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WEED CONTROL BY WATER STEAM USING A SELF-PROPELLED MACHINE EQUIPPED WITH A CONDENSATION CHAMBER

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ABSTRACT In the last years public concern about environmental pollution due to pesticides has been growing and, among other consequences, this situation boosted research on physical weed control methods as an alternative to herbicides. Recent researches have been carried out about the feasibility of the use of water steam as a replacement of chemical weeding in particular conditions where no chemical residues are allowed, e.g. in organic farming. Tests carried out with a steam jet directed on the weeds confirmed its effectiveness in killing weeds, but also showed high energy requirements and very low working speed despite the high thermal contents of steam. To improve weed control efficiency, a chamber where the steam can condense on the surfaces of the plants was developed in order to exploit the high efficiency of latent heat transfer of condensing water steam, as suggested by a theoretical analysis. Preliminary lab test confirmed the validity of this approach, showing higher energy efficiency in respect to the direct application. Following these encouraging results a self-propelled machine was equipped with a condensation chamber specifically designed to perform field tests on 5 species (two dicots and three grasses), to be treated at two different growth stages. The dose-response curves obtained after treating the plots with 5 to 6 different travel velocities showed good effectiveness. The dicots were effectively controlled with doses lower than 500 kJ m-2 (corresponding to 2 km/h travel speed), while maize was able to regrow after the treatment, requiring about twice the dose.

Keywords: Thermal weed control, Water steam, Heat transfer.

INTRODUCTION The reduction of the environmental impact of pesticide use, with particular consideration to surface, ground waters and air pollution, the protection of biodiversity and the care of the rural landscape, is one of the most important topics in the recent agro-environmental policy in European Union. The recently issued Directive 2009/128/EC about the sustainable use of pesticides, promotes the use of low input or pesticide-free crop farming, encouraging the development of alternatives methods to control pests and weeds.

In recent times, non-chemical weeding methods have been considered in the framework of integrated pest management. These methods are a key tool in organic farming systems, where chemical weeding is not permitted (Bond & Grundy, 2001), given that organic farmers refer to weeds as the most significant production trouble they encounter (Stopes & Millington, 1991). Furthermore, physical weed management is acquiring a growing importance in urban areas: the number of municipalities that have decided to convert to Integrated Pest Management methods or that have pesticide bans is increasing.

Among physical weed management methods, the thermal ones have been studied extensively and weed control based on flaming (Ascard, 1995), hot water (Hansson & Ascard, 2002) and microwaves (Sartorato et al., 2006) has been considered to perform post emergence weed control.

Thermal weed control, beside the positive aspects shared with other mechanical methods, like the absence of chemical residues, of weed resistance phenomena and of toxic hazard for operators, does not disturb the soil and therefore does not stimulate new weed emergences.

For all these approaches energy requirement is the critical aspect, some authors indicate steaming as a convenient alternative to flaming (Hansson & Ascard, 2002; Kerpauskas et al., 2006) and in recent past a certain number of portable steam/hot water killing devices were developed and patented (Langshaw, 1995; Simpson, 2000).

The use of water steam has been proposed several years ago, particularly to sterilize the soil and control both weeds and pathogens (van Loenen et al., 2002). Most of the studies carried out on hot steam weed control referred to devitalization of the seeds in the soil. To do this, a considerable amount of energy is needed to raise the temperature of the soil mass to the required value. The use of specific devices to treat only the band of soil were the crop will be drilled, has been evaluated in some studies as a possible energy saving method compared with the treatment of whole plant bed.

More recently steaming has been tested in cultivated fields to investigate its feasibility for post-emergence weed control. First findings indicated that best results could be reached by steaming plants up to two leaves; application to weeds at later stage was ineffective (Kerpauskas et al., 2006). Besides the growth stage of the plants, the effectiveness of the treatment depends on other factors, such as species' sensitivity, vegetation density on treated area, microclimate characteristics, application technique, etc.

The condensation of water steam releases a high amount of energy, the latent heat of condensation being 2.26 MJ kg^{-1} at 100 °C and atmospheric pressure, and this energy can be transferred with a very high efficiency to the surface where condensation happens. On the basis of this observation Baldoin et al. (2008) carried out two sets of dose-response laboratory tests using experimental equipment fitted with a specifically built condensation chamber. The preliminary results on seedlings of different species and growth stages were encouraging, therefore a subsequent field experiment with a self propelled machine fitted with a large condensation chamber was performed. In this paper a theoretical justification of the approach is given and results of the field experiment are reported.

