Weed Technology

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Evaluation of a laser diode array as an efficient approach to laser weeding

Michael Walsh[1], Erik Muller[2] and Guy Coleman[3]

[1]Professor, Gulbali Institute, Charles Sturt University, Wagga Wagga, NSW, Australia; [2]Senior Technical Officer, Australian Center for Field Robotics, University of Sydney, Sydney, NSW, Australia and [3]Postdoctoral Researcher, Department of Plant and Environmental Sciences, Faculty of Science, University of Copenhagen, Taastrup, Denmark

Research Article

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Nomenclature:
Rigid ryegrass; *Lolium rigidum* Gaud.; wild radish; *Raphanus raphanistrum* L.

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Laser weeding; laser diode array; annual ryegrass; wild radish; nonchemical weed control; precision weed control; site-specific weed control

Corresponding author:
Michael Walsh; Email: michwalsh@csu.edu.au

Abstract

In-crop site-specific weed recognition systems have enabled precise and selective use of alternative nonchemical weed control technologies to provide much-needed support for weed management programs in large-scale cropping systems. Laser weeding has long been proposed, but only recently has it been commercialized as a highly precise, nonchemical weed control option for cropping systems. The weed control efficacy of several laser types (e.g., CO_2, diode, fiber, and Nd:YAG) has been identified; however, no studies have investigated the use of readily available, high-power, low-cost consumer-grade laser diode arrays. The weed control efficacy of a 97-W, 445-nm laser diode array was investigated with the aims of evaluating 1) the irradiation energy requirement (as determined by treatment duration) of spot laser treatments required to control key grass (rigid ryegrass) and broadleaf (wild radish) weeds and 2) the influence of growth stage on energy requirement for annual ryegrass and wild radish control. Seedlings of rigid ryegrass and wild radish at growth stage 1 (GS1) were controlled by low laser energy densities of 0.2 to 0.5 J mm^{-2}. As plant size increased, the energy densities required to control the seedlings increased substantially. For example, 2.0 J mm^{-2} was required to control GS4 rigid ryegrass, representing a 10-fold increase over that required for GS1 seedlings. Similarly aged but substantially larger wild radish seedlings remained mostly uncontrolled by 2.0 J mm^{-2} treatments. Wild radish was consistently more tolerant of laser treatments than annual ryegrass, but this difference was likely due to the more rapid growth rate that resulted in larger plants at the time of treatment, especially during warmer growing conditions. These results clearly define the potential for laser weeding using laser diode arrays and also identify the need for additional testing across a wider range of weed species with higher-powered, affordable diode arrays.

Introduction

Alternative nonchemical treatments are needed to sustain the ongoing efficacy of weed management programs in large-scale cropping systems. The reliance on herbicides for weed control has ultimately led to frequent and widespread evolution of herbicide resistance in many problematic weed species of the world's cropping regions (Heap 2024; Peterson et al. 2018). Herbicide resistance, reduced herbicide development, negative public perception of herbicide use, and increasing regulations are collectively threatening weed control capability in cropping systems, posing a significant risk to food security (Duke 2012; Peters and Strek 2018). The loss of highly effective herbicide options has created a pressing need for the development of feasible alternative weed control solutions, especially for large-scale cropping systems.

The development of in-crop weed recognition by machine vision systems enables the selective use of alternative weed control technologies in large-scale cropping systems. Identified as site-specific weed control (SSWC) technologies, the combined ability to recognize individual weed plants within a crop enables the selective use of nonselective and alternative weed control treatments (Coleman et al. 2022). Although research and development of alternative nonchemical weed control options has been underway for several decades (Ascard et al. 2007; Bond and Grundy 2001), there has been slow progress to commercializing them owing to high costs and a lack of in-crop selectivity. Where commercialization has been achieved, the high cost of the technology has often restricted its use to intensive, high-value production systems. For example, the Carbon Robotics LaserWeeder G1 costs US$1.2 million, according to a recent farmer case study (WGCIT 2024). Thus a need exists to capitalize on the developments in SSWC for nonchemical weed control options by enabling the development of low-cost options suitable for use across all production systems, including large-scale cropping (Bauer et al. 2020; Coleman et al. 2019).

Implementing site-specific weed control with nonselective alternative weed control treatments requires reliable and precise weed detection. This technology is now well advanced;

for example, at the highest spatial resolution for weed detection, recent assessments of instance segmentation for common weeds have demonstrated the opportunity to selectively target the meristematic tissue of grass and broadleaf weeds (Champ et al. 2020; Lottes et al. 2019; Zhang et al. 2024). This level of detection accuracy enables the use of high-precision weed-targeting treatments such as lasers for targeting the growing points of weed plants (Xu et al. 2024).

Since the 1970s, intermittent research has been conducted on the use of various laser forms for weed control (Andreasen et al. 2022). Laser, as an acronym, stands for "light amplification by stimulated emission of radiation." Simply put, varying the stimulation method and the stimulated media alters the wavelength, emission type (pulsed, continuous, and quasi-continuous), and quality of light. A common form, CO_2 lasers use a high-voltage electric discharge to excite a gas mixture of N_2, helium, and CO_2, resulting in light emission within the infrared wavelengths, typically 10,600 nm. This part of the spectrum is readily absorbed by water molecules and often used by the health care industry for this reason. Fiber lasers operate with a glass fiber "doped" (deliberately contaminated) with specific rare-earth materials such as thulium and neodymium (Nd). Crystal, solid-state lasers such as the Nd:YAG (Nd^{3+} ions substituted into an yttrium aluminum garnet [YAG]) welding laser (1,064 nm) have been used by Langner et al. (2006) with limited success, explained by targeting inaccuracy and the advanced growth stage weeds when the device was tested. Diode lasers are more widely available and compact. They are commonly found in laser pointers. The choice of semiconductor material determines the wavelengths and typically range from 400 to 2,000 nm. Given their presence in consumer electronics, diode lasers are generally lower in cost and without large gas tubes, they can be more robust, compact, and cheaper; however, power output and beam quality can be limited, hence industrial preference (e.g., welding) for alternatives. Power output limitations can be overcome while retaining diode laser benefits by stacking multiple laser diodes into laser diode arrays, without substantial increases in cost. As such, laser diode arrays are widely used as coherent and efficient light sources for modern digital laser projectors, thus representing a substantial opportunity to reduce the capital expense of laser weeding. Nevertheless, there has been no published research on the benefits of this approach.

Irrespective of laser method, laser-based cellular ablation and pyrolysis seek to disrupt the cellular function of the apical meristem through exposure to high temperatures. Over the last 50 yr of laser weeding research treatments with CO_2 lasers (10,600 nm) have been shown to substantially reduce the growth of many weed species such as water hyacinth (*Eichhornia crassipes* [Mart.] Solms), volunteer rye (*Secale cereale* L.), and wild oat (*Avena fatua* L.) (Bayramian et al. 1993; Couch and Gangstad 1974). Recent assessments by Sosnoskie et al. (2025) have confirmed the real-world benefits of the approach, with the performance of a commercial LaserWeeder system (Carbon Robotics, Seattle, WA) that uses CO_2 lasers demonstrating equivalent or better control than herbicide-only treatments.

