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Integrating preventive and curative non-chemical weed control strategies for concrete block pavements

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Summary

Reduction in herbicide use in non-agricultural areas is being imposed by a growing number of governments, triggering the development of alternative strategies for weed prevention and control. This study aimed to determine the weed preventive abilities of different paving types, the required treatment frequency of non-chemical weed control scenarios on these pavements and the associated weed species composition. A test parking area, constructed with four concrete paving types, was sown with a mixture of dominant weed species. Six scenarios with repeated use of a single weed control method (brushing with waste removal, hot air, selective application of hot water and three scenarios with flaming) and two scenarios with alternating use of brushes and hot air were applied to control the weeds during two growing seasons. Treatments were applied at well-defined intervention moments, based upon weed development. Over 2 years, the paving types differed in weed coverage (up to a fourfold difference) and required varying treatment frequency (up to a 11-fold difference) with lowest values for pavings with porous pavers. Within most paving types, up to 28% lower treatment frequencies were found for selective application of hot water, as compared with all other single method scenarios. Shifts in weed composition occurred in plots treated repeatedly with the same technique. Paving type determined the chances for the establishment of different weed species and alternating non-chemical control methods with different modes of action offered the best opportunity to keep weeds under control.

Keywords: hard surfaces, non-chemical weed control, thermal weed control, mechanical weed control, weed brushing, urban areas, permeable pavement, porous paver.

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Introduction

In many European countries, awareness is increasing about the use of pesticides in public urban amenity areas (Kristoffersen *et al.*, 2008a). In Flanders (northern part of Belgium), for example, the government has imposed a reduction programme, with a complete phase out of herbicide use on public pavements by 2015. However, herbicides (mainly glyphosate) are still widely used to control weed growth on pavements (Augustin *et al.*, 2001; Kempenaar *et al.*, 2007; Hanke *et al.*, 2010). Compared with agricultural use of herbicides, non-agricultural use of herbicides is more prone to run-off and therefore contributes disproportionately

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to surface water contamination (Ramwell, 2005; Kempenaar *et al*., 2007).

This increased awareness has triggered the development of alternative strategies for weed prevention and control. On existing pavements, regular sweeping can prevent weed growth by reducing accumulation of organic matter (Kempenaar *et al*., 2009). Weed growth on newly constructed pavements can be prevented by a good design and placement (Guldemond *et al*., 2007; Rask & Kristoffersen, 2007). Although conventional concrete pavings are widely used, the use of water permeable pavement systems is continuously increasing, as they first appeared in Germany in the early 1980s. Today, water permeable pavings have been installed throughout North America, Australia and North-west Europe (Scholz & Grabowiecki, 2007). These systems allow local infiltration of storm water, decreasing fast run-off and flood risk and enhancing groundwater recharge and stream base flows (Brattebo & Booth, 2003; Scholz & Grabowiecki, 2007), as well as allowing herbicide residues to reach groundwater. Water permeable pavement systems are not characterised with respect to their weed preventive abilities. Due to their low level of plant-available water, it is probable that they allow less weed growth than conventional pavings. On the other hand, different water permeable pavement systems have a large open area, making them prone to weed growth.

There is a plethora of techniques for non-chemical weed control on hard surfaces. These can be divided according to their mode of action into thermal control (e.g. flaming, application of hot air, application of hot water) and mechanical control (e.g. weed brushing) (Rask & Kristoffersen, 2007). Non-chemical weed control needs more frequently repeated treatments than the application of glyphosate, which causes an almost complete kill of the existing higher plants with one to two treatments a year (Augustin *et al*., 2001; Rask, 2012). This makes non-chemical weed control less cost-effective than herbicide spraying. Non-chemical methods often use large amounts of fuel, thus contributing to atmospheric sink effects (greenhouse gasses, smog, ozone layer) (Kempenaar *et al*., 2007).

The effectiveness of the different non-chemical weed control methods has, up till now, mainly been studied *in situ*, on pavements that differed in environmental conditions, weed species composition and usage (Hansen *et al*., 2004; Vermeulen *et al*., 2006; Kristoffersen *et al*., 2008b; Rask, 2012). Non-chemical weed control was mostly studied as a repeated use of a single method, and not as scenarios comprising alternating use of different methods. Repeating single methods and alternating different methods are expected to provoke a different selective pressure on the weed flora, resulting in a different flora composition (Fagot *et al*., 2011).

We hypothesised the following: (i) different pavement types have a strong influence on the prevention of weeds, (ii) there is a minimum frequency of curative treatments to maintain an acceptable appearance (people's perception of street cleanliness with regard to the weed growth) and (iii) different non-chemical methods provoke different species compositions. Hence, our study aimed at quantifying the following: (i) the weed preventive abilities of conventional and water permeable paving types, (ii) the frequency of different curative scenarios to maintain a minimum appearance on these pavements and (iii) the accompanying shift in weed flora.