METHODS

Mathematical background Starting from the heat transfer laws a model was derived to estimate the treatment time needed to kill plants of different height; it was assumed, as a first approximation, that the plants stem can be considered as solid cylinder and that a critical temperature must be reached at the cylinder axis to kill the plant.

Syrvidas et al. (2002) pointed out that thermal weed control using water steam is more efficient than flaming, the traditional method based on hot combustion gases, because of a much higher efficiency in heat transfer; the convective heat transfer coefficient (*h*) of steam condensing on the plant surface ranges from 5000 to 50000 W $m^{-2}K^{-1}$, while for a hot gas it is much lower (5-50 W $m^{-2}K^{-1}$) and only partially compensated by a higher temperature difference between heating fluid and plant surface (about ten times in respect to water steam). Mafart (2004), for a long cylindrical object with vertical axis, found a heat transfer coefficient of about 17000 W $m^{-2}K^{-1}$, an intermediate value between the limits indicated by Syrvidas; this value will be used in the following calculation.

The heat exchange between water steam and the model plant is driven by two heat transmission processes:

- an external exchange between the heating fluid and the plant surface by convection, described by the Newton law:

$$q = h \cdot A \cdot \left(T_v - T_s\right) \qquad (1)$$

where h = convective heat transfer coefficient, A = the area of the surface exposed to heat of the cylinder-plant, T_v = fluid temperature and T_s = surface temperature

- an internal exchange inside the plant, due to conduction and driven by the first law of Fourier:

$$q = \frac{\lambda}{l} \cdot A \cdot \left(T_s - T\right) \qquad (2)$$

where λ is the thermal conductivity of the plant (0.57 W $m^{-1}K^{-1}$), T is the variable temperature at the cylinder axis and l is the *characteristic length*, that is the thickness where the heat exchange takes place; l can be identified as the radius R of the cylinder, provided that the length/diameter ratio is higher than 5, as it is in the case of plants.

The Biot number *Bi*, the ratio between the conductance external and internal of the plant, defines the regime of heat transfer and, in the case of a merely conductive thermal exchange, it assumes the typical form:

$$Bi = \frac{h \cdot l}{\lambda} = \frac{h \cdot R}{\lambda} \cong 30000 \cdot R \qquad (3)$$

with a minimum value of 30, when R = 1 mm, a value close to the stem radius of the smallest treated plants, and a maximum of 120 when R = 4mm, as for the tallest treated plants. These values are relatively higher than the empirical limit above which external conductance can be considered as approaching to infinite respect to the internal one, therefore the temperature profile is as shown in fig. 1.

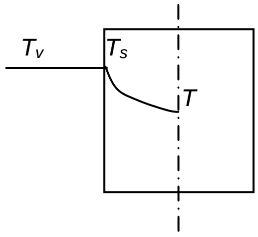

Figure 1. Heat transmission, external from T_v to T_s and internal from T_s to T, in non-stationary state for Bi>40.

The heat flow does not encounter any resistance to cross the boundary layer of the external fluid and therefore, as a consequence of the high values of Bi before mentioned, it can be deemed that the temperature of this last one is the same as at the surface T_v=T_s as shown in fig. 1.

Plant temperature T varies either in time and space, according to the second law of Fourier, which for cylindrical long objects is:

$$\frac{dT}{dt} = a \cdot \left(\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} \right) \qquad (4)$$

where a=1.4·10^{-7} is the thermal diffusivity (m^{2}s^{-1}), given by $a = \frac{\lambda}{c \cdot \rho}$ where c=specific heat capacity (J kg^{-1}K^{-1}) and ρ= density (kg m^{-3}), both related to the plant.

The solution of this differential equation describes the trend of plant temperature in relation to time and space. Its analytical integration is feasible for the cylinder, where thermal diffusivity is retained to be invariant respect to temperature, but it is a complex task, given that its solution is mathematically figured as an infinite series of exponential and Bessel functions.

Anyway, after a certain heating time the ratio $\frac{T - T_v}{T_0 - T_v}$ where T_0 is the initial temperature and T the temperature at the axis of the cylinder, i.e. at the core of the plant, tends asymptotically to an exponential function:

$$\frac{T - T_v}{T_0 - T_v} = j \cdot e^{-S \cdot \frac{a \cdot t}{l^2}} = j \cdot e^{-S \cdot Fo} \qquad (5)$$

where j and S are constants, depending on the plant geometry. In the case of the elongated cylinder with radius R, always with reference to the temperature at its geometrical axis, j and S result:

j = 2.04 $\qquad$ S = 5.783

The time t since which the (5) is applicable is not absolute, but is related to an adimensional number, the *characteristic length* l=R, and to the thermal diffusivity a of the object. By combining adimensionally these three entities the number of Fourier (Fo) can be obtained:

$$Fo = \frac{a \cdot t}{l^2} = \frac{a \cdot t}{R^2} \qquad (6)$$

The value of this “adimensional time”, for the applicability of the (5) is Fo > 0.1. When Fo = 0.1 a less than 5% error is made, which decreases quickly when Fo > 0.1. When F_0

