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Weed occurrence on pavements in five North European towns

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Summary

Weeds on pavements in urban areas are unwanted mainly because they cause an untidy appearance or sometimes structural damage. Glyphosate has been the principal weed control method for years, but policies in several European towns have changed to lower dependence on herbicides. Instead, less effective and more species-dependent non-chemical methods are used, but little is known about the pavement flora. Consequently, we surveyed the flora on pavements in five North European towns [Braunschweig (DE), Malmö (SE), Næstved (DK), Royal Leamington Spa (UK) and Wageningen (NL)] by recording weed species and their coverage in 56 recording points randomly placed in each town. Weeds were recorded at several dates in 2005 and 2006 and no weed control was applied apart from sweeping. Weed coverage increased during the survey (averaging 1.4% in late 2006) and was highest in the towns having the strictest policies limiting herbicide use. Most coverage (averaging 2%) was found along the pavement edge away from the road. *Poa annua* was the most frequently recorded species, followed by bryophytes (mainly mosses), *Sagina procumbens* and perennial grasses. Grasses and some other species frequently found, notably *Taraxacum officinale*, should receive particular attention when planning a non-chemical weed control campaign on pavements.

Keywords: glyphosate, hard surfaces, weed coverage, *Poa annua*, mosses, non-chemical weed control.

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Introduction

Weeds colonise pavements despite them being an environment hostile to plant growth. The surface of pavements mostly consists of asphalt, paving-stone or concrete, offering very few opportunities for weeds to establish. However, any open spaces, such as joints between paving-stones or cracks in asphalt and concrete caused by wear or damage, make it possible for weeds to grow. Weed undesirability is attributable to unsightliness, functional damage and public health considerations (Benvenuti, 2004).

Public authorities responsible for the maintenance of pavements invest considerable funds and time for keeping pavements clear of unwanted weed growth and in a good state of maintenance. In addition to regular sweeping, glyphosate spraying is the predominant method of weed control on pavements in most European towns, usually requiring two applications per year for satisfactory control (Augustin *et al.*, 2001).

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However, the weed control effort is normally graduated among the three main town zones: town centres, residential and industrial areas. Town centres are typically swept most frequently, with industrial areas receiving least attention. Prioritisation, surroundings and various other factors, e.g. pedestrian traffic, bordering vegetation and shading, all affect weed occurrence within and between the zones (Benvenuti, 2004). Herbicide use on hard surfaces is now under pressure in some North European countries, due to the risk of leaching of herbicides into ground water and nearby surface waters. For example, studies in the UK and the Netherlands have shown that significant quantities of chemicals can be lost from concrete and asphalt surfaces, if application is poorly timed relative to rainfall events (Ramwell, 2005; Kempenaar *et al*., 2007). These concerns have influenced policy making in some North European countries, leading to federal restrictions in the use of herbicides on hard surfaces (Kristoffersen *et al*., 2008). Several municipalities in the Netherlands, Denmark and certain regions of Germany and Sweden have now restricted the use of herbicides and there has been a shift towards non-chemical methods.

Glyphosate application is an easy method to use for council and road workers, because it requires little specific knowledge about the weed species present. Glyphosate provides an almost complete kill of the living vegetation, except for e.g. mosses and *Equisetum arvense* L. (Torstensson & Borjesson, 2004). However, the situation is very different for non-chemical methods. A general feature of these methods is that effective control necessitates more treatments than chemical weed management, which among other factors make non-chemical methods more costly (Kempenaar & Saft, 2006; Rask & Kristoffersen, 2007). The effectiveness of many non-chemical methods is strongly related to weed species and their growth stage at the time of treatment. For example, *Poa annua* L. and other grasses that have protected growing points are less susceptible to flame weeding than species with unprotected growing points. *Taraxacum officinale* Weber and other perennials with below-ground meristems capable of re-growing after defoliation are also difficult to control physically (Stewart-Wade *et al*., 2002; Ascard *et al*., 2007).

Weed management on pavements using less herbicides or even omitting herbicides requires an improved knowledge about the pavement flora (Rask & Kristoffersen, 2007). Information about the occurrence of weed species and their total weed coverage in pavements is lacking for Northern Europe. Current weed management is largely driven by unacceptable 'plant' occurrence, without taking notice of the species concerned. Knowledge about the principal species would help both the planning of practical weed control programmes and the direction of future research projects. Weed coverage is an important criterion for initiating weed control, because it shows the level of weed infestation and unsightliness (Hansen *et al*., 2004).

