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Technical Note

Testing of Roller-Crimper-and-Undercutting-Blade-Equipped Prototype for Plants Termination

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Abstract: The use of roller crimpers to terminate plants and obtain a natural mulch before cash crop establishment has been identified as a valid and sustainable approach to control weeds. Several enhancements have been evaluated to improve and speed up plant termination to avoid delays in cash crop planting and consequent yield losses, which can occur with standard roller crimpers. In the present study, a new prototype machine provided with a roller crimper and an undercutting blade, allowing it to simultaneously crimp plant stems and cut root systems, has been designed, realized, and tested. The aim of the research was therefore to evaluate the effectiveness of the prototype for plant termination and to compare it with a commercial roller crimper. The termination was performed on a spontaneous vegetation cover (weeds). A monophasic exponential decay model to evaluate the weed termination rate over time was performed. The fitted model showed that the prototype is able to achieve a greater and faster weed devitalization compared to the commercial roller crimper, with a lower plateau (0.23 vs. 5.35 % of greenness of plant material, respectively) and higher constant of decay (1.45 vs. 0.39 day^{-1}, respectively). Further studies are needed to evaluate the prototype's effectiveness in relation to different soil textures, moisture conditions, and amounts of plant biomass to manage, to further improve the machine and extend its use in a broad range of situations, including cover crop termination.

Keywords: mechanical termination; minimum soil tillage; non-chemical methods; cover crops; dead mulch; sustainable agriculture

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1. Introduction

Mulching could play a key role in the current agri-food system's transition toward sustainability as a valid physical preventive method for weed control that is useful to reduce reliance on chemical herbicide applications [1–3]. This practice, which consists in covering the soil with organic or synthetic material, prevents weed seeds' germination and emerging seedlings' growth, while favoring water conservation and avoiding temperature fluctuations [4]. Among the available strategies, the termination of cover crops and spontaneous vegetation and the maintenance of their residues as dead mulch on the soil surface (i.e., without disturbing the soil) represents a promising solution that can also improve soil quality by increasing the organic matter content [5,6]. In no-till-based arable and vegetable cropping systems, this practice is usually carried out prior to or simultaneously with cash crop planting, which can take place by means of no-till drills, planters, or transplanters [7–10]. The amount of plant residues plays a key role in terms of weed control effectiveness, as weed emergence tends to decrease as the mulch biomass on the soil's surface increases [11]. The use of the roller crimper to terminate cover crops and obtain a natural mulch has been identified as a valid approach to control weeds that is also able to enhance cash crop yields [12,13]. This device consists of a cylindrical drum with several blades of different shapes placed on the outside. Roller crimpers come in a variety of designs and dimensions, with widths ranging from 2 to 6 m [14–16]. The blades crimp plant stems, cause plant injury, and accelerate senescence, thus terminating them [17,18]. The action of roller crimpers consists in crushing, but not completely cutting, plant stems at equal intervals [17]. Roller crimpers provide intact cover crop residues, ensuring a longer mulch persistence compared to PTO (power take off)-powered mulchers, whose smaller residues degrade more rapidly and are more subject to wind or water displacement [8,19,20]. Roller crimpers also ensures a homogeneous mulch distribution compared to mowing, which together with its long persistence are essential requirements for effective weed control [19,21]. Furthermore, as the cover crop remains anchored to the ground through the roots, there are few probabilities of dragging mulch when the cash crop is planted [16]. Cover crop termination with roller crimpers also showed substantial energetic and agro-ecological advantages compared to the green manure practice commonly used in organic systems, such as higher energy efficiency, higher carbon stored in the soil [22], reduced risk of N leaching [23], and higher predation rate of pests by insects [24].

Roller crimpers ensure a high cover crop termination rate when used from the anthesis of grasses or the 70% flowering stage in forbs [25]. If the cover crop termination is performed before the specific phenological stages, cover crops can survive and compete with the cash crop [25]. A cover crop that has not been killed completely can cause significant yield losses of the cash crop [7,26]. However, in cases of cover crop mixture, it is difficult to find all the species in the appropriate phenological stage for termination at same time [25].

