A review of non-chemical weed control on hard surfaces

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Summary

Weed control research to date has mainly focused on arable land, especially regarding herbicides, but also regarding non-chemical methods. Some of these experiences can be applied to hard surface areas. However, weeds on hard surface areas cause problems that are different from those on arable land. Additionally, crop tolerance does not need to be considered when choosing an appropriate weed control method on these areas. The aim of this review is to describe current knowledge of weeds and weed control methods on hard surface areas and reveal potential ways of advancement. One of the shortcomings of non-chemical weed control on hard surfaces thus far, is a lack of proper definition of efficiency of the weed control methods. To obtain effective control, more frequently repeated treatments are required than chemical weed management, thereby increasing the costs of labour and fuel. One way to reduce costs can be by adjusting the level of control to the required visual street quality. Weeds are adapted to the hard surface environment and may be less susceptible to certain control methods. This review indicates that for efficient weed control on hard surfaces there is a need for combining weed control techniques, applying sensors for detecting weeds, adapting the energy dose to type of weed flora and prevention of weeds by improved construction of new surfaces.

Keywords: thermal weed control, mechanical weed control, flaming, steam, brushing, urban areas, pavement, hard surfaces.

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Introduction

The use of pesticides in non-agricultural areas may lead to different environmental issues from their agricultural use and these need separate consideration (Spliid *et al.*, 2004). Hard surfaces are often constructed for rapid penetration of water or to encourage surface run-off to avoid flooding; this can result in contamination of nearby ditches, drains, sewage systems or ground water (e.g. Allender, 1991; Nitschke & Schüssler, 1998; Skark *et al.*, 2004; Ramwell *et al.*, 2002). Consequently, there is minimal opportunity for herbicide sorption and/or degradation (Ramwell *et al.*, 2002; Cederlund & Stenström, 2004; Strange-Hansen *et al.*, 2004; Phillips & Bode, 2004), whilst the potential for herbicide removal to surface water bodies is high. Water-quality monitoring studies have demonstrated that there is a disproportionate contamination of waters by non-agricultural pesticide use (Nitschke & Schüssler, 1998; Lotz *et al.*, 2000; Augustin, 2003b; Skark *et al.*, 2004). In many countries, the risk for pollution of the environment and drinking water reservoirs has led to several restrictions on the use of herbicides for weed control in urban areas (e.g. Lefevre *et al.*, 2001; Hansson, 2002; Augustin, 2003b; Kristoffersen *et al.*, 2004), which increase the need for alternative control methods.

Hard surface areas are defined as areas with a ground-covering, such as asphalt, paving-stone and concrete, or surfaces with a top layer of sand, gravel or crushed material (Kortenhoff *et al.*, 2001). Weeds grow easily in the open spaces present, such as joints and cracks. There are several reasons for the undesirability of weeds in these areas. Weeds can cause damage to the hard surfaces by breaking up asphalt and the edge of the

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road seal or enlarging cracks and thereby shortening their lifetimes (Holgersen, 1994; Zwerger *et al*., 2000). Additionally, weeds can make asphalt footpaths slippery. Accumulation of plant residues can impede storm water run-off and make a substrate for new weed establishment. At road verges, they can impair the visibility of traffic indicators and thereby cause accidents. Besides, weeds make the streets and pavements unsightly and the presence of weeds tends to be perceived as an indicator of a city in decline (Popay *et al*., 1992; Benvenuti, 2004).

Weed control research to date has mainly focused on arable land, but only some of these experiences can be applied to hard surface areas. Weeds on hard surfaces cause problems that are different from those on arable land and different issues concerning prevention of establishment and weed control need to be considered. One of the essential differences to weed control in agriculture is that crop tolerance does not need to be considered, as total vegetation control is required. This increases the applicability of several non-chemical control methods for these areas. On the other hand, weeds on pavements are not subjected to the periodic soil tillage disturbance in conventional agro-ecosystems and this favours the growth of perennial weeds, which are mostly very tolerant to e.g. thermal weed control (Ascard, 1995b; Hansson, 2002). There is no risk of soil compaction on hard surfaces, but large heavy machines cannot be used on vulnerable pavements, such as bicycle lanes with a thin layer of asphalt (Kristoffersen & Larsen, 2005). When treating weeds along railway banks, a high travel speed is necessary to avoid rail traffic delays (Hansson *et al*., 1995).