Evidence of the effectiveness of laser pyrolysis with diode and CO_2 lasers has been observed with the control of cultivated tobacco (*Nicotiana tabacum* L.) (Wöltjen et al. 2008), barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv.] (Marx et al. 2012; Wöltjen et al. 2008), and redroot amaranth (*Amaranthus retroflexus* L.) at the seedling, 2-leaf, and 4-leaf growth stages. Andreasen et al. (2024a) treated the seedlings of 12 monocot weed and a dicotyledonous crop species with a 50W thulium-doped fiber laser (2,000 nm) achieving complete control of all species at cotyledon and 1-leaf stages. However, regrowth was common in plants that had been treated at the 4-leaf stage, even at the highest energy dose of 12.7 J mm^{-2}. Investigating the efficacy of a near infrared (NIR) 925-nm, 25-W fiber-coupled diode laser on rigid ryegrass between the 3-leaf and late-tillering growth stages, Coleman et al. (2021) found only a 60.2% biomass reduction at the mid-tillering stage using 76.4 J mm^2 with no control. A biomass reduction was not observed in the largest late-tillering plants. Besides this study, research to date has focused on the laser treatment of weeds in early growth stages (seedling to 4-leaf). Mwitta et al. (2022) evaluated low-cost diode lasers between 1.2 W and 6.1 W (450 nm) finding 80% efficacy at 0.5-s and 1-s dwell times, and 100% control with 1.5-s treatment on seedling Palmer amaranth (*Amaranthus palmeri* S. Wats.) and smallflower morningglory [*Jacquemontia tamnifolia* (L.) Griseb.]. A 5-W diode laser (450 nm) was subsequently integrated by the same authors (Mwitta et al. 2024) on a robotic platform, with the 2-s dwell time resulting in control rate of successfully targeted weeds of between 77% and 87%. While these results are promising, a challenge for laser weed control has been controlling perennial weeds, or weeds with belowground growing points. Andreasen et al. (2024b) addressed this challenge with laser treatment of couch grass [*Elymus repens* (L.) Gould] rhizomes, finding good susceptibility for rhizomes with one or two nodes under 20 J mm^{-2} of laser energy. This growing body of research highlights the potential of using lasers for weed control; however, cost and accessibility are frequently cited as major barriers to their research, development, and adoption (Lu et al. 2025; Yaseen and Long 2024).

Research to date has focused on singular and often costly laser forms (CO_2, Nd:YAG, fiber, and diode) with highly precise targeting; however, limited research has been conducted to assess the benefits of low-cost, yet powerful diode laser arrays with larger treatment areas. With the promising nature of this field, there is a need to understand whether these represent viable alternatives with the potential for reduced targeting precision and cost. Thus, to develop an understanding of weed control potential, this research aimed to evaluate 1) the irradiation energy requirement (as determined by treatment duration) of spot laser treatments to control representative grass (rigid ryegrass) and broadleaf (wild radish) weed species, and 2) the influence of growth stage on energy requirement for rigid ryegrass and wild radish control.

Materials and Methods

Laser Diode Array Test Rig

Constructing the test rig involved integrating both off-the-shelf and bespoke units, assembling with safety considerations, and operational simplicity. A NUBM31 laser diode array (Nischia Corporation, Tokushima, Japan) was used to apply laser treatments (Figure 1). The array outputs a total of approximately 97 W of optical light, peaking at a wavelength of 445 nm. It consists of a 5×4 element laser diode array, each with a beam divergence of 3 degrees. Without any supplementary optical equipment, the array has spot treatment dimensions of 17.5×24 mm (420 mm^2).

Laser System

The laser diode array and control system consisted of a cooling block with the diode array mounted at the top, pointing downward (Figure 2), supported with a combined 3-D printed and metal structure. A wooden base was used to mount the system.

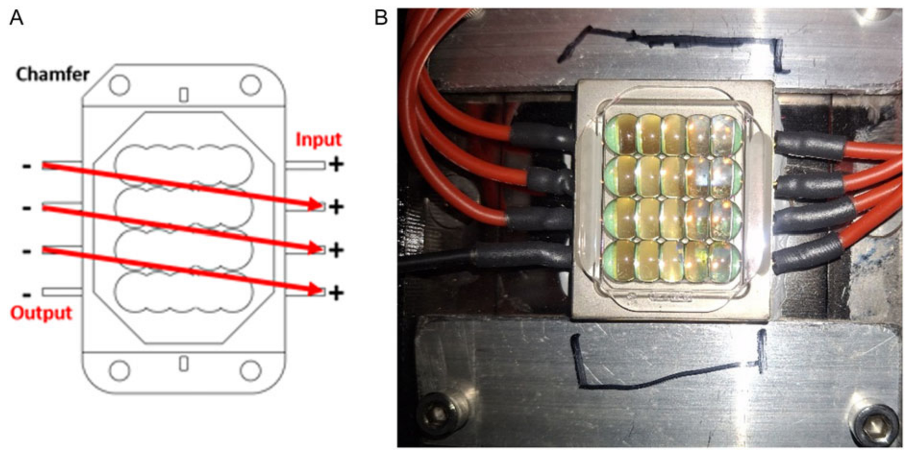

Figure 1. Schematic wiring diagram for the NUBM31 laser diode array (Nischia Corporation, Tokushima, Japan) used in the study(A); bottom view of mounted laser diode array, showing wiring (B).

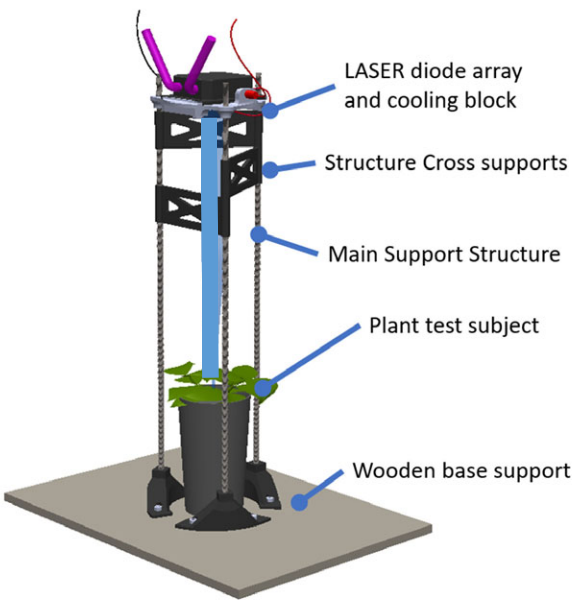

Figure 2. Laser rig schematic showing alignment of the laser support hardware, test sample in place, and the stand used for testing laser diode array energy density treatments.

The power to the laser diode array was provided through an MP3091 switch-mode laboratory power supply (Powertech, Malaga, Australia), via a bespoke DC/DC converter. Laser operation was controlled via a custom Python interface that modulated duty cycle to control laser intensity.

The laser diode array was integrated as part of a safety interlock subsystem (Figure 3), which encompasses the array and a cooling system. A light and a camera were used to accurately locate plants beneath the beam and to monitor laser treatments. Not shown is the safety interlock switch mounted on the door, which interrupts power to the laser while the door is open.

