COMPARISON OF THE EFFECTIVENESS OF DIFFERENT MECHANICAL TOOLS FOR THE TERMINATION OF COVER CROPS USING A MODULAR PROTOTYPE

Highlights

- Cover crops are crops that cover the bare soil, providing multiple benefits.
- Cover crops must undergo a termination which can be based on mechanical methods.
- A modular prototype has been developed to evaluate different types of tools.
- The synergic use of multiple tools in combination yields better results.

ABSTRACT. *Cover crops are crops that occupy the soil between the end of a cash crop and the beginning of the next one, providing both agronomic and environmental benefits. To allow for the subsequent cultivation of the cash crop, cover crops must undergo an appropriate termination process based on winter frost, on herbicide chemical treatments or on mechanical methods. For this latter approach, previous published research has only examined the effectiveness of termination obtained with individual mechanical tools, without considering the possible synergistic effects of multiple tools with complementary actions. To address this gap, in this work a modular multi-tool prototype has been developed. It allows to evaluate the effects of different types of tools, both individually and in combination. The working modules of the prototype include: 1) tine cultivator, 2) disk harrow, and 3) crimper roller. Field trials were carried out in 2021 and 2022 on three fields of approximately 6000 m^2, which were divided into 60 plots each and sown with vetch and barley. The plots were mechanically terminated with the prototype in different configurations, and the effectiveness of the of the different modules and their combinations was subsequently evaluated by measuring the NDVI index by using ground sensing technology. The results indicate that the disk harrow 15°, used alone and in combination with other tools considered (crimper roller and tine cultivator for barley, crimper roller for vetch), offered the best termination effectiveness for both barley and vetch with a termination rate of greater than or equal to 85%.*

Keywords. *Conservation agriculture, cover crops, crimper roller, disk harrow, mechanical termination,*

tine cultivator.

INTRODUCTION

Cover crops are crops that occupy the soil or between the end of a cash crop and the beginning of the next one, or as intercropping (inter-seeded in the cash crop) or as living mulch in no-till soil management. In this way, they cover the soil during periods when it would otherwise remain bare, allowing for agronomic and environmental benefits (Justes, 2017, Wright et al., 2017).

The adoption of a cover crop improves soil structure (Ren et al., 2019; Restovich et al., 2019) and increases its organic matter content (Cavalli et al., 2019, Smit et al., 2019, Wulanningtyas et al., 2021), protects against water and wind erosion, (Kaspar et al., 2001, Barthès et al., 2005, Mohammed et al., 2021) and allows for the capture of nitrogen present in livestock effluents, reducing losses through leaching and making it available for the subsequent crop (Tonitto et al., 2006, Valkama et al, 2015; Justes, 2017). Furthermore, cover crops contribute to the containment of weeds development through competition for light, water, nutrients (Teasdale, 1996, Shrestha et al., 2002) or, in some cases, through the emission of allelopathic substances (Kunz et al., 2016).

To allow for the subsequent cultivation of the cash crop, cover crops must undergo an appropriate termination process, unless they are used as living mulch. This can occur either in advance or simultaneously with the sowing of the cash crop in a single operation with combined equipment. The choice of the optimal termination timing depends on the characteristics of the subsequent crop and the necessary conditions for its growth (Ketterings et al., 2015, Cavalli et al., 2019), as well as the type of cover crop adopted, its development, and the termination technique used (Reiter et al., 2008, Keene et al., 2017, Bavougian et al., 2018).

Termination can occur spontaneously due to winter frost for those cover crops defined as "frost-sensitive", including black oat (*Avena strigosa*), white mustard (*Sinapis alba*), tillage radish (*Raphanus sativus*), and bengal vetch (*Vicia benghalensis*). Devitalization occurs as a result of exposure to temperatures below 0°C for an adequate period in terms of duration and intensity (Cavalli et al., 2019).

Chemical termination, on the other hand, involves the use of non-selective herbicides, such as glyphosate. The distribution in the field is carried out by sprayer or, sometimes, in combination with other termination machines to increase its effectiveness (i.e. crimper roller, Kornecki et. al. 2009a). The use of herbicides does not present particular phenological constraints; however, the suppression effect is not equivalent for all cover crops (ranging from 80 to 100% depending on the species, Hoffman et al., 1993, Ashford and Reeves, 2003).

To limit the use of synthetic herbicides (which are not allowed, for example, in organic farming), other means of terminating cover crops have recently been considered, particularly mechanical methods. Specifically, termination using mechanical equipment involves total or partial burial of the biomass or the maintenance of plant residues on the surface, creating a mulching layer.

In the first case, termination occurs through the traditional plowing operation, characterized by complete burial of the plants due to the turning effect of the plow. The incorporation of the aboveground biomass increases nitrogen release (Tosti et al., 2012) and has positive effects on soil moisture (Krstić et al., 2018).

Termination through plowing, however, nullifies the soil cover effect; furthermore, during processing, whole and live plants can interfere with the complete turning of the soil slice, clogging the working tools (Sapkota et al., 2012). If operating according to a conservation agriculture approach, to avoid turning of the soil layers, a harrowing with disc (Tursun et al. 2018; Bavougian et al., 2018) or tines is typically carried out, depending on the presence of a large or small amount of biomass.

The termination carried out with such operating machines is based on the action of eradicating, ridging, cutting, and partially burying the cover crop. Among the benefits are the faster execution (compared to plowing) and the rapid decomposition of the cover crop with nutrient release, thanks to the greater contact surface between the residues and the soil. (Coppens et al., 2007, Jani et al., 2016).

In the second case, when it is intended for the devitalized biomass to remain on the surface with a mulching effect, the cover crop is terminated through operations such as mowing and shredding. Possible disadvantages include the risk of regrowth, especially if termination is carried out during vegetative stages preceding flowering (Wilkins and Bellinder, 1996, Cavalli et al., 2019).

A rather recent method of termination is based on the use of crimper rollers, which have the function of mechanically suppressing cover crops by forming a compact and orderly layer of vegetation. The plants are lodged under the weight of the roller, and the devitalization is caused by the compression/incision of the stems, with subsequent breaking of the vascular system, via blades protruding 30-60 mm from the roller surface. (Cavalli et al., 2019, Frasconi et al., 2019, Kornecki et al., 2006, Kornecki et al, 2009b, Kornecki and Balkcom, 2020).

From a mechanical point of view, crimper rollers are simple and economical machines (Creamer and Dabney, 2002), with high working capacity and that require low power for their operation (Canali et al., 2013, Alonso-Ayuso et al., 2020, Calcante et al., 2022). Their limitations are related to the following: 1) the need for an adequate growth stage of the cover crop and proper soil moisture conditions, 2) the risk of regrowth and vegetative resprouting during the next crop cycle, and 3) the potential difficulty in seeding the cash crop due to excess biomass present on the soil surface (Altieri et al., 2011, Kornecki et al., 2009b, Luna et al., 2012).

