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Evaluation of Diode Laser Treatments to Manage Weeds in Row Crops

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Abstract: Herbicides have been the primary weed management practice in agriculture for decades. However, due to their effects on the environment in addition to weeds becoming resistant, alternative approaches to weed control are critical. One approach is using lasers, particularly diode lasers because of their portability, low power demand, and cost effectiveness. In this research, weeds' response to diode laser treatments was investigated. Three experiments were conducted. The first experiment involved treating two species of weeds with four different laser powers to determine the time it takes to sever the weed stem. The second experiment involved monitoring the status of two species of weeds for a week after treating them with two lasers at constant application times of 1 s, 2 s, and 3 s. The third experiment was a repeat of the second with higher laser powers and shorter treatment times. The results showed diode lasers have a potential to be an effective weed controlling tool. Weed stem diameter, laser power, treatment duration, and distance between laser and weed were all statistically significant in weed mortality, with weed species having no significance. Furthermore, it was found that weed management is possible by exposing the stem of the two weed species between 0.8 and 2.65 mm diameter to a laser beam dosage without necessarily severing it, with 80% effectiveness at 0.5 s treatment time, and 100% effectiveness using a 6.1 W laser for 1.5 s.

Keywords: laser weeding; precision weeding; non-chemical weed elimination

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1. Introduction

Weed management in agricultural fields is an important whilst challenging endeavor. Weeds are causing a tremendous economic loss in agriculture by reducing crop yield [1,2] which make them a major threat to food security [3].

Treating weeds with chemical herbicides has been the most effective and most used method of weed management [4,5]. However, there is a growing concern that herbicides are becoming ineffective as weeds become resistant. There are also environmental and health concerns with the overuse and mishandling of chemicals [6]. The alarming rate at which herbicide-resistant weed populations has been increasing, combining with herbicide costs, have made farmers seriously question the use of herbicides as the primary weed control mechanism [7–9]. Mechanical non-chemical weed control methods like cultivation and hand pulling are generally more labor-intensive [10], and in addition, they can increase soil erosion and leaching of plant nutrients [11]. All these reasons necessitate research into alternative methods of weed management.

Advances in technology, like the emergence of faster portable processors, artificial intelligence, advances in robotic technology, modern computer vision algorithms and equipment, modern mechanics, deep learning technology, and others, have provided an ample opportunity to explore smart and precision methods of weeding. A broad range of new tools for precision agriculture are growing at a rapid rate, technologies such as geo-positioning services from satellite systems, yield monitors and mapping software, geographical information systems (GIS), automatic guidance and steering of vehicles, have been implemented over the past decades [12].

The introduction of deep learning technology and image processing in agriculture have made real-time weed detection possible [13–17]. Precision weed elimination may be achieved using a robotic platform by targeting the individual weeds detected by these deep learning models. Research of targeted weed elimination such as, mechanical weed removal using robotic cutters [18] and precision spraying [16,19,20] have been successfully conducted to prove the potential of robotic weeding.

Lasers have emerged as one of the solutions that have a potential to be effective in targeted elimination of weeds. Treating weeds with laser beam can be efficient in controlling the growth of weeds [21–27]. Using narrow CO_2 laser beams (output powers of 4 W, 10 W, and 20 W), Heisel et al. [21] were able to cut weed stems, while using diode lasers (5 W and 90 W), Mathiassen et al. [25] showed laser beam can raise the temperature of the water in the plant cells and delay or stop its growth without the need to cut the stem completely. Woltjen et al. [27] studied the effects of both CO_2 and diode lasers treatments on plants and discovered different degrees of effectiveness in hindering the growth of plants. Furthermore, using a 25 W fiber-coupled diode laser Coleman et al. [26] demonstrated the potential of lower energy laser in controlling weeds at different growth stages.

Weed management using lasers is a relatively new endeavor, there are not many systems currently in the market that have implemented this technology, however, several solutions have recently been implemented combining laser equipment, weed detection and robotics to control weeds (e.g., https://carbonrobotics.com, accessed on 15 June 2022; https://welaser-project.eu, accessed on 15 June 2022; https://weedbot.eu, accessed on 15 June 2022).

Targeted narrow laser beams have the potential of removing not only the inter-row weeds but also the intra-rows weeds with proper detection, localization and laser targeting hardware and software. In addition, effects on soil health and non-targeted organisms will be minimized, avoiding interference with other crop activities, and preserving beneficial organisms [28].

The main objective of this study was to investigate the effectiveness of low power diode lasers on killing weeds. Diode lasers (Figure 1) emit the beam by passing current through a semiconductor. They have the advantage of being small, widely available, inexpensive, requiring low voltage and low current. Their uniqueness in size, weight, costs coupled with their high efficiency and reliability, makes them easier to integrate in systems [29], as opposed to other types of lasers available in the market, such as CO_2 and Fiber lasers. CO_2 lasers are relatively bulky, and require more voltage, current and a separate cooling system when operating in an outside environment while fiber lasers are the most powerful and most expensive of the three. Since the aim is to use the laser in a robotic platform (Figure 2), CO_2 and fiber lasers present a more challenging setup in terms of portability and costs. Furthermore, looking at laser safety, the laser beam turns into heat energy when it hits a surface. High energy lasers can potentially ignite materials and can cause thermal injury to a person [28]. Using diode lasers of low output power present less operational danger than the high-powered and more complicated CO_2 and fiber lasers; however, it can still cause damage to the eyes on exposure, so, proper caution wearing protecting glasses is necessary [28].