Weed Seedling Establishment, Growing Environment, and Experiment Design

Rigid ryegrass and wild radish were used as representative monocot and dicot species, respectively, for laser treatment testing.

Table 1. Dates of wild radish and rigid ryegrass planting, laser treatment, and assessment.[a]

Study points	Run 1	Run 2	Run 3
GS4	August 4, 2023	September 20, 2023	September 22, 2023
GS3	August 11, 2023	September 27, 2023	September 29, 2023
GS2	August 18, 2023	October 4, 2023	October 6, 2023
GS1	August 25, 2023	October 11, 2023	October 13, 2023
Laser treatment	September 8, 2023	October 24, 2023	October 26, 2023
Assessment and harvest	September 15, 2023	October 31, 2023	November 3, 2023

[a]Abbreviation: GS, growth stage.

These species were chosen because they are the most problematic and herbicide-resistant grass and broadleaf weeds in Australian grain production (Broster et al. 2022; Ouzman et al. 2025; Owen et al. 2015). Seeds of these species were separately planted to a depth of approximately 5 mm into 0.5-L pots (85 mm × 85 mm). Once established at the one-leaf stage, seedlings of both species were thinned to one plant per pot. The pots were watered as required with a complete liquid fertilizer, applied weekly once seedlings had reached the 2-leaf stage. To establish four growth stages (GS1 to GS4) at the time of laser treatment, rigid ryegrass and wild radish planting was repeated at weekly intervals for 4 wk (Table 1 and Figure 4).

The seedlings were grown in a shade house at the University of Western Australia Shenton Park field station (31.95ºS, 115.79ºE) where the growth environment consisted of fluctuating temperatures and rainfall typical of the conditions in the Western Australia grain production region. The shade house was not temperature controlled but provided wind protection and a moderated environment (cooler or warmer) against temperature extremes (e.g., approximately 2 to 5 C). In all three experimental runs, weed seedlings were established and grown during the late winter to late spring (August to October) in 2023. Temperature data were accessed from a nearby (4 km) Bureau of Meteorology weather station to calculate average daily temperature data for Runs 1, 2, and 3, which were 16 C, 19 C, and 19 C, respectively (BOM 2025).

Each pot had a single plant that represented an experimental unit with four pots (replicates) planted for each growth stage by laser treatment combination. Planted pots were arranged as a randomized complete block design with blocking against potential shading effects from nearby trees.

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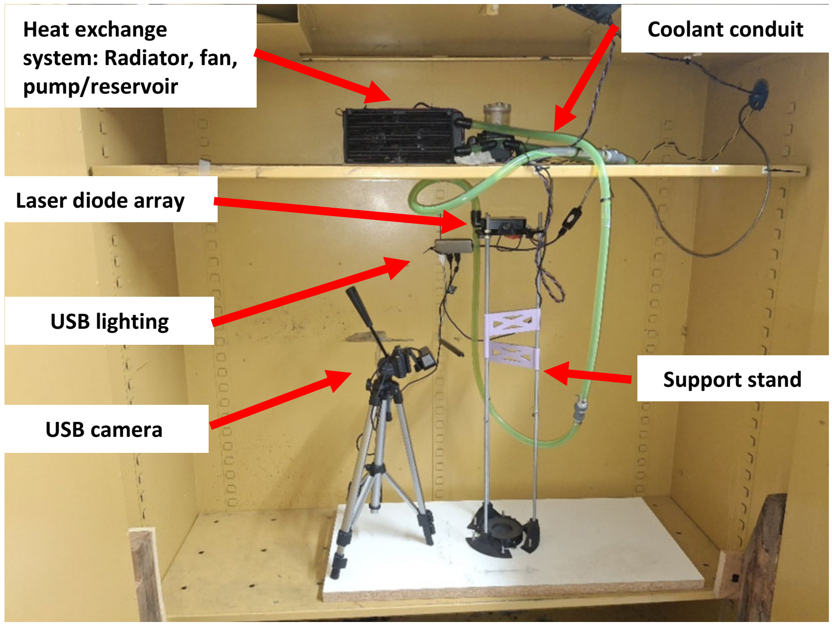

Figure 3. The laser rig, diode array, cooling, lighting, monitoring and system in place in the safety cupboard. An interlock prevented laser diode array operation while the cupboard door was open.

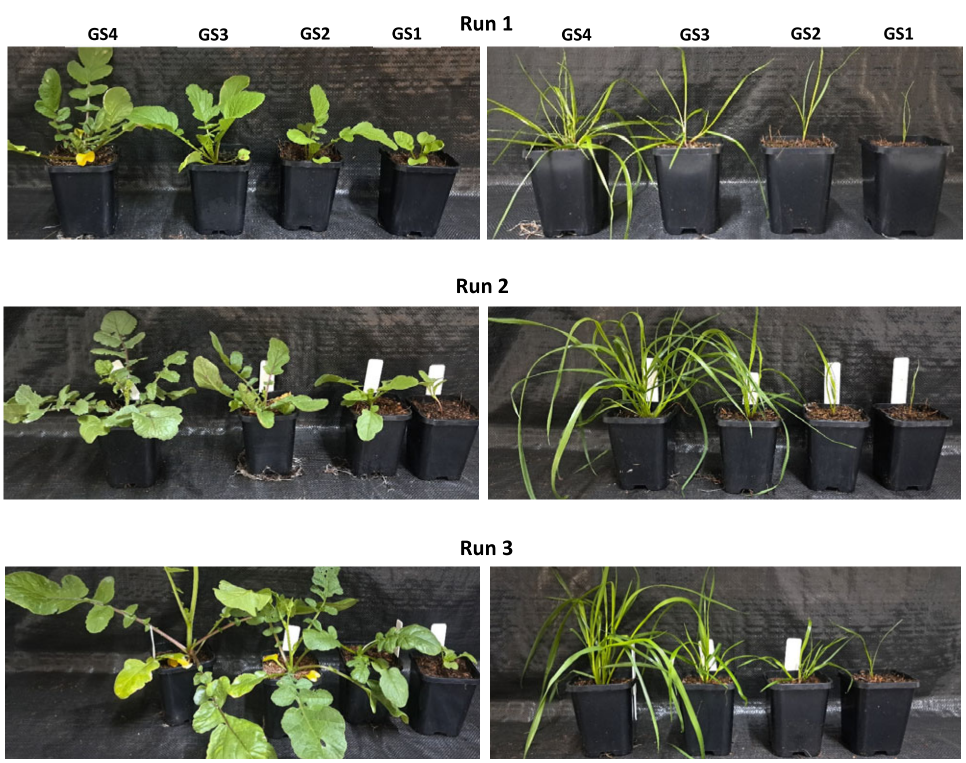

Figure 4. Images of wild radish (left) and rigid ryegrass (right) seedlings at the time of laser diode array treatment across the four growth stages in each of the three experimental runs.

