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The Effect of Laser Treatment as a Weed Control Method

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A laser beam directed towards weeds can be an efficient weed control method as an alternative to herbicides. Lasers may deliver high-density energy to selected plant material, raising the temperature of the water in the plant cells and thereby stop or delay the growth. A commercial use of lasers for weed control, however, require a systematic investigation of the relationship between energy density and the biological effect on different weed species, growth stages, *etc.*

This paper investigates the effect of laser treatment directed towards the apical meristems of selected weed species at the cotyledon stage. Experiments were carried out under controlled conditions, using pot-grown weeds. Two lasers and two spot sizes were tested and different energy doses were applied by varying the exposure time. The biological efficacy was examined on three different weed species: *Stellaria media* (common chickweed), *Tripleurospermum inodorum* (scentless mayweed) and *Brassica napus* (oilseed rape).

The experiment showed that laser treatment of the apical meristems caused significant growth reduction and in some cases had lethal effects on the weed species. The biological efficacy of the laser control method was related to wavelength, exposure time, spot size and laser power. The efficacy also varied between the weed species.

The results indicate that the efficacy of laser treatments can be improved by a more precise pointing of the laser beam towards the apical meristems and optimisation of the energy density (exposure time and spot size of the laser beam). The experiment also showed a significant difference between two wavelengths.

In order to improve the performance and to validate the efficacy on a broader spectrum of weed species, further research and development is needed.

1. Introduction

Increased public concern about herbicides in relation to food safety, farm workers health, biodiversity, and the environment in general have renewed interest in alternative weed control measures. The main alternatives are physical weed control methods such as mechanical hoeing, harrowing, and brushing (Tillett & Hague, 1999; Pullen & Cowell, 1997; Bond & Grundy, 2001), which uproot or cover the weeds by soil, thereby stopping or delaying the growth and thus increasing the competitive advantage of the crop. These methods are normally limited to inter-row weed control and due to their disturbance of the upper soil layer, they may initiate new weed seed germination. This undesirable effect of the weed control action can be eliminated using thermal soil treatment methods (Shaw & Mitchell, 1977; Melander & Jørgensen, 2005) by which weed seeds are killed in a band through an energy-intensive surface steaming process. As a way to better concentrate and control the energy use while avoiding mechanical action, lasers have been considered as a cutting device for physical weed control (Bayramian *et al.*, 1993; Heisel *et al.*, 2001; Christensen *et al.*, 2003).

Notation

b	slope of the dose–response curve around ED_{50i}
C	lower asymptote of the dose–response curve at high energy doses, g/pot
D	upper asymptote of the dose–response curve at zero energy dose, g/pot
ED_{50i}	energy amount required to reduce the biomass by 50% between D and C, J
ED_{90i}	energy amount required to reduce the biomass by 90% between D and C, J
U_i	fresh weight of plants following treatment i, g/pot
z	energy amount, J

Heisel *et al.* (2001) effectively cut weed stems with an average diameter of 1·1 mm by directing a narrow CO_2 laser beam towards the stems. The energy use can be minimised by directing the laser precisely to the stem, guided by *e.g.* computer vision, delivering exactly the amount of energy necessary to cut the stem. Locating the stem may, however, be difficult for some weed species, as practical computer vision related to crop and weed identification typically provide a top-down view of the scene (Søgaard, 2005; Sökefeld *et al.*, 2000). This view, on the other hand, provides a good basis for identifying the apical meristems of most weed species.

To further promote practical use of lasers for weed control, the problems related to the practical implementation must be addressed. The combination of computer vision and laser treatment must be facilitated, and the issue of applying partial damage to the weeds rather than actually cutting the stem must be investigated as a mean to stop or delay the growth of plants. The cost of laser weeding is essential for commercial development and continuous wave diode lasers should be considered as a way to reduce cost while supporting practical implementation.