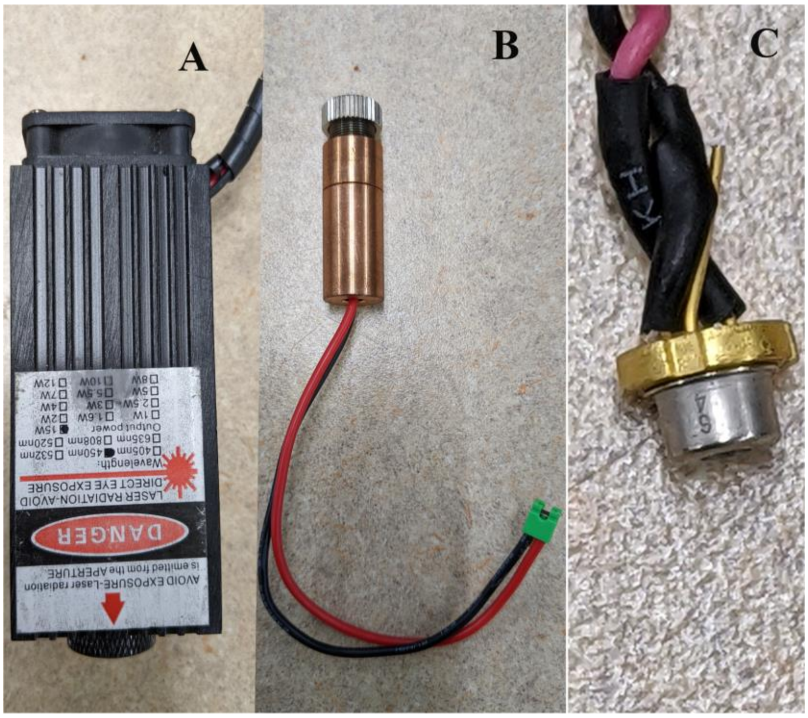

Figure 1. Diode lasers. (**A**) diode laser with heat sink enclosure including a fan, (**B**) diode laser without a cooling fan, and (**C**) exposed diode laser.

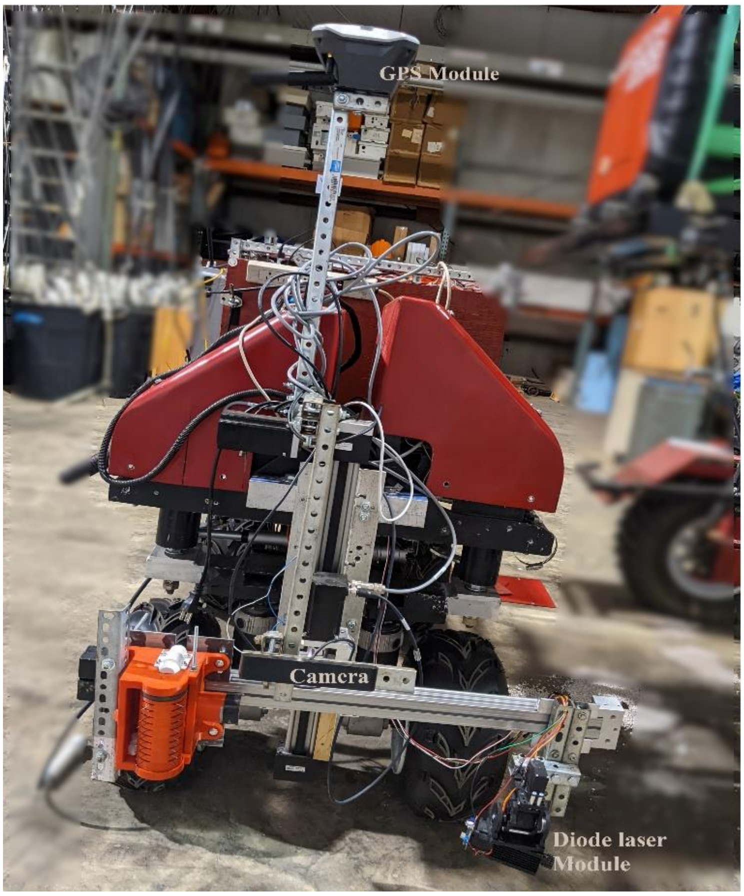

Figure 2. Robotic platform for laser weeding.

2. Materials and Methods

In this study two phenomena of diode lasers treatments on weeds were investigated. The first investigation aimed to find how effective are laser diodes with different power outputs in completely severing the stems of different weed species and determine the factors that affect the severing effectiveness, since cutting the weed stem completely ensures its elimination. On the other hand, it has been demonstrated that, it is not necessary to cut the weed stem completely for the weed to die, a laser beam can raise the temperature of plant cells, disrupt their structure and kill or stunt their growth [25,27], so, the second set of experiments aimed to investigate the effectiveness of diode lasers exposure for different durations in killing or stunt the growth of weeds without necessarily severing the weed stem.

2.1. Diode Lasers

Six blue laser diodes were tested in this study. Each of the lasers had an output power of less than 10 W, which is on the lower energy end on most of the laser weed studies. The laser diodes were divided into three classes based on their output power. Each diode laser power output was measured at about 5 cm from the laser lens using a Gentec Pronto-50-W5 (Gentec Electro-Optics, Inc., Quebec City, QC, Canada) portable laser power meter. The first class consisted of the lowest energy laser diodes of the group; a 1.2 W laser diode (Nichia M140, 450 nm wavelength, 2.5 mm beam spot diameter) and a 1.35 W laser diode (Nichia M140, 450 nm wavelength, 2.5 mm beam spot diameter). The second class consisted of a 4.2 W 450 nm laser diode with a spot diameter of about 2.5 mm (Nichia NUBM49) and a 4.5 W 450 nm laser diode with a spot diameter of about 2.6 mm (Nichia NUBM4B). The third class consisted of a 5.1 W 450 nm (Nichia NUBM44) and 6.1 W 450 nm (Nichia NUBM47) with 2.5 mm spot diameter each. These laser diodes were fixed with G-8 lenses to focus the beam.

