Agronomy Research **18**(S2), 1380–1387, 2020
https://doi.org/10.15159/AR.20.135

Experimental efficiency evaluation of 445 nm semiconductor laser for robotized weed control applications

V. Osadčuks[1,*], A. Kostromins[2], A. Pecka[2], V. Koteļeņecs[3] and J. Jaško[3]

[1]Latvia University of Life Sciences and Technologies, Faculty of Engineering, Čakstes blvd. 5, LV-3001 Jelgava, Latvia
[2]Latvia University of Life Sciences and Technologies, Faculty of Information Technologies, Liela street 2, LV-3001, Jelgava, Latvia
[3]Latvia University of Life Sciences and Technologies, Institute for Plant Protection Research "Agrihorts", Paula Lejina iela 2, LV-3004 Jelgava, Latvia
*Correspondence: vtl@tvnet.lv

Abstract. Robotized weed control is one of perspective approaches for decreasing ecological impact of farming. Although current level of technology development allows robotized weed control to be economically reasonable only in specific applications, it is only a matter of time to introduce them in full-scale industrial farming. In general terms weed control using agricultural robots consist of two parts: recognition and spatial localization of weeds (distinguishing them from crops) and precision application of some kind of growth limiting activity. Recognition and localization is usually carried out using computer vision solutions (image filtering and transformations, artificial neural networks etc.). Growth limiting in its turn is performed by mechanical, precise chemical, thermal, cryogenic or other means. This article covers application of laser radiation for thermal destruction of unwanted plant canopies. In most cases CO_2 type lasers with 10.6 µm wavelength is used as they are affordable and they are applicable to use with plant biomass due to their spectral characteristics. Drawbacks of CO_2 lasers are low efficiency, size, weight and complex maintenance. In recent years relatively powerful short-wavelength semiconductor lasers have became broadly available on market. Light absorption of healthy green leaves is much better in blue-UV spectrum than in green, far infrared and near infrared, which is almost completely reflected by leaves. Thus an experimental study of using 12 W output 445 nm blue semiconductor laser for weed canopy cutting was carried out. The experiments were performed with direct laser radiation, the laser module was positioned using robotic manipulator with different speeds and cutting patterns.

Key words: weed, laser, efficiency, robot.

INTRODUCTION

Organic farming has increased substantially in EU during last decade. The total organic area in the EU-28 was 13.4 million hectares (ha) in 2018 compared to 10.05 million ha in 2012 (Eurostat, 2020). Weed management is considered one of the most technically challenging issues in organic agriculture, especially for delicate crops like carrots (Peruzzi et al., 2007; Peruzzi et al., 2017). New technical solutions are needed in horticulture to manage weeds with high precision and low energy consumption (Marx et al., 2012).

Thermal treatment by high intensity laser beam belongs to innovative physical methods which lacks extensive study (Pannacci et al., 2017), however along with other types of thermal treatment (Mojžiš et al., 2017) it seems to be promising approach. Visible and IR lasers cause explosive ejection, i.e. ablation of plant tissue generated by multiphoton and avalanche electron ionization (Bloembergen, 1974). Multiple research results have been published describing laser impact on plant growth (Sato et al., 2000; Mathiassen et al., 2006; Heisel et al., 2008; Marx et al., 2012). Studies typically combine different factors to determine optimal weed thermal treatment. In (Marx et al., 2012) authors evaluate the influence of 10.6 µm CO_2 laser radiation combining three laser spot diameters, three laser spot positions and six laser intensities. The treatment was applied on three growth stages of two weed species (monocotyledonous: *Echinochloa crus-galli*, dicotyledonous: *Amaranthus retroflexus*). Research additionally compares two laser guidance patterns: 1) wobbled laser beam with total diameter of 6 mm, 2) static unfocused laser beam with total diameter of 6 mm. The paper reports that lethality was greatest if high intensity treatment was carried out at early growth stages, while unfocused laser beam reduced lethality rate. In (Mathiassen et al., 2006) authors apply direct laser beam on apical meristems at the cotyledon stage of three different plant species: *Stellaria media* (common chickweed), *Tripleurospermum inodorum* (scentless mayweed) and *Brassica napus* (oilseed rape). The research reveals the biological effect by applying combination of two continuous wave diode laser types (5W 532 nm and 90W 810 nm), two spot sizes with a five different energy levels on each weed species. The green laser turned out to be more efficient and lethality was achieved at a much lower energy dose comparing to near infrared laser. In (Sato et al., 2000) authors also test two laser types (532 nm and 1,064 nm) with four emissions. The green laser with intensity between 56.6×4–144×4 GW m^{-2} and a single emission of 342GW m^{-2} affected the leaves physically, while infrared laser with intensity between 83.8×4 to 375×4 GW m^{-2} did not affect the plant at all.