To address this lack of knowledge, we surveyed the pavement flora of five North European towns during two growing seasons. The objective was to identify the weed species and estimate their occurrence and total coverage. Four towns were in transition towards less reliance on glyphosate prior to the survey, while the fifth town still used glyphosate regularly. We hypothesised that: (a) industrial zones would have the highest total weed coverage and occurrence of different weed species; (b) weed coverage would increase under a sweeping regime, being the only weed control applied in the survey period, and mostly so in industrial areas; (c) weed coverage and occurrence of grasses would be higher along pavement edges than in the middle in industrial and residential zones; (d) weed coverage in town centres would be higher along walls than away from walls. Pedestrian traffic is absent close to walls and hindrances, such as downpipes and stairways, make machine- or tractor-mounted weeding operations more difficult.

Materials and methods

Towns and selection of recording points

Characteristics of the five towns selected for the survey are listed in Table 1. The towns were each divided into three zones: town centre, residential and industrial areas. The division was made in collaboration with the local town authorities, who defined and marked out the zones on town maps. In contrast to town centres, industrial and residential zones were mostly not coherent areas but consisted typically of one to five sub-areas separated by other town areas such as parks, shopping areas, residential/industrial areas and the town centre. The town centre was not included for Braunschweig for practical reasons; it appeared impossible to ensure recording points were not weeded. Shopkeepers show absolutely no acceptance of any weed growth on pavements adjacent to their stores.

There were 56 fixed recording points (1 m × 1 m quadrats) in total per town (42 for Braunschweig), randomly selected in each of the three zones; 21 each for residential and industrial areas and 14 for the town centre. Recording positions were scattered evenly over these different zones by placing the positions on town maps before assessments began. For the residential and industrial zones, seven recording points were placed at the edge of the footway closest to the road, e.g. along the kerbstones or grass verge. Seven were placed at the

Table 1 Characteristics and precipitation data for the five towns selected for the weed survey

Town	Country	Inhabitants	Area (km^2)	Geographical position	Total precipitation (mm) April–September	
					2005	2006
Braunschweig	Germany	245 000	192.1	52°16′N, 10°31′E	281	283
Malmö	Sweden	280 000	153.7	55°37′N, 13°1′E	269	420
Næstved	Denmark	40 000	26.8	55°14′N, 11°46′E	291	372
Royal Leamington Spa	United Kingdom	43 000	58.9	52°18′N, 1°32′W	344	284
Wageningen	the Netherlands	35 000	32.3	51°59′N, 5°35′E	438*	474*

*Source: Meteorological Station, Wageningen University, http://www.met.wau.nl.

opposite edge furthest away from the road and seven were placed in the middle of the pavement. In the case of the town centre, seven recording positions were placed alongside neighbouring walls and the remaining seven were situated >2 m away from any wall, preferably in precincts or town squares. The positioning of the recording points on the pavement was made randomly in all zones, and for industrial and residential zones over the sub-areas of the zone. Recording points were placed without any knowledge of the weediness and pavement material, apart from points being placed only where weed control and cleaning were the sole responsibility of the local authorities. We aimed to keep recording points untreated throughout the survey period, apart from the sweeping regimes normally applied. Ongoing weed control programmes could have masked the flora, especially if they had clashed with recording dates. Weed control measures and policies for each town prior to the weed survey are described in Table 2.

Characterisation of the recording points

Each of the 56 recording points were characterised with the assistance of the local authorities. Characteristics

Table 2 Brief descriptions of policies and weed control measures used in each town prior to the survey