The main objective of the present study was to examine the potential of commercially available lasers for weed control and to identify the key factors influencing efficacy. To support current state-of-the-art in computer vision, the investigations are based on a top-down view of the scene. Taking advantage of the plan view of the scene, increasing energy amounts (or alternatively energy with a higher density) were guided towards the apical meristems. This potentially induces increasing damage to the plant tissue, preventing or reducing new growth. The envisioned laser weed control system and its components are outlined in *Fig. 1*.

The specific aim of the experiment was to obtain generic knowledge of the efficacy of guiding a laser beam towards the apical meristem of the weed species. Another objective was to study the implications of different energy delivery methods to the plant tissue. The laser beam is typically delivered through a thin flexible fibre fitted with various optical tips, resulting in different spot sizes. A small spot size may be desirable from an energy density point of view, but at the same time the optimum spot size may be one that allows energy to be delivered to a larger area, covering the entire apical meristem. To support future development, focus was on commercial continuous wave diode lasers. Such lasers are available in the visible range (wavelengths of 750–400 nm), and in the infrared range (IR) (wavelengths of 1 mm–750 nm). Visible and IR lasers applied to plant material act *via* explosive ejection, *i.e.* ablation of plant tissue generated by multiphoton and avalanche electron ionisation (Bloembergen, 1974).

Two lasers (one in the visible and one in the IR range), and two spot sizes were used in the present study. Each combination was tested on three different weed species using five different exposure times resulting in increasing energy amounts (doses). The number of surviving plants and the fresh and dry weights of the treated plants were recorded. The experiment showed that laser exposure of the apical meristem can be used as a method of physical weed control.

2. Materials and methods

The common weed species *Stellaria media* (common chickweed), *Tripleurospermum inodorum* (scentless mayweed) and *Brassica napus* (oilseed rape) were grown outdoors in 2/*l* pots in a potting mixture consisting of sandy-loam soil, sand and peat (2:1:1 w/w%) containing all essential nutrients. The pots were sub-irrigated with de-ionised water up to five times daily. Prior to treatment the number of plants per pot was reduced to three (*S. media*) or four (*T. inodorum* and *B. napus*).

The treatments were carried out on 16 July 2004 at the cotyledon stage of the weed species as shown in *Fig. 2*.

Two different types of continuous wave diode lasers were tested—a 5 W, 532 nm laser using a spot diameter of 0·9 or 1·8 mm (corresponding to a spot size area of 0·6 and 2·5 mm^2), respectively, and a 90 W, 810 nm laser using a spot diameter of 1·2 or 2·4 mm (spot size area of 1·1 and 4·5 mm^2). Each combination was tested using five different exposure times resulting in increasing