To avoid issues during planting and competition for resources with the cash crop, it is suggested to plant the cash crop after rolling once the residues have reached an appropriate level of desiccation and are easy to penetrate with the equipment [17]. Adapting cash crop planting with the optimal cover crop termination stage may: (i) reduce the time between rolling and planting, causing issues with residues' inadequate desiccation, thus hindering planting [17]; and (ii) delay the cash crop planting with consequent yield losses [27,28]. In the Mediterranean area, timely planting of the spring cash crop is crucial to avoid drought stress issues in the summer period [29]. Several enhancements have been evaluated to improve and speed up cover crops' termination by roller crimpers, even with cover crops at an early phenological stage. To increase their effectiveness, roller crimpers with various designs have been developed, for example with different blade configurations, two-stage roller crimpers, or a water-ballastable sealed roller to provide additional weight [14,30,31]. Herbicide applications have been successfully implemented along with rolling to speed up the cover crop termination in order to allow the planting of the subsequent cash crop at the optimal time [17]. In organic systems where herbicide application is not allowed, Frasconi et al. [5] tested the effect of rolling in combination with flaming. However, the current high operational costs associated with flaming hinder its wider adoption by farmers. Kornecki et al. [32] examined recurrent rolling on cover crops to assess whether biomass termination was accelerated, but this strategy may involve labor management issues and the risk of soil compaction due to multiple passages of the tractor over the same farming land [33]. Antichi et al. [7], on the other hand, evaluated roller-crimping in conjunction with direct drilling of the cash crop, to disturb the cover crop both with the crimping action and the cut performed by the metal disk of the drilling machine. Nevertheless, especially when the intervention was performed on the cover crop at early phenological stages, without the application of glyphosate, plant termination was incomplete, with consequent negative effects on the following cash crop yield.

With the aim of increasing the effectiveness of non-chemical devitalization of both spontaneous vegetation and cover crops, a new prototype machine has recently been developed by the University of Pisa. This machine combines a roller crimper with an undercutting blade working shallowly below the soil surface. This implement, by cutting and therefore damaging the root system, should favor and speed up plant withering, and help to prevent plants regrowth. A machine designed to operate in this way could be very useful, as standard roller-crimpers, acting only on the aboveground portion of plants, cannot prevent in some cases (e.g., in early terminated and vigorous cover crops, or in cover crops stands with high weed infestation) plants' regrowth from the basal buds. To the best of our knowledge, a machine that allows to simultaneously crimp plant stems and cut root systems for an optimal plant termination has never been tested. The aim of the present study is therefore to evaluate the effectiveness of this prototype for the termination of the plant material, in comparison with a commercial roller crimper.

