Localised weeding techniques adaptable to be used on a robotic arm in organic farming

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Key words: in-row localised weeding, organic farming, robot

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Introduction

Weeding is an important step in the cropping cycle. Indeed, the competition between crops and weed for soil resources is likely to decrease crop yield. Without weeds competition it's possible to improve the yield from 33 to 66 % (Wortman *et al.,* 2020). Usually, in conventional farming, herbicides could be used. In organic farming, only organic herbicides are authorised that why some alternatives are needed. Lots of them are adapted for an inter-row weeding. For intra-row there is a lot of manual weeding. But this technic takes a lot of time, around 300 h/ha in onion and 500 h/ha in carrots (Pannacci *et al.,* 2017) that why this technic is expensive. Moreover, labourers could be difficult to find.

That why, some researchers and companies try to find alternative techniques for intra-row weeding. In this context the Start-up Odd.bot, in Netherlands, would like to adapt weeding techniques on a delta-robot or on a weeding car of Andela company.

The biggest difficulty is to find techniques which are adaptable for this means of transport. Indeed, some techniques could demand few particular equipment more or less extensive. But the use of a robot has lots of advantages. Firstly, the robot enables to limit the working time of workers, because it can treat weeds ahead of the weeding team. So, that could represent an economic gain on wages. Then, some weeds need to be cut at an early stage of growth, it's possible to pass more regularly. In fact, even if the robot isn't really fast, it could work 24 hours a day every day. But there are also some inconveniences with the use of a robot. For example, the autonomy can be really limited and can create logistic problems. On the same topic, there might also be different consumables needed depending on the technique which is chosen. This consumption is a key point in the choice of the weeding technique. Because, if the machine needs to be often replenished, that could create losses of time and productivity. Moreover, maintenance of the weeding equipment should also be part of the reflexion.

In this literature review, seventeen weeding techniques are explained and compared using different parameters. There are mechanical, thermals and other types of weeding techniques. Then, there are comparison of efficiency range and some positive and negative effects of those techniques. Finally, there is a comparison of energy use and worked time with a concrete example.

1. Existing weeding techniques

- <u>Cutting blade/scissors:</u>

This method aims to defoliate weeds. Thanks to the study of Evert *et al.* (2020), a severe defoliation for 3 months allows having a complete cessation of leaf growth. But, during their experiments regrowth was limited by a lack of water. After 2 or 3 defoliation, the leaf area of the weed was so small and has a negligible impact on the crop. Those experiment was done with Rumex, and 5 to 7 defoliation per season for 6 years allows reducing Rumex abundance by 60 %. Furthermore, this technique is more efficient when it's applied before the compensation point of weeds. The compensation point is the point when newly formed leaves will start to increase the rate of respiration and the plant will win weight. When weed are cutting before this point, their fresh weight will decrease and conducting to the death of the plant with time. This technique has the advantage that mechanical knives could be quickly placed and rapidly cut the weed (Slaughter, Giles & Downey, 2008).

A start-up Nexus Robotics create a prototype which is capable of cutting weed (Figure 1). This robot is equipped with a blade and a nozzle. The advantage to have these two tools it that the robot can choose the more efficient way to kill the weed.

Figure 1: Nexus Robotic Prototype and his blade (source: http://cbe.ca)

After, a team of researchers has developed the TrimBot2020 for pruning topiary or cut rose (Figure 2). An adaptation of tools can be possible to use them to cut weeds.

Figure 2: TrimBot2020 topiary trimming tool and rose clipping tool (source: www.wur.nl)

- <u>Tube stamp:</u>

This system uses a stamp to weeding and it's present on the robot Bonirob (Figure 3). This system works in 3 phases:

- 1: all elements are reset, in starting position
- 2: the tube touching the ground around the weed and holds it
- 3: the stamp penetrates the soil around 47 mm and damaged the plant with his sharpened head. Finally, the stamp and the tube return to staring position

The cycle takes less than 600 ms and the system is powered by a motor of 70 W. According to the tests, around 83 % of weeds are fatally damaged by this technique. The system on the robot can treat 1.75 weeds/s at a speed of 3.7 cm/s (Langsenkamp *et al.*, 2014) .

Figure 3:BoniRob robot (Amazone and Bosch) and his tube stamp (source: www.researchgate.net)

- <u>Uprooting with grippers</u>

This technique aims at uprooting the weed plant and leave it on the ground to dry up and die. But in wet conditions there are regrowth risks because the weed couldn't dry out. However, the gripper allows to be precise.