A few studies have been made to simulate field conditions (Nadimi et al., 2009; Xiong et al., 2017) for laser treatment approach. The mobile robot prototype was developed equipped with two servo driven low power laser pointer lasers (Xiong et al., 2017). They simulated laser irradiation and focused mainly on traveling over the weed trays at laboratory conditions evaluating the optimum laser beam path traveling algorithm from weed to weed. Different approach was proposed by (Nadimi et al., 2009) where three conveyor belts were used to transport weed pots thus simulating mobile robot moving in the field.

All pointed studies were carried out in ideal laboratory conditions not taking into account the field environment such as soil irregularity, dust, wind, sun etc. Each of these factors can negatively impact success rate of precise laser application over apical meristems due to optical distortions (dust, sun, moisture) and non static target due to wind. According to (Marx et al., 2012) wobbled laser pattern is more efficient in case of smaller values of applied energy. Moreover, due to lower laser power (CO_2 25W), the risk of local perforation caused by intensive thermal impact reduces, thus the amount of energy not being absorbed decreases. Based on these facts in our study we focus on pattern use over weed canopy area instead of precise finding of weak spot – apical meristem. For majority of weed species, their external look change after first treatment

(Marx et al., 2012) what in field conditions will disallow to effectively find the weak spots. Therefore possible solution would be to recognize individual plant of the crop and consider as weeds all other green biomass regardless of its to species, stage of growth, anomalies in development etc.

While most of the studies regarding laser weed control rely on precise weak spot treatment or laser cutting, aim of this study was to develop robust methodology for effectiveness evaluation of weed treatment using laser patterns over green biomass that could be used in the field trials afterwards and deliver preliminary results on pattern and speed effect.

MATERIALS AND METHODS

The properties of laser treatment process evaluated in this study: treatment speed and energy required to limit or stop growth of a weed plant.

To evaluate performance of the laser in weed treatment an experimental setup was designed (see Fig. 1). Semiconductor laser module PLH 12000 with 12 W optical output power and 445 nm peak wavelength was used. The module was mounted on an industrial robot manipulator Universal Robots UR10. The robot was controlled remotely from a PC using server-client approach (Universal-Robots, 2020) over TCP protocol, thus it was possible to easily adjust laser moving speed, treatment pattern trajectory and output power. To ensure reliable real-time operation a full list of pattern trajectory coordinates are sent to robot controller before irradiating desired weed area.

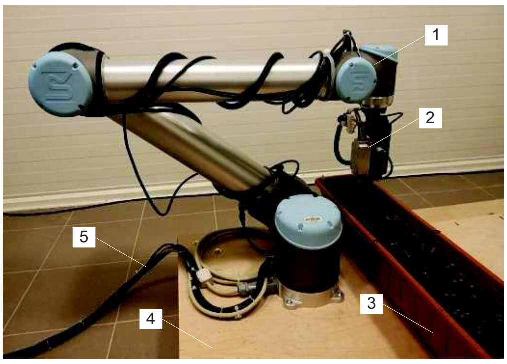

Figure 1. Experimental setup: 1 – UR 10 robot manipulator; 2 – PLH-12000 laser module; 3 – pot with weeds under treatment; 4 – moveable platform; 5 – power and communication cables to robot controller.