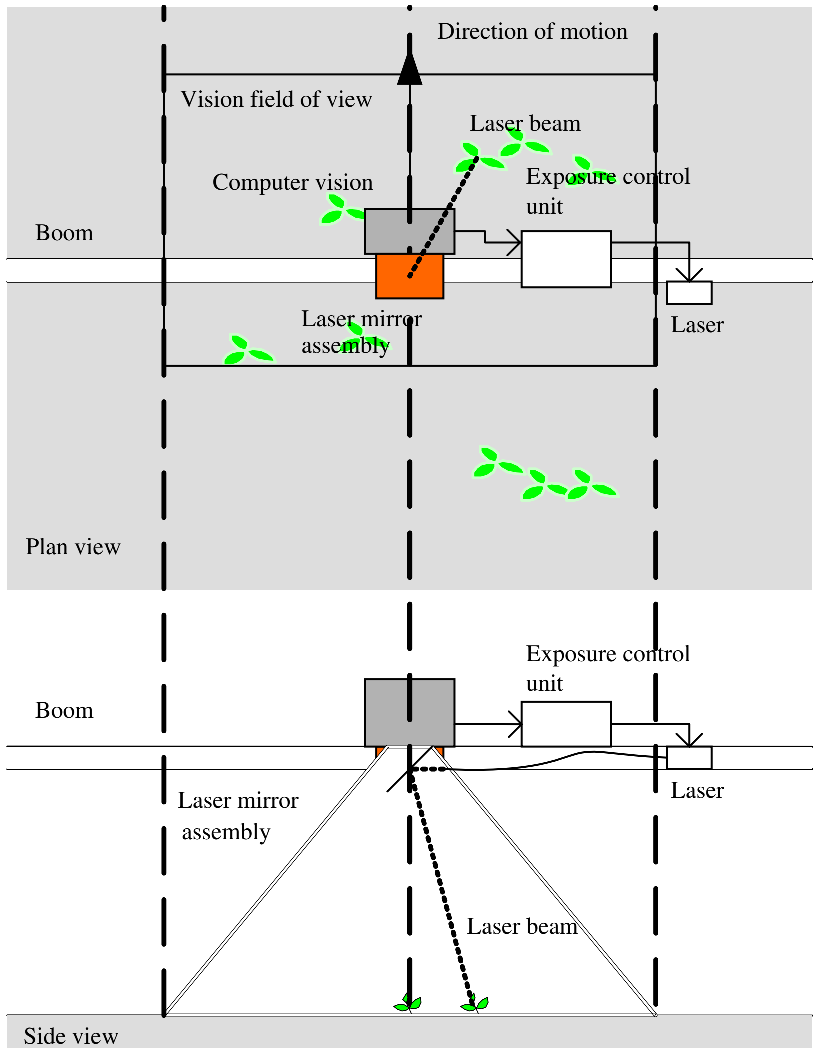

Fig. 1. A laser weeding tool comprising a computer vision system that classifies weeds and identifies apical meristems from a top-down point of view; the laser is pulsed with a required dose of energy and uses a mirror, directed towards the targeted plant tissue

Fig. 2. Photographs of weed seedlings prior to laser treatment; the targeted apical meristems are highlighted with a circle: (a) Stellaria media, (b) Tripleurospermum inodorum and (c) Brassica napus

energy amounts (doses) and energy densities as shown in Table 1. Each treatment was replicated three times.

The laser beam was delivered through a thin 1000 μm flexible fibre to an optical hand piece with a standard focus length of 11, 20 and 30 mm. The optical handpiece was held at a distance of approximately 11, 20 and 30 mm from the targeted plant tissue to ensure focus. The laser was targeted at the apical meristem of each

Table 1
The combination of lasers exposure times, spot diameter, energy amounts and energy densities used in the experiment

Laser	*Spot diameter, mm*	*Dose*	*Exposure time, ms*	*Energy, J*	*Energy density, J/mm²*
5 W, 532 nm	0·9	1	70	0·35	0·6
		2	130	0·65	1·0
		3	250	1·25	2·0
		4	500	2·5	3.9
		5	1000	5	7.9
	1·8	1	250	1·25	0·5
		2	500	2·5	1·0
		3	1000	5	2·0
		4	2000	10	3·9
		5	3000	15	5·9
90 W, 810 nm	1·2	1	70	6	5·3
		2	130	12	10·6
		3	250	23	20·3
		4	500	45	39·8
		5	1000	90	79·6
	2·4	1	160	1	3·1
		2	320	29	6·4
		3	640	58	12·8
		4	1260	113	25·0
		5	2500	225	49·7

plant. A distance of 11 mm was used with the 532 nm laser and 0·9 mm spot diameter. A distance of 20 mm was used with the 532 nm laser and 1·8 mm spot diameter and the 810 nm laser combined with 1·2 mm spot diameter. Finally the 30 mm distance was used with the 810 nm laser and 2·4 mm spot diameter. The focusing and targeting was done by hand using a top-down perspective on the weed species and supported by a red guidance light and small support beams on the hand piece (see *Fig. 3*). The laser was operated in continuous mode, with pulse lengths and other treatment parameters controlled *via* an electronic timer on the laser system.

After treatment the pots were re-placed on outdoor tables. Seedlings emerging after the treatments were removed daily up to 1 week after treatment. *Brassica napus* was harvested 16 days after treatment and *S. media* and *T. inodorum* were harvested 24 days after treatment. Fresh and dry weights were measured and the number of surviving plants per pot was recorded.