Town	Policy	Weed control measures
Braunschweig	Glyphosate spraying forbidden, wiping of glyphosate or spraying with acetic or pelargonic acids are allowed on specific approval. Residential areas are maintained by contractors. Industrial areas have lowest priority	Wiping of glyphosate in residential and some industrial areas. Sweeping and occasionally flaming are used. Manual weeding is frequently used, especially at touristic and other relevant places
Malmö	Decision in 2003: herbicides are phased out before 2008. Acetic acid was the only herbicide used in 2005. No herbicides were used in 2006	Sweeping every 2 weeks in town centre and residential zones, frequency may vary. One sweeping per year in the industrial areas. Flaming on curb stones and traffic islands
Næstved	Target application of glyphosate to limit waste is permitted. <10% of the pavements are treated annually. Non-chemical methods must be used whenever relevant. Town centre has highest priority and industrial areas least	Target application of glyphosate with knapsack sprayers or lances. Occasionally flaming. Weekly sweeping in the centre, 4–5 times per year in residential zones and once a year in industrial areas
R.L. Spa	Glyphosate is permitted and used to target plants only in areas of concern	Centres are swept weekly or on demand. Other zones are swept every 6 weeks. Only specific areas are targeted for spraying with glyphosate twice yearly
Wageningen	Herbicide use is banned on hard surfaces. A max. weed coverage of 25% of joints and a max. weed height of 10 cm are tolerated. Spread of pollen must be prevented. The centre has the highest priority	Sweeping weekly in the centre, every 2 weeks in residential and industrial areas but locally less according to the conditions. Weed control frequency: whenever the acceptance level is exceeded. Weed control mainly by hot water

recorded included the percentage of bare soil (arising from cracked tarmac or joints in stoned pavement), the level of pedestrian traffic (high, medium or low), adjacent vegetation (none, mowed vegetation, non-mowed vegetation) and shading (strong, medium, absent). The percentage of bare soil was obtained in an objective manner by measuring joints and cracks. Although cracks do not necessarily contain soil, they still constitute a habitat for plant growth and for simplicity were classed as 'bare soil'. The percentage of bare soil expresses the opportunity for weeds to colonise the pavement (except for mosses, liverworts, lichens and algae). It also reflects whether a tarmac is old and deteriorated, or whether a stoned pavement has many open spaces for plant growth. Descriptions of pedestrian traffic and shading did not follow common standards for all towns. Therefore, these characteristics were not included in the statistical analyses, but were only used in the discussion of the results.

Weed assessments

The weed assessments were made on several occasions in the growing seasons of 2005 and 2006 in each town (Table 3). The range and frequency of weed species occurring in the 56 recording points in each town were obtained by recording every single species present within each quadrat at each recording date. A digital image was then taken of the whole quadrat from a perpendicular position above the centre of the quadrat. The images were subsequently analysed in the laboratory by overlaying electronically a 20×20 grid, and the number of grid intersections touching living plant tissue on the image were counted. Percentage weed coverage in the quadrat was then calculated by dividing by the total of 400 intersections. Coverage was not estimated for each species but was simply the coverage of all species combined. Counting intersections was considered to be a more objective method than visual scores of weed coverage made by different personnel in each country.

Statistical analyses

Weed coverage

The influence of recording date, zone and recording position on weed coverage was analysed using a general linear mixed model (McCullagh & Nelder, 1989). Data were not normally distributed and we assumed them to follow a Poisson's distribution. Number of 'green' intersections was the response variable and a full model included the fixed effects of recording date category (Table 3), zone and recording position. Town was considered as a random effect, and with the split-block-like randomisation of zone and recording position, the interactions town*zone, town*position and town*zone*position were also included as random effects. If the number of fixed effects was reduced, for example when testing the effects of recording position in town centres only, the number of random effects was correspondingly reduced. The repeated nature of the data with several recordings in the same recording points was accounted for by including recording date as a repeated effect with recording point nested under town as the subject. An unstructured correlation structure and variance was assumed between recording dates.

The parameters of the models were estimated using residual likelihood estimations. Calculations were made using the GLIMMIX procedure of SAS (available in SAS release 9.13), and means were calculated as least square means (LSM). GLIMMIX fits generalised linear mixed models to data with discrete distributions like binary, Poisson and binomial distributions. The response variables were log-transformed in all analyses (a link function in GLIMMIX), and '1' was added to all values before taking the logarithm to account for '0' values. Weed coverage for LSM was then calculated using the ILINK (inverse link) option, subtracting '1' from LSM and dividing by 400. The denominator degrees of freedom in *F*-tests and *t*-tests for mean separations were calculated using the option SATTERTH in GLIMMIX (adapted from Satterthwaite, 1946).