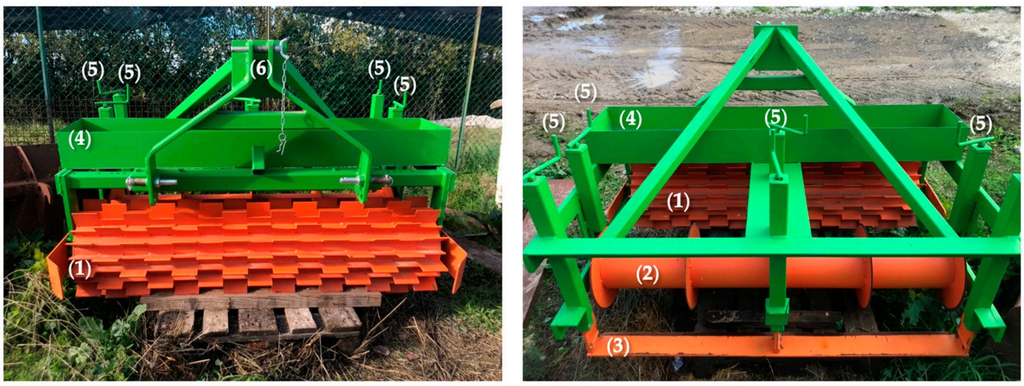
2. Materials and Methods

2.1. The Experimental Layout

The experiment was carried out at the Centre for Agri-environmental Research "Enrico Avanzi", San Piero a Grado (Pisa), Italy (43°40′48′′ N, 10°20′49′′ E, 1 m.a.s.l., [34]) on a field with homogeneous coverage of spontaneous flora. According to the analysis conducted by the Center for Agri-environmental Research "Enrico Avanzi", the soil was sandy loam (57.07% sand, 22.45% loam, 20.48% clay, 1.92% organic matter, pH = 7.5). From autumn 2019 to spring 2022, the selected field was managed as a permanent grassland through periodic mowing of the vegetation cover. The effectiveness of the prototype in terminating the spontaneous vegetation was evaluated in comparison with a commercial roller crimper on 25 May 2022. The adopted experimental design was a randomized complete block design with three replications.

2.2. Description of the Prototype and the Commercial Roller Crimper

The prototype consists of a three-point-hitch-provided main frame supporting a 1.5 m wide Clemens roller crimper, Eco-Roll 1500 type (Clemens Technologies, Wittlich, Germany); a 1.5 m wide cylindrical drum (Ø 0.20 m) with five vertical cutting discs (each with an external diameter of 0.385 m); and a 1.5 m wide horizontal undercutting blade in hardened steel with a thickness of 8 mm (Figure 1). The cylindrical drum with the cutting discs is positioned between the roller crimper and the undercutting blade, with the function of cutting the crimped vegetable biomass to avoid its accumulation and dragging by the blade (Figure 2). The undercutting blade's working depth can be adjusted by means of telescopic servo rudders, in a range from 3 to 6 cm, according to the characteristics of cover crops and/or spontaneous vegetation. The machine presents a working width of 1.5 m. The mass of the prototype is equal to 610 kg. A hopper has been mounted on the frame to provide additional weight to the prototype to increase the effectiveness of crimping on plant stems when needed. During the experiment, the prototype operated with a working speed of 4 km·h^{-1}, and the working depth of the undercutting blade was set to 4 cm.



(a) (b)

Figure 1. Front (**a**) and rear (**b**) view of the prototype: (**1**) roller crimper; (**2**) cylindrical drum with five cutting discs; (**3**) undercutting blade; (**4**) hopper; (**5**) telescopic servo rudders; (**6**) three-point hitch.

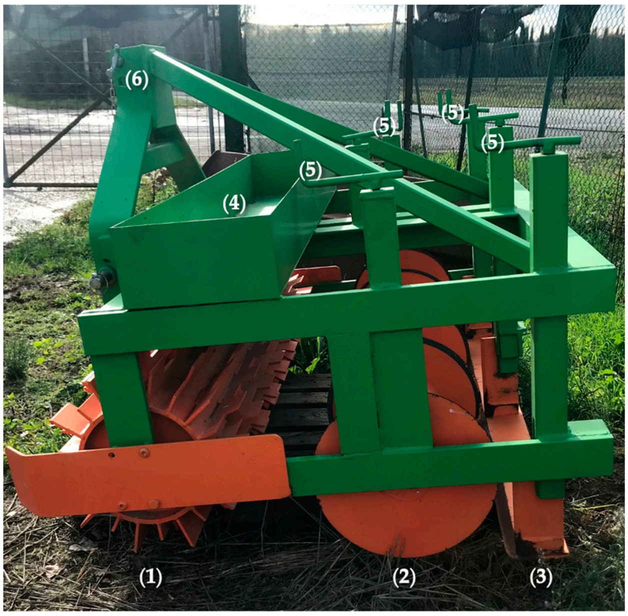


Figure 2. Lateral view of the prototype: (**1**) roller crimper; (**2**) cylindrical drum with five cutting discs; (**3**) undercutting blade; (**4**) hopper; (**5**) telescopic servo rudders; (**6**) three-point hitch.

The commercial roller crimper was a Clemens Eco-Roll type with hexagon frame (Figure 3). The machine is provided with two connected roller crimpers, each 1 m wide. The working width can be adjusted hydraulically in the range from 1.10 m to 1.95 m. A tank with maximum capacity of 300 L was attached to the frame, which, when completely filled with water, allows the mass of the machine to increase up to 950 kg. During the experiment, the commercial roller crimper was set to work at 7 km·h^{-1} with a working width of 1.95 m, and the tank was completely filled with water. Both the prototype and the commercial roller crimper were coupled with a Fiat DT 70-90 tractor (FiatAgri, Torino, Italy) powered by a 52.2 kW diesel engine.