In any case, the effectiveness of mechanical termination is determined by a variety of factors, the most important of which are the cover crop's growth stage, the working parameters (i.e. forward speed, working depth, pressure on the working tools, tool geometry adjustment), the amount of aboveground biomass of the cover crop, the type of root system, and the weather conditions following the intervention.

Crimper rolling, for example, is ineffective against cover crops at an early stage of development (typically before the boot stage for graminaceous plants), a situation that can easily arise when winter cover crops are followed by cash crop sowing in early spring.

The studies present in the scientific literature describe experiments on the effectiveness of termination obtained with individual tools (Kornecki et al. 2012; Wortman et al., 2013), without however considering the possible combined effects of multiple tools with complementary actions. For example, there is a lack of scientific evaluations regarding the effectiveness of termination through the combined action of crushing and/or cutting the aboveground part in combination with eradication and overturning.

For this purpose in this work, a modular multi-tool prototype for mechanical termination of cover crops has been developed, which allows evaluating the effects of different types of tools, testing both single use and in combination. The working modules of the prototype, individually adjustable in their operating parameters, are: 1) tine cultivator, 2) disk harrow, 3) crimper roller.

The characteristics of the developed prototype are described in this study, as are the results of a series of field experiments to determine the effectiveness of different combinations of tools in the termination of two species of cover crop at two different growth stages.

MATERIALS AND METHODS

A MULTI-TOOL MACHINE FOR MECHANICAL TERMINATION OF COVER CROPS

The semi-mounted operating machine designed consists of a multi-purpose frame with square section longerons (Figure 1). Designed to operate on experimental plots, the machine has a working width of 1.5 m. Its length is 5.2 m, while the overall width is 2.2 m.

Figure 1. The multi-tools machine for the mechanical termination of cover crops. Configuration with tine cultivator (front) and disk harrow (rear).

Posteriorly, there is a pair of pivotable support wheels, adjustable in height by means of a double-acting hydraulic actuator, serving both as support during road transfer and for adjusting the frame height during work. In the front position, there is a structure that allows coupling with the tractor's three-point hitch.

The machine frame presents two internal three-point hitch attachments with automatic hooks, allowing for simultaneous connection and use of up to two different working modules. For each module, the working depth can be independently adjusted, thanks to single-acting pre-loaded hydraulic actuators. The developed working modules are:

1. Tine cultivator: it consists of two rows of tines with lateral blades for undercutting effect, positioned at a distance of 600 mm, one front row with three tines and one rear row with four tines (Figure 2A). Each anchor mounts wide-blade goosefoot tool arranged in a staggered manner to ensure continuous processing over the entire working width and allow for the outflow of soil and crop residues. The angle of incidence of the tines with respect to the ground allows reaching a maximum working depth of 15 cm, which is more than sufficient since this termination operation is typically carried out at a depth of 8-10 cm (Creamer et al., 1995).
2. Disk harrow: similar to the classic "offset" disk harrow, it consists of two raw disks angled between them. The angle is adjustable via a hydraulic actuator, ranging from a minimum of 0° where the disks are completely parallel to each other, to a maximum angle where the two rows are arranged at ±15° with respect to the transverse axis of the frame (Figure 2B). The disks are arranged in a staggered position on the two rows, with a spacing of 250 mm between them, and each row mounts six disks. During the design phase, wavy profile disks with a diameter of 500 mm were chosen. The working depth is adjustable up to a maximum of 20 cm, which is more than sufficient since,

typically, the termination by using the disk harrowing is carried out at a depth of 12-15 cm (Creamer et al., 1995).

3. Crimper roller: it consists of a single roller with a rigid frame and a diameter of 500 mm (Figure 2C). On its surface, there are 80 mm high blades, inclined from the center towards the outside at an angle of 15°. The blades have a flat shape and a smooth profile in order to minimize the roller vibrations due to rolling. The mass of the roller can be increased up to approximately 600 kg (corresponding to a unit mass per working width of 400 kg/m) by filling it with water through a lateral hole.

In the configuration with the crimper roller and disc harrow, the total mass of the prototype is about 2000 kg.

Figure 2. A) The tine cultivator with evidence the two rows of tines. B) The disk harrow in the fully open position (15°, right). C) The crimper roller.

EXPERIMENTAL FIELD TESTS

The experimental trials were carried out at the "A. Menozzi" educational and experimental farm located in Lombardy Region-Northern Italy in two consecutive years, 2021-22. The termination trials were conducted on a 2 ha field divided into three homogeneous zones of approximately 6000 m^2 each. A barley cover crop (Hordeum Disticum L. var. "Sfera", 160 kg ha^{-1}) was sown on two zones, while velvety vetch (Vicia villosa Roth. var. "Minnie", 60 kg ha^{-1}) was sown on the remaining zone. The soil, with a sandy loam texture, has the following characteristics: organic carbon: 1.3% - 1.5%, total nitrogen: 1.3 - 1.6 ‰, cation exchange capacity: 10-12 cmol (+) kg^{-1}, pH: 6.6. In both years, before sowing, the field was fertilized with cattle slurry, providing 150 kg ha^{-1} of nitrogen.

Each of the three zones was divided into 60 rectangular plots with a length of 30 m and a width of 3 m.

For each considered year, three termination events were carried out: one at the beginning of spring for barley in the end of tillering stage (BBCH 29), one in late spring for vetch in the early flowering stage and the last for barley in the early milk stage (BBCH 73).

The prototype, coupled with a 110 kW 4WD tractor weighing 6000 kg, was tested in the following configurations: 1) tine cultivator, 2) disk harrow with opening of 7°, 3) disk harrow with opening of 15°, 4) crimper roller, 5) crimper roller + disk harrow with opening of 15°, 6) crimper roller + tine cultivator, 7) disk harrow with opening of 15°+ tine cultivator. Each treatment was replicated at two different working speeds: 6 km h^{-1} and 12 km h^{-1}. In addition, a plot terminated with Glyphosate (dose: 4.5 L ha^{-1}) and a control treatment consisting of untreated plots were included.

For each configuration, three experimental replicates were carried out, according to a block design as illustrated in Figure 3.

Block 1	C1 –S1	C4 –S1	C7 –S2	C6 –S1	Control plot
	C3 –S1	C6 –S2	C2 –S2	UNUSED	C5 –S1
	C7 –S1	C5 –S2	Control plot	C1 –S2	Glyphosate
	Glyphosate	C2 –S1	C3 –S2	UNUSED	C4 –S2
Block 2	C2 –S1	Control plot	C7 –S2	C3 –S1	C5 –S2
	UNUSED	C3 –S2	C1 –S1	C4 –S2	C7 –S1
	Glyphosate	C6 –S1	C4 –S1	C5 –S1	C2 –S2
	UNUSED	C1 –S2	C6 –S2	Control plot	Glyphosate
Block 3	UNUSED	C4 –S2	C2 –S1	UNUSED	C6 –S1
	Glyphosate	C7 –S1	C5 –S2	C6 –S2	Control plot
	C4 –S1	Control plot	C3 –S2	C1 –S1	Glyphosate
	C5 –S1	C2 –S2	C1 –S2	C7 –S2	C3 –S1

C1: cultivator
C2: disk harrow 7°
C3: disk harrow 15°
C4: crimper roller
C5: crimper roller+disk harrow 15°
C6: crimper roller+cultivator
C7: disk harrow 15°+cultivator
S1: 6 km h^{-1}
S2: 12 km h^{-1}

Figure 3. The block design of the 54 experimental plots.