2.2. Weed Species

Seedlings from two weed species Palmer amaranth (*Amaranthus palmeri*) and small-flower morningglory (*Jaquemontia tamnifolia*) were collected from the University of Georgia research fields near Ty Ty, GA (31.50973° N, 83.65588° W), then planted in pots and transferred to a greenhouse (Figure 3). Four 8 by 16 seedling pot trays were used for planting these weeds about 2 weeks after their emergence. The weeds were grown for another week before laser treatment (about 3 weeks after emergence).

Figure 3. Collected weeds in the pots in greenhouse before treatment. Small flower morningglory (**A**), and Palmer Amaranth (**B**).

2.3. Experiment 1—Severing the Stem

The first experiment aimed to investigate how long it takes for low-power diode lasers to sever the weed stem and what factors affect the effectiveness of the diode lasers

Four diode lasers, 1.2 W, 1.35 W, 4.2 W, and 4.5 W were used to treat weed stems of the two weed species until they were severed. The laser diodes were placed at three different distances of 5 cm, 10 cm, and 15 cm from the weed stems.

The laser was setup as in Figure 4; an Arduino Uno microcontroller (Open-source electronics platform) controls the laser beam through TTL (Transistor to Transistor Logic) signal sent to the constant current source laser driver. A button press-and-hold turns the laser diode on and hits the weed stem until it cuts through. Once the weed stem is severed, the button is released, and the Arduino records the duration the button was pressed.

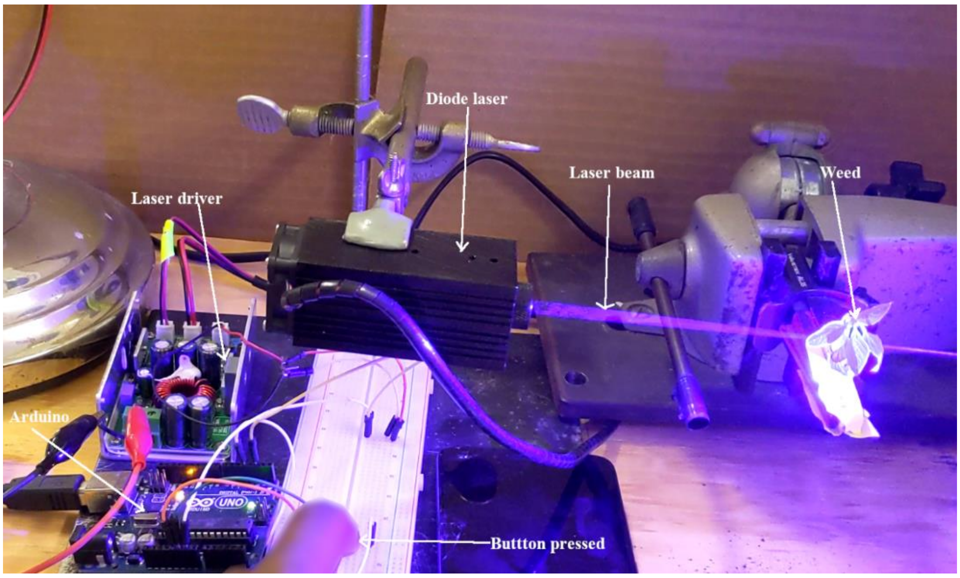

Figure 4. Laser setup to cut the weed stem completely.

The laser beam hit the weed perpendicular to the stem at approximately the center of the stem.

This was arranged as a factorial experiment with 4 laser output powers, 2 weed species, and 3 distances between the laser and the weed stems, for a total of 24 individual treatments. The experiment was replicated 5 times

The data for laser power, distance between the laser diode and weed stem, diameter of the stem, weed species, and treatment duration were recorded for each treatment. The diameter of stem at the point of the laser application was measured using an electronic caliper. Statistical analysis of the data was done by performing the analysis of variance (ANOVA) on the linear regression model of the data with a continuous dependent variable (time taken to sever the stem) using R programming language [30] at 5% significant level and means compared using *t*-test and Tukey method since the dependent variable (time taken to sever stem) is continuous.

2.4. Experiment 2—Time Limited Laser Treatment

This experiment aimed to investigate the effect of laser diodes when directed to weed stems for fixed time durations without necessarily severing the stem.

Since there was no difference in effects of the laser diodes within the classes (Section 3.1), only two diodes were used for this experiment; 1.2 W and 4.2 W, and since the diodes were more effective between 5 cm and 10 cm from the weed stem, the laser diodes were placed at approximately 5 cm and perpendicular to the weed stems.

Weed stems of the two weed species were treated with laser beams from the two laser diodes for the fixed durations of 1, 2, and 3 s. The weeds were treated while inside the pots to not interfere with their normal growth (Figure 5), the untreated weeds in the pots were left as a control group. The laser side setup was the same as in Figure 4, except now the treatment duration was fixed, so, once the button was pushed, the weed stem would be exposed to the laser beam for the set duration or dosage.