The fresh and dry weight data of each weed species were subjected to non-linear regression analyses using a logistic dose–response model (Seefeldt *et al.*, 1995)

$$U_i = \frac{D - C}{1 + \exp[2b_i(\log(ED_{50i}) - \log(z))]} + C \qquad (1)$$

where: U_i is the fresh or dry weight of plants in g/pot in treatment *i*; z is the energy amount (dose) in J; D and C are the upper and lower asymptotes of the dose-response curves in g/pot at zero and very high-energy amounts; ED_{50i} is the effective dose in energy amount in J required to reduce the biomass by 50% between D and C; and b_i is the slope of the dose–response curve at ED_{50i}.

Fig. 3. Targeting the apical meristem with a hand-held laser tool

The parameter ED_{50i} in Eqn (1) can be replaced by an alternative parameter, such as ED_{90i} that is of more practical relevance than ED_{50i} resulting in the logistic dose–response model

$$U_i = \frac{D - C}{1 + \exp[2b_i(\log(ED_{90i}) + 1{\cdot}099/b_i - \log(z))]} + C \tag{2}$$

The assumption that logistic dose–response curves could be fitted to the data was assessed by a test for lack of fit comparing the residual sum of squares of an analysis of variance and the non-linear regression. A Transform-Both-Sides method was applied to stabilise the variance (Rudemo *et al.*, 1989). Within each weed species the results of treatments with the two laser types and the two spot sizes were fitted to the model in Eqn (1) assuming similar D and C parameters for all treatments. The non-linear regressions showed that the C parameter was not significantly different from zero; hence the C parameter was omitted from the model in Eqn (1).

3. Results and discussion

The number of surviving plants for *S. media* and *T. inodorum* is shown in *Fig. 4*; all *B. napus* plants survived the treatments. In five pots with *S. media*, the number of living plants at harvest was four indicating that one plant had escaped the daily control and removal of emerging non-treated seedlings. Thus, these pots were regarded as true outliers and excluded from the statistical analyses. The fresh and dry weight results of the treatments are shown in *Fig. 5*.

3.1. *Effect on number of surviving plants*

The 5 W laser caused lethal effects on the weeds at a much lower energy level compared with the 90 W laser. The spot diameter had no influence on the mortality of *S. media* when using the 5 W laser, while with the 90 W laser application with the small spot tended to be more lethal compared with the larger spot. In contrast, the mortality of *T. inodorum* was increased with both lasers when the spot size was increased.

In general, a higher mortality was obtained on *T. inodorum* compared with *S. media* with three of the four tested combinations of lasers and spot sizes (5 W, 532 nm laser applied with 1·8 mm spot diameter, the 90 W, 810 nm laser with the 0·9 and 1·8 mm spot diameter). These results indicate that it is easier to target the apical meristem of *T. inodorum* precisely than that of *S. media* (*Fig. 4*). A possible explanation of the different susceptibility of the weed species is that the cotyledon leaves of *S. media* are petiolated, *i.e.* the apical meristem of *S. media* is located between the petioles and is partly concealed whereas the apical meristem of *T. inodorum* is less protected and easier to target with a laser beam. Similar to *S. media*, the apical meristem of *B. napus* is located between the petiolated cotyledon leaves; however, the size of the apical