Kurstjens & Kropff (2001) has studied the impact of uprooting on three species (*L. perenne, L. sativum and C. quinoa*). To do that, there have studied the mortality of weed with uprooting and with uprooting and covering of weed. Most of the time, covering weed has decreased the mortality of uprooting. Uprooting was responsible for 60 % of mortality for *L. perenne*, 93 % of *L. sativum* and 95 % of *C. quinoa*. But authors said that the importance of climatic conditions and soil moisture should be studied, because mortality results could change with different experiment conditions. But, uprooting makes it possible to win time due to the re-allocable of energy reserves of the plant. During this time, the competition between crop and weed will be reduced.

Al-Sahib & Majeed (2012) created a robot with mechanical grippers to uproot weeds, the pioneer p3-dx. Auto roboculture (2019) has published an article in which they show the Nindamani robot (Figure 7). It's a robot which uprooting weeds with a gripper attached to the robot with a delta arm. As we can see in the video, the gripper takes around 5 – 7 s/weed. The gripper is positioned under the plant to uproot it.

Figure 4: The Nindamani robot and his gripper (source: www.hackster.io)

- <u>Drilling:</u>

This technique permits uprooting taproot weed. The company Natuiton has created a robot with a sommelier tool (Figure 8) which treat 6 weeds/min and it could be weeding 7 500 m^2 at 10 h. This technique could be used in any climatic condition and the robot will be commercialised at the end of 2021.

Figure 5: Sommelier robot tool from Natuition (source: natuition.com)

- <u>Flame weeding:</u>

There are two different types of burner:

- Open flame with a cover with a maximal temperature of 1,900 °C
- Open flame without a cover with a maximal temperature of 1,500 °C

The temperature is higher with the same consumption of energy with a cover because there is less losses of energy.

A dose of 36 to 42 kg/ha of liquid petroleum gas provides a good weed control in a blanket inter-row application in corn (Martelloni *et al.*, 2016). A dose of propane from 10 to 40 kg/ha is efficient to destroy 95 % of weeds if there are between 0 and 4 leaf stage of growth. Plants between 4 and 12 leaf stages of growth needs 40 – 150 kg/ha of propane (Rask *et al.*, 2007).

According to Rask *et al.* (2013), 5 to 5.5 treatments are needed to have a weed cover less than 2 % in the field. There are species that became tolerant after regrowth (*Capselle bursa-pastoris* L. and *Matricaria discoidea* DC.) so they can be killed only with a treatment at an early stage of growth (Rask *et al.*, 2007).

There is no application for an intra-row treatment, but that could be possible when crops are not too close and with some protections around the flame to avoid fire risk and crops damages.

- Laser:

Ultraviolet (UV), infrared (IR) and far infrared (FIR): cut with ablation of plant tissues due to electron ionisation. According to Xiong *et al.* (2017), a robot could weed at a speed of 29 mm/s with a high average hit rate of 97 %. That is done with a laser of 90 W and 810 nm, with a time of exposure of 640 ms. It's possible to increase the efficacy of the laser treatment by pointing the laser beam towards the apical meristem (Mathiassen *et al.*, 2006). Mathiassen *et al.* (2006) used two types of lasers: a 5 W and 532 nm and a 90 W and 810 nm. They find that the 5 W laser has lethal effect at lower energy than the other laser to kill weed at the cotyledon stage of growth with a time of exposure of 3 s. When weeds are bigger it's more difficult to kill them with the 5 W laser, the time of exposure need to be longer. They also find that the diameter of the spot has no influence on the weed mortality. A special equipment should be used to prevent fire risk, due to the elevation of temperature in plant. According to Fennimore *et al.* (2016), the 5 W laser is the most efficient with a lower power.

CO2: cut the plant because of the great light absorption in tissue water, which causing strong heating and explosive boiling in plant. The laser is more efficient for cutting when it moves around the weed. Then it should be close to the weed (less than 3 cm from the focal plane) to limit energy losses. Heisel *et al.* (2001) experimentations show that 0.7 to 3.5 J/weed is enough to cut stem from 0.8 to 1.5 mm in diameter when the laser is moving around the plant and with a time of exposure for 1.73 s. The exposure time could change with the thickness of the plant, more the thickness is important, more energy demand to cut the stem or more the time of exposure will be larger (Heisel *et al.*, 2002). The CO2 laser uses less energy than IR and UV lasers. Also, laser uses a quarter of energy use by propane flaming to obtain the same result.