Area with weeds was treated individually by applying specific laser movement pattern and varying its size and movement speed. The laser was always operated at constant maximum optical output power therefore irradiation energy per square unit of area in a pattern was affected only by laser head speed. The pattern was applied to the center of a plant canopy (or pot) without taking into account plants size and individual form. Patterns were generated and sent from PC custom written software, pre-defined spiral drawing algorithm was used (Draw an Archimedes spiral, 2020).

This approach was chosen instead of precision treatment of leaves to bring the experiment conditions closer to real life situation with a mobile robot on field. In such conditions precise position of weed is complicated to determine, as well as other sporadic factors like close proximity of cultivated plants and wind effect will result in some portion of laser radiation not to reach intended target.

The following three experiment types were performed.

1. Experiment for determination effect of different treatment patterns. Two treatment patterns were used: spiral-shaped 10 mm in diameter, 8 evenly distributed loops and 'zig-zag'-shaped covering 10×10 mm square, 6 lines. Laser movement speeds were selected so that whole pattern would be drawn in approximately in the same time for both cases. One treatment per plant.

2. Experiment for determination treatment effect on multiple plants at once. Whole vegetating pot was treated using 30 mm s^{-1} or 90 mm s^{-1} speed, while all other parameters were the same. Spiral pattern was used with total diameter of 60 mm and 24 loops, all individual plants were located inside it. One treatment per pot.

3. Experiment for determination of laser energy amount on individual plants. Individual plants were treated using 30 mm s^{-1} or 90 mm s^{-1} speed, while all other parameters were the same. Spiral pattern was used with total diameter of 15 mm and 12 loops. One treatment per plant.

Table 1. Summary of experimental laser movement patterns and amount of applied energy

Exp. type	Laser movement speed, mm s^{-1}	Pattern diameter or side length	Area, mm^2	Treat-ment time, s	Total energy, J	Energy per length unit, J mm^{-1}	Energy per area unit, J mm^{-2}
1	22	10	100	6.04	72	0.60	0.725
1	20	10	79	5.88	71	0.59	0.898
2	30	60	2,827	74.50	894	0.40	0.316
2	90	60	2,827	25.28	303	0.13	0.107
3	30	15	177	9.12	109	0.38	0.619
3	90	15	177	3.38	41	0.14	0.229

Summary of experimental patterns is given in Table 1. Fig. 2 shows graphical details for each pattern. Calculations of applied energy were made for constant maximum laser output of 12W.

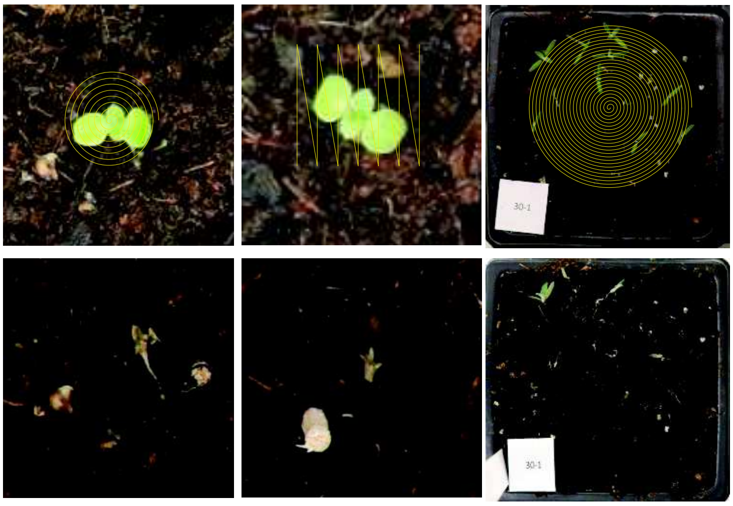

Figure 2. Laser movement patterns used during plant treatment: upper row – individual plant spiral, individual plant 'zig-zag', whole pot spiral; lower row – respective treatment results.