Comparisons of all three zones were analysed differently, as recording position in the town centre was

Table 3 Recording dates of weed species and coverage in the five towns

Date category	Braunschweig	Malmö	Næstved	R.L. Spa	Wageningen
1	–	–	20 April 2005	26 May 2005	2 May 2005
2	–	–	12–13 July 2005	28 July 2005	23 August 2005
3	–	–	5–7 October 2005	22 September 2005	17 October 2005*
4	22–24 May 2006	5 May 2006	8–9 May 2006	2 May 2006	30 May 2006
5	11–13 July 2006	28 June 2006	6 July 2006	2 June 2006	–
6	8–10 September 2006	13 August 2006	24 August 2006	29 August 2006	25 August 2006
7	22–24 October 2006	29 September 2006	4 October 2006	17 October 2006	26 October 2006

*Only weed species were identified, no estimation of weed coverage.

different from the other zones. A new data set was created where percentage of weed coverage was calculated for each zone in each town (Braunschweig excluded), essentially leading to four replications of each zone. These figures were achieved by averaging weed coverage across recording dates and recording positions. These data were normally distributed and zone differences were compared on the basis of *t*-tests.

Species composition

Multivariate statistics were used to analyse the species composition, according to the class variables: town zone, recording position and adjacent vegetation. Six binary environmental variables were needed to code the information, two for each class variable. A species presence–absence matrix was constructed with 266 rows presenting the $3 \times 56 + 42$ recording quadrats and 30 columns representing the species most frequently present. Less common species were excluded, to increase the robustness of the analysis. As a result, only species present in at least nine quadrats were included. A species was regarded as present in a quadrat, if it had been observed at least once during the survey (for complete species list, see Appendix S1). The potential 266 quadrats were reduced to 229 in the analysis, as 37 quadrats had none of the top-30 species present.

CANOCO 4.5.5 software (PRI, Wageningen, the Netherlands) was used to carry out two types of direct gradient analysis: canonical correspondence analysis (CCA) and redundancy analysis (RDA). Both aim to explain the species composition by the environmental variables (ter Braak, 1995). The five towns were specified as random effects in the analyses. The CCA yielded ordination axes so short (less than 2 standard deviations) that the nonlinear model assumed by CCA was not supported. Hence, all analyses reported here were based on RDA, which is based on a linear model (cf. ter Braak, 1995). The software was used to pick statistically significant environmental variables one by one until none significant were left. A significance level correcting for the total number of environmental variables was used, $\alpha = 0.05/6 = 0.0083$. Subsequently t-biplots were used to find those species that were significantly explained by the environmental variables at $\alpha = 0.05$. This is an approximate, visual method (ter Braak, 1990). Finally, the analysis was repeated including only those species that were found to be significantly explained by the environmental variables.

Results

Weed coverage

Industrial zones and especially Braunschweig had a high percentage of recording points with more than 5% and 10% weed coverage respectively (Table 4). Also, the town centre of Wageningen was remarkably weedy compared with the other town centres. Generally, there was a poor relationship between weed coverage and

Table 4 The percentage of records in each zone in each of the five towns that had either >1%, >3%, >5%, >10% weed coverage respectively

Town	Zone	>1%	>3%	>5%	>10%
Braunschweig					
No. recording points: 42	Industrial (84 records)	65	51	39	27
No. recording dates: 4	Residential (84 records)	68	56	40	14
Total no. records: 168					
Malmö					
No. recording points: 56	Industrial (84 records)	73	58	42	15
No. recording dates: 4	Residential (84 records)	6	0	0	0
Total no. records: 224	Centre (56 records)	13	4	2	2
Næstved					
No. recording points: 56	Industrial (147 records)	29	20	16	4
No. recording dates: 7	Residential (147 records)	17	5	3	1
Total no. records: 392	Centre (98 records)	16	7	2	0
R.L. Spa					
No. recording points: 56	Industrial (147 records)	44	30	24	12
No. recording dates: 7	Residential (147 records)	18	14	12	9
Total no. records: 392	Centre (98 records)	46	20	8	0
Wageningen					
No. recording points: 56	Industrial (105 records)	46	31	22	12
No. recording dates: 5	Residential (105 records)	52	30	19	4
Total no. records: 280	Centre (70 records)	64	51	34	19

Values are expressed in percentage.

percentage of bare soil (data not shown) in towns having some variation in the bare soil percentages (Næstved, Braunschweig and partly R.L. Spa, Table 5).