- Hot water:

Hot water is sending on weed and cause death by dehydration (Hansson & Mattsson, 2002), because that cause destruction of cells and denaturation of proteins. According to this study, a water above 60 °C is effective for killing plants within a short exposure time. Hot water has a lower heat transfer coefficient than steam, that's why more energy is needed to obtain the same effect. And less energy is needed to decrease the fresh weight of plants than to decrease the number of plants. Decrease the fresh weight so the size of the plant permit to limit the competition phenomenon between the crop and weeds. To improve the penetration of water in the plant it was observed that coarse and medium droplets are more efficient than fine droplets. This is due to a longer time to cool down by coarse and medium droplets. To kill old weed, it's possible to use higher water flows to be more efficient (better penetration of water in plants). According to Rask *et al.* (2013), 3 treatments per year are needed to have a weed cover less than 2 %.

According to De Cauwer *et al.* (2015), the more efficient treatment on weed with hot water was with a flow of 2 L/min (2 L/m²/treatment) of water at 98 °C every 3 weeks and that with an energy of 819 kJ/m².

The company Oliatech created a prototype adapted for arboriculture (Figure 5). This machine uses 1,500 L of water/ha, water is at 120 °C and has a driving speed of 2.5 km/h. The consumption of fuel is 25 L/ha (www.pleinchamp.com).

Figure 6: Hot water weeder from Oeliatech (source: www.pleinchamp.com)

- <u>Steam:</u>

This method consists to send steam near the soil surface on weeds to kill them. Steam is produced by a steam generator and could be in different states: saturated steam or superheated steam. Steam could enter in the soil at 20 cm deep, and the soil surface temperature could reach 100 °C. Nishimura *et al.* (2015) obtain 90 % of mortality on weed with an exposure time of 1 or 2 s. But results should be taking carefully because the season and conditions of steaming have big impacts on results. Indeed, the maximal temperature can vary of 20 °C between the seasons. Steam treatment is also used for the soil disinfection, so steam could have an impact on the soil fauna. The impact on soil life is due to the augmentation of the soil temperature (63 °C with a dose of 2.78 kg of steam/ha) (Raffaelli M. et al. 2016).

According to Rask *et al.* (2013), an average of 5.5 treatments are needed to have less than 2 % of weed cover in the field.

- <u>Hot foam :</u>

This method aims at transfer heat energy from the foam to the plant and kill the plant with the destruction of cells and denaturation of proteins. Martelloni *et al.* (2020) had used a Foamstream of the company Weedingtech for their experiments. The foamstream had a flow of 0.2 L/min and they had used a dose of 8.33 kg/m² (96 % of water and 4 % of Foamstream 4 composed of organic oil). 1 day after treatment all the weed cover was destroyed. The regrowth of weed cover at 80 % take 27 days.

The company Technovict developed a machine prototype which submits foam at 70 °C on the soil (Figure 6). The foam is composing of water and foaming agents of plant origin. The water consumption is around 0.30 L/m² thanks to the constructor. The driving speed has no influence on the efficient because the foam acts just after the application and disappears in few seconds, with their machine it's possible to have a maximum speed of 4 km/h. The hot foam destroys weeds by the denaturation of proteins. That's why this technique could be difficult to use on field crops, because if there is a contact between crop and foam that could destroy the crop.

Figure 7:The hot foam weeder from Technovict (source: www.fr.technovict.com)

- Microwave weeding:

The system created for the research generate 60 °C of temperature on the surface of the soil and could kill young weeds (Khan & Brodie, 2018). It's a system of 4 transmitters of 2 kW of 11 cm wide with a driving speed of 1 km/h, a reduction of 85 % of weed pressure has been observed. The efficacy of the system is around 75 – 80 %, so there is a loss of energy.

- Freezing:

The aim of this method is to freeze weeds to death with liquid nitrogen or liquid carbon dioxide (LCD). Mahoney *et al.* (2014) are testing some prototypes of freezing machines. They tested a prototype which sends 3 kg LCD/min and another with a flow of 0.5 kg LCD/min. The observed than the control was better a 1, 2, 3 or 4 leaf stage of growth than at 1 or 2 tiller stage. With the prototype at 3 kg LCD/min, an exposure time of 15 s permit a weed control from 27 to 94 % seven days after treatment and an exposure time of 30 s a weed control of 45 to 96 %. With the second prototype, 5 s of time exposure permits weed control of 92 to 93 % from one to four leaf stage of growth.

Liquid nitrogen could also be used, the consumption was similar to flame weeding. But this technique could kill only the base of the plant and not roots. When leaves protect the base of the plant, weed could survive the treatment.