Figure 3. Front (**a**) and lateral (**b**) view of the commercial roller crimper Clemens Eco-Roll type: (**$1_{a,b}$**) roller crimpers; (**2**) hexagon frame; (**3**) tank; (**4**) three-point hitch.

2.3. Data Collection

The spontaneous vegetation was assessed immediately before the termination treatment, both quantitatively and qualitatively. Therefore, weed biomass was measured by cutting and collecting the aboveground biomass present inside a square frame of 0.5 m^2 (1 m long, 0.5 m wide), both in plots subsequently managed with the prototype and in those managed with the commercial roller crimper. Total aboveground fresh biomass was then oven-dried at 100 °C for 3–4 days (until constant weight), and dry biomass was determined. One measurement per replicate of weed biomass before treatment was carried out. Weed flora was characterized by identifying the growth form, growth stage and determining the average height and visual soil cover of the main spontaneous plant species present inside the sampling areas. Two measurements per replicate before treatment were performed for weed height and cover. Average weed height and cover of the experimental field were then determined.

The weed termination rate over time after the machines' intervention was estimated as percentage of greenness of the plant material. The estimate was performed with the analysis of digital images taken on the felled weed [5], using the app Canopeo (Mathworks, Inc., Natick, MA, USA) [35]. The app provides, for each image processed, the percentage of green pixels calculated on the total number of pixels. This method was used because the color of the tissues of a devitalized plant, in which the photosynthetic activity should have been compromised, tends to turn more or less quickly towards colors other than green. Digital images were taken, one for each replicate, inside a 0.5 m^2 square frame, on the day of weed termination (0), and at 1, 2, 3, 4, 5, 6, 8, 10, 12, and 14 days after termination; therefore, on May, 25, 26, 27, 28, 29, 30, and 31, and June 2, 4, 6, and 8, 2022, respectively.

The fuel consumption per hectare related to the machines' performance was estimated on the basis of the theoretical working capacity (which considers that the tractor coupled with the operating machine effectively work at the optimal working speed, and operate for the entire width of action) and the hourly fuel consumption.

The hourly fuel consumption was estimated using the following equation:

$$Ch = W \times d \times Cs \quad (1)$$

where Ch is the hourly fuel consumption of the tractor (kg·h^{-1}), W corresponds to the tractor engine power (kW), d is the effort percentage of the tractor engine required by the operation, and Cs is the tractor engine energetic efficiency (kg fuel·kWh^{-1}). In the present study, based on the tractor characteristics, Cs was estimated at 0.25 kg of fuel·kWh^{-1}, while d was assigned according to the machine type. Values of d equal to 0.35 and 0.55 have been attributed to the commercial roller crimper and the prototype, respectively, considering that the prototype, in addition to rolling, also performs cutting with the vertical cutting discs and the undercutting blade.

2.4. Statistical Analysis

Weed biomass was analyzed with the two-tailed *t*-test using the statistical software SPSS (IBM Corp, Armonk, NY, USA) to assess any variations in weed infestation before treatment between the plots managed by the two machines in comparison [36]. Weed termination rates over time measured for the plant material felled by the prototype and the commercial roller crimper were analyzed with the statistical software GraphPad Prism version 9.4.1 (GraphPad Software, San Diego, CA, USA) [37]. The software predicted the use of a nonlinear regression by adopting the following monophasic exponential decay model:

$$Y = (Y_0 - Plateau) \times e^{(-kX)} + Plateau \quad (2)$$

where:

- Y corresponds to the dependent variable (i.e., the percentage of green pixels of the felled plant biomass);

- Y_0 is the value of the dependent variable at time 0 (i.e., the percentage of green pixels of the felled plant biomass immediately after the machines' intervention);
- *Plateau* is a parameter estimated by the software and corresponds to the asymptotic value of the dependent variable (i.e., the percentage of green pixels of the felled plant biomass, which occurs at an infinite time);
- X is the independent variable (i.e., the time, which in this case corresponds to days after termination);
- k corresponds to the constant of decay (i.e., a constant estimated by the software that presents as unit the inverse of X (in this case days^{-1})).