Two analyses on the effects of recording date, zone and recording position on weed coverage according to the availability of the data are shown in Table 6. Only significant main effects were found in both analyses. The highest weed coverage was seen at the two latest date categories in both analyses and with 2006 being weedier than 2005 in Analysis 2. The industrial zone tended to have higher weed coverage than the residential zone in both analyses. However, due to a low denominator degree of freedom, and a particular large variance component of town*zone in Analysis 1, differences between zone were not significant. Weed coverage was higher along the pavement edge further from the road than in the middle, although this was only significant in Analysis 1. Running Analyses 1 and 2 again on town centres only showed no differences in recording position (street vs. wall) and the weed coverage was quite stable over recording dates.

In the analysis comparing town centres with the other town zones (Braunschweig excluded), weed coverage of centres was intermediate (averaging 1.4%) between industrial and residential zones. Industrial zones with 3.5% coverage differed from residential zones averaging 0.9% coverage ($P < 0.05$), the only significant effect found.

Species composition

The 10 most frequently recorded types or species of weeds in the five towns when including all recording points and dates are listed in Table 7. Complete species lists with species ranked according to their presence in (i) recording points and (ii) total number of records (both recording points and dates) are available in Appendixes S1 and S2. Identification of some plants at the species level was impossible because of small size and damage caused by pedestrians and sweeping. Some species were also impossible to distinguish from other closely related species within the same genera. Consequently, it was necessary to group some of the species into types of weeds, e.g. *Sonchus* spp., *Geranium* spp. and perennial grasses (*Poaceae* sp., where *Poa pratensis* spp. *pratensis* L., *Poa trivialis* L., *Festuca rubra* L., *Lolium perenne* L., *Dactylis glomerata* L., *Bromus* spp., *Agrostis stolonifera* L. and *Holcus mollis* L. were identified in several cases). Some species unfortunately had to be classified as 'unknown'. However, there was still a remarkable consistency in the occurrence of weed species among the five towns. In total, 86 individual species were identified. The remaining species were grouped in 16 genera, 'unknown' and one family (*Poaceae* sp.). Mosses were also recorded but not distinguished on species level. However, we believe that *Bryum argenteum* Hedw. was the most commonly seen

Table 5 Number of recording points consisting of tarmac or paving-stones and the corresponding percentages of bare soils with standard errors in parentheses shown for all towns and zones

		Paving material				Total
		Tarmac		Paving-stone*		
Town	Zone	No. recording points	% bare soil	No. recording points	% bare soil	% bare soil
Braunschweig	Industrial	3	5.00 (1.732)	18	7.50 (0.657)	7.14 (1.174)
	Residential	2	0.00 (0.00)	19	11.31 (0.548)	10.24 (1.483)
	All	–	–	–	–	8.69 (0.965)
Malmö	Industrial	–	–	21	2.40 (0.000)	2.40 (0.000)
	Residential	–	–	21	2.40 (0.000)	2.40 (0.000)
	Centre	–	–	14	2.94 (0.543)	2.94 (0.543)
	All	–	–	–	–	2.54 (0.136)
Næstved	Industrial	19	3.37 (1.330)	2	5.26 (1.080)	3.55 (1.209)
	Residential	20	0.72 (0.329)	1	9.70 (–)	1.14 (0.530)
	Centre	–	–	14	10.46 (2.531)	10.46 (2.531)
	All	–	–	–	–	4.38 (0.928)
R.L. Spa	Industrial	16	0.03 (0.016)	5	0.09 (0.036)	0.04 (0.016)
	Residential	21	0.00 (0.001)	–	–	0.00 (0.001)
	Centre	1	0.00 (–)	13	0.07 (0.014)	0.07 (0.014)
	All	–	–	–	–	0.03 (0.008)
Wageningen	Industrial	–	–	21	0.90 (0.167)	0.90 (0.167)
	Residential	–	–	21	1.59 (0.116)	1.59 (0.116)
	Centre	–	–	14	0.26 (0.000)	0.26 (0.000)
	All	–	–	–	–	1.00 (0.103)

*Cobble stones or concrete slabs of various sizes, arranged in various patterns.