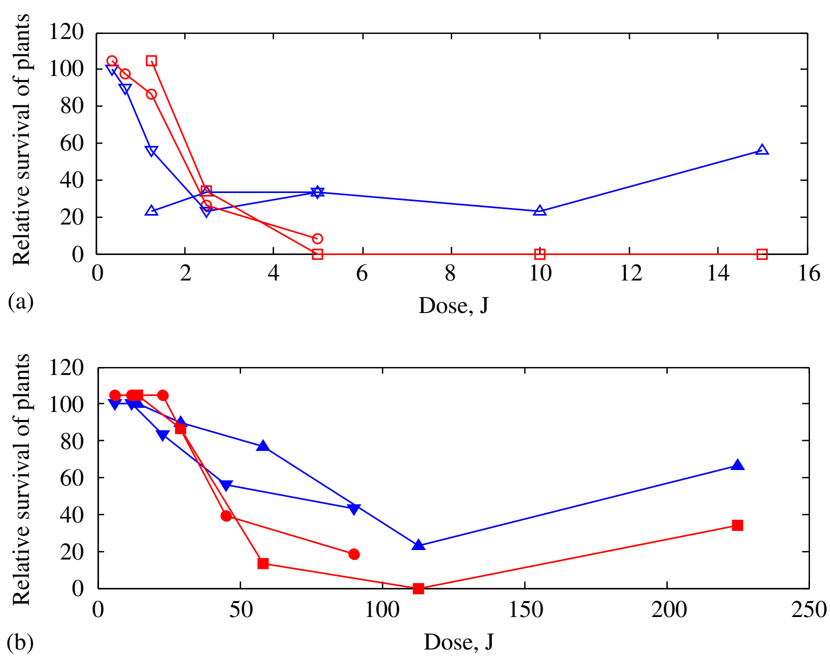

Fig. 4. Relative survival of Stellaria media and Tripleurospermum inodorum at increasing energy dose. (a) 5 W 532 nm laser: ▽, 0·9 mm for S. media; △, 1·8 mm for S. media; ○, 0·9 mm for T. inodorum; □, 1·8 mm for T. inodorum (b) 90 W 810 nm laser, ▼, 1·2 mm for S. media; ▲, 2·4 mm for S. media; ●, 1·2 mm for T. inodorum; ■, 2·4 mm for T. inodorum