The company Arctic Inc. use liquid carbon dioxide to kill weeds with a Frostbite sprayer. According to the Farm Show Magazine (2015), a system converts liquid CO_2 in dry ice frost and an application of 1 s is sufficient to kill plants. For annual plants the effect of the method could be seen until 2 days after the treatment, but for other weeds first effects can be seen after 20 min (Reschke, 2015).

- <u>Water jet:</u>

Send high-pressure water onto weeds to destroy them. Caffini company has commercialised the Grasskiller (Figure 4), it's a machine which use this method. It uses water at 1,100 bar, the water is sent to plants and enters in soil at 2 or 3 cm deep. The consummation of water is 1,000 to 1,400 L/ha with a speed of 2 km/h, and 2 to 4 treatments are required per year to destroy all the weed (www.caffini.com).

In Australia, Butler (2019) used horizontal water jet at a pressure of 3,800 Bar to cut cotton stems. This system has been created by the company AquaTill and it's usually used to cut plants residues in the field and to make furrow for sow (www.aquatill.com). But we can imagine adapting this technique to weeding with great pressure control to have a minimum of soil disturbance. This system could cut stem horizontally or try to cut roots with a vertically jet by targeting the apical meristem.

Figure 8:The Grasskiller machine from Caffini (source: www.caffini.com)

- <u>Electricity:</u>

There are two methods:

- Spark discharge pair of electrodes or an electrode above the plant. Short pulse or a series of short pulses are sent to the plant.
- Continuous contact: an electrode touching the weed and electric current passes for the duration of the contact period.

For continuous contact, it's possible to treat 1 ha at 8 – 15 kV and 50 kW an infestation density of 2,000 stems/ha (Diprose & Benson, 1984). According to Dirpose and Benson (1984), with a density from 2,000 to 6,000 stems/ha two passes are required. With an infestation rate above 6,000 stems/ha electric method becomes insufficient due to the power of an electrical machine which was insufficient.

Blasco *et al.* (2002) has used a system of 15 kV and 30 mA. The robot is able to treat 1 weed per second with a speed of 0.8 km/h in the field. 100 % of small weed was destroyed (less than 5 leaf growth stage) 3 or 4 days after treatment.

If weeds are close to the crop, it's very important to have a good probes control and uniform soil to avoid contact between probes and soil or between probes and crop. These methods could have very different efficacy (50 – 90 %), that depends on the voltage, the number of passes and weeds characteristics (Diprose & Benson, 1984). Sometimes, some weeds are not dead and regrowth.

- <u>Abrasion:</u>

This technique uses abrasive material (sand, crushed cores, crushed corn stalks…) sent with high pressure on the crop row and destroy a part of weed. Erazo-Barradas *et al.* (2019) tested several treatments with one, two or three grit application on corn. Three applications have better weeding efficiency than one or two applications, but this technique alone is not sufficient to have a 100 % of weed control. Furthermore, to use this technique it's necessary that crops are denser than weeds.

Forcella *et al.* (2011) used a blaster with a pressure of 500 kPa, and the distance between the blaster and plants was 300 mm. 85 % of plants at 2 or 3 leaf stage of growth were killed and 97 % of plants at 0 or 1 leaf stage of growth were killed with one pass and the other was killed during the second passes.

Wortman *et al.* (2020) used a tractor of 65 horsepower and a grit application which consuming 7.6 L of diesel/h. The treatment takes 1.02 h/ha with an average weeds density of 45 weed/m², and to have a better efficient 2 passes are needed.

- <u>Weed blower:</u>

This technique uses compressed air to control weed and to send them out of the crop row (Van Der Weide *et al.*, 2008). The advantage of this technique is that plant couldn't be resistant to the compressed air and this technique could be used on lots of stages of growth of the weed. But this tool can make severe damages to the crop if the weed is too close to the crop plants. The aggressiveness is more important when the plant is close to the nozzle. In his study, Lütkemeyer (2000) use a compressor of 60 kW to treat 6 rows. The treatment was more efficient with a lower driving speeds and a high air pressure. According to Van der Schans *et al.* (2006) it's possible to do 1 ha/h with a 3 m working width.

- <u>Organic herbicide application:</u>

This method consists to spray only weeds which are detected by the camera. According to Loghavi *et al.* (2008), with this technique it's possible to have a saving of 69,5 % of herbicide. The drop-on demand system permit to savings more than 90 % of herbicide, this system is used on several robots like the AgBot II prototype created by Queensland University of Technology (Utstumo *et al.*, 2018). This technique could also be used in organic farming with organic oil for example (Thomas, 2018). The company EcoRobotix (Figure 9) created an autonomous robot able to drive at a speed of 0.4 m/s while the robotic arm making 4,000 moves/h. This robot uses solar energy and it has 2 tank of 15 L to work during more than a day (www.ecorobotix.com).