Laser Treatment

At the time of treatment (Table 1) all plants in an experimental run, including nontreated controls, were moved to the laser treatment laboratory. Plants in pots were placed beneath the laser rig and aligned so that the growing point was situated within the 17.5 mm × 24 mm treatment zone. This was achieved by operating the laser in the low power, targeting mode (300 Hz, and 65% duty cycle), which delivered under 2 W. Preliminary testing determined that there was no effect of the low power targeting treatment on plant growth (data not presented). Once the plant was correctly aligned the interlock was set, and laser treatment was applied in the high power settings (50 Hz, 5% duty cycle). Seven laser treatments of 0, 0.07, 0.13, 0.25, 0.5, 1.0, and 2.0 J mm^{-2} were achieved through increasing durations

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Table 2. Parameter estimates of models for survival of wild radish and rigid ryegrass plants exposed to increasing laser energy treatments at four growth stages in three experimental runs.[a]

Species	Run	Growth stage	*b*	*e*
Wild radish	1	1	3.33 (1.45)	0.23 (0.05)
		2	3.18 (1.38)	0.44 (0.11)
		3	3.93 (1.85)	0.77 (0.16)
		4	14.16 (69.04)	1.09 (0.08)
	2	1	22.51 (953.01)	0.27 (0.55)
		2	3.14 (1.42)	0.92 (0.24)
		3	28.82 (150.84)	1.42 (2.57)
	3	1	33.82 (357.69)	0.35 (1.27)
		2	3.74 (1.74)	0.72 (0.17)
		3	3.71 (1.95)	1.41 (0.32)
Rigid ryegrass	1	1	15.16 (75.18)	0.15 (0.05)
		2	16.17 (147.87)	0.27 (0.02)
		3	16.77 (130.45)	0.25 (0.13)
		4	17.12 (147.57)	0.51 (0.28)
	2	1	35.31 (465.67)	0.18 (0.81)
		2	19.56 (312.55)	0.27 (0.24)
		3	21.27 (473.54)	0.53 (0.61)
		4	35.96 (586.52)	1.39 (7.30)
	3	1	20.03 (364.52)	0.23 (0.23)
		2	19.21 (293.40)	0.26 (0.23)
		3	18.37 (297.33)	0.98 (0.05)
		4	19.89 (373.55)	1.03 (1.07)

[a]Three-parameter dose-response curves were fitted where the upper limit, *d*, was fixed at 1.0, *b* is the shape parameter, and *e* is the inflection point. Values in parentheses are the standard errors for each parameter estimate.

Table 3. Estimated parameters of the models for biomass of wild radish and rigid ryegrass plants exposed to increasing laser energy treatments at four growths in three experimental runs.[a]

Species	Run	Growth stage	*b*	*d*	*e*
Wild radish	1	1	2.05 (0.74)	105.9 (14.0)	0.13 (0.03)
		2	1.04 (0.37)	96.5 (14.4)	0.20 (0.10)
		3	2.26 (1.30)	90.3 (9.6)	0.83 (0.23)
		4	4.00 (4.19)	77.90 (7.4)	1.06 (0.21)
	2	1	10.66 (47.17)	94.3 (8.8)	0.27 (0.07)
		2	7.32 (15.90)	99.3 (6.9)	1.17 (0.34)
		3	7.07 (22.28)	80.3 (7.4)	1.10 (0.31)
	3	1	11.29 (102.43)	124.0 (13.2)	0.29 (0.42)
		2	4.18 (2.73)	118.9 (11.8)	0.74 (0.18)
		3	4.80 (3.58)	118.2 (10.6)	1.41 (0.32)
Rigid ryegrass	1	1	4.18 (4.51)	94.9 (15.0)	0.14 (0.03)
		2	2.49 (0.99)	103.5 (12.7)	0.21 (0.05)
		3	3.30 (1.06)	117.9 (11.9)	0.18 (0.03)
		4	1.90 (1.57)	89.7 (19.4)	0.27 (0.14)
	2	1	28.85 (302.74)	129.7 (9.0)	0.20 (0.70)
		2	1.48 (0.62)	98.4 (16.0)	0.12 (0.05)
		3	5.83 (8.38)	92.0 (8.2)	0.57 (0.10)
	3	1	3.74 (2.23)	124.3 (18.1)	0.15 (0.04)
		2	13.63 (390.94)	123.2 (13.7)	0.29 (1.31)
		3	3.63 (3.31)	106.2 (12.3)	0.97 (0.26)
		4	13.21 (171.50)	103.6 (10.6)	1.17 (2.81)

[a]Three-parameter dose-response curves were fitted where *b* is the shape parameter, *d* is the upper limit end *e* is the inflection point. Values in parentheses are the standard errors for each parameter estimate.

of laser applications of 0, 0.5, 1.0, 2.0, 4.0, 8.0, and 16 s, respectively. After treatments, all plants in the experiment were returned to the shade house where they remained until assessment.

Plant Assessment

At approximately 7 d after treatment survival was assessed by determining whether each plant was either alive or dead. Plants that were unaffected or had regrown were deemed to be survivors. To determine the effect of laser treatments on plant growth, aboveground biomass of surviving plants was harvested by cutting the plants at the soil surface. Assessments were conducted at 7 d after treatment, much earlier than for herbicide treatments, because laser effects are more rapid and growth suppression effects need to be recorded earlier before rapid regrowth masks treatment differences. The collected biomass samples were oven dried at 70 C for 72 h and weighed.

Statistical Analysis

Adopting the approach described by Coleman et al. (2021) for standardizing laser dose, treatment duration was converted to energy density using Equation 1:

$$\rho_{enery} = \frac{P \times t}{A_{beam}} \qquad 1$$

Energy density (ρ_{energy}) is measured in J mm^{-2}, and calculated using laser power in watts (P), treatment duration (t), and treated area (A). An analysis of variance determined run as a significant effect ($P < 0.05$); therefore, each experimental run was analyzed and presented separately. Dry weight and survival data were analyzed with R Studio software using the dose-response curve (DRC) package (Ritz et al. 2015) to determine laser energy dose effects as influenced by growth stage and weed species. Survival was analyzed with a two-parameter binomial function where the upper limit, *d*, was fixed at a survival probability of 1. The estimated model parameters with standard errors for survival probability curves developed for each weed species × growth stage combination in each run are presented in Table 2.

To allow comparison of results across runs, dry weight biomass was normalized as the percentage of nontreated control. For dry weight analysis against increasing energy doses, a three-parameter, symmetric log logistic model was fitted with the DRC package using Equation 2:

$$y = c + \frac{d - c}{1 + \exp(b(\log(x) - \log(e)))} \qquad 2$$

where the lower limit c was fixed at 0; d denotes the upper limit; b is the slope at the point of inflection, and e is the ED_{50} value, which is the energy dose required to achieve a 50% reduction in plant dry weight. The estimated model parameters with standard errors for biomass responses of each weed species × growth stage combination in each run are presented in Table 3.

Growth stage GS4 was excluded because the model would not converge or it resulted in a lack of model fit due to the limited effect of laser treatment (e.g., wild radish GS4 Runs 2 and 3; rigid ryegrass Run 3). Lack of fit tests were conducted for all models ($P > 0.05$).