Materials and methods

Design

In September 2009, a strip-plot experiment was established on a test parking in Sterrebeek, Belgium (50°50′53″N, 4°30′44″E), which was structurally designed for an average daily traffic of <500 light vehicles per day. The experiment comprised four different paving types (horizontal strips) and eight different curative weed control scenarios (vertical strips) in four blocks. Each experimental plot (i.e. intersection plot between a vertical and horizontal strip) was 1.6 m wide by 7.5 m long. Paving types (Table 1, Fig. 1) included one conventional (not permeable) concrete block paving with conventional pavers and three types of water permeable pavings: porous concrete block pavers, concrete block pavers with draining holes and concrete block pavers with enlarged joints. Contrary to all other pavers used, porous pavers are made from pervious

Table 1 Characteristics of the paving types

Paving type	Commercial name	Belgian manufacturer	Surface open area (%)	Dimensions (length x width x height, cm)
Conventional pavers	Classic	Ebema	7	22 × 11 × 10
Porous pavers	Aquapave – waterdoorlatend	Ebema	6	22 × 11 × 10
Draining holes	Percola	Bleijko	12.5	20 × 20 × 8
Enlarged joints	Aquapave – waterpasserend	Ebema	15	22.5 × 11 × 8

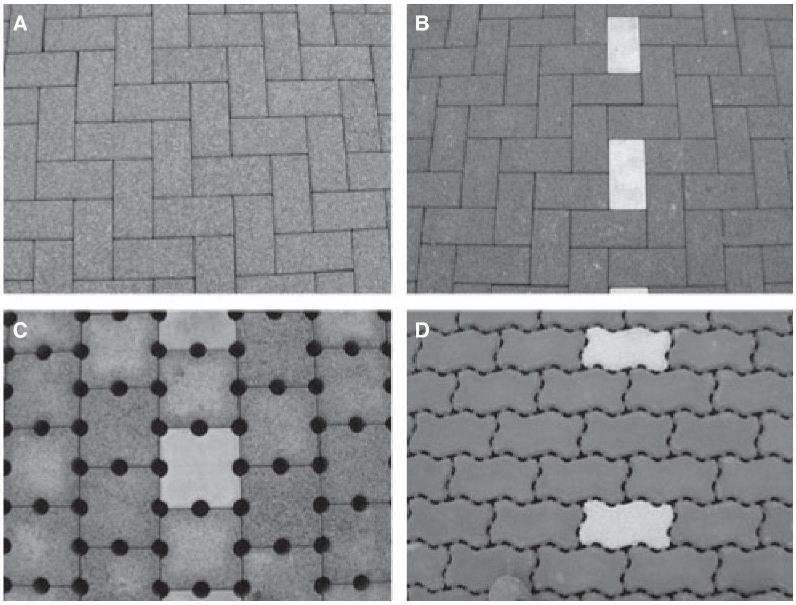

Fig. 1 Concrete pavings used in this study: paver type and corresponding laying pattern (in brackets). (A) Conventional pavers (herringbone pattern), (B) porous pavers (herringbone pattern), (C) pavers with draining holes (running bond) and (D) pavers with enlarged joints (running bond).

concrete lacking fine aggregates. Hence, porous pavers have many voids enhancing quick water movement through the paver cross section. For pavers with draining holes or enlarged joints, high permeability is achieved by the large open surface area filled with water permeable joint filler. If properly designed and constructed, the high draining ability of all the aforementioned water permeable pavings is guaranteed to last at least a decade (Beeldens *et al*., 2009). The pavers were laid upon a 4-cm bedding layer, technically suitable for the construction: sand with a grain size of 0/7 mm (i.e. sizes ranging from 0 to 7 mm) for the pavings with narrow joints (porous pavers and conventional pavers) and 2/7 mm for the pavings with wide joints (pavings with draining holes and pavings with enlarged joints). This bedding layer was supported by a base layer (18 cm, crushed porphyry with a grain size of 7/20 mm) and a sub-base layer (34 cm, crushed limestone with a grain size of 7/32 mm). Thickness of layers and choice of unbound materials fulfilled the requirements given in the widely adopted technical specification PTV827 (http://www.copro.eu) in relation to permeability of the soil, frost protection and traffic load. Narrow joints were filled with sand of Lustin (sandstone with grain size of 0/2 mm coming from a Belgian sand mine), and wide joints were filled with porphyry (grain size of 2/6.3 mm). Fine compost (air-dried; maximum particle size of 3 mm) and a weed seed mixture were mixed with the joint-filling materials, using a concrete mixer. Fine compost was added up to 10% by volume, to mimic *in situ* organic pollution in joints and to create a worst-case point of departure. This pollution level corresponds with about 2% fine compost by weight, depending on the used joint-filling material, and is comparable with the organic matter content *in situ*. Preliminary research indicated that organic matter content (estimated by loss on ignition) in narrow joints (2–5 mm) of 33 old *in situ* pavements ranged between 1.8% and 11.3% by weight, with a median of 5.4%. Seven dominant hard to control weed species on pavements were selected, based on presence *in situ* (Fagot *et al*., 2011). Nomenclature of species follows Van Der Meijden (2005). A seed mixture of these species was added to the joint fillers containing up to 2000 germinable seeds m^{-2}, assuming that seeds will be able to germinate up to 1.5 cm depth. The sown weed species were *Taraxacum officinale* F.H. Wigg. (dandelion), *Poa annua* L. (annual meadow-grass), *Plantago major* L. (greater plantain), *Trifolium repens* L. (white clover), *Cerastium fontanum* subsp. *vulgare* (Hartm.) Greuter & Burdet (common mouse-ear), *Sagina procumbens* L. (procumbent pearlwort) and *Conyza canadensis* (L.) Cronq. (Canadian fleabane/horseweed).