3. Results and Discussion

The two-tailed *t*-test revealed no significant differences in terms of weed biomass before treatment between plots where the prototype and the commercial roller crimper were compared, with average values of 337.2 g·m^{-2} and 348.6 g·m^{-2}, respectively. Therefore, it is possible to state that weed biomass before treatment was homogeneous in the experimental field.

The characteristics of the main spontaneous plant species present on the experimental field before treatment, such as growth form, growth stage, average height, and cover, are shown in Table 1.

Table 1. Characteristics of the weed flora present on the experimental field before the treatment.

	Growth Form [1]	Growth Stage (BBCH) [2]	Average Height (m)	Average Cover (%)
Avena sterilis L.	T scap	65	0.70	2.5
Convolvulus arvensis L.	G rhiz	40	0.15	6.2
Lolium multiflorum Lam.	T scap	41	0.40	26.5
Picris echioides L.	T scap	19	0.20	62.0
Verbena officinalis L.	H scap	51	0.25	1.8
Others	-	-	-	1.0

[1] Growth form: T scap—Therophytes scapose; G rhiz—Geophytes rhizomatous; H scap—Hemicryptophytes scapose [38]. [2] Phenological growth stages and BBCH-identification keys of weed species: 65—full flowering: 50% of flowers open, first petals may be fallen; 40—vegetative reproductive organs begin to develop (rhizomes, stolons, tubers, runners, bulbs); 41—flag leaf sheath extending; 19—nine or more true leaves, leaf pairs, or whorls unfolded; 51—inflorescence or flower buds visible [39].

Weed flora identified before the treatment on sampling areas was representative of the Mediterranean area in late spring, and it was mainly composed of species with therophytes scapose growth forms, at different growth stages.

The nonlinear regression conducted on the values of the weed termination rate over time as the percentage of green pixels has preliminarily showed that data relating to the prototype and the commercial roller crimper are better described by two distinct curves (extra sum-of-squares F-test $p < 0.0001$). The parameters shown in Table 2 confirm the goodness of adaptation of the temporal trends of the two machines' weed termination rate to the two different curves, and therefore to the monophasic exponential decay model adopted.

Table 2. Degrees of freedom, coefficient of determination, and coefficient of determination adjusted for the regressions carried out on the temporal trends of weed termination rate of the two machines in comparison.

	Prototype	Commercial Roller Crimper
Degree of freedom	30	30
R^2	0.985	0.981
R^2 adjusted	0.984	0.979

The two monophasic exponential nonlinear regression curves obtained from the percentage of green pixels over time of weeds felled by the prototype and the commercial roller crimper and the main parameters values are shown in Figure 4 and Table 3, respectively.