The experiments were performed on plants grown under controlled conditions in a research greenhouse at Institute for Plant Protection Research 'Agrihorts' with day temperature 21°C and night temperature 19 °C, relative humidity 60%, with natural and artificial lighting for 16h. Watering of plants was done by immersion method – every working day vegetation pots were immersed in a tap water 2 cm deep for 1 hour.

Plants with fully emerged cotyledons or emerging first true leaves were used in experiments, growth stage (GS) 11–12. Plant species for each experiment – (1) quickweed (*Galinsoga parviflora*); (2) pigweed (*Chenopodium album*); (3) cleavers (*Galium aparine*).

Evaluation of laser treatment effect on plant biomass was done after 7 days. Plants were cut just above the substrate and mass was measured on analytical balance (KERN ALJ 160-4AM).

To evaluate effectiveness of three different treatment approaches with limited samples, calculations were made with assumption that average mass of treated plants without treatment would be the same as for control group according to the following formulae.

$$\eta_w = 100 - \frac{\overline{m}}{\overline{m}_{control}} \cdot 100\% \qquad (1)$$

where η_w – relative weeding effectiveness showing decrease in average mass of individual plant in 7 days after laser treatment; $\overline{m}$ – average mass of individual plants in experimental group; $\overline{m}_{control}$ – average mass of individual plants in experimental group.

$$\eta_E = \frac{E}{\overline{m}_{control} - \overline{m}} \text{ (J m}^{-1}\text{)} \qquad (2)$$

where η_E – relative energy effectiveness showing how match optical laser energy was used to decrease mass of individual plant; E – total energy used in treatment.

RESULTS AND DISCUSSION

Results of the effect of laser treatment on changes in plant biomass are summarized in Table 2 and graphically in Fig. 3.

Although experimental data are not fit for statistical analysis due to small number of plants,there is clear tendency observed that proposed laser treatment approach limit weed growth. As expected, an increase in treatment time and thus in total treatment energy gives better result in limiting weed growth for experiments 1 and 2. Only exception is experiment (3), where slightly lower mass after 7 days of post-treatment vegetation is for group treated with lower energy. This could be explained with low number of plants and subsequent increase in fluctuations in results.

Table 2. Summary of experimental results by type of experiment: 1 – different laser treatment patterns on quickweed (*Galinsoga parviflora*); 2 – different treatment speeds, spiral pattern over multiple plants on pigweed (Chenopodium album); 3 – different treatment speeds, spiral pattern over individual plants on cleavers (*Galium aparine*)

Group	Total mass, g	Plant count	Average mass per plant, mg
1 – spiral	0.0147	9	1.6
1 – zigzag	0.0154	9	1.7
1 – control	0.2245	16	13.8
2–30 $\text{mm}\cdot\text{s}^{-1}$	0.2118	34	6.0
2–90 $\text{mm}\cdot\text{s}^{-1}$	0.4096	34	11.8
2 – control	0.6054	38	15.9
3–30 $\text{mm}\cdot\text{s}^{-1}$	0.2499	9	27.8
3–90 $\text{mm}\cdot\text{s}^{-1}$	0.2225	9	24.7
3 – control	0.7828	18	43.5