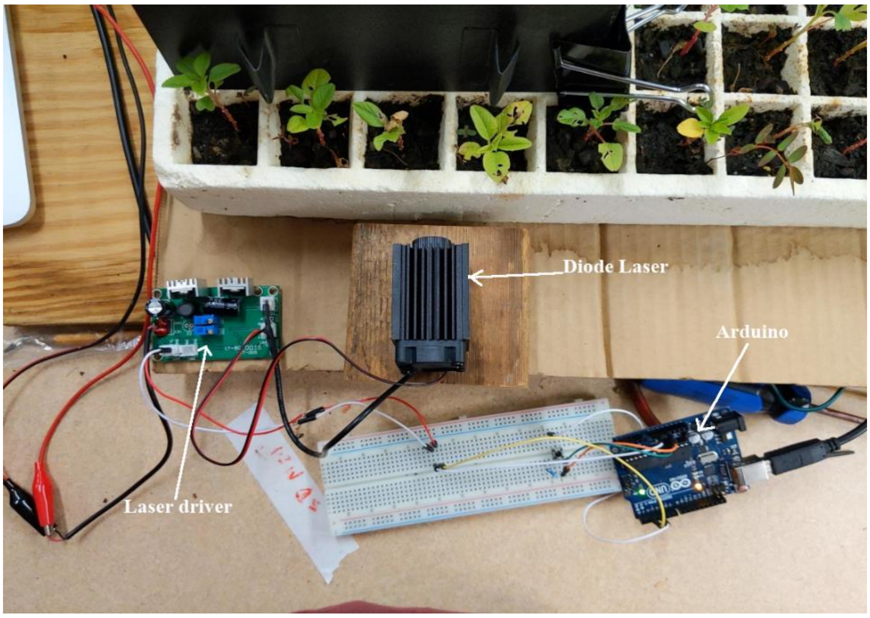

Figure 5. Weeds in the pots being treated by a diode laser.

The experiment was arranged as a factorial experiment with 2 laser output powers, 2 weed species, and 3 treatment times for a total of 12 individual treatments and was replicated 5 times.

The data for laser power, diameter of weed stem, treatment duration, and weed species were recorded for each treatment. The weeds were monitored for a week, then the status of each treated weed was recorded (killed/survived). Since the dependent variable (status) of our data was categorical with two levels (killed/survived), the statistical analysis was done on a logistic regression model of the data using R programming language [30] by fitting a generalized linear model with binomial family and evaluated at 5% significant level.

2.5. Experiment 3—Time Limited Laser Treatment with More Power

For the laser diodes to be effective on a weeding robot in the field, the treatment time needs to be as short as possible. The 3 s treatment time which was the most effective using the 4.2 W diode laser in Section 3.2 would not be efficient in a field application. So, we investigated the effect of increasing the laser output power and lowering the treatment time. Like in experiment 2, the two species of weeds inside the pots were treated with laser beams from laser diodes positioned about 5 cm and perpendicular to the weed stems, but now the laser powers were 5.1 W and 6.1 W, and the treatment duration was 0.5, 1, and 1.5 s.

This was designed as a factorial experiment with 2 laser output powers, 3 treatment times, and 2 weed species for a total of 12 individual treatments and was replicated 5 times.

The data for laser power, weed species, diameter of weed stem, and treatment duration, were recorded for each treatment. The weeds were monitored for a week, then the status of each treated weed was recorded (killed/survived/stunted). Stunted status was added to the experiment results due to the observations in experiment 2. Statistical analysis was done on a multinomial logistic regression model of the data using the package ***nnet*** in R programming language [30] at 5% significant level since the dependent variable is categorical with more than two levels (killed/survived/stunted).

3. Results

3.1. Experiment 1 Results

The mean treatment time for each laser power shown in Table 1 demonstrates the effectiveness of the lasers as power is increased. Analysis of variance of a model with R^2 value of 91.7% showed that, the effects of laser power, diameter of stem, and distance between laser diode and stem were all significant, however, weed species effect was not significant in determining the time taken to cut the stem completely. Figure 6 demonstrates the effect of laser power on the treatment time in which the lower power lasers (1.2 W, 1.35 W) had slower response (about 5 s) than the high-power ones of 4.2 W and 4.5 W (about 2 s), the distance between laser and weed had a minor effect on the treatment duration, especially at 15 cm, while it seemed to have approximately the same effect at 5 cm and 10 cm. Small flower morningglory was cut quicker than Palmer amaranth, however, that is attributed to the difference in average diameter between the two species (Figure 6D).

Table 1. Mean time taken by each diode laser to sever weed stems at 5, 10, and 15 cm.

Laser Power (W)	Distance (cm)	Time (s) Mean	Standard Deviation
1.2	5	4.84	0.29
	10	5.23	0.69
	15	6.05	0.76
1.35	5	4.97	0.55
	10	4.94	0.47
	15	5.46	0.65
4.2	5	2.1	0.11
	10	2.04	0.19
	15	2.25	0.60
4.5	5	1.83	0.09
	10	1.95	0.16
	15	2.38	0.79