Weeds can be prevented on hard surface areas by changing the design of the surface and by selecting suitable materials and construction techniques. However, the conversion of surfaces will take a long time and incur high investment costs. The issues concerning these preventive methods are not included in this review.

A comprehensive review of non-chemical weed control techniques and systems in organic farming has been made by Bond and Grundy (2001), whereas knowledge of the state-of-the-art methods, applicability and equipment for weed control on hard surfaces is not available. The aim of this paper is to describe current knowledge of weeds and non-chemical weed control methods on hard surface areas and to review potential advances. The paper examines the characteristics of weeds in urban areas, developments in control methods and the possibilities and constraints for applying the methods on hard surface areas. The most recent advances are often presented in symposium papers, magazine articles or national reports that have not been exposed to peer review. Nevertheless, references to these publications have been included to make the review as complete as possible.

Weeds on hard surfaces

Knowledge on the species distribution and developmental stage of weeds can be used to inform weed control strategies. Each of the various ecological niches offered by the urban environment (pavements, road verges, walls, railway embankments, etc.) feature certain species that are particularly suited to persisting in the given habitat (Benvenuti, 2004). Cities are often defined as heat islands, as the temperature is typically higher than in the surrounding countryside (Johnson *et al*., 1974). In cities with a warm climate, this results in a higher frequency of species exhibiting C4 photosynthesis (Sattin *et al*., 1996). Additionally, pavement cracks, corners of masonry or small fissures between paving blocks are characterised by aridity, favouring the growth of xerophytes (Benvenuti, 2004).

Pavements that are affected by trampling are frequently inhabited by species with their growth meristems located at the axilla of the basal leaves and are therefore protected against trampling damage, e.g. grasses, several Plantaginaceae or Asteraceae at the phenological stage of the rosette (Benvenuti, 2004). Thus, non-chemical methods, such as thermal treatments have lower efficacy on these weed species as compared with weed species with more exposed growth meristems, such as *Chenopodium album* L., *Fumaria officinalis* L., *Urtica urens* and *Stellaria media* (L.) Vill. (Ascard, 1995b). Perennial weeds thrive especially well in urban environments due to vegetative propagation and/or having growth meristems located below the surface, e.g. *Elytrigia repens* (L.) Desv. ex Nevski, *Cirsium arvense* (L.) Scop. and *Equisetum arvense* L. (Ascard, 1995b; Torstensson & Borjesson, 2004).

Dicotyledonous weeds are generally more susceptible than monocotyledonous ones when subjected to a thermal treatment (Parish, 1989b, 1990b). Ascard (1995b) and Hansson (2002) have divided weed species into four groups depending on their morphology and tolerance to thermal treatment. Although the tolerance principally depends on the location of the growth meristems, other factors, such as a covering of hair, high moisture content (Lalor & Buchele, 1970) and protective layers of bark increase the heat tolerance of plants (Vines, 1968; Christiansen, 1978).

Applying non-chemical treatments to hard surfaces

A common feature of non-chemical methods is that effective control needs more frequently repeated treatments than chemical weed management (Nyström & Svensson, 1988; Popay *et al.*, 1992; Elmore, 1993; Augustin *et al.*, 2001; Reichel, 2003; Kristoffersen *et al.*, 2004). Non-chemical treatments mainly affect the above-ground plant parts, whereas systemic herbicides, such as glyphosate kill the entire plant and therefore only require one or two applications per year (Popay *et al.*, 1992; Augustin *et al.*, 2001). The treatment frequency depends on factors, such as the weed species composition, weed cover, weed acceptance level, weed control method, climate and type of hard surface. Hansson and Ascard (2002), for example, have suggested treatment intervals of 25 days for hot water treatment on hard surface areas and Kreeb and Warnke (1994) concluded that flame treatment intervals of 2–5 weeks should be performed on railway banks to keep weed density at an acceptable level. Hansen *et al.* (2004) have performed experiments with different thermal methods and brushing on pavements during a 3 year period. In their experiments, 11–12 treatments per year were necessary to achieve acceptable weed control on areas heavily infested with perennial weeds, irrespective of the method applied. Dutch experimental research on pavements (e.g. Vermeulen *et al.*, 2006) had used fewer treatments: 4–6 treatments of brushing, 3–5 treatments of flame weeding and 3–5 hot water treatments per year. Lefevre *et al.* (2001) suggest that the efficacy of techniques should be monitored over a period of several years to resolve the following questions:

- Can the number of operations be reduced in the course of time?
- What is the long-term effect of each weed control technique on different weed species?