Table 6 Two analyses on the fixed effects of recording date category (Table 3), zone and recording position on weed coverage showing log-LSM with corresponding weed coverage for each level of the significant main effects. Maximum standard errors of differences (SED) between log-LSM are shown in italics

Main effect	Level	log-LSM	Weed coverage (%)	Significance between levels (*t*-test)
Analysis 1: 2006 data for all five towns, town centres excluded				
Recording date ($P < 0.001$)	May 2006 (a)	1.47	0.84	a vs. b, NS
	Jun/Jul 2006 (b)	1.47	0.84	a vs. c, $P < 0.001$
	Aug/Sep 2006 (c)	1.86	1.36	a vs. d, $P < 0.001$
	Sep/Oct 2006 (d)	1.84	1.32	b vs. c, $P < 0.001$
	SED	*0.085*		b vs. d, $P < 0.001$
				c vs. d, NS
Recording position ($P < 0.05$)	Along the road (a)	1.72	1.15	a vs. b, NS
	Middle (b)	1.35	0.71	a vs. c, NS
	Opposite (c)	1.9	1.42	b vs. c, $P < 0.05$
	SED	*0.211*		
Analysis 2: 2005 and 2006 data for Wageningen, Næstved and Royal Leamington Spa, town centres excluded				
Recording date ($P < 0.001$)	Apr/May 2005 (a)	1.19	0.57	a/b/c/d/e*, NS
	Jul/Aug 2005 (b)	1.15	0.54	a vs. f, $P < 0.01$
	Sep/Oct 2005 (c)	1.17	0.56	a vs. g, $P < 0.01$
	May 2006 (d)	1.1	0.5	b vs. f, $P < 0.001$
	Jun/Jul 2006 (e)	1.2	0.58	b vs. g, $P < 0.01$
	Aug/Sep 2006 (f)	1.59	0.98	c vs. f, $P < 0.01$
	Sep/Oct 2006 (g)	1.55	0.93	c vs. g, $P < 0.01$
	SED	*0.142*		d vs. f, $P < 0.001$
				d vs. g, $P < 0.001$
				e vs. f, $P < 0.01$
				e vs. g, $P < 0.01$
				f vs. g, NS
	Contrast 2005 vs. 2006			$P < 0.05$

NS, not significant.
*No significance between levels a and e.

moss species. Liverworts and lichens may also have been present, but for simplicity these and the mosses are named bryophytes.

The species most frequently seen at the beginning of the survey were generally the same at the end. However, some species demonstrated emergence patterns attributed to their seasonal growth. *Erophila verna* (L.) Chevall. and *Arabidopsis thaliana* (L.) Heynh. were only observed in spring, while *Conyza canadensis* (L.) Cornq. mainly occurred in autumn. In contrast, *P. annua* and *Sagina procumbens* L. were observed evenly throughout the season.

The RDA identified three environmental variables that explained the species composition: industrial zone, no adjacent vegetation and the pavement edge away from the road. An inspection of the t-biplots filtered out 12 species that were not significantly explained by the environment, leaving 18 types and species of weeds in the final analysis (Fig. 1; species numbers below refer to this figure). The t-biplots of the final analysis revealed these relations: Fifteen types or species of weeds were most prevalent inside the industrial zone and two species outside: *P. annua* (1) and *S. procumbens* (3). Two species were most prevalent at sites with some adjacent vegetation (whether mown or unmown), *P. annua* (1) and *T. officinale* (8). In addition, both species, together with grasses (4) and *Trifolium* spp. (23), were most prevalent at the pavement edge away from the road.

Thus the environmental gradients defining species composition were dominated by town zone (industrial vs. the other town zones), with minor roles played by the adjacent vegetation (present or not) and pavement position (away from the road or not).

Discussion

Weed coverage

Braunschweig, Wageningen and Malmö were generally weedier than Næstved and R.L. Spa, presumably due to their restrictions on glyphosate use prior to the survey. Industrial zones were generally weedier than the other zones, but Hypothesis (a) was only statistically supported in one analysis. Hypothesis (d) was not supported, while (c) was supported for the pavement edge opposite to the road. The lower weed coverage in the

Table 7 Number of records of the 10 most frequently recorded types (bryophytes, *Poaceae*, 'unknown', etc.) and species of weeds in the five towns during the entire survey (complete species lists in Supporting information)