The working depth for the tine cultivator and for the disk harrow in both configurations (7° and 15° inclined discs) was set to about 10-12 cm. This value was intentionally chosen to perform only the termination of the cover crops (cutting of roots and/or their eradication) and not to obtain any minimum tillage of the soil. Each plot underwent a single pass of the machine.

The plots were designed considering a maneuver and acceleration lane 20 m long, followed by a terminal portion of 10 m actually worked with the machine "at full capacity." In the subsequent evaluation surveys of termination effectiveness in each plot, only a portion 1 m wide of the central portion actually terminated (working width of 1.5 m) was considered in order to remove any effects of trampling by the tractor used (internal track width of 1.2 m). Therefore, the actual portion of the plot considered for the experimentation had an area of 10 m^2.

Experimental Survey

Characterization of field conditions at termination

At the termination stage, field operational conditions were characterized by direct sampling of plants to measure the amount of biomass present, and of soil to determine its moisture content. To determine biomass, in each block, samples were taken along the two diagonals, resulting in a total of 20 evenly spaced sampling points. One square meter of above-ground biomass was cut and removed from each point. The samples were then placed in a oven at 105°C for 24-48 hours until a constant weight is achieved. and subsequently weighed. Additionally, soil strength measurements in each block were made along the two diagonals using a hand penetrometer (Royal Eijkelkamp mod. 06.01, Royal Eijkelkamp, Giesbeek, The Netherlands), yielding a total of 20 evenly spaced sampling points. Two measurements were made for each point at increasing depths (0–10 cm and 10–20 cm). Finally, the average monthly temperature and precipitation data for the two-year period were collected using the on-site meteorological station.

Monitoring the effects of termination on the cover crop

As an indicator of the effectiveness of the different termination treatments tested, the fraction of surface covered by living (green) vegetation in each plot was used, compared to that measured on the same date within the untreated control plots.

Considering the large number of plots and the extent of the surface area to be monitored, a fast measure was applied to separate and quantify the vegetated fraction from the devitalized (covered by senescent and dry tissue) or bare (soil) fraction based on the high spatial resolution NDVI spectral index derived from proximal multispectral images acquired in each plot at different times after termination.

For this purpose, a Parrot Sequoia™ camera (Parrot SA, Paris, France) that provides multispectral images (1280×960 pixels) in four channels, namely the green (550 nm, bandwidth 40 nm), red (660 nm, bandwidth 40 nm), red-edge (735 nm, bandwidth 10 nm), and NIR (790 nm, bandwidth 40 nm) channels, was mounted using a special mounting frame at the end of a front-end loader of a 77 kW 4WD tractor used to monitor the plots.

The registration (alignment) of the images from the four spectral channels and the normalization of pixel intensities were performed in post-processing using a reference panel kept within the field of view of the camera, fixed to the support frame at a constant height above that reached by the cover vegetation. The panel contained two black square markers on a white background for channel registration, and a rectangular gray reference made of plastic material with known reflectance, constant within the considered range, to allow for image normalization across different spectral channels.

During all the measurements, the camera was maintained at a fixed height of 2 m above the ground (Figure 4), allowing for the acquisition of multispectral images with a nominal resolution of approximately 2 mm $pixel^{-1}$.

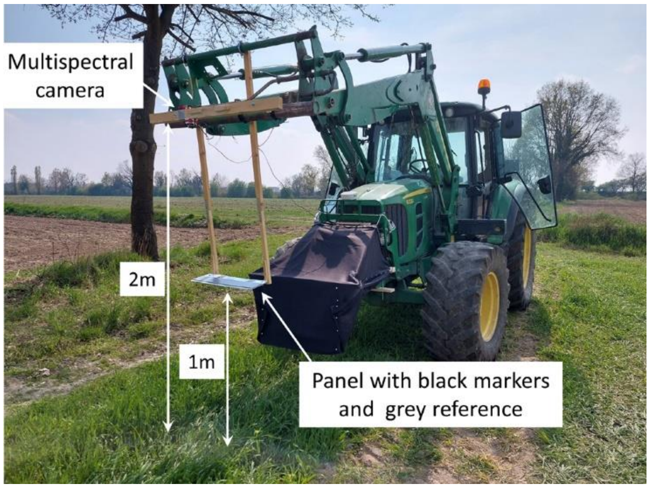

Figure 4. The frame fixed at the end of the tractor front loader with the Parrot Sequoia multispectral camera and the reference panel with the respective quotes.

At different times following each termination, specifically 7, 14, and 21 days, a survey was conducted in each plot to determine the fraction of surface covered by green vegetation (FCover) after the corresponding treatment. To do this, the tractor equipped with the multispectral camera was driven straight at a speed of 3 km h^{-1} in each plot, sequentially acquiring multispectral images at six sampling points that covered the entire 1x10 m^2 surface area effectively considered for the study.

Image processing and quantification of the FCover for each plot

The multispectral images acquired in the surveys were subsequently analyzed through post-processing software specially developed by us in Matlab R2022a environment (MathWorks Inc., Natick, Massachusetts, USA).

To each multispectral image acquired, the analysis software performs the following steps:

1. red and NIR images extraction: extraction of monochrome images (960 x 1280) corresponding to the red and NIR channels.
2. Grey reference value computation: separately for the red and NIR channels, extraction of a rectangular ROI (Region of Interest) of 200 x 40 pixels at a predetermined position corresponding

to the grey reference (Figure 5 left) and calculation of the mean intensity value of the pixels in the ROIs, to be used as the reflectance reference value in the corresponding channel.

3. Channel normalization: for each pixel in the red and NIR images, calculation of the ratio between the intensity value and the corresponding reflectance reference value defined in step 2. The normalized images make acquisitions carried out on different dates or under different lighting conditions comparable.
4. Red and NIR images registration: identification in the two monochrome images of the black squares on a white background present in the reference panel and calculation of the centroids' coordinates (Figure 5 right). The difference between the coordinates obtained in the red and NIR images defines the magnitude of the translation applied to obtain the registration of the two images and thus reconstruct a pixel-by-pixel correspondence between the red and NIR channels.