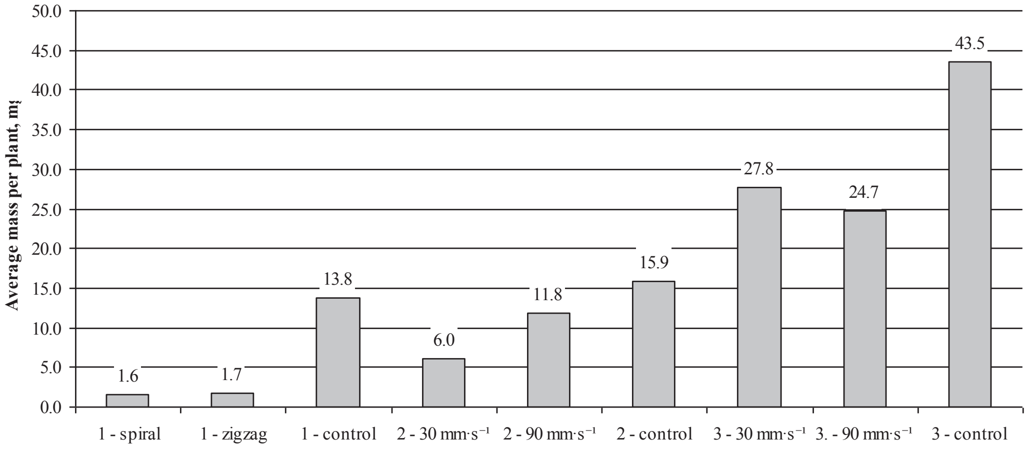

Figure 3. Average mass per plant for each experimental group after 7 days of post-treatment vegetation by type of experiment: 1 – different laser treatment patterns on quickweed (*Galinsoga parviflora*); 2 – different treatment speeds, spiral pattern over multiple plants on pigweed (*Chenopodium album*); 3 – different treatment speeds, spiral pattern over individual plants on cleavers (*Galium aparine*).

Different plant species can show different reaction to laser irradiation. This can be clearly seen on Fig. 4, where *Galium aparine* plants were able to regrow new leaves.

Table 3 shows relative performance of laser treatment in comparison to control group in each experiment according to equations (1) and (2).

If compared to two other experiments in experiment 2 total effectiveness is lower. It can be explained by the fact that distance between circles of treatment pattern was relatively large comparing with size of the leaves, which resulted in less effective coverage of all plants in the pot.

Energy amounts used for area treatment in our experiment are comparable to lower end values in other similar research with precision spot treatment: 0.6 to 5.9 J mm^{-2} with green 532 nm laser (Mathiassen et al., 2006) and 0.4 to 20 J mm^{-1} CO_2 10,600 nm laser (Heisel et al., 2008). Authors in these studies focused on achieving lethal outcome on plant during single laser treatment. Although there were only few lethal cases for plants after area treatment, mass reduction achieved in our experiments can serve as basis for further study with area treatment using laser patterns with presented methodology.

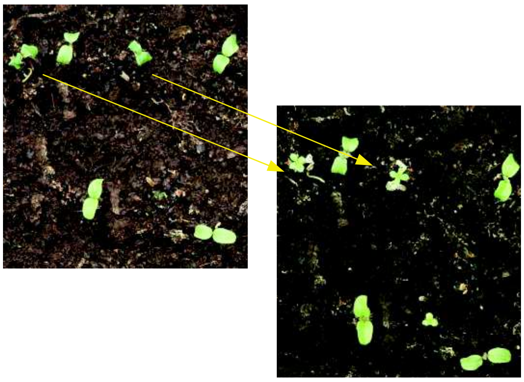

Figure 4. Experiment (3) with laser treatment of *Galium aparine*: right after treatment (top) and after 7 days of post-treatment vegetation (bottom). Yellow arrows show regrown leaves.

Plant biomass measurement is a destructive (plant should be cut down) and time intensive. For next experiments alternative methods to measure treatment effectiveness are going to be considered, especially ones based on leaf area optical measurement.

Table 3. Relative performance of laser treatment: 1 – different laser treatment patterns on quickweed (*Galinsoga parviflora*); 2 – different treatment speeds, spiral pattern over multiple plants on pigweed (*Chenopodium album*); 3 – different treatment speeds, spiral pattern over individual plants on cleavers (*Galium aparine*)

Group	Relative weeding effectiveness η_w, %	Relative energy effectiveness η_E, J·mg^{-1}
1 – spiral	88.2	0.221
1 – zigzag	87.6	0.179
2–30	62.0	0.128
2–90	25.8	0.105
3–30	36.2	0.039
3–90	43.2	0.012

Our proposed laser application method for weed control is simple to implement using current computer vision technologies and available plant datasets and does not require precision plant weak spot identification, which could be very cumbersome in real-life conditions. Moreover by simple identification of green biomass it is easy to do weeding repeatedly, even if weeds are partly damaged and visually differ from normal plants.