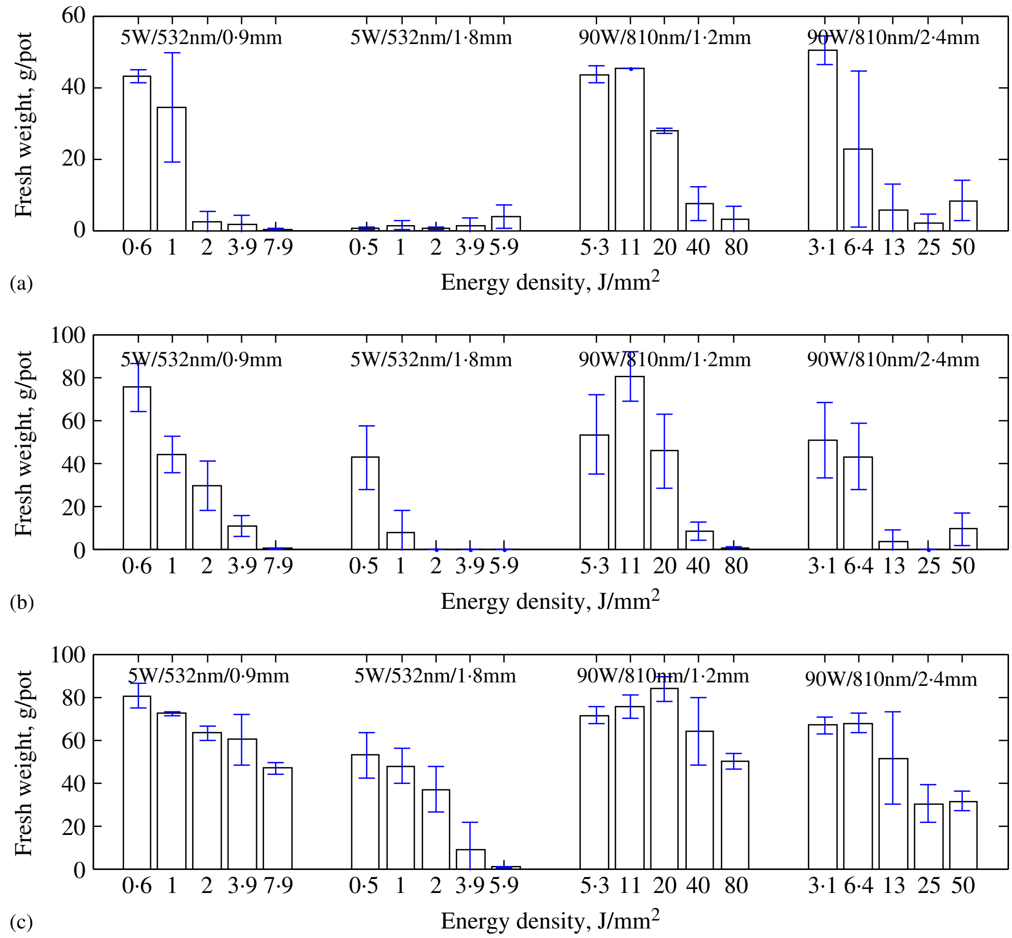

Fig. 5. Fresh weights of three weed species following increasing doses of laser energy applied with four different combinations of lasers and spot sizes; the doses refer to equivalent lasers, exposure times, spot sizes, energy amounts (doses) and energy densities, as outlined in Table 1; standard deviations are indicated by error bars: (a) Stellaria media; (b) Tripleurospermum inodorum; (c) Brassica napus

meristem of *B. napus* is much larger, *i.e.* it is easier to detect and target precisely. *Brassica napus* was less susceptible to laser treatment than the other species and only the 5 W laser applied with a spot diameter of 1·8 mm diameter at 3000 ms killed the plants. Obviously, more energy is required to kill the *B. napus* plants possibly due to the larger size and a higher number of cells in the apical meristems.

3.2. *Effects on biomass*

The biological effect of applying increasing doses of laser energy is a significant reduction in the growth rate up to a certain level when it becomes lethal (*Fig. 5*).

A pre-requisite for fitting the model in Eqn (1) to data is that the biomass responses support a non-linear curve in the range of the selected laser doses. The responses of *S. media* to treatments with the 90 W, 810 nm laser and the 5 W, 532 nm laser with a spot diameter of 0·9 mm support non-linear curves in the range from 0% and 100% effect. A test for lack of fit showed that the model was acceptable. In contrast, all doses applied with the 5 W, 532 nm laser and a spot diameter of 1·8 mm totally killed the *S. media* seedlings; hence, it was not possible to fit the model to these data.

The data from all treatments of *T. inodorum* and data from the treatment of *B. napus* with the 5 W, 532 nm laser and a spot diameter of 1·8 mm performed a good fit to Eqn (1). The fitness of data from the treatment of *B. napus* with the 5 W, 532 nm laser with a spot diameter of 0·9 mm and the 90 W, and the 810 nm laser with spot diameters of 1·2 and 2·4 mm were generally too low only covering the upper and middle part of the dose-response curves.

The dose–response curves of *S. media* and *T. inodorum* are shown in *Figs 6 and 7* and the estimated ED_{90} doses are shown in Table 2. The ED_{90} level of

S. media was 1·4 J when the 5 W, 532 nm laser was used with a spot diameter of 0·9 mm. However, if the spot diameter was increased to 1·8 mm the 90% level was much lower than 1·25 J (*Fig. 5*). In comparison, the estimated ED_{90} 'doses' following exposure to the 90 W, 810 nm laser were much higher. With a spot diameter of 1·2 mm the ED_{90} 'dose' was 58 J while at 2·4 mm spot diameter the required energy 'dose' for obtaining 90% efficacy was approximately a factor two higher. The effects of the laser treatments on *S. media* plants exposed to different 'dose' levels of two treatments are shown in the photograph in *Fig. 8*.

The two spot sizes with the 5 W, 532 nm laser performed equally on *T. inodorum* and the amount of energy required for obtaining 90% effect on biomass was significantly higher than on *S. media*. However, using the 90 W, 810 nm laser and a spot diameter of 1·2 mm, the value of ED_{90} for *T. inodorum* was similar to that for *S. media,* while a significantly lower dose was required with the 2·4 mm spot diameter. In general, the dose–response curves for *S. media* and *T. inodorum* of treatments with a spot diameter of 1·2 mm were steeper than the dose–response curves of treatments with the 2·4 mm spot diameter. This difference was related to the responses to the dose of 50 J being lower than the responses to 25 J. If these results are excluded from the analyses, the value for the parameter *b* and the ED_{90} for the two spot sizes are similar for both weed species. A review of treatment procedure could not explain any deviation in spot diameter or exposure time, *i.e.* there is no explanation of the deviation in the steepness from the other dose–response curves.