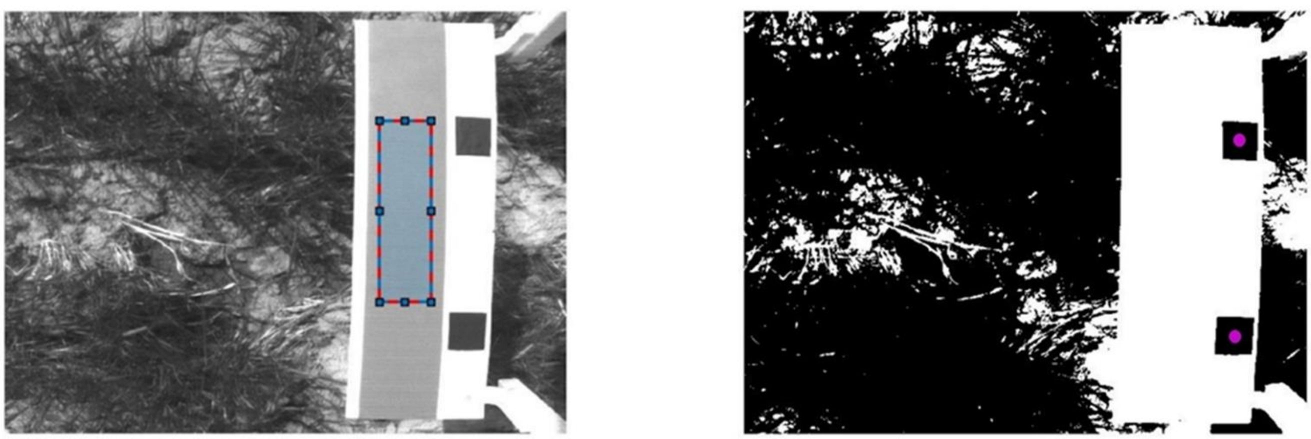

Figure 5. Example of ROI (200 x 40 pixel) extracted on the grey reference (left) and identification of the black markers with their respective centroids (right).

5. NDVI image computation: computation of an NDVI image by applying equation 1 (Rouse et al., 1974), pixel by pixel, to the intensity values of red and NIR registered images (Figure 6 left):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{red})}{(\mathrm{NIR} + \mathrm{red})} \qquad (1)$$

6. Quantification of green vs dead vegetation or soil: segmentation of the obtained NDVI image by applying a predefined threshold of 0.4 (see below for the derivation). After noise removal obtained by morphological opening operation, the area covered by green vegetation was computed by counting the pixels with NDVI value ≥ threshold, while the remaining pixels belonging to the plot surface were classified as area covered by dead vegetation or soil (NDVI value < threshold) (Figure 6 right).

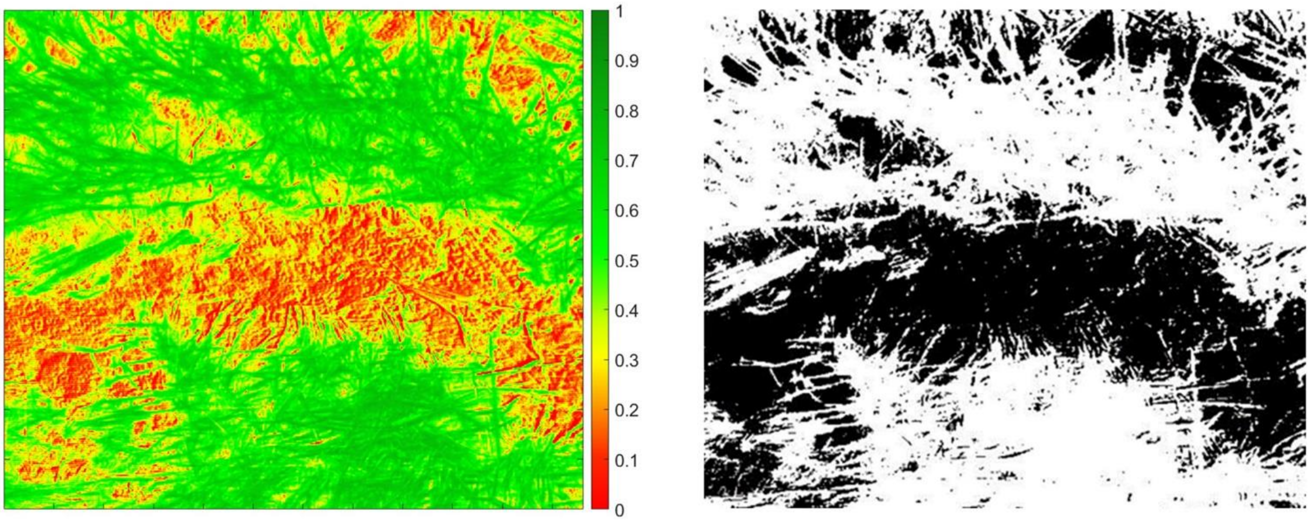

Figure 6. NDVI image as generated by the software (left). On the right, binarization of the NDVI image using a reference threshold: devitalized (black pixels) and green vegetation (white pixels).

The software adds up the total values of area covered by green vegetation and of the area covered by dead vegetation or soil found in the sequence of images acquired in one specific plot p, at one monitoring date t, and finally providing a measure of the fraction of surface covered by green vegetation FCover for each plot p at time t (Eq. 2):

$$FCover(p,t) = \frac{Total\ area\ of\ green\ vegetation\ (p,t)}{Total\ area\ of\ green\ vegetation\ (p,t) + Total\ area\ of\ dead\ vegetation\ or\ soil\ (p,t)} \quad (2)$$

The optimal threshold value of NDVI at 0.4, useful for discriminating between green vegetation and devitalized vegetation or soil under different lighting conditions during surveys, was determined by applying a sensitivity analysis to a sample of specifically chosen images.

To this end, three reference plots with particular vegetative conditions were identified for each monitoring day: 1) untreated control (indicative images of completely live vegetation), 2) herbicide treatment (indicative images of completely devitalized vegetation), and 3) treatment with disk harrow 15° at 12 km h^{-1} (intermediate images with partially live and partially devitalized vegetation).

For these sample images, the live/terminated vegetation fraction was calculated using the algorithm described above, applying increasing NDVI thresholds between 0.2 and 0.6 at progressive intervals of 0.025. The chosen threshold value was finally determined as the one corresponding to the lowest sensitivity of the live/terminated cover fraction obtained, i.e., the value around which the land cover curves in the three cases considered showed the least variation (i.e. the slope) with changing NDVI thresholds.

This NDVI value corresponds to 0.4 and represented the threshold applied to discriminate between live and dead vegetation.

As a final result, the effect of the termination in one plot *p*, observed at time *t* after the corresponding treatment, is evaluated as the ratio between its fraction of surface covered by green vegetation *FCover(p,t)* and the mean of the fraction values computed for the untreated control plots c_i at that same date time *t* (Eq. 3):

$$Effectiveness\ of\ termination\ (p,t) = 1 - \frac{FCover\ (p,t)}{mean[FCover(c_1 \dots c_n,\ t)]} \qquad (3)$$

According to Mirsky et al., (2009) the achievement of a threshold value equal to 85% of devitalized plants compared to the control was considered optimal as a benchmark to evaluate the effectiveness of the termination of the various treatments carried out.