Curative weed control scenarios

Curative weed control treatments started in May 2010 and were carried out during two growing seasons up to December 2011. Average temperature and rainfall values during the experimental period are given in Fig. 2. The test parking was kept free of traffic during the entire duration of the experiment, to exclude the mechanical impact of tyres on weeds and to keep the weed growth uniform. No de-icing salt was used, as this can inhibit weed growth. Influx of seeds from the environment was limited by mowing the adjacent roadsides.

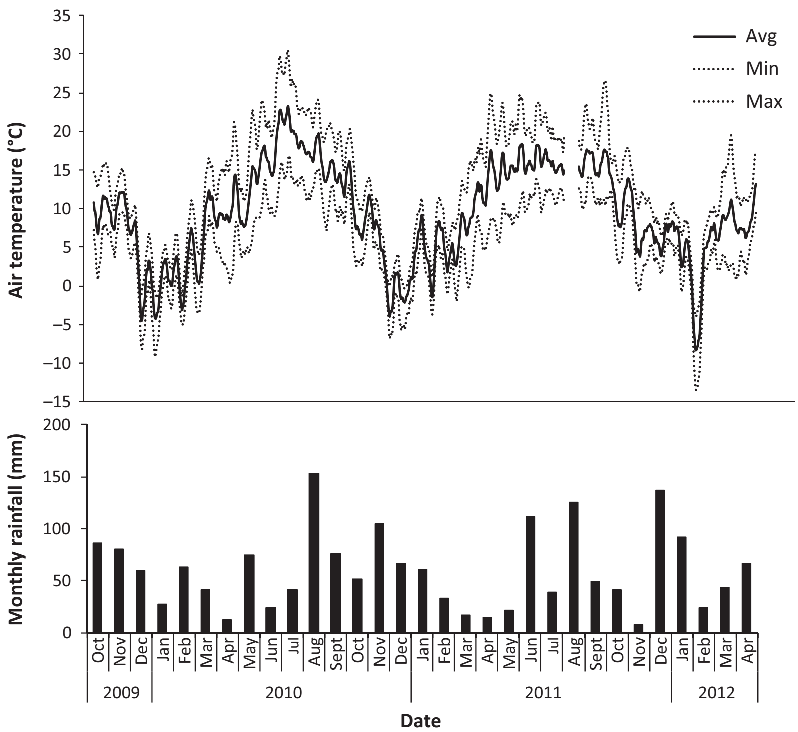

Fig. 2 Air temperature (°C) and rainfall (mm) data, collected *in situ*, during the experimental period (October 2010–April 2012).

Curative weed control was conducted using six scenarios with repeated use of a single weed control method (brushing with waste removal, application of hot air, selective application of hot water and three scenarios with flaming) and two scenarios with alternating use of brushes and hot air (Table 2). These methods represent the different modes of action (mechanical, thermal conductive, thermal convective) for non-chemical weed control that are most frequently used on Belgian pavements. Together with every brushing operation, the resulting waste was removed, to avoid accumulation of organic material and thus reducing future weed growth. Due to a lack of space on the conventional pavers, they were only treated with repeated use of brushes (scenario 1) and hot air (scenario 2). Brushing was not applied on pavings with draining holes, as there was a risk of emptying the joints with this technique. Instead, three scenarios with flaming were applied on these pavings (scenarios 6–8). This design resulted in 17 factorial combinations of scenario and paving type (Table 2).

The weed control treatments were conducted with self-propelled machines (Table 3), operated by one single qualified person per technique. The machine applying hot water only supplied hot water (98°C) to sensor-detected weeds. Treatments were only conducted under optimal circumstances; thermal weeding was not performed shortly after rain or on a wet pavement. In line with current practices, the entire parking was swept and sweeping waste was collected.

Table 2 Overview of the applied weed control scenarios

Scenario	Energy dose	Applied on	Intervention policy†
1 Brushing*	ED80	Conventional pavers Porous pavers Enlarged joints	Normal
2 Hot air	ED80	Conventional pavers Porous pavers Draining holes Enlarged joints	Normal
3 Selective hot water	NA	Porous pavers Draining holes Enlarged joints	Normal
4 Brushing*/ Hot air	ED80	Porous pavers Enlarged joints	Normal
5 Brushing*/ Hot air 14d later	ED80	Porous pavers Enlarged joints	Normal
6 Flaming	ED80	Draining holes	Normal
7 Flaming	ED80	Draining holes	Strict
8 Flaming	ED60	Draining holes	Normal

NA, not applicable.
*With waste removal.
†Normal policy = max. 6, 3 or 2% weed coverage for weeds with an average height of <1, 1–3 or >3 cm respectively. Strict policy: max. 3, 1.5 or 1% weed coverage for weeds with an average height of <1, 1–3 or >3 cm respectively.

This was conducted after the last treatment of each year.

The energy dose applied by the weed control equipment was regulated by the driving speed (Table 3).