Results and Discussion

Plant Survival

When used to target the growing point of rigid ryegrass and wild radish plants, the laser diode array consistently controlled smaller seedlings (GS1 and GS2) at low energy densities (<2.0 J mm^{-2}), establishing the weed control potential of this novel laser treatment. Small, 2- to 3-leaf (GS1) rigid ryegrass and wild radish

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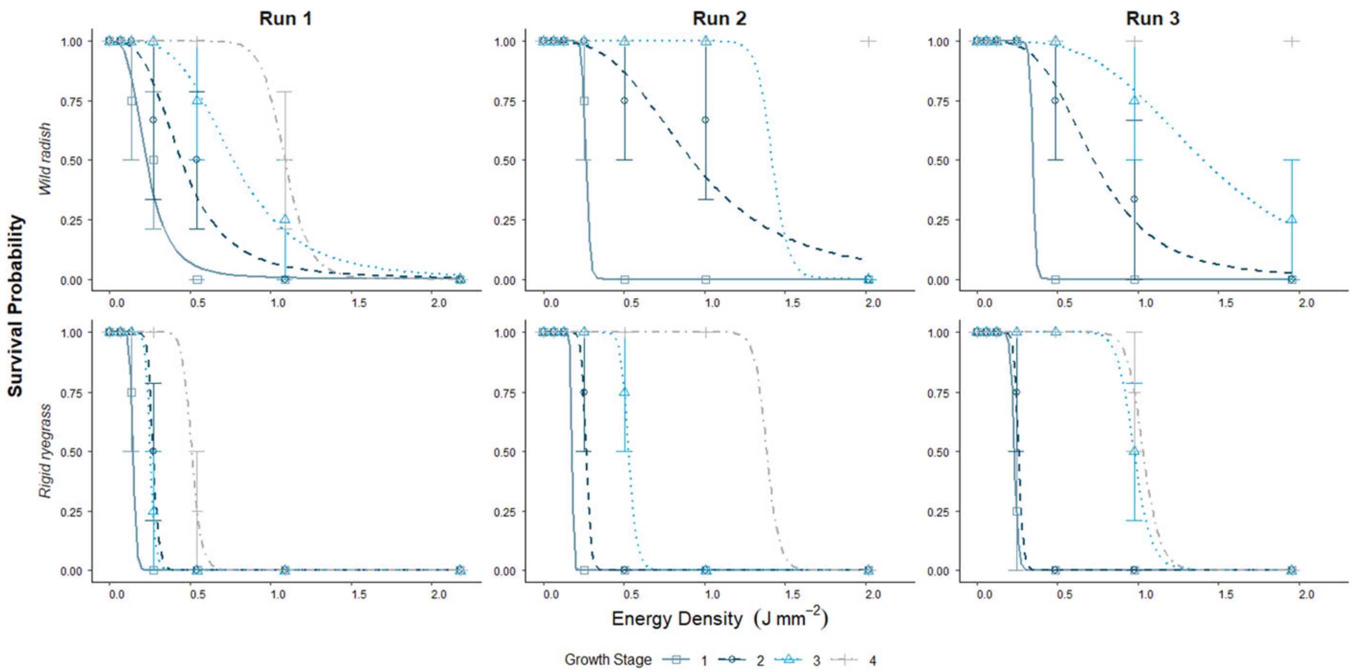

Figure 5. Influence of increasing laser diode array energy densities on the survival probability of wild radish and rigid ryegrass plants treated at four growth stages in three pot-based experimental runs. Rigid ryegrass survival was consistently lower than that of wild radish at each growth stage and in each run at all energy density treatments. Bars represent the standard errors for the mean of four replicates.

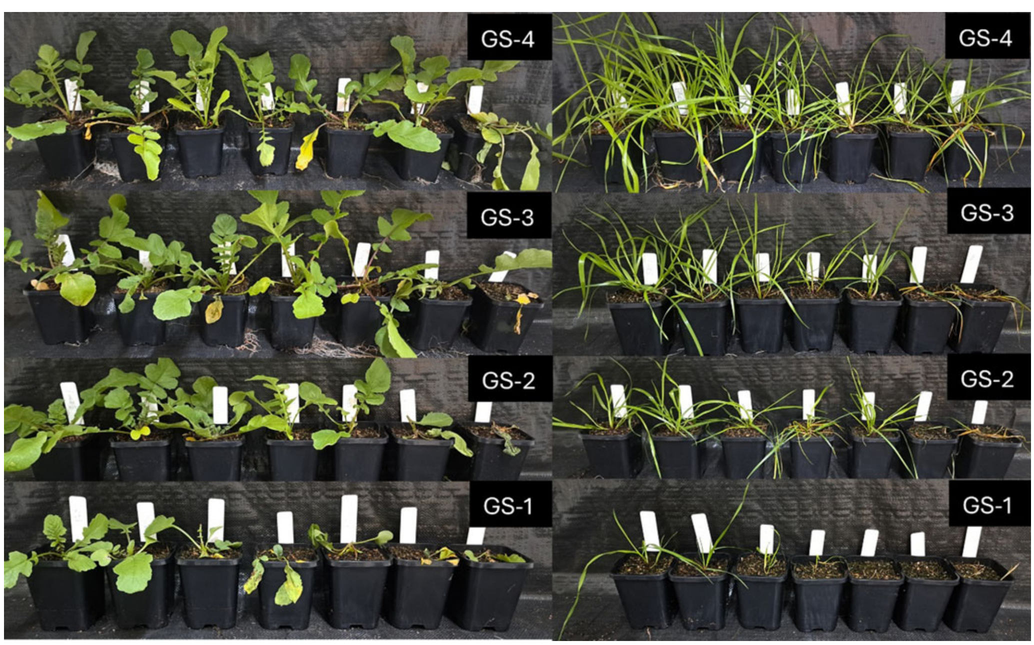

Figure 6. Images of wild radish (left) and rigid ryegrass (right) seedlings at four growth stages in the first experimental run, showing the effects of laser diode array treatments at 7 d after application.

seedlings were consistently controlled at <0.5 J mm^{-2} (Figures 5 and 6). Slightly higher energy density requirements to control similarly sized (2- to 3-leaf) seedlings have been reported for other grass weed species, approximately 3 to 7 J mm^{-2} with CO_2 (10,600 nm) and single diode lasers (940 nm) to control barnyardgrass (Marx et al. 2012; Wöltjen et al. 2008) and approximately 4 J mm^{-2} (thulium-doped fiber laser) to control blackgrass (*Alopecurus myosuroides*) (Andreasen et al. 2024a). In the only other reported study on rigid ryegrass, 2- to 3-leaf seedlings were controlled with approximately 20 J mm^{-2} delivered by a 25-W NIR (975 nm) fiber-coupled diode laser with a spot treatment (Coleman et al. 2021). Given the low absorption by grasses at the NIR part of the light spectrum (Wöltjen et al. 2008), it is likely this difference is in part due to the greater energy absorption of the 475-nm laser used here. Additionally, the reduced consistency in targeting the growing point with a small single diode laser area (20 mm^2) compared to the larger laser diode array treatment area (420 mm–^{2}) is likely to have contributed.