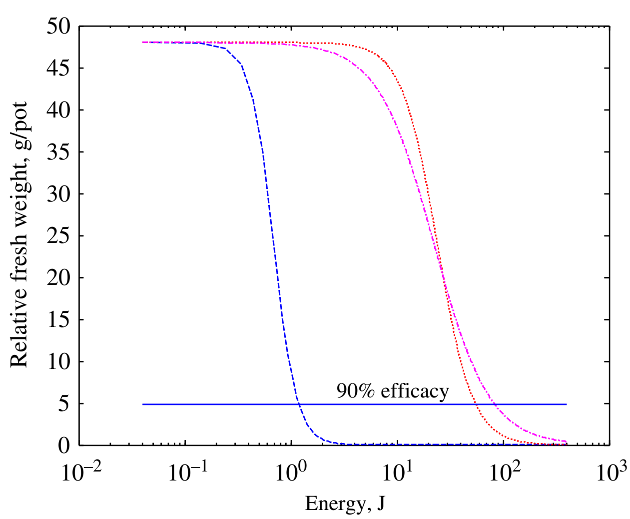

Fig. 6. The dose–response relationship between the fresh weight of Stellaria media and increasing doses of laser power, wave length and spot diameter: – – –, 5 W, 532 nm, 0·9 mm; ········, 90 W, 810 nm, 1·2 mm; –·–·–, 810 nm, 2·4 mm

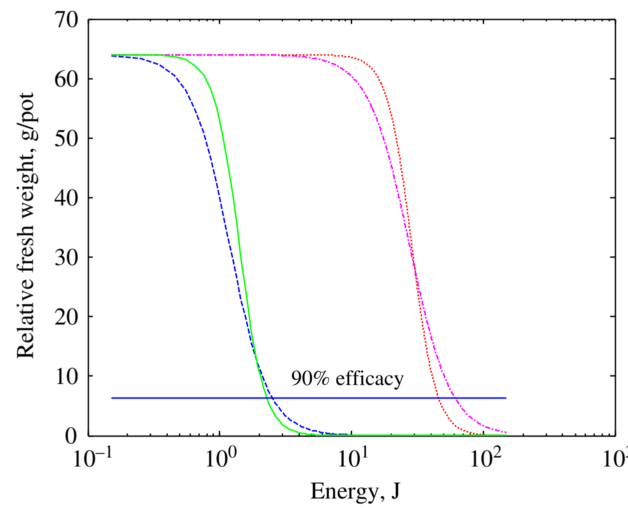

Fig. 7. The dose–response relationships between the fresh weight of Tripleurospermum inodorum and increasing doses of laser energy for three combinations of laser power, wavelength and spot diameter: – – –, 5 W, 532 nm, 0·9 mm; ········, 90 W, 810 nm, 1·2 mm; –·–·–, 810 nm, 2·4 mm; ——— 5 W, 532 nm, 1·8nm

Obviously, *B. napus* is much less susceptible to a laser treatment than the other species as the required doses for obtaining a 90% effect are much higher. It is not possible to compare the efficacy of treatments with different spot diameter on *B. napus* as values for ED_{90} could only be estimated for the largest spot diameter of each laser. The results, however, clearly show that much less energy is required to obtain a specific effect level when using the 5 W, 532 nm laser compared with the 90 W, 810 nm laser.

The similarity in steepness of the dose–response curves among the three weed species and the majority of treatments indicates that the biological effect on the species are the same irrespectively of laser type or spot size, *i.e.* the main effect is related to heating or explosive boiling of the cells in the apical meristem. The different doses required to obtain a certain level of efficacy is then related to the absorption of the two wavelengths and the size or number of cells of the apical meristem. The results indicate a better absorption of the 532 nm compared with the 810 nm wavelength.