= 0.2 the error is negligible. Combining (5) and (6) we can get the time to reach the temperature needed to kill the core of the plant, which is suggested by Syrvidas et al. (2002) to be 60°C:

$$t = \frac{R^2}{S \cdot a}\left(Ln(j) - Ln\left(\frac{T - T_v}{T_0 - T_v} \right) \right) \qquad (7)$$

Finally, introducing in the (6) the values of thermal diffusivity *a*, of the time got from the (7) and the radius *R* of the stem, the number of Fourier *Fo* results equal to 0.245>0.1, thus confirming the applicability of the (7) itself.

Assuming T_0 = 20 °C and T_v = 100 °C, the resulting parabolic relationship between radius *R* and time *t* from equation (7) is shown in figure 2, it indicates that treatment time should range from about 2 to about 30 seconds to completely devitalize plants with a stem radius from 1 to 4 mm.

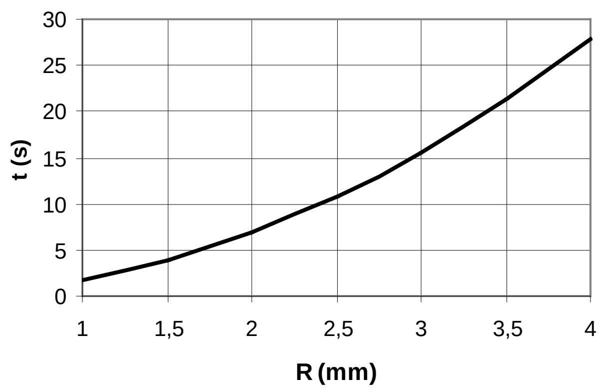

Figure 2. Heating time to *T* = 60°C at the axis of the plant stem as a funtion of stem radius *R*.

Equipment A custom-built condensation chamber (1.20 W x 0.77 L x 0.50 H m) was used for the field experiment. The shape of the condensation chamber was derived from the smaller one used in the previous laboratory experiments (Baldoin et al., 2008) and actual dimensions were dictated by the available steam generator (delivering 480 kg h^{-1} of steam), installed on a self propelled machine manufactured by Celli S.p.A., Forlì – Italy. This approach could permit a comparison with the results of the preliminary laboratory tests. The equipment is shown in figure 3.

From theoretical treatment times estimated above and from chamber length, the corresponding range of travel speeds of the machine was calculated, as well as the actual energy doses range. The applied dose was expressed as the applied energy (latent heat of condensation of water steam) on area basis (kJ m^{-2}).

The adopted speed settings and corresponding treatment times and energy doses are reported on table 1.

Figure 3. The self moving steam generator (Celli – Forlì) with the condensation chamber

Field experiment A dose-response field experiments was carried out on pure stands in 2009 at the University of Padova experimental farm (north-eastern Italy, lat. 45° 21'N) on a loamy soil, to test the response of 5 different plant species to water steam application. Plants were treated at 2 to 4 true leaf stage (I treatment stage) and at 5-6 leaf stage (II treatment stage), plant height at treatment varied from 3-4 cm of velvetleaf at the first stage to about 25 cm of the maize plants at the second growth stage. The 5 to 6 water steam doses, i.e. the different times of application, were obtained varying the machine speed. Adopted speed and related doses are shown on table 1.

The experimental layout was a randomized block design with 3 replicates, for a total of 210 experimental units (5 species * 7 doses, including untreated plots * 2 growth stages * 3 replicates). Each units consisted in two 0.5 m-long rows (inter row distance 15 cm) with an average number of 85 plants of each species; plants were counted at treatment time and late emerged seedlings removed to achieve a uniform stand.

For each dose and stage the five species (units) were pooled within one single plot. Plots were at about 7 meter each other to allow for adjustment of machine speed.

Table 1. Travel speed settings, duration of treatment and energy amount adopted in the dose-response field trial.