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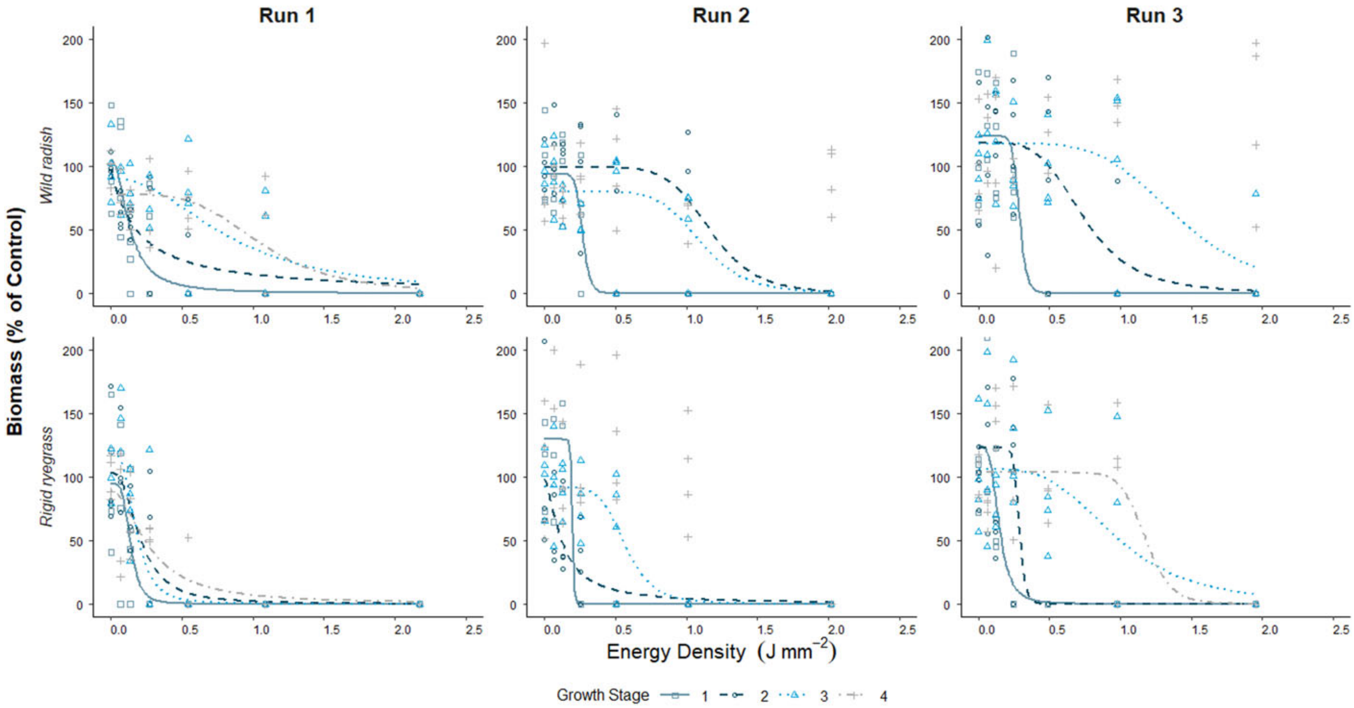

Figure 7. Dose-response analysis of dry weight of wild radish and rigid ryegrass as a percentage of the nontreated control at four growth stages in three pot-based experimental runs. Rigid ryegrass was observed as being more susceptible to laser treatment than wild radish.

No studies have previously examined laser treatment effects on wild radish, however, other studies have been conducted with dicot weeds. Mathiassen et al. (2006) found that cotyledon-stage broadleaf weeds including common chickweed (*Stellaria media*) and scentless mayweed (*Tripleurospermum inodorum*) were controlled with approximately 5 J mm^{-2} energy density delivered with a diode laser. Similarly, 1-leaf redroot amaranth seedlings were controlled with 2.5 J mm^{-2} energy density treatment in a study by Marx et al. (2012). In an extensive study using a thulium-doped 50-W fiber laser, dicot species a the 11 cotyledon stage were controlled by 1.6 J mm^{-2}, with 10 of the species controlled at 0.8 J mm^{-2} (Andreasen et al. 2024a). Mwitta et al. (2022) achieved 100% control of seedling-stage Palmer amaranth and smallflower morningglory with an energy density of 1.86 J mm^{-2} delivered by a low-cost 6.1-W diode laser (450 nm),. This declined to 80% when the dose was reduced to 0.62 J mm^{-2}.

At each growth stage and in all three runs the energy densities required for wild radish control were consistently higher, frequently more than double, those needed to control rigid ryegrass (Figures 5 and 6). The requirement for higher energy to control the dicot species in this study contrasts with the results from a previous study by Marx et al. (2012) who identified increased susceptibility to CO_2 laser treatments of the dicot species, redroot amaranth, than the monocot species, barnyardgrass, at a similar growth stage. These authors concluded that the increased susceptibility of the dicot was due to the more exposed meristematic tissue of this species compared to that of the monocot. Similarly, Wöltjen et al. (2008) found another dicot, cultivated tobacco, was more susceptible to laser treatments than similar-aged barnyardgrass plants. Evaluating the responses of 12 weed species (1 monocot and 11 dicots) to laser treatments indicated that different responses to laser treatments between weed species at the same growth stage appeared to be related more to weed seedling biomass rather than plant type (Andreasen et al. 2024a). A key difference is that the laser spot treatment area (approximately 1 to 3 mm^2) of all previous studies was smaller than the 420-mm^2 area of the laser diode array used in this study. Although it was not examined in this study it is possible that a larger treatment area will improve the ability to target meristematic tissue, particularly for grass species in which this tissue is frequently located below the soil surface. Supporting this is a study by Marx et al. (2012) that found that increasing the laser spot area from 7 to 28 mm reduced the energy required to control 1-leaf seedling redroot amaranth and barnyardgrass by 30% and 40%, respectively. However, if the overall effectiveness of a larger spot area is due to the increased likelihood of contacting the meristematic tissue, then more precise growing point targeting with smaller areas of laser treatment will potentially lead to savings in laser energy requirements. On the other hand, precise targeting of lasers is highly complex and time consuming in the variable terrain of production fields (Lu et al. 2025; Mwitta et al. 2024). This process significantly limits forward speed when compared to herbicide applications (Sosnoskie et al. 2025). Adoption of lower-cost laser alternatives that reduce or remove stringent targeting requirements, through a site-specific yet blanket application of laser energy akin to targeted spraying, would improve accessibility of this technology for larger-scale production systems.

As weed seedlings grew and developed, laser energy requirements for the control of rigid ryegrass and wild radish plants increased substantially. Rigid ryegrass seedlings at GS1 consistently required just 0.2 J mm^{-2} (Runs 1 and 2) to 0.5 J mm^{-2} (Run 3) J mm^{-2}, whereas the control of the most developed and largest rigid ryegrass plants (GS4) required more than 1.0 J mm^{-2} (Run 1) and 2.0 J mm^{-2} (Runs 2 and 3) (Figures 5 and 6). Thus, over the 21-d growth period there were 5- to 10-fold increases in the energy required to control older and larger plants. Similarly, wild radish seedlings at GS1 were consistently controlled by 0.5 J mm^{-2}, while control of GS4 plants was achieved only in Run 1 at the highest energy density treatment. Similar to the results presented here, a comprehensive study by