- Pine tree oil (Thomas, 2008): This oil can destroy 100 % of the dicotyledons with a dilution at 10 % for the cotyledon stage of growth and 20 % for more than 5 leaf stage of growth. Cereals are resistant to treatment when there are more than 5 leaf stage of growth. This treatment cost is around 600 €/ha with a full dose.
- Soybean oil (Thomas, 2008): this oil has a drying effect on weeds. But there are difficulties for the application due to the mix of water and oil in the tank. But a dilution of 5 % permit to kill 66 % of weed on 1 to 2 leaf stage of growth.
- Suppress (Thomas, 2008): This bioherbicide is efficient on dicotyledons and grass. It's composed of fatty acid (caprilyc and capric acid). The dilution should be between 3 and 9 % to have the better efficient. According to the article, the average of dilution used is 6 % for a dose of 230 L/ha. The herbicide for the treatment cost around 250 €/ha with a blanket spraying.

Figure 9: Avo robot from EcoRobotix (source: www.letemps.ch)

2. The efficiency range

	Required time to die	**Duration of exposure/treatment**	**Closest distance to the crop plant**	**Weed size/stage of growth**	**Energy use**
Cutting blade/scissors (Evert *et al.*, 2020)					
Tube stamp (Langsenkamp *et al.*, 2014)		0.6 s	Very close to the crop		70 W
Gripper uprooting (www.hackster.io)	Time to dry	5 - 7 s	Close to the crop		
Drilling (www. natuition.com)		10 s	Close to the crop	Weed less than 40 cm in diameter	240 Wh
Flame weeding (Martelloni *et al.*, 2016)	2 – 3 days			– From emergence up to 4 leaves	39 kg liquid gas petroleum/ha; 25 kg propane/ha
Laser (523 nm) (Mathiassen *et al.*, 2006)		0.25 – 2 s	Very close to the crop	Cotyledon stage	1.3 – 9.9 J/weed
Laser CO_2 (Heisel *et al.*, 2001; Heisel *et al.*, 2002)		1.73 s	2 mm	Small diameter	10 W
Hot water (Hansson & Mattsson, 2002)	1 – 2 days	0,6 s (98 °C)		Young and mature weeds	819 kJ
Steam (Nishimura *et al.*, 2015)	Immediately	1 – 2 s		Young and mature weeds	202 - 215 kW (superheated steam) 201 – 214 kW (saturated steam)

	Required time to die	Duration of exposure/treatment	Closest distance to the crop plant	Weed size/stage of growth	Energy use
Hot foam (Martelloni *et al.*, 2020)	1 day		Very close to the plant	Young weed	
Microwave weeding (Khan & Brodie, 2018)	immediately	60 s		Young weeds	2 kW (= 400 – 500 J/cm^{-2})
Freezing (Mahoney *et al.*, 2014)	20 min – 2 days	5s – 30 s		1, 2, 3 or 4 leaf stage of growth	0.5 kg LCD/min
Water jet (www.caffini.com)	Immediately			Young weeds	
Electricity (Blasco J. *et al.*, 2002)	3 – 4 days	1 s	Very close to the crop	Fewer than 5 leaves	450 W
Abrasion (Wortman S. E. et al. 2020)	Immediately	1 s	0 mm	1 – 2 leaf growth stage	
Weed blower (Van Der Weide *et al.*, 2008)				From emergence up to 4 leaves	10 kW/row
Localised spraying (Loghavi & Behzadi Mackvandi, 2008**)**			1.25 cm of the crop		

3. Positives and negative side effects

	Positives effects	Negative effects
Cutting blade/scissors	No soil disturbance	Don't cut roots
Tube stamp	limited soil disturbance	
Uprooting	Precise	Soil disturbance A risk of weed regrowth if rain/irrigation happens closely after uprooting
Drilling	Precise	Soil disturbance Can damage crop roots if it weeds too close to crops
Flame weeding	Absence of residues in the soil No resistance to flames	
Lasers	No soil disturbance Quick and precise IR laser is not disturbed by the sunlight	
Hot water	Limited soil disturbance No risk of contamination of soil or water	
Steam	No soil disturbance Seed mortality of 90 % (Nishimura *et al.*)	Impact on the soil fauna More energy losses than hot water (steam is more volatile)
Hot foam	Quickly visible effects Long time to regrowth	
Microwave weeding	No soil disturbance	Kill earthworms and macrofauna on the surface of the soil (less than 5 cm deep) Need a lot of energy After 120 s of exposure, formation of nitrite
freezing	No soil disturbance Quickly visible effects	
Water jet	Work in all climatic conditions Precise (AquaTill)	Soil disturbance (4 – 6 cm deep) (limited if there is horizontal jet)
Electricity	Limited soil disturbance	Fire risks
Abrasion	Limited soil disturbance	Don't permit a 100 % of weed control
Weed blower	No soil disturbance	Can damaged crop if the weed is to close
Localised spraying	No soil disturbance	Possible to have herbicides resistance