Several non-chemical weed control methods have been tested for their applicability on hard surfaces and some of them are used in practice (Table 1). Thermal and mechanical weeding are examined below and the use and limitations of each method is described.

Thermal weed control

Thermal control methods can be divided in two groups according to their mode of action (a) the direct heating methods (flaming, infrared weeders, hot water, steaming, hot air) and (b) indirect heating methods (electrocution, microwaves, laser radiation, UV-light), with freezing as a third and opposite plant stress factor. The effects of the indirect methods have not been tested specifically for hard surface weed control, but the information available will be evaluated. Because of the wide range of equipment used in the experiments, varying doses, weed control levels, etc., it is difficult to compare the effect of the respective methods. Besides, in many cases important information on equipment, doses, etc. is lacking, as mentioned by Ascard (1998). However, the obtained results and general trends will be summarised.

Several studies aiming to improve agricultural weed control have shown the importance of the developmental stage of the weed plants at treatment (Parish, 1989b, 1990b; Casini *et al.*, 1993; Ascard, 1994, 1998; Daar, 1994; Hansson & Ascard, 2002). Treatment at an early developmental stage reduced fuel input and thereby increased driving speed and lowered the costs. Ascard (1994) found weed density to be of minor importance in flame weeding.

The energy dose applied by weed control machinery is mainly regulated by the driving speed (Ascard, 1995b; Hansson, 2002). A combination of driving speed and length of equipment determines the treatment time. The driving speed is usually quite low to achieve sufficient thermal weed control and reduce weed regrowth (Table 2) and thereby the treatment time and costs are increased.

Table 1 Weed control methods, stage of technological development and specific challenges for future research

Weed control method	Developmental stage	Specific challenges for future research
Flaming	Used on hard surfaces	
Infrared radiation	Used in agriculture	
Hot water	Used on hard surfaces	Reduce energy input and water loss
Steaming	Used on hard surfaces	
Hot air	Used on hard surfaces	Reduce energy input
Electrocution	Experimental stage/ railways	Reduce hazards
Microwaves	Experimental stage	Reduce hazards and energy input
Laser radiation	Experimental stage	
Freezing	Experimental stage	Reduce energy input
UV-radiation	Only laboratory experiments	Reduce hazards and energy input
Brushing	Used on hard surfaces	Reduce wear to the surface and vibration levels
Sweeping	Used on hard surfaces	
Hand hoeing	Used on hard surfaces	
Harrowing	Used on gravel surfaces	

Table 2 Some of the experimental dose-response results obtained during the last decades that have been carried out on hard surfaces, or as laboratory experiments or non-crop field experiments