Run	1st stage			2nd stage		
	Working speed ($m\ h^{-1}$)	Duration of treatment (s)	Energy amount ($kJ\ m^{-2}$)	Travel speed ($m\ h^{-1}$)	Time of treatment (s)	Energy amount ($kJ\ m^{-2}$)
1	430	6.4	2408	430	6.4	2408
2	910	3.0	1139	670	4.1	1544
3	1270	2.2	822	1060	2.6	981
4	2370	1.2	439	1270	2.2	822
5	4870	0.6	214	2370	1.2	439
6	-	-	-	4870	0.6	214

The tested species were two dicots: white mustard (*Sinapis alba* L.) and velvetleaf (*Abutilon theophrasti* Medicus) and three monocots: wild proso millet (*Panicum miliaceum* L.), sudan grass (*Sorghum bicolor* Pers.) and maize (*Zea mays* L.).

To check for damage evolution over time, four visual assessments were made of the weed control level attained between treatment and harvest: each plot was scored between 0 and 10, with 0 equaling completely devitalized plants and 10, healthy plants.

The percentage of biomass reduction in comparison to an untreated check was assessed seven days after treatment.

Statistical analysis The relationship between applied steaming energy (Dose) and plant dry weight at harvest (DW) was analyzed using the log-logistic curve described by Streibig et al. (1993) for herbicides:

$$DW = C + \frac{D - C}{1 + \exp\left(b\left(\ln(\text{Dose}) - \ln(ED_{50})\right)\right)}$$

where C is the lower asymptote (aboveground dry weight of plants treated with highest energy dose), D is the upper asymptote (aboveground dry weight of untreated plants), ED_{50} is the level of Dose causing a reduction of plant dry weight half way between the upper and lower asymptote and b is the curve slope around ED_{50}. To facilitate the comparison among plants of different species and height relative data were used (percentage dry weight (DW) in comparison to untreated plants), so that the upper asymptote was set to 100.

RESULTS

Dose-response trial The overall efficacy of the steam application was high, soon after the treatments almost all the plants appeared as dead even at low doses; after few days maize plants, and at lower extent also the other monocots, began to recover and to produce new leaves.

It was possible to fit the logistic dose-response curve to all the ten “species * stage” combinations, but in four cases some of the estimated parameters did not result as significant, all the fitted curves are anyway reported in figure 4 to highlight the trend of the response. Dicots resulted as the more sensitive to the treatment and all the species but maize were almost completely devitalized with a dose of 820 kJ m^{-2}, corresponding to a travel speed of about 1.3 km h^{-1}. The lowest applied dose (214 kJ m^{-2}) was still too high to permit a robust estimation of the dose-response curve parameters, given that the majority of the estimated ED_{50} levels (table 2) were below this dose.

Response trends resulted very similar between growth stages, indicating a null or limited effect of the plant size.

Energy related aspects A fuel consumption of 39.2 L h^{-1} of diesel fuel was measured; assuming a lower heating value of 35.64 MJ L^{-1} (density 0.835 kg L^{-1}), a total energy consumption of 1397 MJ h^{-1} can be calculated. Considering the latent heat of vaporization of water steam and a boiler delivery of 480 kg h^{-1} of steam, the resulting amount of available energy for killing weeds (about 1090 MJ h^{-1}), corresponds to an overall efficiency of the machine of about 78%.