Furthermore, thanks to the three monitoring, it was possible to observe the effect of the termination over time, and specifically to highlight any possible recovery or regrowth of the cover crop after the treatment.

Finally, an analysis of variance ($p < 0.05$) was performed to verify the possible influence of working speed on termination effectiveness. The effectiveness of termination (Eq. 3) results were statistically analyzed to assess their relationship with applied treatments and potential influence from other experimental factors. In overall, the effectiveness of termination data obtained from the two years of experiments fail to satisfy the normality assumption for ANOVA, as indicated by the Shapiro-Wilk normality tests. For this reason, for statistical analysis of the experimental data we opted for a multivariate approach, with model fitting using least squares method.

Given that the three cover crop conditions considered (barley at growth stage I, barley at growth stage II, and vetch) represent distinct application scenarios, a separate analysis was undertaken for each of the three experimental cases. The independent variables included in the multivariate model were treatment, working speed, year, and days after treatment (i.e., the monitoring date), as linear terms, along with their corresponding pairwise interactions. The response variable (measured variable) was the effectiveness of termination for the specific cover crop under consideration. All the analysis was conducted with the statistical software package JMP 17 (SAS Institute Inc., USA).

RESULTS AND DISCUSSION

Table 1 reports the termination dates of barley and vetch with the corresponding phenological stages, and the dates when the monitoring was carried out. Table 2 shows the soil condition and the amount of biomass present on the days of termination. Table 3 shows the maximum and minimum monthly temperatures and the cumulative precipitations observed over the 2021-22 period.

Table 1. Timetable for field operations and the vegetative stages of cover crops.

Year	Cover Crop	Sowing date	Termination date	Phenological phase	Monitoring 1	Monitoring 2	Monitoring 3
2021	Barley I	13/10/2020	18/03/21	End of tillering (BBCH 29)	25/03/21	01/04/21	08/04/21
	Barley II	13/10/2020	23/04/21	Early milk (BBCH 73)	28/04/21	06/05/21	13/05/21
	Vetch	29/09/2020	23/04/21	Beginning of flowering	28/04/21	06/05/21	13/05/21
2022	Barley I	12/10/2021	30/03/22	End of tillering (BBCH 29)	06/04/22	13/04/22	20/04/22
	Barley II	12/10/2021	04/05/22	Early milk (BBCH 73)	11/05/22	18/05/22	25/05/22
	Vetch	30/09/2021	30/03/22	Beginning of flowering	06/04/22	13/04/22	20/04/22

Table 2. Soil moisture, soil strength, and biomass of the cover crop measured during the termination days.

Year	Cover Crop	Termination date	Soil moisture (%)	Soil strength (MPa)		Dry biomass (t ha^{-1})
				0 -10 cm	10 – 20 cm	
2021	Barley I	18/03/21	24.5 ± 1.6	0.62	0.61	0.92 ± 0.15
	Barley II	23/04/21	18.5 ± 2.9	0.80	0.75	2.99 ± 0.50
	Vetch	23/04/21	25.6 ± 1.9	0.58	0.59	4.45 ± 0.96
2022	Barley I	30/03/22	15.7 ± 1.0	1.81	1.85	0.34 ± 0.11
	Barley II	04/05/22	12.0 ± 0.6	3.85	3.31	3.07 ± 0.72
	Vetch	30/03/22	14.2 ± 2.2	1.49	1.43	2.48 ± 0.19

Table 3. Maximum and minimum monthly temperatures and cumulative precipitations observed over the 2021-22 period.

	Year 2021			Year 2022		
	Montly cumulative precipitation (mm)	Min. monthly temperature (°C)	Max. monthly temperature (°C)	Montly cumulative precipitation (mm)	Min. monthly temperature (°C)	Max. monthly temperature (°C)
January	130.0	0.3	6.8	28.0	-0.2	8.1
February	50.0	4.4	12.2	16.0	2.4	13.8
March	8.8	3.3	17.1	9.8	2.8	16.2
April	70.6	7.7	18.8	25.0	7.8	21.1
May	60.8	12.8	24.6	62.0	16.5	28.7
June	15.8	19.3	32.8	10.6	20.0	33.9
July	38.8	20.0	33.0	39.8	21.4	36.3
August	18.4	18.9	32.2	34.4	20.3	33.9
September	75.2	16.7	28.8	14.0	15.9	27.9
October	52.0	9.7	20.0	9.4	13.7	25.1
November	165.6	6.7	12.8	101.6	6.4	14.5
December	46.0	0.6	6.4	97.6	4.4	7.7

BARLEY I

Table 4 displays the results of the termination of barley at the first growth stage considered (end of tillering), obtained in the two years 2021 and 2022. For the first year, surveys conducted at 7, 14, and 21 days after termination showed that both treatments with disk harrow at 15° and those with a combination of disk harrow 15° and tine cultivator, carried out at both speeds of 6 km h^{-1} and 12 km h^{-1}, showed a high termination effectiveness, sometimes exceeding 90-95%. The use of only tine cultivator allowed achieving a termination effectiveness between 70-80%, showing a certain capacity to regrow by the cover after 21 days, due to the fact that the terminal tool tended to lift the soil clod without completely eradicating the plants. The crimper roller, on the other hand, offered a termination effectiveness of less than 10%, due to the too early phenological stage of barley, which resumed its vegetative growth in the following weeks.

Table 4. Termination of barley at growth stage I: results of the 2021-22 biennium with the related standard deviations.