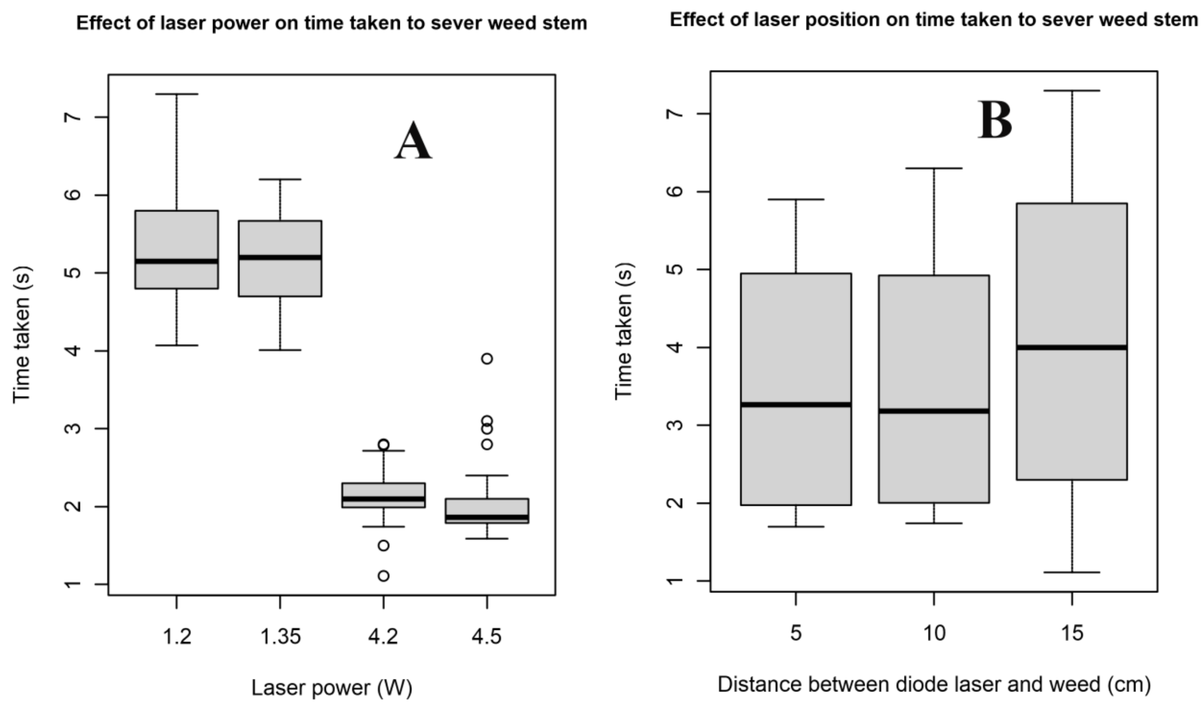

Figure 6. *Cont.*

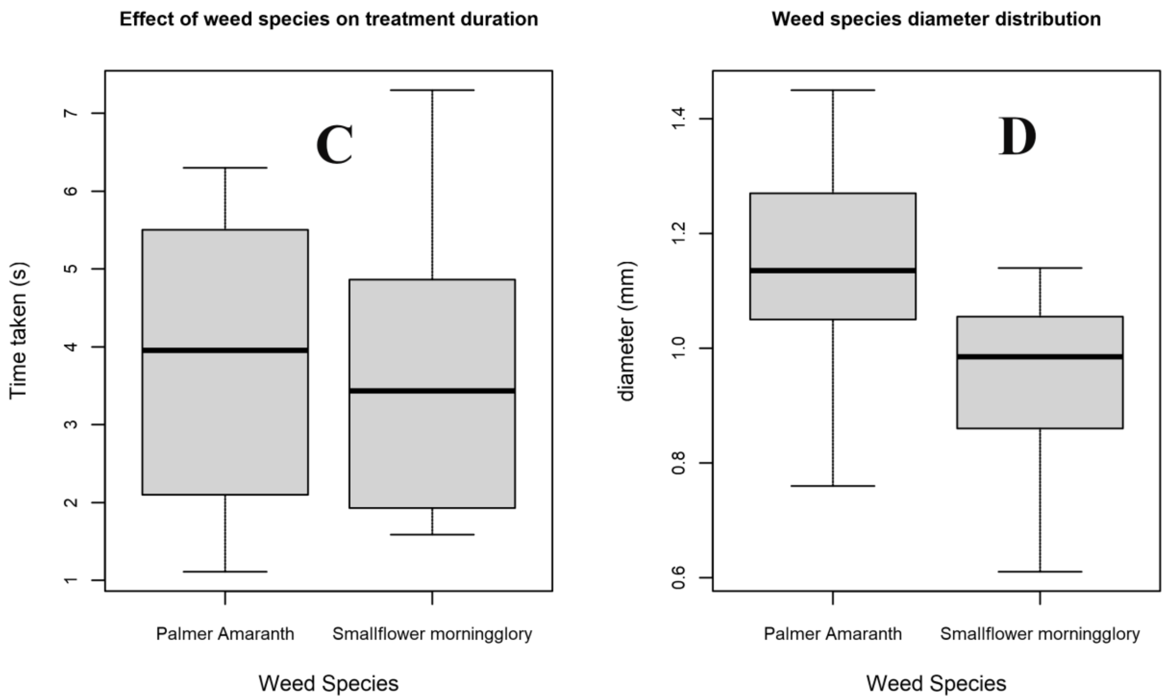

Figure 6. Box and whisker plots of the time taken to cut the weed stem vs. three factors, and the diameter data for each weed species. (**A**) shows the laser power effect where the error bars for first class (1.2 and 1.35W) lasers overlap significantly, likely, the second class (4.2 and 4.5W) lasers overlap, while the two classes not overlapping, hence the statistical significant difference between the classes while no difference within classes, (**B**) shows the effect of distance between laser diode and weed stem where the error bars overlap more between 5 and 10cm with less overlap at 15cm which caused the statistical difference, (**C**) represents the effect of species where the error bars overlap with no statistical difference, and (**D**) represents the diameters data for each weed species with palmer amaranth having slightly higher average diameter than smallflower morningglory.

Multiple comparisons for the laser power treatment means showed no statistical difference between the effect of 1.2 W and 1.35 W laser, as well as no statistical difference between the effect of 4.2 Wand 4.5 W laser treatments.