Table 3 Technical details of the curative weed control machines. Driving speed is average ± standard error in brackets

Weed control technique	Machine type	Working width (cm)	Carrier type	Driving speed (km h^{-1})	Fuel for weed control	Gas pressure (bar)	Brush speed (rmp)	Energy dose to plant (kJ m^{-2})*
Brushing	Egholm 2200 weed brush (mix of flat steel bristles and steel wire) with waste removal	67	Egholm 2200T	1.64 (0.024)	Diesel		114	
Hot air	Zacho UKB 1000/1200 hot air weed blaster	100	Egholm 2200T	1.21 (0.021)	LPG	1.4		266
Selective application of hot water	WAVE weed sensor (Sensor Series 1.0) based hot water machine	160	Holder Mulitpark C2.42 Digital	1.23 (0.032)	Diesel			295†
Flaming ED80	Ecoflame City Comfort Plus 100 flaming unit with two burners	100	Multi One	1.21 (0.027)	LPG	1.9		245
Flaming ED60	Ecoflame City Comfort Plus 100 flaming unit with two burners	100	Multi One	2.16 (0.078)	LPG	1.9		137

*46 MJ kg^{-1} LPG; 36 MJ l^{-1} diesel.
†When applied whole field, hot water (98°C) application rate is 1.7 mm m^{-2}.

Preliminary tests were conducted to determine the effect of a single application of different energy doses. Therefore, an old pavement in Vilvoorde (50°56′26″N, 4°25′53″E) was used, with a relatively uniform, high weed coverage (8.6–28.9%) and a high species diversity (including *P. annua*, *T. officinale*, *S. procumbens*, *T. repens*, *P. major* and mosses). Dose-response curves were determined, based on driving speed and reduction in weed coverage, for a single application of each weed control method, except selective application of hot water. This revealed the effective dose of the different driving speeds. We aimed to apply all techniques at the same effective dose, thus eliminating energy dose as an explanatory factor for observed differences in treatment frequency. In scenarios 1, 2, 4, 5, 6 and 7, the applied energy dose corresponded with the dose required to achieve an 80% reduction in weed coverage (ED80). The applied energy dose of hot water (scenario 3) could not be controlled, as the machine automatically adjusts the amount of hot water sprayed to the driving speed. In practice, the effective dose of a single application of hot water with this machine approaches ED_{80} dose for the plot, as verified two days after the first curative treatment. As the small weeds are not detected by the sensor, they are not sprayed with hot water and remain untreated in the pavement after the curative operation. In scenario 8, flaming was applied at an additional dose (ED_{60}), to compare the effectiveness of a treatment with different energy doses. The amount of energy applied by the thermal weed control methods was determined by measuring the LPG use (hot air and flaming) or the diesel use for a certain amount of water (hot water).

For each experimental plot, a start and stop zone of 2.5 m was provided in the length direction. This guaranteed a central zone where the machines reached their optimal constant driving speed. Speed was recorded for verification during every application. As not all machines had the same working width (Table 3), some needed more than one transit over the plot: three for the weed brush, two for hot air and flaming and only one for selective hot water. Overlap zones were not included in this study.

Recorded parameters

During the period May 2010 to December 2011, weed coverage and vegetation height were recorded every 14 days during the growing season in six fixed 40 cm × 40 cm quadrats per plot. Quadrats were placed centrally in the length direction of the plots. Crosswise, care was taken to place them outside the overlap zone of the machines. Weed coverage (expressed in % coverage of the paving surface) was recorded by taking pictures of each quadrat at right angles from a height of 60 cm above the ground and determined using IMAGE J software. Average weed coverage and vegetation height were calculated over the four replicates.

To detect shifts in weed flora composition, springtime species composition was recorded each year (May 2010, April 2011 and May 2012). In each plot, weed species importance, reflecting their biomass share in the total biomass, was recorded according to the combined frequency-rank method of De Vries (De Vries & De Boer, 1959). For each species, species importance (expressed in %) was derived from its presence in 24 fixed 10 cm × 10 cm quadrats per plot (subsets of the fixed quadrats for determination of weed coverage). The dimension of all quadrats used in this study results from a preliminary study where we searched for optimal efficiency and accuracy (data not shown).

Threshold for treatment

All plots received their first treatment at the start of the first growing season (May 2010). Succeeding treatments were applied each time the paving exceeded a predefined maximum appearance based upon weed coverage and vegetation height (Table 2). Indeed, administrators' and citizens' perceptions of the street scene will not only depend on total weed coverage, but also on vegetation height. Tall species generally will have a more negative impact on public perception of street cleanliness than low-growing species. For scenarios 1–6 and scenario 8, an appearance was determined, comparable with what is generally used by municipalities as a threshold for weed control at moderately prioritised areas in Belgium. Intervention policies aiming at this appearance are referred to as 'normal' in the text. We applied a more rigid policy (referred to as 'strict' policy) in scenario 7, assuming that a more frequent treatment on very young weeds would reduce the weediness and improve the appearance. In Belgium, this strict policy is applied at highly prioritised areas, for example (historical) city centres. In scenarios 4 and 5, where brushing was alternated with hot air, brushing was applied when the desired appearance was exceeded. In scenario 4, hot air followed as soon as the tolerated appearance was exceeded, while in scenario 5 hot air was applied 14 days after the brushing, irrespective of the appearance. The working hypothesis was that striking weeds by hot air in their early recovery after being damaged by brushing, eventually allows for a lower treatment frequency.