Termination of barley at growth stage I		Effectiveness of termination (as % than the control)			
		Year 2021		Year 2022	
		Speed 6 km h^{-1}	Speed 12 km h^{-1}	Speed 6 km h^{-1}	Speed 12 km h^{-1}
Glyphosate	7 days after termination	73.40 ± 6.8		70.73 ± 8.7	
	14 days after termination	99.67 ± 0.2		100.00 ± 0.0	
	21 days after termination	99.96 ± 0.0		100.00 ± 0.0	
Tine cultivator	7 days after termination	78.9 ± 0.3	83.6 ± 4.5	96.6 ± 1.8	95.8 ± 3.4
	14 days after termination	80.4 ± 2.6	86.9 ± 5.6	92.0 ± 2.2	94.7 ± 4.3
	21 days after termination	69.9 ± 9.8	77.8 ± 8.9	87.6 ± 4.1	89.9 ± 4.4
Disk harrow 7°	7 days after termination	56.5 ± 8.1	75.9 ± 3.9	84.0 ± 4.5	83.3 ± 5.3
	14 days after termination	46.2 ± 5.5	68.5 ± 9.5	83.6 ± 3.5	86.9 ± 5.5
	21 days after termination	22.8 ± 6.3	39.5 ± 5.7	81.5 ± 4.4	84.9 ± 5.7
Disk harrow 15°	7 days after termination	83.3 ± 9.9	93.7 ± 1.1	94.1 ± 4.8	95.6 ±3.0
	14 days after termination	84.7 ± 9.9	94.8 ± 1.1	93.5 ± 4.9	93.4 ± 3.1
	21 days after termination	85.5 ± 9.5	96.8 ± 0.8	89.9 ± 6.3	92.1 ± 2.7
Crimper roller	7 days after termination	16.8 ± 7.0	14.8 ± 5.6	18.4 ± 5.7	14.4 ± 1.3
	14 days after termination	9.2 ± 7.5	5.7 ± 5.2	15.9 ± 1.3	7.1 ± 3.9
	21 days after termination	9.5 ± 4.2	5.2 ± 9.9	11.6 ± 4.2	5.3 ± 4.1
Crimper roller + Disk harrow 15°	7 days after termination	65.8 ± 4.5	83.7 ± 8.2	94.0 ± 2.7	93.7 ± 3.6
	14 days after termination	72.4 ± 2.2	85.5 ± 8.9	91.4 ± 2.8	92.9 ± 4.4
	21 days after termination	75.0 ± 9.7	81.9 ± 8.8	90.3 ± 0.9	93.4 ± 1.5
Crimper roller + Tine cultivator	7 days after termination	68.8 ± 3.0	79.6 ± 4.5	96.7 ± 2.7	98.1 ± 0.8
	14 days after termination	77.9 ± 6.3	76.4 ± 9.4	95.9 ± 2.5	96.9 ± 1.7
	21 days after termination	72.8 ± 8.2	79.1 ± 4.5	91.4 ± 4.4	94.5 ± 3.3
Disc harrow 15° + Tine Cultivator	7 days after termination	96.9 ± 1.8	95.9 ± 0.2	99.3 ± 0.7	99.8 ± 0.1
	14 days after termination	96.6 ± 0.7	96.9 ± 0.7	99.8 ± 0.2	99.7 ± 0.2
	21 days after termination	96.8 ± 2.3	98.4 ± 1.0	99.2 ± 0.7	98.9 ± 0.6

Similarly insufficient was the use of disk harrow 7°, especially when operated at 6 km h^{-1}. As for the influence of the forward speed on termination effectiveness, only for the disk harrow 15° and the crimper roller + disk harrow 15° combination, a significant difference was observed between the work carried out at 6 km h^{-1} and that carried out at 12 km h^{-1}, with the best results obtained at the higher speed.

In the 2022 trials, the disk harrow 15° and the combinations of disk harrow 15°+ tine cultivator and crimper roller + tine cultivator at both speeds showed a termination effectiveness of over 90-95%, comparable to that achieved with chemical weeding. Even the sole use of tine cultivator was able to terminate over 90% of the cover crop. The use of 7° disk harrow, particularly at 12 km h^{-1}, allowed for an effectiveness of termination around 80-85%. The crimper roller once again showed very low effectiveness (between 5 and 20%), confirming that at early phenological stages the crop can resume its vegetative growth in the following weeks. Regarding the influence of the working speed on the effectiveness of termination, no significant differences were observed in all treatments.

In 2022, the termination effectiveness of the tine cultivator, used both individually and in combination with other tools, significantly improved thanks to the addition of lateral blades on the terminal tool. In this way, effective root cutting action was added to plant eradication.

Statistical analysis was specifically focused on the results obtained at 7 days after termination, aligning with the most common farming practices where sowing of cash crop promptly follows cover crop termination. On this monitoring date, the effectiveness of termination on barley at the first growth stage was significantly influenced by the treatment (P-value < 0.0001), year (P-value < 0.0001), speed (P-value = 0.002), and the interaction treatment*year (P-value < 0.0001); additionally, a weaker influence was observed for the treatment*speed interaction (P-value = 0.065). The latter two terms indicate that some specific treatments exhibited coherent differences in effects for the two years, and for different speeds, as underlined in the discussion above. Other interactions were found to be not significant (P-value > 0.25) and, therefore, were excluded from the model fitting.

The fitted linear model was able to estimate the effectiveness of termination from the considered independent variables with R^2 of 0.98 (predicted vs measured) along with the 95% confidence intervals. The estimates of the model coefficients found for individual variables reflected the relative differences in effectiveness discussed above (larger for disk harrow 15°+ tine cultivator and poorer for weaker for7° disk harrow). All the linear terms coefficients indicate their consistency with the model (*p*-value < 0.0001), except for 7° disk harrow (*p*-value = 0.312).

Table 5. Termination treatments categorized (from the most to the least effective) based on the effectiveness of termination measured at 7 days after treatments for: A) barley at growth stage I, B) barley at growth stage II, C) vetch. Significant statistical differences were assessed through pairwise comparisons using least squares means Tukey's HSD (treatments with the same letter do not differ statistically at a significance level α=0.05).

A – barley at growth stage I	
Disc harrow 15° + Tine Cultivator	a
Disk harrow 15°	a b
Tine cultivator	b c
Crimper roller + Tine cultivator	b c
Crimper roller + Disk harrow 15°	c
Disk harrow 7°	d
Glyphosate	d
Crimper roller	e

B – barley at growth stage II	
Disc harrow 15° + Tine Cultivator	a
Crimper roller + Disk harrow 15°	a
Disk harrow 15°	a
Crimper roller + Tine cultivator	b
Glyphosate	b c
Tine cultivator	c
Disk harrow 7°	c
Crimper roller	d

C - vetch	
Disk harrow 15°	a
Crimper roller + Disk harrow 15°	a
Disk harrow 7°	b
Glyphosate	c
Crimper roller	c

A closer analysis of the effects of termination treatments only, was achieved through pairwise comparisons of the effectiveness using least squares means Tukey's HSD. On this date (7 days after treatments), the treatments were grouped based on statistical differences (α=0.05) as illustrated in table

5A. Results at later monitoring dates (14 and 21 days after treatments) confirmed the same trend, with the only exception being glyphosate which achieved the highest effectiveness group (letter a).

Barley II

Table 6 displays the results of the termination of barley at the second growth stage considered (early milk), obtained in the two years 2021 and 2022. In the first year, the combinations of disk harrow 15°+tine cultivator and crimper roller+ disk harrow 15° provided termination effectiveness ranging from 80 to 90%.

Table 6. Termination of barley crop at growth stage II: results of the 2021-22 biennium with the related standard deviations.