3.2. Experiment 2 Results

Results shown in Figure 7 and Table 2 demonstrate only 15% of the weeds were killed using 1.2 W laser when treated for 1 s and 2 s, while 70% of the weeds were killed when treated for 3 s. The 4.2 W laser killed 40% of weeds when treated for 1 s, 70% of weeds when treated for 2 s, and 100% when treated for 3 s. The laser power, diameter of the stem, and treatment duration were all significant, while the weed species was not significant. Diameter of the stem played a significant role in determining whether the weed was killed or survived, that is, Palmer amaranth was killed more than small flower morningglory because of the overall lower average stem diameter as demonstrated in Figure 8. Some treated weeds were not killed but appeared to have stagnated in their growth and some slightly wilted.

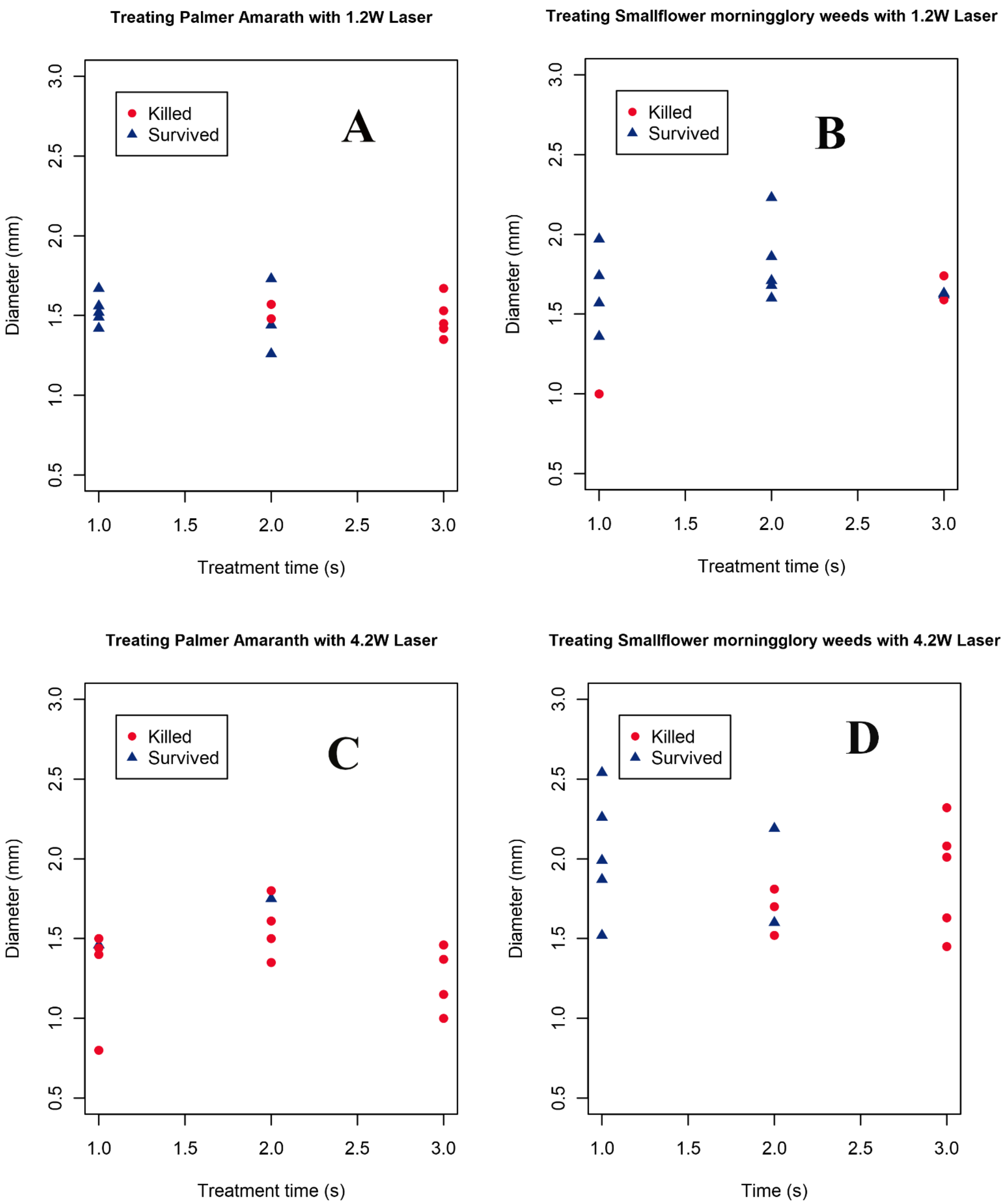

Figure 7. Status of weeds after 1 week of monitoring. (**A**) using 1.2 W laser on Palmer amaranth, (**B**) using 1.2 W laser on smallflower morningglory, (**C**) using 4.2 W laser on Palmer amaranth, (**D**) using 4.2 W laser on smallflower morningglory.

Table 2. Percentage of weeds killed after 1 week of monitoring.

Treatment Time (s)	Laser Power (W)	Weeds Killed (%)
1	1.2	10
	4.2	40
2	1.2	20
	4.2	70
3	1.2	70
	4.2	100