Control method	Researchers	Experimental conditions	Working width m	Consumption kg h^{-1}	Dose kg ha^{-1}	Travel speed km h^{-1}	Test species	Developmental stage	Control level
Flaming	Ascard (1994)	Field expt. (cropfree)	1	6.82	25	1	*Sinapsis alba* (L.) (high density)	0–2 leaves	95% Reduction in fresh weight
	Ascard (1994)	Field expt. (cropfree)	1	6.82	45	0.5	*Sinapsis alba* (L.) (high density)	2–4 leaves	95% Reduction in fresh weight
	Ascard (1995a) (Expt 4†)	Field expt. (cropfree)	1	6.82	8	8.3§	*Chenopodium album* (L.)	2 leaves	95% Reduction in fresh weight
	Ascard (1995a) (Expt 4†)	Field expt. (cropfree)	1	6.82	23	2.9§	*Chenopodium album* (L.)	6–12 leaves	95% Reduction in fresh weight
	Expt 4	Field expt. (cropfree)	1	6.82	35	1.9§	*Chamomilla Suaveolens* (P.)	2–4 leaves	95% Reduction in fresh weight
	Expt 4	Field expt. (cropfree)	1	6.82	141‡	0.5§	*Chamomilla Suaveolens* (P.)	>10 leaves	95% Reduction in fresh weight
	Ascard (1998)	Field expt. (cropfree)	1	6.82	60	1.18	*Sinapsis alba* (L.)	4 leaves	95% Reduction in fresh weight
	Bolognesi (2005)*	Granite sett pavement	0.15	.	94	Not stated	Natural weeds	Not stated	100% Reduction in weed cover after 2 treatments
	Nemming (1994)	Field expt. Pre-emergence	3	137	65	8	Natural weeds	Not stated	Not stated
	Nemming (1994)	Field expt. Pre-emergence	2.5	25	22	5	Natural weeds	Not stated	Not stated
Hot water	Kempenaar and Spijker (2004)	Hard surface (no foam added)	1	.	Not stated	5	Natural weeds	Not stated	27% of control weed cover
	Kempenaar and Spijker (2004)	Hard surface (no foam added)	1	.	Not stated	7	Natural weeds	Not stated	25% of control weed cover
	Kempenaar and Spijker (2004)	Hard surface (foam added)	1	.	Not stated	5	Natural weeds	Not stated	12% of control weed cover
	Kempenaar and Spijker (2004)	Hard surface (foam added)	1	.	Not stated	7	Natural weeds	Not stated	12% of control weed cover
	Hansson and Mattsson (2003) (Expt 1)	Laboratory (temp. 7°C)	0.8	.	172**	Not stated	*Sinapsis alba* (L.)	4 leaves	90% Reduction in fresh weight
	Hansson & Mattsson, 2003 (Expt 1)	Laboratory (temp. 18°C)	0.8	.	172**	Not stated	*Sinapsis alba* (L.)	4 leaves	90% Reduction in fresh weight
	(Expt 2)	Laboratory (rain)	0.8	.	264**	Not stated	*Sinapsis alba* (L.)	4–6 leaves	90% Reduction in fresh weight
	(Expt 2)	Laboratory (no rain)	0.8	.	217**	Not stated	*Sinapsis alba* (L.)	4–6 leaves	90% Reduction in fresh weight
	Hansson and Ascard (2002) (Expt 1)	Field expt. (cropfree)	1	15.8¶	126**	1.26	*Sinapsis alba*	2 leaves	90% reduction in fresh weight
	Hansson and Ascard (2002) (Expt. 1)	Field expt. (cropfree)	1	15.8¶	360**	0.44	*Sinapsis alba*	6 leaves	90% Reduction in fresh weight
	(Expt 3)	Gravel surface	0.3	4.8¶	356**	0.47	Natural weeds	Well-established weeds	90% reduction after 7 days
	(Expt 3)	Gravel surface	0.3	4.8¶	530**	0.32	Natural weeds	Well-established weeds	90% Reduction after 15 days
	(Expts 4 and 5)	Railway embankment	0.3	14.3¶	571**	8.3	Natural weeds	50–100 mm high weeds	90% reduction after 5 days
	(Expts 4 and 5)	Railway embankment	0.3	14.3¶	530**	0.9	Natural weeds	50–100 mm high weeds	90% Reduction after 14 days

*Doctoral thesis.

†Other species were also included in the study.

‡Uncertain estimate, outside observed dose range.

§Calculated by authors (thermal value of gas: 12.8 kWh kg^{-1}): travel speed (km h^{-1}) = 85.25 kWh h^{-1} × 10000 m^2 ha^{-1} m^{-1}working width × (kg ha^{-1} × 12.8 kWh kg^{-1} gas) × 1000 m km^{-1}.

¶Calculated by authors (thermal value of diesel: 11.9 kWh kg^{-1}): consumption kg h^{-1} = (km h^{-1} × m working width × 1000 m km^{-1} × (kg ha^{-1} × 11.9 kWh kg^{-1})/10000 m^2 ha^{-1})/11.9 kWh h^{-1}.

**Hansson & Mattsson and Hansson & Ascard presented the results as kJ m^{-2}. We have used following conversion: 1 kJ m^{-2} = 3.596 kg ha^{-1}. The diesel powered equipment had a thermal efficiency around 75% and the calculated doses are therefore divided by 0.75 (Hansson, pers. comm.).

Flaming

Flame weeding is the most commonly applied thermal weed control method on hard surfaces and is regularly used for weed control in Denmark and Sweden (Hansen *et al.*, 2004; Schroeder & Hansson, 2006). In Germany, a train equipped with flame weeders has been used to control weeds on railway embankments (Kreeb & Warnke, 1994). Several kinds of equipments have been developed that are specially designed for weeding on hard surface areas, such as tractor-mounted flamers for footways and road verges and hand-pushed or handheld aggregates for weeding around obstacles and for private households (Tvedt & Kristoffersen, 2002; Quarles, 2004; Schroeder & Hansson, 2006). Flaming controls a wide range of annual weed species, some of which are tolerant or resistant towards herbicides (Ascard, 1995b). The main disadvantage of flaming is the fire hazard, and therefore, the method is no longer used on areas that pose a fire risk, e.g. on railway embankments in Sweden (Hansson, 2002; Wood, 2004).