Treatment frequency obtained in this study was defined as the number of treatments required to guarantee the desired appearance of the paving over the course of two growing seasons. The average interval between two treatments was calculated for each year separately, as the number of days between the first and the last treatment, divided by the number of treatments. In scenario 5, this interval was calculated between the brushing operations to determine the interval between the entire treatment cycle (brushing + hot air 14 days later).

Statistical analysis

Differences in weed coverage between the different paving types prior to any curative treatment were analysed by ANOVA using Statistica 7 (Statsoft, Tulsa, OK, USA). Data were square-root transformed to meet normality assumptions. Differences between group means were compared using Tukey's HSD test at the 5% significance level. Differences in species importance of five main species were analysed with the same software package. Important data of *T. officinale* were left untransformed. As important data of the other tested species (*P. annua*, *T. repens*, *C. fontanum* and mosses) did not meet normality assumptions, even after transformation, they were tested with a nonparametric Kruskal–Wallis ANOVA.

Analysis of the weed community composition was performed on arcsine-transformed data of species importance. To examine shifts in weed species composition, a principal components analysis (PCA) was carried out. As the detrended correspondence analysis (DCA) gradient length was lower than 2.5 SED, this linear analysis was considered most appropriate (Ter Braak & Smilauer, 1998). Robustness of the multivariate analysis was increased by only including the more common species that had a species importance higher than 2% in at least one plot. The gradient analysis was carried out using CANOCO for Windows 4.5 software (PRI, Wageningen, the Netherlands).

Results

Weed growth prior to curative treatments

Total weed coverage, eight months after installation and before any curative treatment, differed significantly between paving types (Table 4). Pavings with draining holes showed largest coverage, while porous pavers were least covered by weeds. Pavings with enlarged joints and conventional pavers showed intermediate weed coverage. *Taraxacum officinale*, *P. annua*, *T. repens* and *C. fontanum* germinated and grew well on the parking (Table 4). Mosses (Musci) were present, particularly on the porous pavings. *Plantago major*, *S. procumbens* and *C. canadensis* were not able to establish after sowing (species importance <2%). *Cerastium fontanum* was the most important species on pavings with draining holes and with enlarged joints, while *P. annua* was most important on pavings with porous and conventional pavers. *Trifolium repens* had a low importance on pavings with enlarged joints and porous pavers. Before curative treatments, *T. officinale* was less important than *P. annua* or *C. fontanum*.

Table 4 Weed coverage and relative species composition of the most important species, prior to curative treatments (May 2010). Values are means ± standard errors. Square-root transformed data in italics

Paving type	Total weed coverage (%)	Relative species importance (%) *Taraxacum officinale*	*Poa annua*	*Trifolium repens*	*Cerastium fontanum*	Musci
Conventional pavers	*1.42 ± 0.108* b 2.10 ± 0.294	15.7 ± 2.09a	40.3 ± 4.10a	10.7 ± 3.70a	29.3 ± 2.69b	0.0 ± 0.00c
Porous pavers	*0.82 ± 0.065* c 0.75 ± 0.101	7.0 ± 0.83b	35.1 ± 2.00a	0.3 ± 0.15b	23.6 ± 2.20b	33.1 ± 3.64a
Draining holes	*2.12 ± 0.050* a 4.56 ± 0.213	9.1 ± 0.92b	33.6 ± 0.53a	5.1 ± 0.81a	49.4 ± 0.51a	1.3 ± 0.19b
Enlarged joints	*1.62 ± 0.038* b 2.66 ± 0.126	8.6 ± 0.74b	37.3 ± 0.86a	0.5 ± 0.21b	50.2 ± 0.79a	2.7 ± 0.38b

Mean values within columns followed by the same letter are not significantly different at $P = 0.05$ according to the Tukey's HSD test (in case of homoscedasticity) or the Bonferroni test (in case of heteroscedasticity).

Treatment frequency in relation to paving type

Treatment frequencies over the 2 years were sevenfold to 11-fold higher for conventional pavers, pavings with draining holes and enlarged joints, than for porous pavers, irrespective of the weed control scenario (Table 5). In all non-porous paving types, the treatment frequency was higher during the second year than during the first year, irrespective of the weed control scenario.

Lowest frequencies were recorded for hot water (scenario 3), irrespective of non-porous paving type. The difference in treatment numbers between hot water and the other scenarios was obvious during the first growing season, but disappeared during the second growing season (Fig. 3B). Hot air (scenario 2) needed one more treatment than flaming (scenario 6) over the 2 years. Flaming at a strict weed growth policy (scenario 7) or at a lower energy dose (ED_{60}, scenario 8) resulted in one extra treatment over the 2 years (Fig. 3A). Regrowth after treatment was slower in scenario 7 than in other flaming scenarios, particularly during the second year (Fig. 3A); the number of days weed coverage was lower than 3% divided by the treatment frequency was 37.5, 26.4 and 21.7 days per treatment for scenario 7, 6 and 8 respectively. Flaming at ED_{60} (scenario 8) resulted in a less severe drop in weed coverage than flaming at a higher energy dose (Fig. 3A); on average, for the period July to October 2011, a single flaming operation decreased coverage by 79.5 and 69.8% in scenario 6 and 8 respectively (Fisher's LSD = 8.2%). This implies that