CONCLUSIONS

Preliminary results show, that 445 nm blue semiconductor laser can be effectively used for weed management. The best energy effectiveness is for treatment area, which is close to the size of plant canopy. Type of treatment pattern turned out not to be a significant factor in our experimental setup.

Particular plant species can regrow their leaves after laser treatment so this issue needs to be taken into account when frequency of field applications is calculated. Number of plant samples should be increased to statistically eliminate various random factors affecting both laser treatment process and plant development after it.

The following directions for further experimental studies can be formulated:

Test variable energy amount per square unit of area to find dependency curves and minimum energy necessary to limit plant development;

Search for optimum treatment pattern size by maximizing relative energy effectiveness factor;

Test treatment at different growth stages, especially for fast growing weeds.

ACKNOWLEDGEMENTS. This study is a part of project ‘Development of a robotic weed management equipment’ No. 18-00-A01612-000024 and co-financed by European Union - European Agricultural Fund for Rural Development. Project is supported by Latvian Ministry of Agriculture and Rural Support Service within National Development Plan 2020.

Authors wish to acknowledge the help provided by staff of Laser Technology Center of Rezekne Academy of Technologies and especially Dr. Pavels Narica.

REFERENCES

Bloembergen, N. 1974. Laser-induced electric breakdown of solids. *IEEE Journal of Quantum Electronics QE,* **10**, 375–386.

Draw an Archimedes spiral in C# – C# Helper. *http://csharphelper.com/blog/2018/10/draw-an-archimedes-spiral-in-c/.* Accessed: 31.01.2020.

Eurostat, Organic farming statistics 2020. *https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Organic_farming_statistics#Total_organic_area.* Accessed: 31.01.2020.

Heisel, T., Jørgen, S., Christensen, S. & Andreasen, C. 2008. Cutting weeds with a CO_2 laser. *Weed Research* **41**, 19–29. 10.1046/j.1365-3180.2001.00212.x

Marx, C., Barcikowski, S., Hustedt, M., Haferkamp, H. & Rath, T. 2012. Design and application of a weed damage model for laser-based weed control. *Biosystems Engineering* **113**(2), 148–157.

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. 10.1016/j.biosystemseng.2006.08.010.

Mojžiš, M., Vitázek, I. & Klúčik, J. 2017. Effect of flame weed control on various weed species at various developmental stages. *Agronomy Research* **15**(5), 2004–2011. https://doi.org/10.15159/AR.17.051

Nadimi, E., Andersson, K., Jørgensen, R., Maagaard, J., Mathiassen, S. & Christensen, S. 2009. Designing, modeling and controlling a novel autonomous laser weeding system. 10.13031/2013.29077.

Pannacci, E., Lattanzi, B. & Tei, F. 2017. Non-chemical weed management strategies in minor crops: a review. *Crop Protection* **96**, 44–58. 10.1016/j.cropro.2017.01.012.

Peruzzi, A., Ginanni, M., Fontanelli, M., Raffaelli, M. & Bàrberi, P. 2007. Innovative strategies for on-farm weed management in organic carrot. Renewable *Agriculture and Food Systems* **22**(4), 246–259. doi:10.1017/S1742170507001810

Peruzzi, A., Martelloni, L., Frasconi, C., Fontanelli, M., Pirchio, M. & Raffaelli, M. 2017. Machines for non-chemical intra-row weed control in narrow and wide-row crops: a review. *Journal of Agricultural Engineering* **48**(2), 57–70. https://doi.org/10.4081/jae.2017.583

Sato, K., Umezaki, T., Hoki, M. & Takaki, S. 2000. Fundamental Study of Laser Application for Weed and Pest Control. *Journal of the Japanese Society of Agricultural Machinery, Volume* **62**(5), 98–103. 10.11357/jsam1937.62.5_98

Universal-Robots Script Client-Server example. *http://www.zacobria.com/universal-robots-knowledge-base-tech-support-forum-hints-tips/knowledge-base/script-client-server/.* Accessed: 31.01.2020.

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***, Part B*, 494–503. 10.1016/j.compag.2017.11.023.