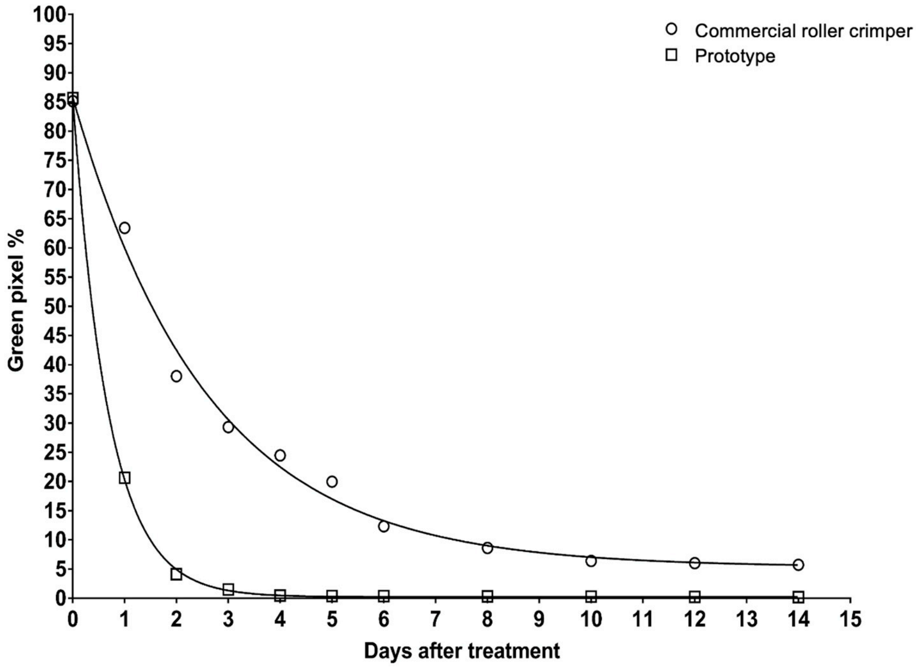


Figure 4. Monophasic exponential nonlinear regression curves of the % of green pixels in the digital images of weed biomass collected at 0, 1, 2, 3, 4, 5, 6, 8, 10, 12, and 14 days after termination.

Table 3. Main parameters of the monophasic exponential nonlinear regression curves.

	Prototype			Commercial Roller Crimper		
Parameters		Ll 95%	Ul 95%		Ll 95%	Ul 95%
Y_0 (%)	85.70	84.76	86.64	85.75	81.82	89.70
Plateau (%)	0.23	−0.11	0.57	5.35	2.73	7.81
k (day^{-1})	1.45	1.40	1.50	0.39	0.34	0.44
Half-life (days)	0.48	0.46	0.49	1.80	1.59	2.04

Y_0 is the percentage of green pixels of the felled weed immediately after the machines' intervention; *plateau* is the percentage of green pixels of the felled weed at an infinite time; k corresponds to the constant of decay; *half-life* is the time (days) required to reach a level of percentage of green pixels equal to 0.5 (Y_0—*plateau*), and it is computed as $\ln(2)/k$; *Ll* corresponds to the lower limit of the confidence interval of the estimate at 95%; *Ul* corresponds to the upper limit of the confidence interval of the estimate at 95%.

From the values of Y_0 and the respective *Ul* and *Ll* of both the tested machines, it is possible to affirm that the prototype and the commercial roller crimper operated under similar conditions of weed cover. This once again supports that the distribution of spontaneous vegetation in the experimental field was rather homogeneous. The *plateau* of the prototype regression curve corresponds to 0.23%. Furthermore, by observing the *Ul* and *Ll* of the parameter's confidence intervals, it is possible to state that the *plateau* of the prototype regression curve does not deviate significantly from the 0% value, with a probability of not less than 95%. This would lead us to hypothesize a greater effectiveness of weed termination of the innovative prototype compared to the commercial roller crimper, whose estimate of the same parameter stands at a value of 5.35%. The higher termination obtained by the prototype could be mainly due to the effectiveness of the undercutting blade. The blade, by separating weed stems from roots, together with the crimping action and the action of the cutting discs, favors a higher withering compared to the commercial roller, which instead only crimps plant stems [40]. However, based on the % of greenness of the felled weeds obtained, it is possible to state that both machines allowed us to reach a plant devitalization above 90%. According to Ashford et al. [18], the achievement of this threshold, in their case with reference to a rye cover crop, is sufficient to plant the cash crop in dried residues without the risk of competition for resources. Concerning the values of the constant of decay *k* and the 95% confidence intervals of the weed termination curves obtained for the machines, the value estimated for the prototype curve is statistically higher, in absolute value, than that of the commercial roller crimper. These first results show that the prototype allows for a faster weed devitalization compared to the commercial roller crimper. The obtained results are also confirmed by the prototype's *half-life* value, which is 3.75 times lower than the commercial roller crimper. The commercial roller crimper's plant termination rate values are consistent with those attained by other authors [41] for a two-stage roller crimper, which led to a plant devitalization of 85% and 96% one and two weeks from the intervention, respectively. Results obtained by the prototype are in agreement with Kornecki and Kichler [42], who found a higher plant termination rate after one and two weeks from the intervention for a flail mower, a machine that performs cutting of plant tissues, compared to roller crimpers. Kornecki [43] observed a significant reduction in the time required to exceed 90% of plant devitalization, similar to that of the prototype, when rolling was performed in combination with chemical herbicide application, and when rolling was carried out three times. However, even if recurrent rolling proved to be a valid alternative to chemical herbicide application to speed up plant termination, multiple passages of the tractor over the same farming land could cause soil compaction [33].