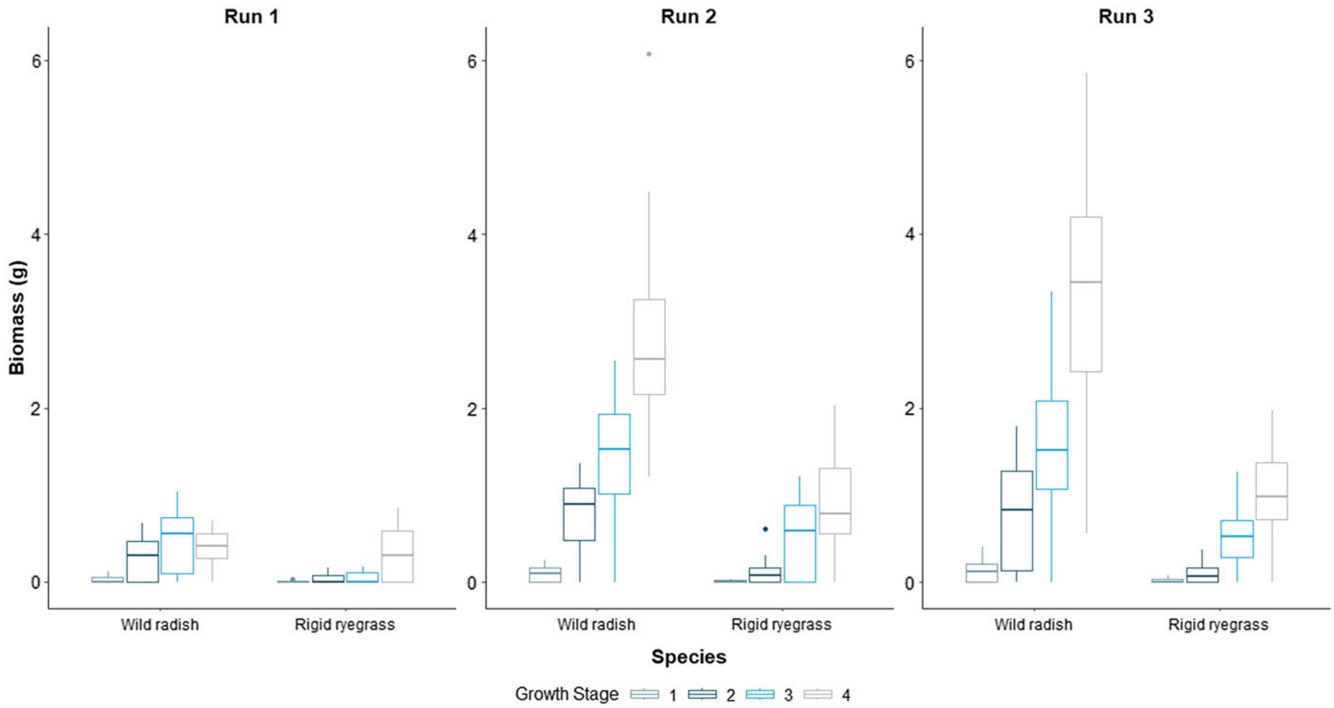

Figure 8. Dry weight of nontreated wild radish and rigid ryegrass plants at four growth stages in each experimental run. Seasonal temperature variations resulted in between-run differences in dry weights at the time of treatment for plants grown over the same duration.

Andreasen et al. (2024a) with 10 dicot weeds determined that incrementally higher energy densities (12.7 J mm^{-2}) were required to control 2- and 4-leaf-stage dicot weed seedlings. Analogous to the results presented here, previous studies consistently reported markedly increased energy requirements to control older plants of both monocot and dicot species (Lu et al. 2025).

Plant Biomass

Older rigid ryegrass and wild radish plants (GS3 and GS4, all runs) required markedly greater (i.e., 4- to 8-fold) energy densities to achieve proportionally similar biomass reductions. When seedlings had reached GS3 and GS4, the laser energy density that consistently controlled GS1 seedlings (0.5 J mm^{-2}), caused biomass reductions of just 6% in wild radish and a somewhat higher reduction of 34% in rigid ryegrass (Figure 7). These results confirmed that plants that survived laser treatments remained robust and continued to grow with little to no apparent lingering effects of the damage caused to the meristematic tissue.

Seedling survival results of wild radish and rigid ryegrass biomass results indicate that growth of the monocot species was consistently more suppressed than that of the dicot by the same laser energy densities. When averaged across growth stages, biomass reductions were consistently larger (20% to 30%) for rigid ryegrass than wild radish at the same energy density treatment (Figure 7). As energy densities increased, reductions in rigid ryegrass biomass were more than double those for wild radish, particularly for plants treated at the early growth stages (GS1 and GS2). These findings support the idea presented by Lu et al. (2025) that more advanced weed recognition systems are required for improved laser weed control, where growth stage and species affect laser treatment duration.

The lowest laser energy density treatment (0.06 J mm^{-2}) appeared to stimulate the growth of wild radish and rigid ryegrass seedlings. Rigid ryegrass biomass increased by approximately 20% on average at all growth stages and in all three runs following treatment with the lowest laser energy density (Figure 7). By comparison, biomass increases by wild radish seedlings in response to this low-dose laser treatment were lower (approximately 5%) and inconsistent. The plant biomass data were highly variable, although there appears to be sufficient consistency, particularly with rigid ryegrass, to indicate a biostimulant effect that requires further exploration. The field of laser-stimulated growth of plant tissues has been well studied (Hernández-Aguilar et al. 2010). For example, low-dose laser energy treatment of crop seeds and seedlings such as wheat (*Triticum aestivum* L.), cultivated oat (*Avena sativa* L.), soybean [*Glycine max* (L.) Merr.], and canola (*Brassica napus* L.) has been identified in numerous studies (as reviewed in Hernández-Aguilar et al. 2010; Klimek-Kopyra et al. 2021) to have a biostimulant effect. In contrast, only limited evidence of a biostimulation effect from low-dose laser energy treatment on weed seedlings has been identified in other studies (Andreasen et al. 2024a; Coleman et al. 2021a). However, these and previous studies did not attempt to identify this effect on plant growth.

Plant size (biomass) at the time of treatment differed markedly between species, growth stages, and runs and greatly influenced the efficacy of the laser diode array (Figures 7 and 8). There was a 7-d period between each of the four designated growth stages (GS1 to GS4) when the average daily biomass increases across them were 0.09 g plant^{-1} and 0.03 g plant^{-1} for wild radish and rigid ryegrass, respectively. Thus, regardless of the same growing environment, the growth rate of wild radish seedlings was more than double that of rigid ryegrass. This resulted in wild radish plants being substantially larger than rigid ryegrass plants at the time of laser treatment, especially at the later growth stages (Figures 7 and 8). There were also marked differences in growth rates between runs, particularly in wild radish plants that grew an average of 0.03, 0.14, and 0.12 g d^{-1} during Runs 1, 2, and 3, respectively. During Runs 2

