MT	11.1[b]	13.9	1.8	13.2
July 25th	DCH	4.9[a]	9.3	118.2	20.1
July 25th	DCH + MT	4.3[b]	10.2	104.1	21.0
Significance of ANOVA					
	May 24th	**	n.s.	n.s.	n.s.
	July 25th	**	n.s.	n.s.	n.s.
$LSD_{0.05}$					
	May 24th	0.69	2.37	0.17	1.88
	July 25th	0.49	1.45	20.13	1.84

Note: Different letters (a, b) indicate significant differences for P = 0.05. ** significant for P < 0.01, n.s. = not significant.

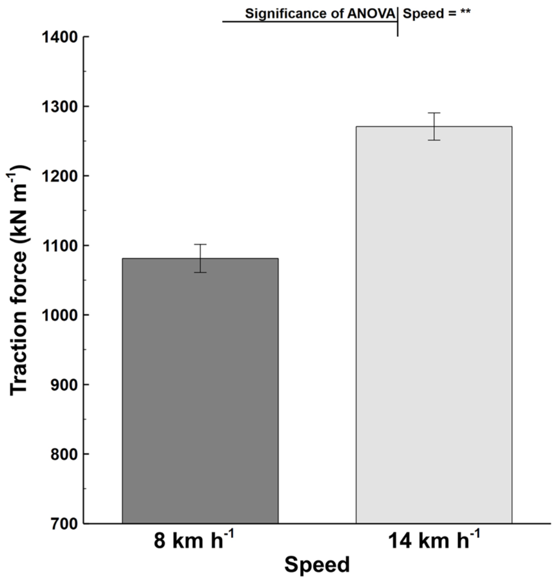

Figure 3. Traction force required to till the soil with the disc chain as a mean of ten replicated passages at the speed of 8 and 14 km h^{-1}.

(Slepenkov *et al.*, 2021). Disc tools with a spherical cross-section also have several problems, including wet soil adhesion, but if the disc can rotate and especially if there is a certain amount of coarse particles (skeleton-rich soils), they generally undergo self-cleaning. In order to adapt to the different situations encountered in the field, the possibility of automatically adjusting and redistributing the load on the discs through a suitable computational model, implementable on hardware to be mounted on board the machine, has been evaluated. In general, with disc harrows, for a given working speed and width, reducing the horizontal working angle of the machine causes a reduction in working depth (Slepenkov *et al.*, 2021). The disc chain harrow tested in our study did not have a load management system, and since the effect of the discs is only based on the weight of each tool, its geometry, and the tensioning and levelling of the catenary, the implementation of the system proposed above could still improve the quality and efficiency of cover crop devitalization in the field.

Table 2. Operational characteristics of disc chain at the speed of 8 and 14 km h^{-1}

Parameters	Nominal speed 8 km h^{-1}	14 km h^{-1}	Notes on data acquisition
Total distance over 10 laps (m)	7277	7265	From tractor (GPS)
Total area (ha)	2.9	2.9	From tractor
Total time (min)	55	33	Measured
Working rate (ha h^{-1})	3.17	5.27	From tractor
Working rate per m of disc chain (ha h^{-1} m^{-1})	0.79	1.32	Based on measured time
Actual mean speed (km h^{-1})	7.7	13.5	From tractor (GPS)
Actual total fuel consumption (L)	10.5	9.6	From tractor
Consumption based on refilling the tank (L)	9.8	10.3	*
Fuel consumption per unit time (L h^{-1})	10.8	16.6	From tractor
Fuel consumption per unit area (L ha^{-1})	3.5	3.3	From tractor
Consumption based on refilling (L ha^{-1})	3.4	3.6	*

*Based on tractor tank fully refilled in the same position after work.