Table 5 Treatment frequency per year (TF) and average interval (TI, days) between treatments in relation to paving type

Scenario		Conventional pavers 2010	2011	Total	Porous pavers 2010	2011	Total	Draining holes 2010	2011	Total	Enlarged joints 2010	2011	Total
1 Brushing	TF	4	5	**9**	1	0	**1**				4	6	**10**
	TI	37.5	47.0								37.5	41.5	
2 Hot air	TF	3	6	**9**	1	0	**1**	4	7	**11**	4	5	**9**
	TI	42.0	39.2					37.5	35.6		41.5	37.5	
3 Selective hot water	TF				1	0	**1**	3	6	**9**	2	5	**7**
	TI							44.3	31.5		66.5	37.8	
4 Brushing/Hot air	TF				1	0	**1**				4	5	**9**
	TI										37.5	38.2	
5 Brushing/Hot air 14d later*	TF				2	0	**2**				6	8	**14**
	TI										36.0	47.8	
6 Flaming ED80 normal	TF							4	6	**10**			
	TI							36.5	30.5				
7 Flaming ED80 strict	TF							5	6	**11**			
	TI							33.6	30.5				
8 Flaming ED60	TF							4	7	**11**			
	TI							36.5	33.7				

*Average interval is calculated between the brushing treatments.

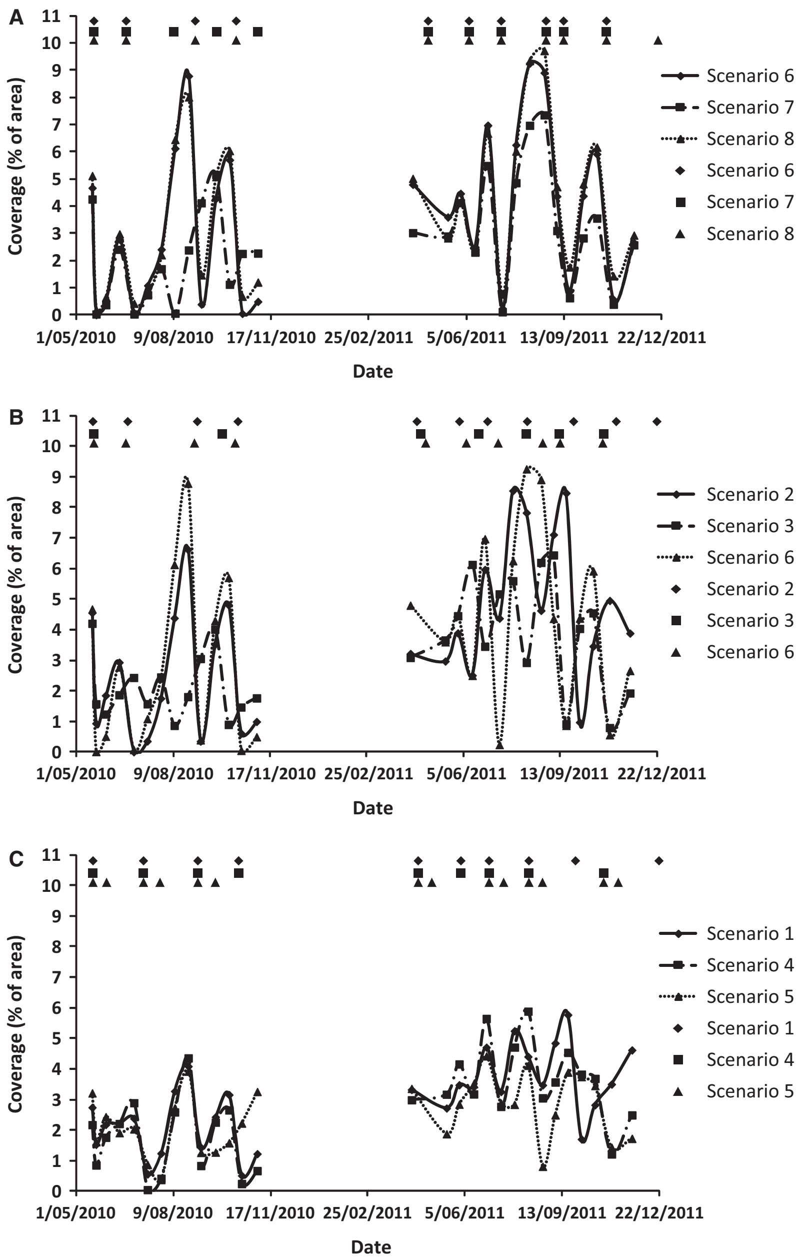

Fig. 3 Weed coverage of two paving types during the experimental period (May 2010–November 2011). Spots on top indicate the time of curative weed control treatments. (A) Scenarios with flaming on pavings with draining holes; (B) scenarios with different thermal weed control methods on pavings with draining holes and; (C) scenarios with alternating use of mechanical and thermal weed control methods, compared with repeated brushing on pavings with enlarged joints. Scenario 1: brushing with waste removal; scenario 2: hot air; scenario 3: selective application of hot water; scenario 4: alternated brushing with waste removal and hot air; scenario 5: brushing with waste removal followed by hot air 14 days later; scenario 6: flaming at ED_{80}; scenario 7: flaming with a strict intervention policy; scenario 8: flaming at ED_{60}.

the pavement was never weed-free and that the general perception of weediness was worse.