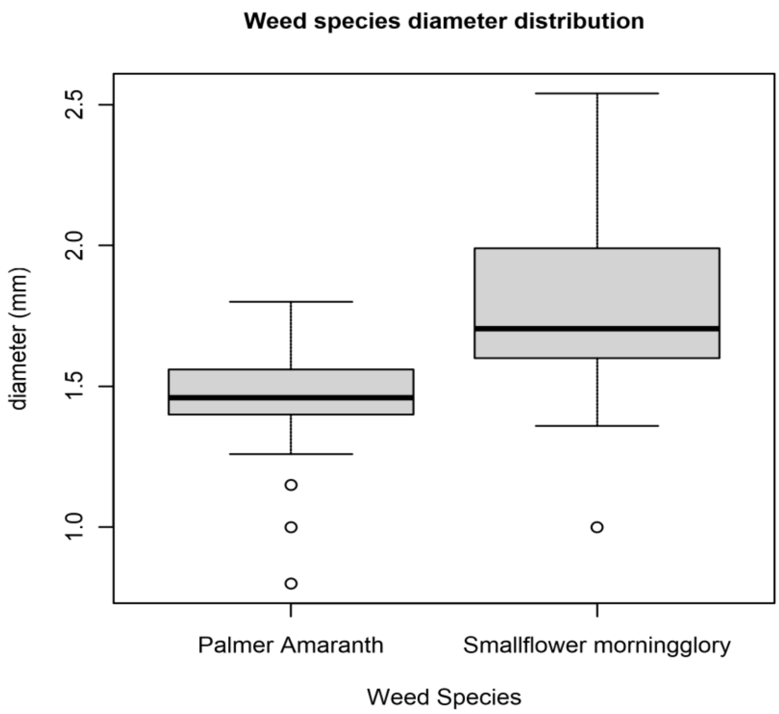

Figure 8. Differences in diameter between weed species tested in Experiment 2 where smallflower morningglory have slightly higher average diameter than palmer amaranth and the error bars slightly overlap to imply a possible statistical difference.

3.3. Experiment 3 Results

Figure 9 and Table 3 show the 5.1 W diode laser was 66.67% effective overall (kill/stunt) for the treatment times, while the 6.1 W diode laser was 80% effective for treatment durations of 0.5 s, and 1 s, but 100% effective for the 1.5 s duration. The diameter of stem and treatment duration were significant while there was no statistical difference between the laser powers. The species of the weed did not have any influence on the results.

Table 3. Percentage of weeds killed or stunted after 1 week.

Treatment Time (s)	Laser Power (W)	Weeds Killed (%)	Weeds Stunted (%)
0.5	5.1	40	20
	6.1	40	40
1	5.1	40	20
	6.1	60	20
1.5	5.1	60	20
	6.1	100	0

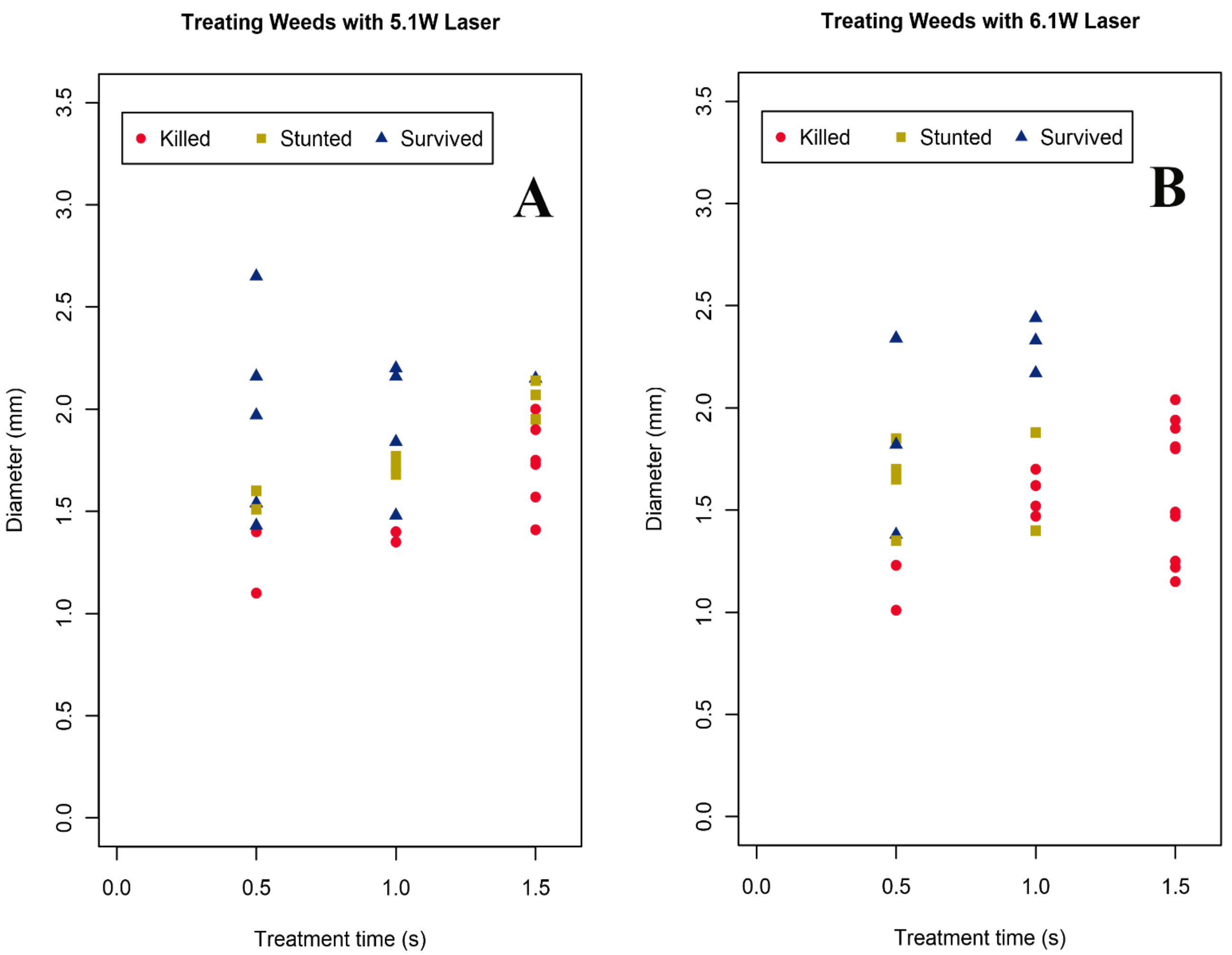

Figure 9. Status of weeds after 1 week of monitoring. (**A**) using 5.1 W laser, (**B**) using 6.1 W laser.