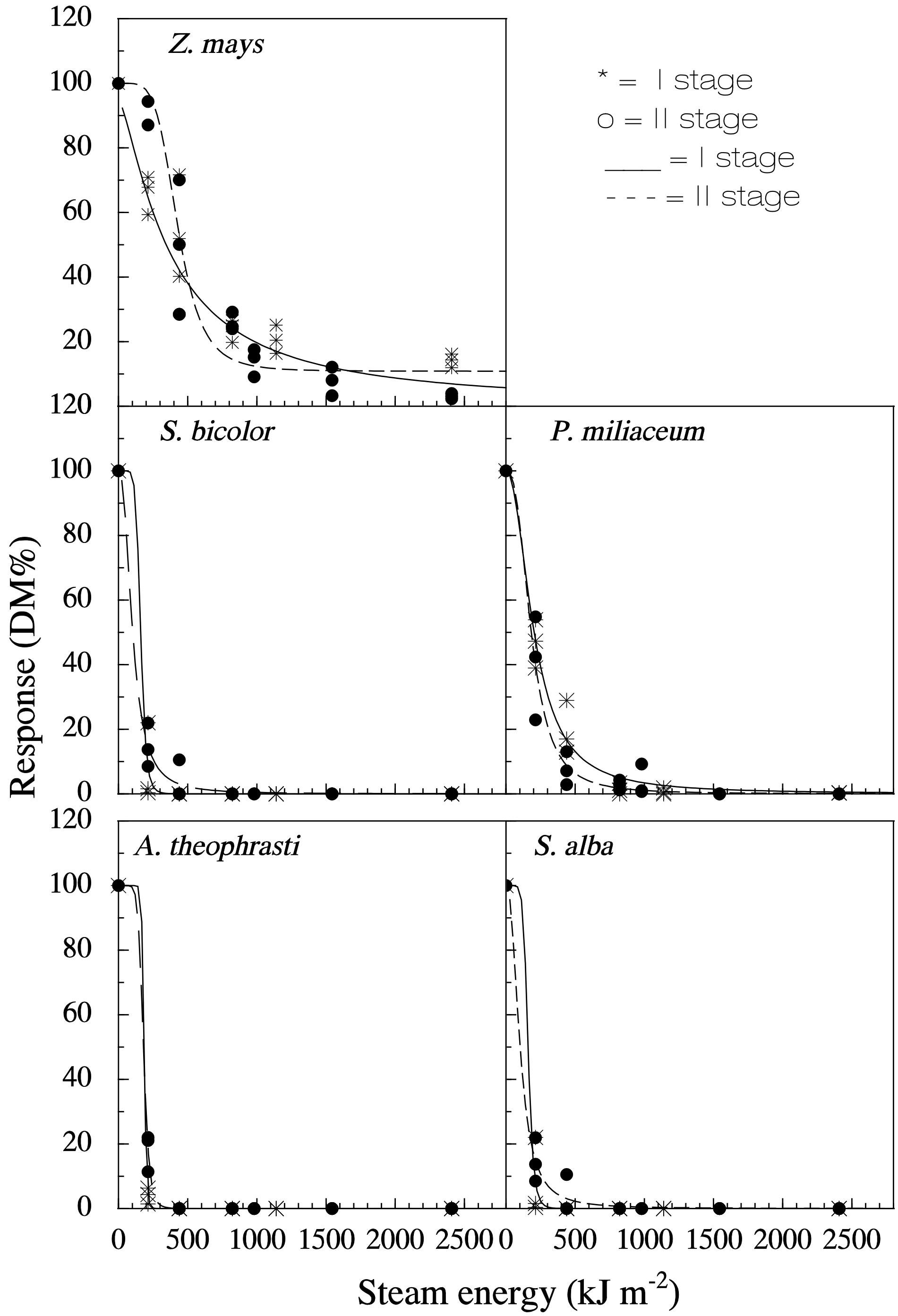

Figure 4. Experimental data and fitted dose-response curves.

Table 2. Water steam energy dose causing a reduction of plant dry weight half way between the upper and lower asymptote (ED_{50}, kJ m^{-2}), and related standard errors, not reported for the species where ED50 estimate was not significant.

Species	1st stage		2nd stage	
	ED_{50}	*s.e.*	ED_{50}	*s.e.*
White mustard	160	-	102	26.4
Velvetleaf	185	-	180	-
Proso Millet	204	11.38	183	13.4
Sudan grass	214	-	302	60.3
Maize	402	41.6	452	40.1

CONCLUSION The field trial showed an efficacy of condensing water steam higher than the one theoretically derived, treatment times of 3 seconds were sufficient to ensure an almost complete control of the vegetation and, within the investigated plant size range, the growth stage did not influence the control efficacy. The partial control obtained on maize could be explained by the protected apical meristem, before the culm elongation phase the apical meristems in monocots is kept at ground level and protected by various leaf sheaths; this plant structure explains why monocots can react to the treatment regenerating the plant after a first phase where plants appeared as completely devitalized. The other two monocots were smaller than maize at treatment time, so the meristem protection was probably not as effective as the one of maize and they were not able to recover after the treatment. The discrepancy between expected and observed plant behavior could also be due to a different heat transfer coefficient, to the effect of the approximation done for plant stem to a solid cylinder and to a combination of these and other unknown factors.

From the practical point of view the field trial demonstrated that a relatively high travel speed, that is a satisfactory working capacity, can be achieved with this method and it could be increased simply increasing the length of the condensation chamber.

It should be also highlighted that the self moving machine in use was not optimized respect to the energy requirements for field testing, but it was a commercial machine designed for steaming the soil and the working speed could be not further increased. A different power train allowing a better choice of working speed should be needed.

In addition the effect of condensation chamber shape and size has to be investigated to define the optimal combination of the different influencing factors on the overall efficiency, anyway the energy requirements of the method will probably remain relatively high and this aspect can limits its diffusion, but it could find his niche of intervention at least in sensitive areas such as horticultural organic farming or urban sites.

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