Termination of barley at growth stage II		**Effectiveness of termination (as % than the control)**			
		Year 2021		**Year 2022**	
		Speed 6 km h^{-1}	**Speed 12 km h^{-1}**	**Speed 6 km h^{-1}**	**Speed 12 km h^{-1}**
Glyphosate	7 days after termination	21.8 ± 8.4		89.9 ± 8.3	
	14 days after termination	99.8 ± 0.3		99.9 ± 0.0	
	21 days after termination	100.0 ± 0.0		99.7 ± 0.2	
Tine cultivator	7 days after termination	48.1 ± 7.7	59.17 ± 9.9	46.1 ± 7.8	60.1 ± 4.9
	14 days after termination	35.4 ± 6.0	48.1 ± 9.4	39.4 ± 7.6	54.5 ± 5.2
	21 days after termination	29.4 ± 9.3	46.1 ± 9.8	52.9 ± 9.2	59.4 ± 7.5
Disk harrow 7°	7 days after termination	25.5 ± 9.1	49.9 ± 9.7	55.9 ± 8.0	60.9 ± 7.5
	14 days after termination	23.7 ± 9.0	36.4 ± 9.8	60.9 ± 8.5	65.7 ± 9.2
	21 days after termination	11.5 ± 4.4	17.3 ± 9.5	68.2 ± 8.6	69.2 ± 8.8
Disk harrow 15°	7 days after termination	68.9 ± 9.4	75.6 ± 1.4	95.2 ± 2.4	95.7 ± 1.9
	14 days after termination	73.1 ± 9.9	80.7 ± 6.8	97.4 ± 1.4	99.1 ± 0.2
	21 days after termination	68.7 ± 8.1	65.9 ± 6.6	96.2 ± 0.4	97.0 ± 0.9
Crimper roller	7 days after termination	4.2 ± 0.0	2.8 ± 0.2	50.6 ± 8.7	52.6 ± 7.0
	14 days after termination	6.2 ± 5.5	2.1 ± 2.2	40.8 ± 9.3	42.9 ± 5.8
	21 days after termination	5.3 ± 5.8	1.5 ± 2.3	45.1 ± 6.9	33.5 ± 4.7
Crimper roller + Disk harrow 15°	7 days after termination	79.6 ± 7.6	81.3 ± 9.9	96.6 ± 0.6	97.6 ± 1.2
	14 days after termination	80.0 ± 9.4	82.2 ± 9.9	97.7 ± 1.4	97.7 ± 1.4
	21 days after termination	70.1 ± 9.1	77.9 ± 9.4	97.6 ± 0.3	96.4 ± 2.3
Crimper roller + Tine cultivator	7 days after termination	51.5 ± 6.3	70.5 ± 8.9	64.9 ± 1.2	66.4 ± 6.8
	14 days after termination	51.5 ± 6.0	68.7 ± 5.2	51.1 ± 6.8	61.1 ± 7.3
	21 days after termination	53.4 ± 10.0	60.8 ± 6.9	48.4 ± 7.8	45.0 ± 9.6
Disc harrow 15° + Cultivator	7 days after termination	79.8 ± 7.8	88.9 ± 4.7	98.0 ± 1.7	98.9 ± 0.9
	14 days after termination	83.9 ± 5.8	88.9 ± 3.3	98.9 ± 0.6	99.2 ± 0.8
	21 days after termination	84.5 ± 5.9	86.7 ± 3.6	98.0 ± 0.9	98.3 ± 0.5

The crimper roller provided non-significant results (termination effectiveness around 5%) because, even at this phenological stage, barley plants still had very elastic stems. Therefore, after the passage of the roller, they resumed their upright position and resumed normal vegetative activity, practically without having suffered any damage.

The tine cultivator, the disk harrow 7°, and the crimper roller+tine cultivator combination produced unsatisfactory results, with a limited termination effectiveness between 45% and 60%. Regarding the influence of the forward speed on the termination effectiveness, a significant difference was observed between the operation carried out at 6 km h^{-1} and that carried out at 12 km h^{-1} in the case of the crimper roller and the crimper roller+tine cultivator and disk harrow 15°+tine cultivator combinations.

In 2022, the termination of barley at growth stage II showed that the disk harrow 15° and the combinations of disk harrow 15°+tine cultivator and crimper+disk harrow 15°, at both working speeds, provided a termination effectiveness above 95%, values close to those achievable with a chemical treatment. The crimper roller, although it had an effectiveness around 50-60%, was still unsatisfactory as, similarly to the previous year, numerous barley plants had very elastic culms that, despite the passage of the roller, regained their upright position and resumed normal vegetative activity. It is worth noting that, despite the modification made, the tine cultivator used singularly did not provide high termination effectiveness (around 60% at 12 km h^{-1}). This was due to the fact that, due to the exceptionally dry season, the soil was extremely hard and compact (-65% reduction in precipitation compared to 2021 has been observed; soil strength by penetrometry in the first 10 cm was 3.85 MPa and between 10 and 20 cm was 3.31 MPa, values over four times higher than in 2021), and the tools struggled to bury themselves to the working depth. This highlights the need to perform mechanical termination with the soil under optimal moisture conditions. Finally, regarding the influence of the working speed on termination effectiveness, no significant differences were observed in all treatments.

Statistical analysis of results obtained at 7 days after termination, indicate that the effectiveness of termination on barley at the second growth stage was significantly influenced by the treatment (P-value < 0.0001), year (P-value < 0.0001), speed (P-value = 0.0002), and the interactions treatment*year (P-value < 0.0001) and treatment*speed interaction (P-value = 0.009). The latter indicating that some specific treatments exhibited coherent differences in effects for the two years, and for different speeds, as underlined in the discussion above.

The fitted linear model estimated the effectiveness of termination from the considered independent variables with R2 of 0.96 (predicted vs measured). All the linear terms coefficients for individual variables indicate their consistency with the model (*p*-value < 0.0001), except for Crimper roller + Tine cultivator (*p*-value = 0.704).

Pairwise comparisons of the effectiveness of termination treatments only with least squares means Tukey's HSD, enabled to group the treatments based on significant statistical differences (α=0,05) as illustrated in table 5B. Results at later monitoring dates (14 and 21 days after treatments) confirmed the rank, again with the only exception of glyphosate which exhibited the highest effectiveness (letter a), while other groups differed statistically (letters from b to f).

VETCH

The results of mechanical termination on vetch for the biennium 2021-22 are shown in Table 7. In

2021 (phenological stage: beginning of flowering), the disk harrow 7° operated at 6 km h^{-1}, the disk harrow 15°, and the crimper+ disk harrow 15° combination at both speeds provided termination effectiveness higher than 85%. The use of the tine cultivator, either alone or in combination, was unsuitable for vetch termination due to clogging of the working parts caused by the abundant and particularly tangled cover biomass. The crimper roller at both speeds had no effect on the vegetation cover. Regarding the influence of the forward speed on termination effectiveness, no significant difference was observed in all treatments.

Table 7. Termination of vetch: results of the 2021-22 biennium with the related standard deviations.