4. Example

According to Van der Weide *et al.* (2008), the intra-row density is around 10 to 100 weeds/m². We will make the hypothesis that the average weed density intra-row is 100 weeds/m² and the robot only do an intra-row weeding (Koenis, 2020). The field size is 1 ha (100 m x 100 m) with an intra-row of 15 cm and an inter-row of 75 cm and 111 rows (row surface = 1,665 m²), so the robot could treat 166,500 weeds. The average size of weeds is 0.0009 m² in this example. With this detail the rate of weed cover is 1.49 % of the surface (0.0150 ha).

	Specific equipment	Quantity (energy, substance)	Time to weed the field
Cutting blade/scissors	Blade/scissors motor		
Tube stamp (motor of 70 W, 0.6 s/weed)	Tube stamp Motor	6.99×10^6 J 1.94 kWh	27.75 h/ha
Uprooting (6 s/weed)	Gripper Motor		277.5 h/ha (11.6 days/ha)
Drilling (10 s/weed)	Battery corkscrew	8.64×10^8 J 240 kWh	462.5 h/ha (19.27 days/ha)
Flame weeding (39 kg liquid gas petroleum/ha; 25 kg propane/ha)	Liquid gas petroleum or propane tank pump	0.585 kg liquid gas petroleum 0.375 kg propane	
Laser UV, IR, FIR (5 W, 1.125 s/weed, 5.6 J/weed)	Laser	$9{,}32 \times 10^5$ J 0.260 kWh	52.03 h/ha
Laser CO_2 (10 W, 1.73 s/weed)	Laser	2.88×10^6 J 0.800 kWh	80.01 h/ha
Hot water (2 L/min, 814 kJ/m²)	Tank for water Boilers Pump Hot water applicator	3,330 L of water 1.23×10^8 J 34,125 kWh	27.75 h/ha
Steam (1.5 s/weed, 209 kW superheated steam and 207 kW saturated steam)	Tank for water Steam generator/boilers Pump	Superheated steam: 5.22×10^7 J 14.5 kWh Saturated steam: 5.17×10^7 J 14.36 kWh	69.4 h/ha
Hot foam (0,3 L H_2O/m², 4 km/h)	Tank for water and foaming agent Pump Boilers?	499,5 L of water 50 kg of foam agent	2.77 h/ha
Microwave weeding (450 J/cm², 2.71 L fuel/m²)	Electricity generator Microwave transmitter	1.99×10^{10} J 5,550 kWh 4512.5 L fuel/ha	2775 h/ha (115.6 days/ha)
Freezing (0.5 kg LCD/min, 5 s exposure time)	Liquid carbon dioxide tank Sprayer	6,937.5 kg LCD/ha	231 h/ha

	Specific equipment	Quantity (energy, substance)	Time to weed the field
Water jet (1,200 L H_2O/ha, 2km/h)	Water jet Water tank High-pressure pump	18 L of H2O	5.55 h/ha
Electricity (450 W, 1 weed/s)	Electricity generator Fuel tank for the generator	7.50 x10^9 J 20.81 kWh	46.2 h/ha
Abrasion (150 kg/ha)	Tank for abrasive material Air compressor Nozzle and tubing	2.25 kg of abrasive material 17.176 L of fuel/ha	46.25 h/ha
Weed blower (10 kW/row)	Air compressor Electric generator nozzle	1,100 kW	
Localised spraying (Supress: 230 L/ha, 0.4 m/s)	Tank pump nozzle	3.45 L of solution 0.21 L of Supress	7.71 h/ha

Conclusion

To conclude, seventeen techniques which are adaptable on a robotic arm and in organic farming have been explained. They are at different development stages, from prototype to commercialised products. Each technique has its own advantages and inconvenient. So, it's difficult to make a reliable and complete comparison of parameters like energy use and work time, because with new studies both parameters will evolve a lot.