Comprehensive investigations of flaming can be found in Ascard (1995b) and Storeheier (1991), the first mainly dealing with the development of dose–response relationships and the second with the design of flamers. With regard to the design of flamers, it is generally suggested that flamers should be shielded, preferably with a long and relatively low roofed shield (Storeheier, 1994) to keep combustion gases close to the ground for as long as possible; the burner angle should be 22,5° to 45° to the horizontal (Bond & Grundy, 2001). Tandem burners did not increase effective ground speed compared with single burners (Ascard, 1997).

According to Ascard (1994, 1995a), propane doses of 10–40 kg ha^{-1} were required to achieve 95% control of sensitive species with 0–4 leaves, whilst plants with 4–12 leaves required 40–150 kg ha^{-1} (Table 2). Species with protected meristems, such as *Capsella bursa-pastoris* (L.) Medik. and *Matricaria discoidea* DC, were tolerant due to regrowth after flaming and they could only be killed completely in their early stages. *Poa annua* L. could not be completely killed with a single flame treatment, regardless of developmental stage or propane dose. Considerably lower doses (40%) were required in years with higher precipitation compared with a dry year.

Infrared radiation

Infrared weeders have been tested primarily on arable land and the method is not regularly used on paved areas. However, Augustin (2003a) compared the effect of an infrared weeder with other non-chemical control methods and chemical control in a field study on paved and gravelled urban areas. According to his results, the infrared weeder was the most effective of the non-chemical control options and economically comparable to herbicide treatment. A major disadvantage of the infrared radiators is that they are more expensive than flame burners and the long panels are sensitive to mechanical damage from uneven soils (Ascard, 1998). The last issue is of minor importance on paved areas as compared with agricultural fields.

Infrared radiation uses gas burners, or non-catalytic atmospheric burners, that operate at red brightness temperatures of essentially no visible flame on the combustion surface. These burners heat ceramic and metal surfaces that then radiate heat towards the target. Infrared burners are not affected by wind, in contrast to flame weeders and they cover a more closely defined area (Mätzler, 1993; Ascard, 1998). For efficient plant destruction, an emitter is required which produces high energy intensity at a wavelength which is absorbed, rather than reflected or transmitted, by the plant tissues. To kill young *Sinapis alba* L. plants, an energy density of 200 KJ m^{-2} of medium wave was required, whereas *Lolium* spp. required 400 KJ m^{-2} of short wave or medium wave to severely restrict plant growth (Parish, 1989b). In several studies, infrared radiators have proved to be inferior compared with flame weeders (Ascard, 1988; Nyström & Svensson, 1988; Parish, 1990b), but Ascard (1998) and Parish (1989a,b, 1990a) found the differences in effect to be dependent on the type of thermal weeder, dose, ground speed, burner height, plant size, plant density and plant species (Parish, 1989a); these interactions should be investigated further. However, the studies indicate that infrared burners are more likely to suffer from shading interference in dense vegetation compared with flame weeders that cause turbulence and thereby expose more leaves to the flame.

Hot water

In the USA, hot water equipment for weed control, called Aqua Heat, was introduced in the early 1990s (Berling, 1992). Preliminary studies showed that the hot water method could control most annual and young perennial weeds and the effect was comparable to glyphosate treatments, whereas older perennial weeds required repeated treatments to be controlled effectively (Daar, 1994). Another hot water machine, called 'The Waipuna System' from New Zealand, has specialised in a hot foam system to achieve an insulating effect and keep the hot water in contact with the weeds for a longer time. The foam is derived from coconut sugar and corn sugar (Daar, 1994; Quarles, 2004). In Denmark, the system is available on a lease basis only. In experiments performed in the Netherlands with the 'H_2O Hot Aqua Weeder', addition of a foam cover increased the efficacy of the method significantly, whereas decreasing the driving speed did not have a significant impact (Kempenaar & Spijker, 2004) (Table 2).