The weed species included in this study represent three common Danish broadleaved weed species in terms of different growth habits, different sizes and different leaf surface characteristics. The results showed that the dose requirement for obtaining a specific effect level vary with a factor four to seven between species depending on combinations of laser type and spot size. Similar or higher dose adjustments between species are

Table 2
Results of the non-linear regression analyses; *b*, slope of the dose–response curve; ED_{90}, dose required for 90% effect; values in parentheses are 95% confidence intervals

Laser	*Spot diameter, mm*	*S. media*		*T. indorum*		*B. napus*	
		b	ED_{90}, *J*	*b*	ED_{90}, *J*	*b*	ED_{90}, *J*
5 W, 532 nm	0·9	−4·6	1·4 (0·9–1·8)	−3·4	2·6 (1·7–3·6)	n·e·	> 5
	1·8	n.e.	< 1·25	−5·3	2·7 (1·9–3·5)	−4·7	10·8 (8·4–13·2)
90 W, 810 nm	1·2	−3·0	58·3 (33·3–83·2)	−5·4	44·8 (29·0–60·6)	n·e·	> 90
	2·4	−0·9	104·9 (42·9–166·9)	−3·2	73·8 (45·1–102·4)	−1·6	> 225

n.e., Not estimated.

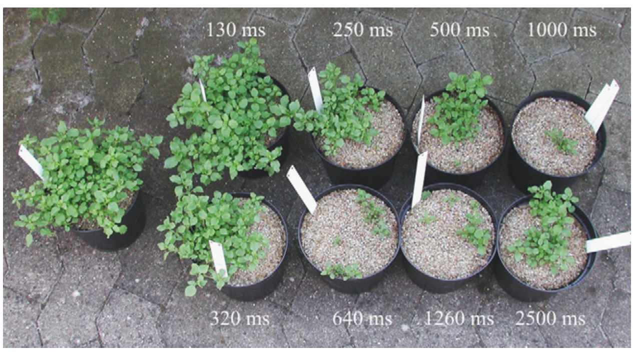

Fig. 8. Photograph of Stellaria media 24 days after treatment of the apical meristem with the 90 W, 810 nm laser. In the front row the laser was applied with a 2·4 mm spot and energy amounts from left to right were 29, 58, 113 and 225 J. In the back row the laser was applied using a spot diameter of 1·2 mm and the energy amounts were 12, 23, 45 and 90 J

common for other weed control methods (Kudsk & Streibig, 2003).

The experiment has revealed that laser exposure of the apical meristems of plants in the cotyledon stage has a potential as a physical weed control method. Addressing plants at the cotyledon stage simplifies the targeting as only the apical meristem needs to be treated. Plants at later stages would potentially require targeting on several areas of each plant in order to stop or delay the growth and thereby complicate the vision guidance of the laser beam.

The results on the three weed species show that the energy requirements are much lower for the 5 W, 532 nm laser treatment compared with the 90 W, 810 nm laser. Although it seems possible to control weeds with all combinations of the tested lasers and spot sizes the results indicate a better performance when larger spot sizes are used.

Further research is needed to document the efficacy on a broader spectrum of weed species and to improve the precision of the laser application method.

4. Conclusion

The experiment showed that laser exposure of the apical meristem of weed species can be used as a method of physical weed control. The efficiency of the laser weed control is related to wavelength, exposure time, spot size and laser power. The efficiency also varies between weed species with *S. media* and *T. inodorum* being much more susceptible than *B. napus*. In general, the highest efficacy was obtained using the 5 W, 532 nm laser and 1·8 mm spot diameter.

The results indicate that it is possible to improve the laser application method and to obtain a better performance by increasing the laser power and exposure time. The experiment also indicated that the efficacy can be improved by a proper selection of wavelength and spot diameter.

In order to improve the performance and to document the efficacy on a broader spectrum of weed species and growth stages, further research and development are needed.

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