With these 2 parameters, it's possible to compare eight techniques: tube stamp, drilling, lasers 532 nm and CO2, hot water, steam, microwave and electricity. According to literature, microwave weeding has the biggest energy use and the longer work time to treat 1 ha. Techniques which has the better results in terms of energy use and speed are tube stamp system, laser 532 nm and hot water weeding. From these three techniques, the simplest to put on the robot arm are tube stamp system and laser. Indeed, the equipment requirement is more important for hot water weeding. Nevertheless, for this comparison only eight techniques on sixteen were compared, because of the lack of information for other techniques. That why, this result should be taking carefully. For example, when only the work time is being compared, better techniques are hot foam, water jet and organic herbicides application.

Some other parameters need to be compared, such as the use of consumables for example. Indeed, some consumables are more or less costly. For example, water is more affordable than fuel. The fewer products are needed, the easier it is to store them on the robot. It is also likely that the more equipment is needed for weeding, the heavier the machine will be. That could provoke soil packing. And if weed is just uprooted, the soil packing could facilitate the rooting of roots and so the regrowth of the weed. With that problematic of consumables, the use of water jet could be interesting, because water is simple to find. Moreover, with this technique there is no need for high temperature, so the losses of energy are minimised. Indeed, if the water jet targets the apical meristem, it could be very efficient to kill weeds with little quantity of water and a minimum of soil disturbance. This technique could allow to be precise, because it's used to make furrow (AquaTill) for sowing at a specific depth.

The available literature has some limits. First of all, the lack of precise data makes it difficult to compare techniques. Moreover, it should be interesting to compare the efficiency of techniques in the same field conditions. Finally, more research should be done on equipment which are needed to use these techniques. This can help with keeping the weight and the bulk of the robot small.

A possible evolution of this project is to adapt a machine or a robot to do intra- and inter-row weeding at the same time. Usually, a machine pass and treat the inter-row and then labourer pass to do manual weeding in the intra-row. That could save a pass from the machine, and could possibly use the same technique localised or not in the inter-row. This adaptation is not necessarily realistic with the delta-robot. At the same, the possibility to keep the same work flow needs to be studied. Maybe it's possible with a second robotic arm.

References

Al-Sahib N. K. A. & Majeed S. R., 2012, «Environmental mobile robot based on artificial intelligence and visual perception for weed elimination», *INCAS BULLETIN*, 4(4), 11–25.

Auto roboculture, 2019, *Nindamani the weed removal robot*, *hackster.io*.

Blasco J., Aleixos N., Roger J. M., Rabatel G. & Moltò E., 2002, «Robotic Weed Control using Machine Vision», *Atomation and Emerging Technologies*, 83(2), 149–157.

Butler G., 2019, «Cotton ratoon termination with AquaTill injecticide», *The Australian Cottongrower*, 20–22.

De Cauwer B., Bogaert S., Claerhout S., Bulcke R. & Reheul D., 2015, «Efficacy and reduced fuel use for hot water weed control on pavements», Do-Soon Kim (ed.), *Weed Research*, 55(2), 195–205.

Diprose M.F. & Benson F.A., 1984, «Electrical methods of killing plants», *Journal of Agricultural Engineering Research*, 30, 197–209.

Erazo-Barradas M., Friedrichsen C.N., Forcella F., Humburg D. & ClayS.A., 2019, «Propelled abrasive grit applications for weed management in transitional corn grain production», *Renewable Agriculture and Food Systems*, 34(1), 33–40.

Evert F. K., Cockburn M., Beniers J. E. & Latsch R., 2020, «Weekly defoliation controls, but does not kill broad-leaved dock (*Rumex obtusifolius*)», *Weed Research*, 60(2), 161–170.

Farm Show, 2015, *Sprayer kills weeds with controlled frost*, 39(1), 11.

Fennimore S. A., Slaughter D. C., Siemens M. C., Leon R. G. & Saber M. N., 2016, «Technology for Automation of Weed Control in Specialty Crops», *Weed Technology*, 30(4), 823–837.

Forcella F., James T. & Rahman A., 2011, «Post-emergence weed control through abrasion with an approved organic fertilizer», *Renewable Agriculture and Food Systems*, 26(1), 31–37.

Hansson D. & Mattsson J.E., 2002, «Effect of drop size, water flow, wetting agent and water temperature on hot-water weed control», *Crop Protection*, 21(9), 773–781.

Heisel T., Schou J., Andreasen C. & Christensen S., 2002, «Using laser to measure stem thickness and cut weed stems», 7.

Heisel, T., Schou, J., Christensen, S. & Andreasen, C., 2001, «Cutting weeds with a CO2 laser», *Weed Research*, 41(1), 19–29.

Khan M.J. & Brodie G.I., 2018, «Microwave Weed and Soil Treatment in Agricultural Systems», *Global Journal of Agricultural Innovation, Research & Development*, 5(1), 1–14.