4. Discussion

The experiments conducted in this study proved that diode lasers can be an effective weed controlling tool. Increasing the diode laser power increased the possibility of killing the weed, this is however affected by the weed stem diameter, the bigger the weed stem, the more difficult to kill. In addition, the more time the weed is exposed to the laser beam, the more laser energy (J) it absorbs which in turn increases the likelihood of it being killed or stunted. Corresponding results from studies which focused on broadleaf weeds at early growth stages [23–25,27] reported similar observation that increasing in laser dosage has the effect of reducing the growth rate (stunt) or kill with variability in the required energy, however, under these studies the laser was positioned vertically targeting the apical meristem of the weed, which might affect the weed response to the treatment. Investigations involving cutting the weed stem with laser by Heisel et al. [21] found that stem thickness was an important factor. Further investigation by Heisel et al. [22] found that more energy was needed as stem thickness increased, which corresponds with our findings.

Using the data from experiment 2 and experiment 3, Figure 10 demonstrates the effect of laser energy (J) which is a product of laser power (W) and the treatment time (s) to the weeds of different diameters. Most of weeds which were exposed to high energy were killed, but as the energy goes down, the effect of diameter become more prevalent.

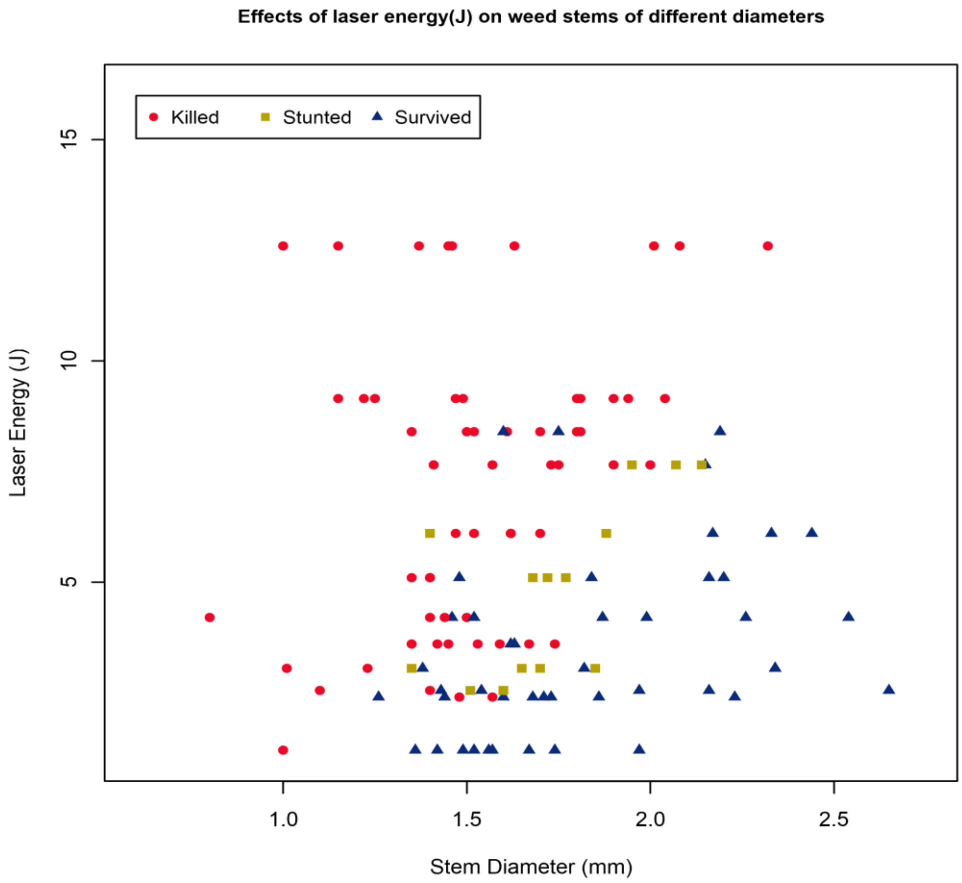

Figure 10. Effects of laser energy (power × treatment time) on weed stems of different diameters.

5. Conclusions

Six diode lasers were tested on their effectiveness in killing or stunting weeds. Three experiments were conducted. The first experiment aimed to determine the time taken to cut the weed stem completely, this experiment showed that weed species was not statistically significant, while the laser power, stem diameter, and distance between weed and laser diode were statistically significant on the survival of the weed. The second experiment demonstrated that weeds may be killed when exposed to a laser beam for a certain duration even when the stem was not cut completely; in addition, the experiment confirmed the conclusion from the first experiment on the significance of laser power and stem diameter, as well as the treatment duration. The third experiment showed that with more powerful diode laser, the treatment time can be reduced significantly for the laser to be effective in the field. With a target treatment time of 0.5 s, a 6.1 W laser was 80% effective in eliminating the weeds.

Due to their portability and low power demand, multiple diode lasers can easily be accommodated on a small robotic system. Treating the weeds with multiple laser beams at once, or in succession, and using a backstop to prevent the beam from hitting non-target plants may be an effective and safe way to reduce the treatment time while avoiding using a single high-powered laser. Future testing will investigate field performance on a small autonomous rover using machine vision for laser aiming and control in addition to observing the laser effect on crops.

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