Hansson (2002) has made a comprehensive study on the potential for improving the efficiency of hot water equipment. The plant stage at treatment was important, as three times more energy was required when *S. alba* seedlings were treated at the six-leaf stage compared with the two-leaf stage (Table 2). The treatment was more effective when plants were water stressed and should not be carried out during rain or when the plants are wet. A longer insulated shield with nozzles or an insulating sheet behind the shield improved control efficiency. Such modifications prolong the time of exposure and improve the weed control effect, partly because of a decreased cooling rate. The effective energy dose in hot water treatments could be decreased by using coarse droplets compared with fine droplets, by heating the water temperature as high as possible and by adding a wetting agent to the hot water, although the effect is only additive.

Hot water can be used where flame weeding is not possible because of fire hazards. According to Hansson and Ascard (2002) the ability of hot water to penetrate into the vegetation is greater than for flaming. However, the energy use is relatively high (Hansson, 2002; Kristoffersen & Larsen, 2005) (Table 2) and the water applicator needs to be improved to decrease heat losses. Patch sprayers guided by digital video cameras would save energy and further increase treatment capacity (Hansson & Ascard, 2002). Recently, equipment with precision application called the 'Wave machine' has been developed in The Netherlands by the company Front2-Front (Wekerom, http://www.front2front.nl), but no experimental results on the efficacy have been published so far. According to Mr. Joop Spijker (Alterra, Wageningen, NL), there have been some monitoring studies in Dutch Municipalities and acceptable efficacy is given with three applications a year.

Steaming

Weed control on hard surfaces by steaming has received increasing attention within the last decade (Bond & Grundy, 2001; Lefevre *et al.*, 2001; Hansson, 2002) and equipment for use on pavements has been developed in Denmark by WR Damp (Soderup, http://www.wrdamp.dk). So far, three machines have been sold to an engineering contractor and they have been used regularly over a number of years. The steam equipment releases vaporised water and water use per unit area is considerably lower in comparison with hot water equipment. Steam has a considerably higher heat transmission coefficient (10 000–28 000 W m^{-2} K^{-1}) compared with hot water (500–5000 W m^{-2} K^{-1}) and may therefore have a higher potential as a weed control method (Hansson, 2002). The higher heat transmission coefficient allows a greater amount of the energy to be transferred to the plant during exposure. However, steam is more volatile than liquid water and that increases the risk of energy losses.

Lefevre *et al.* (2001) evaluated the effect of several non-chemical methods (flaming, sweeping, rotary wire brushes, steaming) on different kinds of hard surfaces. Effects were compared with the effect of glyphosate, and steaming was the only method needing as few operations as the chemical sprayer and without major drawbacks. The only disadvantage was economical, due to the high initial investment. According to Kristoffersen and Larsen (2005), steam equipment with a handheld applicator attached by a hose is advantageous on areas with difficult access, e.g. traffic islands or areas with many impediments, such as traffic signs, street furniture etc.

Hot air

Equipment is commercially available for killing weed seeds in field soil using dry heat (Bond & Grundy, 2001). In Denmark, a hot air machine called the 'ZACHO Turbo Weed Blaster' from Greenflame (Bjedstrup, http://www.zacho.dk) has been developed for hard surface weed control and the effect has been tested experimentally by Kristoffersen and Larsen (2005) on traffic islands. The effect of hot air was comparable to other thermal methods, but the required energy doses were relatively high, resulting in high gas consumption. However, the control method is receiving increased interest from Danish contractors and groundskeepers.

Mayer (1997) compared the effect of 150°C hot air and hot air containing steam. Dry heat was not as effective as hot air containing steam. Increasing the steam content increased working speed of the thermal weeder and thereby lowered the costs.

Electrocution

Diprose and Benson (1984) and Parish (1990b) have reviewed the electrical methods of killing weeds in agriculture. Two methods, spark discharge and electrical contact, are under development, both needing voltages around 20 kV to be effective. In the first case, a pair of electrodes is used, one on each side of the plant, or an electrode is suspended above the plant. The second method employs a high-voltage electrode touching the unwanted plants. The severity of plant damage depends on the voltage and the contact time, as well as the plant species, morphology and age (Vigneault *et al.*, 1990). Unlike most other non-chemical weed control methods, Diprose and Benson (1984) reported some damage to roots and rhizomes of weeds as the current flows through a substantial part of the tissue before leaving the root system, especially when the soil is dry.

Only one electrical contact machine has been commercially available and its high capital cost makes it uneconomical below a usage rate of 900 ha year^{-1} (Kaufmann & Schaffner, 1982). The high voltage required for these machines poses a hazard to operators and passers by, not least in urban areas. On the other hand, the electrical contact method may be a control method applicable on railways, but research and innovation is lacking (Hansson *et al.*, 1995). Parish (1990a) suggests that the energy efficacy of infrared radiation is better than that of electrical treatment.