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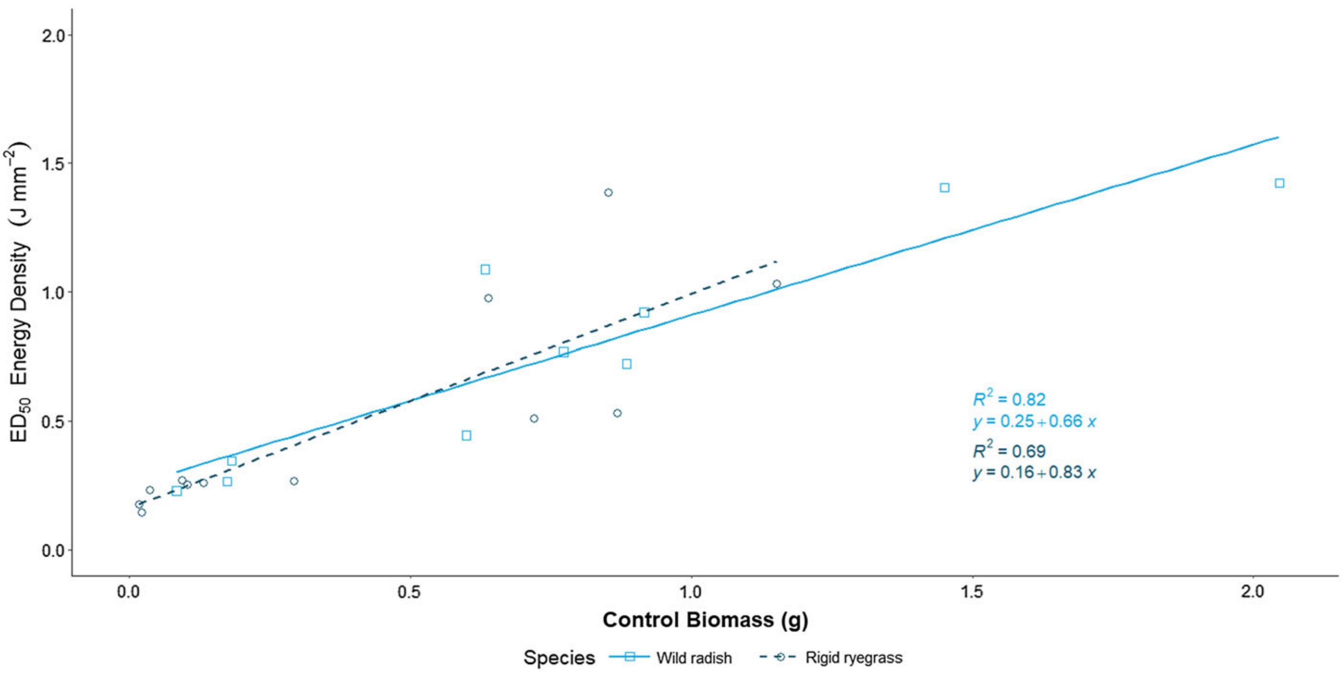

Figure 9. Relationship between biomass of nontreated control plants and the ED_{50} for survival of wild radish and rigid ryegrass following laser treatment at each of four growth stages in three pot-based experimental runs. Although dose-response relationships suggest that rigid ryegrass is more susceptible to laser treatment, the analysis of dry weights of nontreated control plants indicates that plants with the same weight exhibited a similar response.

and 3 the average daily temperature (19 C) was approximately 3 C warmer than during the Run 1 growth period (BOM 2025). The warmer growing conditions were likely responsible for seedling growth being 2.5 to 3 times larger in Runs 2 and 3 than in Run 1, which occurred during the cooler winter months. In contrast to wild radish, annual ryegrass growth rates were more consistent at 0.03, 0.04, and 0.05 g d^{-1} during Runs 1, 2, and 3, respectively, and indicated that plant growth was less affected by seasonal differences between runs. Individual run results appear to support conclusions from previous research identifying differences in laser susceptibility between monocots and dicots (Andreasen et al. 2024a; Lu et al. 2025; Marx et al. 2012). Across all runs, although it appears that species-related differences in response to laser treatments observed in this study were more likely an artefact of plant size at the time of treatment rather than morphological differences and location of meristematic tissue. This is supported by the generally greater tolerance to laser treatment by both rigid ryegrass and wild radish in Runs 2 and 3 compared with Run 1.

The similar slopes of the linear relationships between energy density and plant dry weight for wild radish and rigid ryegrass indicate that plant response to laser treatments was mostly related to plant size (biomass) at the time of treatment rather than species (weed type). Energy density values in joules per square millimeter (J mm^{-2}) required to reduce plant biomass by 50% (ED_{50}) were developed from plant biomass responses to laser treatments for each growth stage of wild radish and rigid ryegrass in all three runs (Figure 9). These 12 ED_{50} values developed for both wild radish and rigid ryegrass when plotted against the dry weight of nontreated plants identified reasonably linear relationships for both rigid ryegrass ($R^2 = 0.69$) and wild radish ($R^2 = 0.82$) seedlings. The linearity of these relationships indicates that for both weed species (weed types) increasing plant size (biomass) requires a consistent increase in energy density to achieve a 50% reduction in growth. As indicated by the slopes, each 1-g increase in biomass required an additional 0.8 J mm^{-2} and 0.7 J mm^{-2} for the similar suppression of rigid ryegrass and wild radish seedlings, respectively. Although the linear relationships developed here are indicative and for just one representative monocot and dicot species, they do suggest that energy density requirements for laser weeding are more related to plant size than plant type.

Practical Implications

The effective control of small rigid ryegrass and wild radish seedlings using a low-cost laser diode array with comparable performance to existing published research has identified the use of an array as an effective option for laser weeding. The low-cost and widely available laser diode array used in this study achieved equivalent and in some cases greater efficacy across a range of growth stages to those of previously reported results that used higher-cost systems (e.g., single diode, Nd:YAG, CO_2, and fiber lasers). Laser diode arrays overcome energy limitations of single diodes by stacking multiple diodes in arrays, improving power output while maintaining low cost and accessibility. Plant-specific treatments in which each plant must be visited by the weed control device (e.g., targeted laser) are inherently limited by precision targeting and treatment delivery requirements. Site-specific, targeted herbicide applications do not suffer from this same limitation. Low-cost and high-power laser diode arrays used in large treatment areas may improve the opportunity for site-specific, not plant-specific, treatment in large-scale production by changing the system design to include multiple adjacent laser arrays, arranged similarly to a precision sprayer. Although the requirement to heat plants to control them remains, the change in approach and decrease in cost per watt over time will improve the feasibility of doing so. The results presented here have identified laser diode arrays as being suitable for further research and development for use in commercial laser weeding systems, with the potential to bring it to scale given its ubiquity and low cost. A significant component of future research would be to identify scalability and in particular the capacity to control large weed plants that commonly occur at low densities during the late postemergence phase in large-scale crop production systems.

Plant size at the time of treatment was found to be more important than plant type (monocot or dicot) in defining the impact of laser energy density on the survival or biomass reduction of weed seedlings. The similar linear relationship between plant biomass at the time of treatment and the energy density required for a 50% biomass reduction for rigid ryegrass and wild radish identified that plant size at the time of treatment was more important than plant type. Although this contradicts observations in previous research, the difference is likely due to the use of a diode array for delivering laser treatments in this study. Although it was not specifically investigated, the large 420 mm^2 treatment area of the diode array laser facilitates targeting of meristematic tissue, compared to the approximately 3- to 5-mm^2 area of previously evaluated lasers (e.g., diode, CO_2, fiber). This larger treatment area reduces the time and energy expended for highly accurate growing point identification and similarly precise targeting with laser treatment.

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