Braunschweig (DE)		Malmö (SE)		Naestved (DK)	
No. recording points	42	No. recording points	56	No. recording points	56
No. recording dates	4	No. recording dates	4	No. recording dates	7
Total no. records	168	Total no. records	224	Total no. records	392
Bryophytes	120	Bryophytes	154	Bryophytes	82
Poaceae sp.	84	*Polygonum aviculare* L.	108	*Poa annua* L.	63
Sagina procumbens L.	81	*Sagina procumbens* L.	103	*Poaceae* sp.	47
Unknown	62	Unknown	98	*Taraxacum officinale* Weber	29
Poa annua L.	57	*Poa annua* L.	83	*Sonchus* spp.	22
Polygonum aviculare L.	54	*Geranium* spp.	47	*Polygonum aviculare* L.	19
Taraxacum officinale Weber	48	*Poaceae* sp.	46	*Conyza canadensis* (L.) Cronq.	18
Conyza canadensis (L.) Cronq.	40	*Capsella bursa-pastoris* (L.) Medik.	41	*Sagina procumbens* L.	16
Arenaria serpyllifolia L.	37	*Sedum acre* L.	37	*Senecio vulgaris* L.	10
Plantago major L.	26	*Arenaria serpyllifolia* L.	33	*Trifolium* spp.	8

R.L. Spa (UK)†		Wageningen (NL)*		Total	
No. recording points	56	No. recording points	56		
No. recording dates	7	No. recording dates	6		
Total no. records	392	Total no. records	336	Total no. records	1512
Bryophytes	90	*Poa annua* L.	196	*Poa annua* L.	457
Poaceae sp.	75	*Sagina procumbens* L.	162	Bryophytes	446
Poa annua L.	58	*Poaceae* sp.	51	*Sagina procumbens* L.	407
Sagina procumbens L.	45	*Taraxacum officinale* Weber	32	*Poaceae* sp.	303
Chamaenerion angustifolium (L.) Scop.	32	*Conyza canadensis* (L.) Cronq.	28	*Polygonum aviculare* L.	206
Taraxacum officinale Weber	31	*Polygonum aviculare* L.	22	Unknown	184
Senecio jacobaea L.	17	Unknown	18	*Taraxacum officinale* Weber	157
Sonchus spp.	14	*Plantago major* L.	10	*Conyza canadensis* (L.) Cronq.	121
Conyza canadensis (L.) Cronq.	8	*Eragrostis pilosa* (L.) Beauv.	7	*Arenaria serpyllifolia* L.	70
Myosotis arvensis (L.) Hill	8	*Stellaria media* (L.) Vill.	7	*Geranium* spp.	66

*Bryophytes were not recorded in Wageningen.
†*Poa annua* was not distinguished from other grasses in R.L. Spa in 2005.

middle of the pavements in the zones outside the town centres could be explained by pavements constructed with tarmac, as particularly seen in Næstved and R.L. Spa. Weeds are also more likely to invade from adjacent vegetation at the edges, notably from grass verges.

The percentage of bare soil did not explain much of the variability of weed coverage. The method for assessing weed coverage seems to explain this. A single plant can cover several intersections and may contribute to a relatively high coverage despite a low bare soil percentage. In particular, *T. officinale* having prostrate and large leaves and *Polygonum aviculare* L. with creeping stems may contribute to a high coverage. Furthermore, grass verges tend to grow laterally from the edges even on tarmac with no bare soil, and bryophytes can grow on top of a hard surface. All these were included by our method, because municipalities would have to deal with such growth.

Weed coverage had increased equally in the industrial and residential zones at the last two recording dates. This does not support Hypothesis (b) fully, although an increase took place. Apparently sweeping was not applied frequently enough to hinder the increase, presumably caused by the higher rainfall in 2006 than in 2005, mainly occurring in August in Næstved, Wageningen and Malmö. Town centres did not have such an increase in weed coverage over time. Adjacent vegetation with spreading weed seeds was mostly absent in the centres, and medium-strong shading and medium-heavy pedestrian traffic mostly characterised this zone. Town centres were also swept more frequently than the other zones.

Species composition

The 10 most frequently recorded weed species did not show any noteworthy shifts during the survey. Species such as *P. annua*, *P. aviculare*, *T. officinale* and some perennial grasses are known to tolerate trampling and compacted and poorly aerated soils, all typical of a pavement environment (Warwick, 1979; Stewart-Wade *et al.*, 2002; Benvenuti, 2004). The high occurrence of *P. annua* reflects the biology of this species. *Poa annua* has a short life cycle where newly produced seeds have little or