Microwaves

Mattsson (1993) reviewed the possibility of using microwaves for weed control. He concluded that microwave power was unlikely to be used for field weed control due to high energy consumption and high microwave power, which could be hazardous. According to recent studies by Sartorato *et al.* (2006) microwave irradiation controlled different weed species effectively, but the energy requirements for satisfactory weed control were very high, ranging from 1000 to 3400 kg diesel ha^{-1}. They concluded that microwave efficiency could be increased by a flux configuration that minimises soil penetration and maximises absorption by plants. The equipment is still at an early experimental stage and needs to be improved to decrease energy consumption and avoid safety risks for the operators.

Laser radiation

Three years of experimentation in the USA on the possibility for controlling *Eichhornia crassipes* (Mart.) Solms (water hyacinth) revealed that laser radiation could retard its growth but not kill the plants completely (Couch & Gangstad, 1974).

UV-radiation

When plants are irradiated with UV, almost all energy is absorbed in the outermost 0.1–0.2 mm layer of the plant tissue (Cen & Bornman, 1993; Day *et al.*, 1993). This results in heating of the plant tissue and thus can have effects similar to the damage to plants from flame weeding. Andreasen *et al.* (1999) have investigated the potential of using UV light for weed control but it remains at an experimental stage. So far, no equipment for weed control has been developed and the potential health hazard and eventual risk of induction of mutations require thorough research.

Freezing

Fergedal (1993) and Larsson (1993) have studied the effect of liquid nitrogen and carbon dioxide snow for weed control. Freezing was effective but energy consumption was similar to flame weeding. Additionally, the freezing media remains close to the soil surface and only destroys the base of the plant, which can sometimes be protected by the plant's leaves. Plants with highly placed growth meristems and leaves protecting the base of the plant may therefore survive the treatment.

Mechanical weed control

Mechanical weed control on hard surface areas include sweeping, brushing, hand hoeing and, on gravel surfaces, harrowing. The equipment can be tractor mounted (sweeping, brushing, harrowing) or hand-pushed (sweeping and brushing). The mechanical methods are more effective when controlling larger weeds or renovating neglected areas, as compared with the thermal methods (Hein, 1990; Svensson & Schroeder, 1992; Kristoffersen & Larsen, 2005; Schroeder & Hansson, 2006), but especially brushing causes wear to the surface. On gravel surfaces, weeds can be protected from the heat of thermal treatments by the stone material and mechanical methods such as weed harrowing are preferable (Svensson & Schroeder, 1992). Additionally, mechanical methods have higher impact on root-propagated weeds compared with thermal treatments like flaming (Hein, 1990).

Brushing

The most common types of brushes used are the vertically rotating cylinder brush and the horizontally rotating 'disc-brush' type (Hein, 1990). The bristles are usually made of polypropylene or steel. Trials carried out in Sweden and Denmark have shown that a fast-rotating disc-brush with steel bristles is the most effective, but steel has a greater wearing effect on the pavement compared with polypropylene bristles (Vester & Rasmussen, 1988; Hein, 1990). When brushing, high vibration levels and excessive noise levels can occur and pose unacceptable working environments for the operator, especially for hand-pushed machines (Hansson *et al.*, 1992).

Hein (1990) recommends that the brushing is carried out twice, back and forwards. The treatment should be carried out in moist weather to improve the efficacy and reduce the whirling of dust (Hein, 1990; Hansson *et al.*, 1992).

According to Lefevre *et al.* (2001) and Wood (2004), rotary wire brushes controlled weeds very effectively, but the technique was not recommendable as it damaged the road surface badly and rendered pavements slippery when wet. Though brushing is considered energy-efficient and effective in the short term on neglected pavements in the Netherlands (Kempenaar & Spijker, 2004; Vermeulen *et al.*, 2006), it is less effective and more damaging to the pavement in the longer term.

Sweeping

Street sweeping is carried out regularly as part of the cleaning operation in many countries, e.g. Denmark, Germany and England. According to Parker and Huntington (2002) and Hansen *et al*. (2004), street sweeping carried out systematically and efficiently will keep weeds down to a minimum. It also removes the weeds and dirt after brushing, although removing soil and surface joint material may not be desirable (Kristoffersen & Larsen, 2001). Lefevre *et al*. (2001) concluded that sweeping 7–10 times per year was very efficient for controlling weeds and no road damage was observed.