This finding is significant since any delay in plant termination treatment can reduce the time interval between rolling and cash crop planting, making planting difficult if plant residues are not adequately desiccated. Therefore, speeding up plant termination is essential to reduce the risk of delaying the following cash crop planting, and the consequent potential negative effects on yield [17].

Table 4 shows the operative characteristics of the two machines in comparison.

Table 4. Operative characteristics of the prototype and the commercial roller crimper.

		Prototype	Commercial Roller Crimper
Parameters			
Working speed	km·h^{-1}	4	7
Working width	m	1.5	1.95
Working capacity	ha·h^{-1}	0.6	1.37
Hourly fuel consumption	kg·h^{-1}	7.18	4.57
Fuel consumption per hectare	kg·ha^{-1}	11.96	3.35

Comparing the working capacity and the fuel consumption of the two machines, it is possible to observe that the prototype presents a lower working capacity, with a decrease of 56.2%, and a greater fuel consumption, with an increase of 257.01%, compared to the commercial roller crimper. The lower working capacity of the prototype is related to its lower forward speed and working width, while the higher fuel consumption is mainly due to the higher effort percentage of the tractor engine required by the prototype operation, which combines rolling and cutting with the vertical discs and the undercutting blade. According to Creamer and Dabney [19], the operation of plant termination by means of a machine that also performs undercutting is slower and may require more power compared to rolling alone. However, as the prototype proved to be more effective at plant termination, repeated rolling or application of flaming, as can occur with ordinary roller crimpers to accelerate plant termination, may not be necessary, thus avoiding the relative disadvantages [32,33]. The lower working capacity of the machine and its higher fuel consumption would make the prototype particularly suitable for more profitable contexts, such as organic horticultural systems. Furthermore, in these contexts, where the creation of raised beds is frequent, the operation of the undercutting blade could also be facilitated [44].

Nevertheless, at this first experimental test, the innovative machine proved to be effective in managing the spontaneous cover, by providing a greater and faster devitalization of weed biomass compared to the commercial roller crimper. Machines that perform plant undercutting, compared to those using other plant termination means, such as mulchers, allow one to create a thicker and longer-lasting mulch, ensuring a greater, season-long weed suppression, and leave a looser soil, facilitating the cash crop planting [44,45]. Furthermore, despite the lower prototype working capacity compared to the commercial roller crimper, the damage to the root system caused by the undercutting blade could contribute to preventing the regrowth of the felled weeds. The optimal and fast termination and the prevention of plant regrowth are crucial to avoid any serious yield losses of the following cash crop [7,26].

4. Conclusions

In the present study, the use of a prototype that simultaneously crimps plant stems and cuts root systems for the management of spontaneous vegetation achieved encouraging results. Indeed, the prototype obtained a higher and faster devitalization of the plant biomass compared to the commercial roller crimper. Therefore, the innovative machine seems to represent a valid tool for the non-chemical termination of spontaneous vegetation or cover crops. A machine with these characteristics can be particularly suitable for horticultural organic systems, allowing the realization of dead mulching, which favors weed control, and other useful ecosystem services such as soil conservation and moisture retention. Further studies are needed to evaluate the prototype's effectiveness in relation to different soil textures, moisture conditions, and amounts of plant biomass to manage, to further improve the innovative machine and extend its use in a broad range of situations. Different shapes, thicknesses, and angles of the undercutting blade should be tested in order to increase the versatility of the prototype in different soil types and moisture conditions. Possible disadvantages have been observed for the prototype's single-termination intervention, such as higher fuel consumption and lower working capacity compared to the commercial roller crimper, as the new machine performs a subsurface cut in addition to rolling. Therefore, it would be desirable to further evaluate the economic aspects and energy consumption within a real farming system. Moreover, it would be useful to investigate the prototype's ability to prevent plant regrowth as a function of the different phenological stage at which plant species are terminated.

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