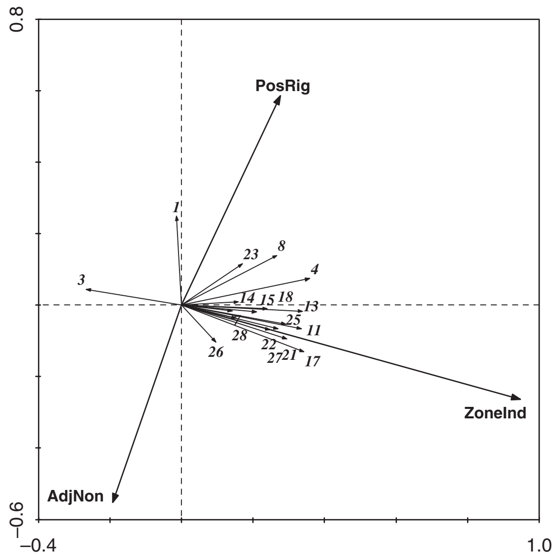

Fig. 1 Redundancy analysis showing the three significant environmental variables [industrial zone (ZoneInd), no adjacent vegetation (AdjNon) and right recording position (PosRig) (i.e. at the pavement edge away from the road)] and the 18 types and species of weeds significantly explained by the environmental variables. Species are: 1. *Poa annua* L., 3. *Sagina procumbens* L., 4. *Poaceae* sp., 7. *Conyza canadensis* (L.) Cornq., 8. *Taraxacum officinale* Weber, 11. *Arenaria serpyllifolia* L., 13. *Geranium* spp., 14. *Stellaria media* (L.) Vill., 15. *Cerastium* spp., 17. *Senecio viscosus* L., 18. *Myosotis arvensis* (L.) Hill., 21. *Sedum acre* L., 22. *Cirsium* spp., 23. *Trifolium* spp., 25. *Erodium cicutarium* (L.) L. Her, 26. *Senecio jacobaea* L., 27. *Veronica hederifolia* L., 28. *Artemisia vulgaris* L.

no dormancy. The seeds can germinate and grow at low temperatures, enabling many generations per year (Warwick, 1979). *Poa annua* grows so quickly that it is likely to build up even under a glyphosate-spraying regime. Other weed species were also well adapted to cope with the pavement environment. For example, joints between paving stones are a well known habitat for *S. procumbens* and *C. canadensis* (Stace, 2001; Benvenuti, 2004).

The RDA revealed that most weed species were associated with industrial areas supporting Hypothesis (a) and secondly where adjacent vegetation was present. Recording points in industrial areas mostly had adjacent vegetation and the high species occurrence in this zone should be seen as a combination of two factors, namely the lower priority of weed control and a higher spread of weed seeds from nearby surroundings. Grasses were prevalent on the pavement edge away from the road side, supporting Hypothesis (c), but also *Trifolium* spp. and *T. officinale* were prevalent in that position. Grasses and *Trifolium* spp. have the ability to grow laterally from grass verges. The higher occurrence of *P. annua* in zones outside industrial areas could be ascribed to its resistance against high disturbance (Benvenuti, 2004).

Importance for weed management

Weed control programmes and research projects aiming for less or even no herbicide use on pavements should in particular address problems with grasses and *T. officinale*, the species consistently recorded in this study. Limited glyphosate use to support non-chemical methods could provide a useful compromise to control these species, until more efficient non-chemical methods are developed. It seems pertinent to define acceptable levels of weed coverage before initiating weed control to limit the burden of non-chemical weed management. Weed coverage varies considerably according to town zone and position on the pavement, indicating that weed control can be applied spatially and differentiated according to priority (Hansen *et al.*, 2004). The development of automated detection systems of weed coverage would help rationalise a graduated weed control programme (Rask & Kristoffersen, 2007). Bryophytes were also frequently recorded, but they should be deemed less important than grasses and *T. officinale*. Normally, bryophytes only cause minor deterioration to the pavement. In contrast, grasses and *T. officinale* can cause severe damage through lifting and cracking the pavement via the pressure exerted through deep tap roots and stem and root expansion. Unsightliness caused by bryophytes is also less pronounced, due to their small stature.

Another important aspect is to look for pavement constructions that minimise opportunities for colonisation (Rask & Kristoffersen, 2007). For example, if a town like Braunschweig aims for a maximum of 3% weed coverage in residential areas, it would be relevant to consider changing the current pavement construction with 10% bare soil to a construction having less bare soil. Then, maintenance by non-chemical weed management might become more feasible.

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Supporting information

Additional Supporting information may be found in the online version of this article:

Appendix S1. Complete species list by point.

Appendix S2. Complete species list by point and date.

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