Hand hoeing

Manual weeding (hand hoeing) is very expensive and it may be difficult to find labour. Additionally, it is strenuous and physically demanding and can cause overload injuries (Hansson *et al*., 1992; Chatizwa, 1997). However, it requires no initial cost of equipment, and can therefore be used on small areas (Hansen *et al*., 2004) or in developing countries where hand labour is readily available at a relative low cost.

Harrowing on gravel surfaces

Harrowing is the most effective non-chemical control method on gravel surfaces and can be carried out at relatively low cost (Svensson & Schroeder, 1992; Tvedt *et al*., 2000). In Denmark, the use of chemicals was banned on churchyards in 1992 and harrowing the gravel surfaces has been the most used weed control method in these areas (Tvedt *et al*., 2000). However, it is important that the gravel surface consists of a distinct, compact base layer that has no large stones embedded in it. The surface layer has to be loose and easy to treat. The treatment should be carried out when the weeds are at an early developmental stage, as large weeds would need to be removed after the harrowing.

Discussion

Non-chemical weed control is generally regarded as less cost-effective compared with chemical weed management. This is mainly due to the fact that all non-chemical weed control methods require repeated treatments and may be labour-intensive. For example, in thermal weed control, the driving speed usually needs to be quite low to achieve sufficient weed control and reduce weed regrowth. Efforts are made to increase effectiveness of the most used methods and thereby lower the costs. However, one of the main shortcomings of non-chemical weed control on hard surfaces thus far, is a lack of proper definition of efficiency of the weed control methods. The literature study reveals a need to standardise the descriptions of experiments to make them comparable. It is suggested that important information on name of equipment, consumption capacity, working width, travel speed, doses and weed control levels should always be included in the experimental descriptions.

There are several ways to improve the weed control on hard surfaces. First of all, an integration of combinations or sequences of weed control techniques could reduce the risk of a selective pressure leading to the predominance of certain species. Repeated use of any weeding method is likely to cause a shift in the weed flora to resistant or tolerant species. Such changes would limit the effectiveness of that particular weeding strategy. Sweeping the pavements regularly for maintenance will remove dirt and thereby reduce the possibilities for weed establishment (Hein, 1990; Hansen *et al*., 2004; Schroeder & Hansson, 2006). Brushing can be used to clean-up heavily infested areas, but may damage vulnerable hard surfaces (Hein, 1990; Lefevre *et al*., 2001). Thermal treatments can be applied at regular intervals throughout the season to keep weeds at a reasonable level. If the use of chemicals is allowed, they can be used to clean-up neglected areas or areas dominated by perennials that are difficult to combat with thermal methods (Reichel, 2003).

Secondly, there is a potential for further development of the existing weed control methods (Table 1). There is also potential for further development of the weed detection technology originally developed for precision pesticide application (Bond & Grundy, 2001), such as the recently developed 'Wave' hot water equipment (http://www.front2front.nl). However, the cost of sophisticated equipment would need to be balanced against faster operation speeds, reductions in water and energy consumption and reduced labour costs. Additionally, there is a potential for adjusting the energy dose to the weed flora, according to the plants' morphology (e.g. position of growth meristems), flowering period (Hartin, 1989; Benvenuti, 2004) and to the stage of development (Hansson & Ascard, 2002). On hard surfaces, the weed control level is often determined by aesthetic considerations and different pavements need different levels of weed control. Therefore, in Denmark and the Netherlands, weed control strategies dividing the paved areas into different classes are being developed, in order to categorise the level of weed control according to the quality, use and placement of the pavements (Hansen *et al*., 2004; Vermeulen *et al*., 2006). The levels range from no weed control at all, to a very high level of weed control (e.g. city centre). The aim of the strategies is to help the road administrators and local authorities to give priority to their weed control effort and to go from the present relative short-term operational planning to longer-term strategic planning (Hansen *et al*., 2004).

Finally, weeds can be prevented on hard surface areas by changing the design of the surface. On established areas this will often require high investment cost and may not find immediate acceptance among municipalities or groundskeepers. However, before constructing new pavements, railway areas or gravelled surfaces it is very important to take the future weed control problems into consideration (Hansson *et al*., 1995; Kempenaar *et al*., 2006; Grundy, 2007).

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