Compared with repeated brushing (scenario 1), the alternating use of brushes and hot air (scenario 4) reduced treatment frequency with one application in the second year on non-porous pavings (Fig. 3A). No differences in treatment frequency were found between repeated application of hot air (scenario 2) and alternating use of brushes and hot air (scenario 4). In scenario 5, where hot air was applied 14 days after brushing, the weed growth limit was exceeded only 7 times, compared with 9 times in scenario 4 (alternating use of brushes and hot air), but at the expense of an expected higher treatment frequency (14 compared with 9 single treatment operations, Fig. 2B).

Weed species composition

The PCA ordination plot of the most important weed species or groups and the paving types with their treatment scenarios over the years (Fig. 4) showed a large distinction between the porous pavers and the other paving types. The porous pavers were characterised by a very high importance of *C. fontanum* (83.2 ± 6.80% − 96.7 ± 1.95%) after 1 year of curative treatments (April 2011) and by mosses (85.8 ± 9.04% − 89.9 ± 5.46%) after 2 years of treatment (May 2012), irrespective of the weed control scenario. The other paving types followed this trend but had a more diverse vegetation composition, irrespective of the weed control scenario. After 1 year of treatment, the pavings had a vegetation community with 2.8 to 12.6 times more *C. fontanum* than after 2 years. Mosses were of no importance on non-porous pavers after 1 year, but became important after 2 years (28.3 ± 9.54% – 70.7 ± 7.94%). While after 1 year, *P. annua* was still present (0.7 ± 0.57% – 9.1 ± 2.67%) in 16 of 17 factorial combinations of scenario x paving type and it survived only in four factorial combinations after 2 years (1.0 ± 0.87% – 2.9 ± 1.73%). Pavings with draining holes had a higher importance of *T. officinale* in spring time than pavings with enlarged joints, particularly when they were treated with hot water (1.6–1.7 times higher after hot air, 1.5–2 times higher after hot water). More than any other technique, brushing favoured *T. officinale* on pavings with enlarged joints (1.4–2.2 times more than other scenarios after 2 years), while consecutive hot air treatments favoured *C. fontanum* (1.2–2.8 times more than other scenarios after 2 years). On the pavings with draining holes, this species was 1.6–2.8 times more important after hot air treatment (scenario 2), and in the scenarios with flaming (scenarios 6–8), than after treatment with hot water (scenario 3). After two growing seasons, mosses were 1.4–1.7 times more important on pavings treated with alternation of brushing and hot air (scenarios 4 and 5) than in brushed pavings.

Discussion

The results of our study show that there are opportunities for weed prevention in the construction of pavements and for optimisation of curative weed control.

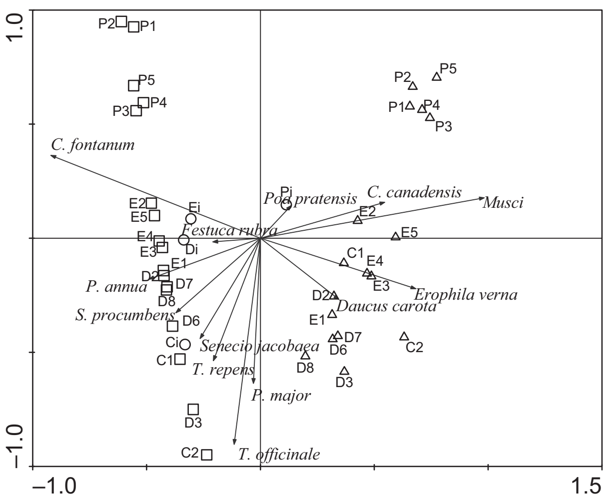

Fig. 4 Principal components analysis ordination plot of the most important weed species or groups and the paving types with their treatment scenarios over the years. Data from 2010, 2011 and 2012 are depicted as circles, squares and triangles respectively. Plots are numbered as follows. C = conventional pavers, P = porous pavers, D = draining holes and E = enlarged joints. The numbers accord with the scenario numbers as indicated in the legend of Fig. 3. i: initial species composition before curative treatments.

Weed prevention

Before any curative treatments took place, there were already large differences in weediness of the different paving types. The paving types with narrow joints (porous pavers and conventional pavers) and hence a small open area were less covered with weeds than the pavings with enlarged joints or pavings with draining holes. The draining property of the pavings did not influence the effect of joint width that has been observed before in conventional pavings *in situ* (Melander *et al.*, 2009; Fagot *et al.*, 2011). Within paving types with narrow joints, weed coverage was lower in porous pavers than in conventional pavers. In pavings with porous pavers, rain water is directed immediately to the lower layers (Beeldens *et al.*, 2009) reducing the plant-available water. Apparently, this is not a problem for the superficially growing mosses, as we observed a higher importance of mosses on porous pavers than on any other paving type. As low-growing species, mosses are not problematic for the general street scene appearance.