Koenis N., 2020, *Odd.bot: Design of an effector for weed control*.

Kurstjens, D.A.G. & Kropff, M.J., 2001, «The impact of uprooting and soil-covering on the effectiveness of weed harrowing», *Weed Research*, 41(3), 211–228.

Langsenkamp, F., Sellmann, F., Kohlbrecher, M., Kielhorn, A., Michaels, A., Ruckelshausen, A. & Trautz, D., 2014, «Tube Stamp for mechanical intra-row individual Plant Weed Control», 12.

Loghavi, M. & Behzadi Mackvandi, B., 2008, «Development of a target oriented weed control system», *Computers and Electronics in Agriculture*, 63(2), 112–118.

Lütkemeyer, L., 2000, «Hydropneumatische Unkraubekämpfung in Reihenkulturen», *Zeitchrift für Pflantzenkrankheiten und Pflanzenschutz*, (17), 661–666.

Mahoney, D.J., Jeffries, M.D. & Gannon, T.W., 2014, «Weed control with liquid carbon dioxide in established turfgrass», *Weed Science Society of America*, 560–568.

Martelloni, L., Fontanelli, M., Frasconi, C., Raffaelli, M. & Peruzzi, A., 2016, «Cross-Flaming Application for Intra-Row Weed Control in Maize», *Applied Engineering in Agriculture*, 32(5), 569–578.

Martelloni, L., Frasconi, C., Sportelli, M., Fontanelli, M., Raffaelli, M. & Peruzzi, A., 2020, «Flaming, Glyphosate, Hot Foam and Nonanoic Acid for Weed Control: A Comparison», *Agronomy*, 10(1), 129.

Mathiassen, S.K., Bak, T., Christensen, S. & Kudsk, P., 2006, «The Effect of Laser Treatment as a Weed Control Method», *Biosystems Engineering*, 95(4), 497–505.

Natuiton, no date, *Violette Le desherbeur autonome pionnier des gazons sportifs*.

Nishimura A., Asai M., Shibuya T., Kurokawa S. & Nakamura H., 2015, «A steaming method for killing weed seeds produced in the current year under untilled conditions», *Crop Protection*, 71, 125–131.

Pannacci E., Lattanzi B. & Tei F., 2017, «Non-chemical weed management strategies in minor crops: A review», *Crop Protection*, 96, 44–58.

Raffaelli M., Martelloni L., Frasconi C., Fontanelli M., Carlesi S. & Peruzzi A., 2016, «A prototype band-steaming machine: Design and field application», *Biosystems Engineering*, 144, 61–71.

Rask A. M., Larsen S. U., Andreasen C. & Kristoffersen P., 2013, «Determining treatment frequency for controlling weeds on traffic islands using chemical and non-chemical weed control», Lotz B. (ed.), *Weed Research*, 53(4), 249–258.

Reschke P., 2015, *Freezing weeds to death*, *Ontario Farmer; London*.

Slaughter D.C., Giles D.K. & Downey D., 2008, «Autonomous robotic weed control systems: A review», *Computers and Electronics in Agriculture*, 61(1), 63–78.

Thomas F., 2018, *Désherbage alternatif : un monde sans glypho mais avec des idées*, *Agronomie, Ecologie et Innovation TCS*, (97), 18–25.

Utstumo T., Urdal F., Brevik A., Dørum J., Netland J., Overskeid Ø., Berge T.W. & Gravdahl J.T., 2018, «Robotic in-row weed control in vegetables», *Computers and Electronics in Agriculture*, 154, 36–45.

Van der Schans D., Bleeker P., Molendijk L., Plentinger M., Van der Weide R., Lotz B., Bauermeister R., Total R. & Baumann D.T., 2006, *Practical weed control in arable farming and outdoor vegetable cultivation without chemicals*, Applied plant research, Wageningen.

Van der Weide R., Bleeker P., Achten V.T.J.M., Lotz L.A.P., Fogelberg F. & Melander B., 2008, «Innovation in mechanical weed control in crop rows», *Weed Research*, 48(3), 215–224.

Wortman S. E., Forcella F., Lambe D., Clay S.A. & Humburg D., 2020, «Profitability of abrasive weeding in organic grain and vegetable crops», *Renewable Agriculture and Food Systems*, 35(2), 215–220.

Xiong Y., Ge Y., Liang Y. & Blackmore S., 2017, «Development of a prototype robot and fast path-planning algorithm for static laser weeding», *Computers and Electronics in Agriculture*, 142, 494–503.