The higher soil moisture in the upper soil layer recorded with the use of the sole disc chain harrow (Table 1) can be relevant in case of dry spring season, as it was in our experiment. Since no irrigation was given at sowing, keeping a higher soil moisture in the top soil layer may be crucial for improving germination and crop establishment. In this regard, the disc chain harrow appears to give similar effects as other conservation tillage practices, and, of course, the benefits with respect to either no-till or conventional deep tillage (e.g., ploughing, ripping, chiselling, etc.) will depend on the soil texture and season weather (Astafyev *et al.*, 2021; Baumhardt *et al.*, 2020; Dang *et al.*, 2018). In our experiment, the different top soil moisture observed in the two treatments (sole disc chain vs. disc chain plus minimum tillage) did not result in different density of emerged soybean plants. Rather, the plant density was lower, although not significant, with the use of the sole disc chain. No observation was made that can help to explain this slightly lower density and maybe this could have been due to the effect of suboptimal seedbed preparation in worsening the work of the seeder and seed germination or in promoting greater seed predation by insects and birds. However, as previously said, the difference was not significant and actually not much relevant. Moreover, the lower plant density recorded with the use of the sole disc chain harrow was associated with a greater, although not significant, individual plant weight, letting predict little differences in total above-ground biomass and grain yield at harvest.

As far as the operational characteristics of the disc chain are concerned (Fig. 3 and Table 2), they appear very good when compared to those of roller crimpers and harrows for shallow tillage, which represent the main alternatives for cover crop devitalization. For example, the roller crimper with undercutting blade used in the work by Sportelli *et al.* (2023), which had a devitalization efficiency comparable to that of the disc chain harrow used here, showed a lower working rate (0.4 ha h^{-1} m^{-1}, based on the width of the machine reported by those Authors) and a higher fuel consumption (around 14 L ha^{-1}). The low working rate of roller crimpers is partly due to high vibrations (Kornecki *et al.*, 2006; Raper *et al.*, 2004). On the other hand, the working rate of an offset disc harrow like that used by Barro *et al.* (2022) can be even much lower, ranging from 0.12 to 0.43 ha h^{-1} m^{-1} depending on the soil and tillage depth and requires about 1.5 kN m^{-1} of width when working at around 6.5 cm depth. In addition, disc harrows have greater fuel consumption, about 5.5 L ha^{-1} or more (Choudhary *et al.*, 2021). Similarly, power harrows, even when working very shallowly (e.g., 6 cm depth), require greater power and imply greater fuel consumption (8 L ha^{-1}) at the speed of 9 km h^{-1} (Balsari *et al.*, 2021). Similar data are available for power harrow, disc harrow, and multitiller from the work of Pochi *et al.* (2009) and for combined (active-passive) and conventional offset disc harrows tested by Upadhyay and Raheman (2020): Most of those tools, for a given working width, have lower working speed and require much more

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energy (MJ ha^{-1}) and fuel than the disc chain harrow tested in this experiment. Overall, the disc chain harrow may give a cover crop devitalization similar to that of the best roller crimpers together with a seedbed preparation not dissimilar to that obtainable with disc harrows but with lower traction force required (kN m^{-1}), higher working rate (ha h^{-1}), and lower fuel consumption (L ha^{-1}). This is because the disc chain harrow tills the soil just very shallowly, well meeting the criteria of soil conservation strategy (Blanco-Canqui and Lal, 2008; Çelik *et al.*, 2019; Dang *et al.*, 2018).

Conclusions

Results demonstrate that the disc chain is a valid tool to terminate a cover crop and prepare the seedbed for the following cash crop with the advantage of keeping a higher soil moisture, which contribute to the success of crop establishment in dry environments and seasons. The quality of work in terms of both cover crop termination and seedbed preparation depends on the kind of disc and on the working speed. Further experiments are needed to better define the best solution in terms of disc type and working speed, and of course, the choice and the outcome will depend also on soil characteristics, in particular soil texture and moisture. In any case, our results show that the disc chain has good operating performance with low mechanical pulling force, low energy requirement for traction, and low fuel consumption as compared to alternative conservation practice tools for cover crop termination and/or shallow soil tillage. Fuel consumption appears substantially the same both at low and high speed. For this reason, it appears advisable to use the disc chain at a higher speed, at least up to 14 km h^{-1}. Overall, the disc chain appears a valid tool for the conservation of soil tillage.

Supplementary material. For supplementary material accompanying this paper visit https://doi.org/10.1017/S001447972400005X

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