Pavings with narrow joints and an appropriate fine-grained joint-filling material have the best opportunities for weed prevention. When a water permeable paving is desirable, weed growth can be prevented more successfully by porous pavers, compared with pavings that achieve water permeability by a large open area (e.g. pavings with draining holes or wide joints). This weed preventive ability lasted over two growing seasons to such an extent that no curative treatments were necessary. However, water permeable pavings are restricted to areas that are not intensively used, and they cannot be applied in groundwater abstraction areas (Beeldens *et al.*, 2008). The use of de-icing salt may harm porous pavers (Beeldens *et al.*, 2008).

Curative non-chemical weed control strategies

Treatment frequencies in our study were comparable with frequencies reported by Vermeulen *et al.* (2006) and Rask (2012), who used single techniques on non-porous pavings. In all non-porous paving types, the treatment frequency was higher during the second year than during the first year, irrespective of the weed control scenario. As the weather conditions in both years were largely comparable (Fig. 2), this indicates that the existing weed flora was not sufficiently depleted by the curative treatments. This suggests that a tougher treatment policy is necessary to deplete them. Scenario

7 with its strict intervention policy supports this hypothesis; it took one more treatment to reach the target in year one, but in the second year, the target was reached with the same number of treatments as in the normal intervention policy. Scenario 8, with its low energy dose, needed one more treatment in the second year to reach the target. We presume that the extra treatments will continue to be needed in coming years, as the low dose only slightly harms the weeds and allows them to grow vigorously.

A large difference in number of treatments existed between hot water and the other scenarios during the first growing season, but it disappeared during the second growing season. This was largely due to the insufficient depletion of *T. officinale* provoked by the larger (as compared with the other scenarios) treatment intervals for hot water in the first growing season (Table 5). The hot water only affects the aboveground parts of *T. officinale*, and it can easily regrow from the thick tap root (Stewart-Wade *et al*., 2002). Brushing has a comparable effect; it cuts the aboveground plant parts but leaves the root intact. Indeed, we observed relatively more *T. officinale* in pavings with enlarged joints after repeated brushing than in the other scenarios. In contrast, after consecutive treatment with hot air or flaming, *C. fontanum* was slightly more important than in the other scenarios. This species is well protected from convective heat transfer (e.g. hot air or flaming) by its hairy leaves. Indeed, leaf hairiness is an important factor increasing the heat tolerance of plants (Hansson & Ascard, 2002), as it creates a protective layer that impairs convective heat transport. Conductive heat transfer (e.g. hot water) does not rely on hot air layers in motion and is therefore not impeded by hairy leaves.

Compared with repeated brushing, the alternating use of brushes and hot air reduced treatment frequency with one application in the second year on pavings with enlarged joints. Repeated brushing excavated joint-filling material (removal of about 5 mm after nine brushing operations) from the joints. When the joints are deepened (the extent of deepening will increase with joint width and number of treatments), the weeds grew out of reach for the brushes and could not be controlled sufficiently. Hence, we presume that the above-mentioned difference in treatment frequency will increase further in coming years. Compared with brushing only, alternating brushing with hot air (scenarios 4 and 5) reduced the importance of higher plants but increased mosses, resulting in a better appearance. For the scenario where hot air was applied 14 days after brushing (scenario 5), this was true at the expense of a higher treatment frequency; eventually, this scenario resulted in an excessive number of treatments, as weeds were treated with hot air prior to their predefined maximum appearance.

Conclusions

All research hypotheses were accepted. A well-prepared design for a paved area (paving type and appropriate joint-filling material) can reduce weed growth substantially. Paving type affects weed coverage and flora composition and hence has an influence on the number of treatments needed to control weed growth. Weed coverage of pavings with porous pavers and conventional pavers with narrow joints was 21–84% lower than coverage of pavings with wide joints. The flora on any of the non-porous pavings consisted of about 50% more higher plants than on porous pavers. For the porous pavers, this implies a sevenfold to 11-fold lower need for curative weed control to keep a minimum appearance standard.

Shifts in weed composition occurred in plots treated repeatedly with a single technique, due to the observed species-specific sensitivity to different modes of action of the techniques. During the first test year, selective treatment with hot water was needed 25–50% less frequently than thermal weed control methods with convective heat transfer (flaming or hot air). During the second year, differences between thermal weed control methods disappeared, probably due to flora shifts. The importance of *C. fontanum* was 1.2–2.8 times higher after repeated treatments with flaming or hot air than after brushing or application of hot water. This indicates that thermal weed control methods with convective heat transfer were less effective in controlling *C. fontanum*, a species with protective hairs. *Taraxacum officinale* was more important after hot water application (1.2–2.0 times more) or brushing (1.5–2.2 times more) than after treatment with flaming or hot air. This species showed a high potential of regrowth and was not appropriately controlled with hot water (conductive heat transfer) or with brushing. Due to flora shifts after repeated use of a single weed control technique, the alternation of techniques with different modes of action (mechanical, thermal convective, thermal conductive) offers the best potential for controlling weed growth, provided treatments are timed optimally.

Overall, our results show that the combination of preventive (using suitable paving materials) and alternating curative methods allowed weed growth to be kept controllable without herbicides for a period of 2 years with a minimum of treatments. As equilibrium in weed development may not have been reached in the 2 years (as far as an equilibrium can ever be reached in heavily disturbed areas like pavement environments), extrapolating our results into the long term should be carried out with due care.

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