Vetch - termination		Effectiveness of termination (as % than the control)			
		Year 2021		Year 2022	
		Speed 6 km h^{-1}	Speed 12 km h^{-1}	Speed 6 km h^{-1}	Speed 12 km h^{-1}
Glyphosate	7 days after termination	4.2 ± 2.2		0.1 ± 0.2	
	14 days after termination	97.1 ± 1.4		46.6 ± 9.9	
	21 days after termination	100.0 ± 0.0		96.5 ± 3.2	
Disk harrow 7°	7 days after termination	74.3 ± 9.4	70.9 ± 8.8	5.5 ± 2.0	15.1 ± 4.3
	14 days after termination	88.9 ± 3.1	81.2 ± 9.2	6.9 ± 2.8	18.9 ± 7.7
	21 days after termination	84.2 ± 7.8	73.5 ± 7.8	0.8 ± 0.7	13.1 ± 9.2
Disk harrow 15°	7 days after termination	78.9 ± 4.7	85.9 ± 3.8	26.8 ± 6.8	64.0 ± 2.8
	14 days after termination	87.1 ± 9.4	92.0 ± 5.5	48.1 ± 8.1	70.8 ± 5.6
	21 days after termination	91.2 ± 1.1	87.2 ± 6.5	51.6 ± 5.8	71.1 ± 8.9
Crimper roller	7 days after termination	2.1 ± 3.5	0.8 ± 1.0	0.1 ± 0.1	0.0 ± 0.0
	14 days after termination	0.8 ± 1.3	0.4 ± 0.5	0.0 ± 0.0	0.0 ± 0.0
	21 days after termination	0.9 ± 0.9	0.2 ± 0.2	0.0 ± 0.1	0.0 ± 0.0
Crimper roller + Disk harrow 15°	7 days after termination	71.0 ± 6.9	69.9 ± 7.0	41.4 ± 6.7	66.4 ± 5.2
	14 days after termination	85.2 ± 5.2	91.2 ± 3.6	57.6 ± 10.0	78.8 ± 1.7
	21 days after termination	73.1 ± 3.4	85.4 ± 9.9	49.5 ± 6.4	73.9 ± 8.3

In 2022 (phenological stage: beginning of flowering), only the disk harrow 15° and the crimper roller + disk harrow 15° combination, both operated at 12 km h^{-1}, provided an effectiveness higher than 70-80%, without reaching the optimal value of 85%. The configurations with crimper roller and disk harrow 7° had a negligible effect on the cover, less than 20%. Similarly to what was found in 2021, the use of the tine cultivator, either alone or in combination, was unsuitable for terminating the vetch due to clogging of the working parts caused by the abundant and particularly intertwined biomass of the cover under examination. Regarding the influence of the forward speed on termination effectiveness, a significant difference was observed between the operation at 6 km h^{-1} and that at 12 km h^{-1} for the disk harrow 7°, disk harrow 15°, and crimper roller + disk harrow 15° combination, with the best results obtained at the higher speed.

Statistical analysis of results obtained at 7 days after termination, indicate that the effectiveness of termination on vetch was significantly influenced by the treatment (P-value < 0.0001), year (P-value < 0.0001), speed (P-value = 0.0003), and the interactions treatment*year (P-value < 0.0001) and treatment*speed interaction (P-value = 0.008). The latter indicating that some specific treatments exhibited coherent differences in effects for the two years, and for different speeds, as underlined in the discussion above.

The fitted linear model estimated the effectiveness of termination from the considered independent variables with R2 of 0.97 (predicted vs measured). All the linear terms coefficients for individual variables indicate their consistency with the model (p-value < 0.0001).

Pairwise comparisons of the effectiveness of termination treatments only with least squares means Tukey's HSD, enabled to group the treatments based on significant statistical differences (α=0,05) as illustrated in table 5C. Results at later monitoring dates (14 and 21 days after treatments) confirmed the rank, again with the only exception of glyphosate which exhibited the highest effectiveness (letter a), while other groups differed statistically (letters from b to d).

DISCUSSION

In general, regarding barley, the tools that worked well in both years of testing and for both phenological stages were the disk harrow 15° and the combinations of disk harrow 15°+crimper roller and disk harrow 15°+tine cultivator. It follows that the disk harrow 15° module is the one that, either alone or in combination with other tools, provided excellent termination results on barley, in agreement with what was observed by Bavougian et al. (2018). The tine cultivator used alone provided excellent results in terminating barley at the early stage of late-tillering, while at the flowering stage, despite the modification made in 2022, it provided a maximum termination effectiveness of 60%, similar to the study by Chapagain et al. (2020) conducted on oats and rye (Figure 7). The disk harrow, used with limited opening between the discs (7°), did not produce good results due to the low-energy action on cover crop and soil. The crimper roller did not prove adequate, providing a maximum termination effectiveness of 50% in 2022 with barley at the flowering stage. This is in agreement with Frasconi et al. (2019), who observed a termination effectiveness of 50% after 15 days on barley using a crimper roller with a unit mass of 1000 kg m^{-1} (approximately double that of the crimper used in this study). It follows that, to use such a tool successfully, it is essential that the crop is at an adequate phenological stage (Mirski et al., 2009).

Figure 7. The tine cultivator in action on the second barley crop. The roller crimper, in this case, is not used.

The vetch cover crop has proven to be difficult to terminate due to the large amount of biomass it can produce and its climbing habit. In 2021, only the disk harrow 15° and its combination with the crimper roller provided good results, while in 2022, despite the biomass being almost halved compared to 2021, it provided lower termination effectiveness (between 50% and 75%). Bavougian et al. in 2018, on the other hand, achieved a much higher result (98-100%). However, in that case, three passes of the disk harrow were made, compared to only one in the present study.

The tine cultivator used individually or in combination with other tools proved to be unusable due to the clogging of the tines by the biomass, which, being unable to be discharged, literally lifted the tines from the ground, preventing plant eradication. Chapagain et al. in 2020 also obtained poor results on crimson clover, red clover, and alfalfa plants, which, however, develop less dense biomass than vetch.

The crimper roller on vetch did not produce any results. This is in contrast with Keene et al. 2017 who observed termination effectiveness of vetch at 40% flowering ranging from 34 to 100%. It should be noted that in this case, the authors considered a hairy vetch-triticale mixture and made a double pass with the crimper roller.

Finally, regarding working speed, statistically significant differences observed suggest that at 12 km h^{-1}, termination effectiveness can be better than at 6 km h^{-1}.

CONCLUSION

The focus of the present study was to test a new modular prototype of a field machine for terminating cover crops in order to evaluate the effects of different types of tools, testing both single use and in combination. The trials were conducted for two years (2021 and 2022) on a grass species (barley) and a legume (velvety vetch). The results obtained show that:

- The tool that offered the best results for both barley and vetch is the disk harrow 15° used alone and, especially, in combination with the other tools considered (crimper roller and tine cultivator for barley, crimper roller for vetch).
- The tine cultivator provided good termination results on barley in 2021, which were not fully confirmed in 2022 due to the hardness of the soil caused by abnormal drought. This prevented proper burial of the anchors and, therefore, incomplete plant eradication, highlighting the necessity to perform mechanical termination with the soil under optimal moisture conditions.
- On vetch, the tine cultivator was unsuitable due to the accumulation of biomass between the tines that prevented burial. Therefore, it is not a usable tool for this type of crop.
- The crimper roller, used in a single pass, did not provide appreciable results. The causes may be due to its relatively low mass and the non-optimal phenological stage of the cover crops, especially barley. To successfully use this particular type of tool, therefore, it is essential to choose the optimal developmental stage of the cover.

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