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Original article

Plant selection for roadside rain gardens in cold climates using real-scale studies of thirty-one herbaceous perennials

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ABSTRACT

Plant selection for rain gardens along streets and roads in cold climates can be complicated, as the plants are subjected to combined stresses including periodic inundation, de-icing salts, road dust, splashes of water from the road, freezing and thawing of soil, and periods with ice cover during the winter. The purpose of this study was to identify species suited to grow in these conditions and determine their optimal placement within roadside rain gardens. Thirty-one herbaceous perennial species and cultivars were planted in real-scale rain gardens in a street in Drammen (Norway) with supplemental irrigation, and their progress was recorded during the following three growing seasons. The study highlights considerable differences between species' adaptation to roadside rain gardens in cold climates, especially closest to the road. Some candidate species/cultivars had a high survival rate in all rain garden positions and were developed well. These were: *Amsonia tabernaemontana, Baptisia australis, Calamagrostis* × *acutiflora* 'Overdam', *Hemerocallis* 'Camden Gold Dollar', *Hemerocallis* 'Sovereign', *Hemerocallis lilioasphodelus, Hosta* 'Sum & Substance', *Iris pseudacorus* and *Liatris spicata* 'Floristan Weiss'. Other species/cultivars appeared to adapt only to certain parts of the rain garden or had medium tolerance. These were: *Calamagrostis brachytricha, Carex muskingumensis, Eurybia* × *herveyi* 'Twilight', *Hakonechloa macra, Hosta* 'Francee', *Hosta* 'Striptease', *Liatris spicata* 'Alba', *Lythrum salicaria* 'Ziegeunerblut', *Molinia caerulea* 'Moorhexe', *Molinia caerulea* 'Overdam', and *Sesleria autumnalis.* Species/cultivars that showed high mortality and poor development at all rain garden positions should be avoided in roadside cold climate rain gardens. These include *Amsonia orientalis, Aster incisus* 'Madiva', *Astilbe chinensis var. tacquettii* 'Purpurlanze', *Chelone obliqua, Dryopteris filix-mas, Eurybia divaricata, Geranium* 'Rozanne', *Helenium* 'Pumilum Magnificum', *Luzula sylvatica, Polygonatum multiflorum* and *Veronicastrum virginicum* 'Apollo'. The study also found considerable differences between cultivars within the same species, especially for *Hosta* cvv. and *Liatris spicata.* Further investigations are needed to identify the cultivars with the best adaption to roadside rain gardens in cold climates.

1. Introduction

Recently, there has been increasing awareness about intense rainy periods and stormwater events due to climatic change. Green infrastructure, like rain gardens and swales, are measures which may reduce the volume of rainwater runoff and flow during moderate stormwater episodes (Lindholm et al., 2008). Kratky et al. (2017) indicated that there are relatively few studies on bioretention systems from cold climate areas, except for the hydrological function and ability of rain gardens to bind toxic metals and remove plant nutrients (Muthanna et al., 2007, 2008; Paus et al., 2014a, 2014b; Paus et al., 2016; Kristvik et al., 2018; Venvik and Boogard, 2020; Kratky et al. 2021; Li et al. 2021). Few studies have been conducted on plant survival in rain gardens in road environments. However, some studies focussed on pollution in urban stormwater, and the pollution load is expected to increase due to the growing population (Malaviya and Singh, 2012; Malaviya et al., 2019).

Perennials are considered multi-functional in rain gardens. Besides enhancing stormwater infiltration and evaporation, they also encourage biodiversity and provide visual aesthetic qualities like variation in blooming periods, forms, flower colours, and foliage texture (Dunnett and Clayden, 2007; Hitchmough and Wagner, 2013). However, plants

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that do not thrive or die are neither aesthetic, appealing, nor biodiverse, and rain gardens without vegetation will eventually fail because roots working through the soil are necessary to avoid clogging the infiltration system (Gonzales-Merchan et al., 2014). Therefore, the right choice of plant species is crucial.

The growing conditions in rain gardens vary from drought to periodic inundation. Plant species that tolerate these conditions are naturally found along waterbodies with fluctuations in water stand or are subjected to significant amounts of rainfall during certain parts of the year, such as those in prairies or hay meadows (Dunnett and Clayden, 2007). Perennials known from the rain garden literature (Dunnett and Clayden, 2007; Schmidt et al., 2007; Steiner and Domm, 2012) have been studied in Sheffield (Yuan and Dunnett, 2018) and north-eastern Italy (Bortolini and Zanin, 2019), and the knowledge from these studies can be used to some extent in Norway and other countries with a similar climate. However, these studies are not always relevant in northern countries because of the shorter growing season, lower temperatures, and winter conditions with snow and frozen soil (Haraldsen et al., 2019). Also, freeze-thaw cycles and ice covers occur more frequently due to climate change (Höglind et al., 2010; Rapacz et al., 2014; Dalmannsdottir et al., 2017; Jørgensen et al., 2020).

Along streets and roads, plants must also withstand splashes and contaminants from the road. The metal tolerance limit differs between species (Singh et al., 2016; Thakur et al., 2022), and Laukli et al. (2022) found considerable differences between species' tolerance to splashes from the road. More importantly, the ability to tolerate de-icing salt, which in cold climates is used regularly for winter maintenance of roads, is crucial (Shaw and Schmidt, 2003; Norwegian Public Roads Administration, 2008). De-icing salt can cause serious injury to plants by absorption from the soil (Fostad and Pedersen, 2000; Fay and Shi, 2012; Kratky et al., 2017) but also through deposition on leaves from salt spray (Demeritt, 1972; Norwegian Public Roads Administration, 2008). However, salt-tolerant plants (halophytes) are found naturally in high saline environments such as seashores, salt marshes, and salt deserts. There is a large variation in salt tolerance among and within species (Demeritt, 1972; Ashraf, 1994; Behadad et al., 2020). A few perennial species were studied in road environments in Norway (Vike and Søyland, 2011). However, this research does not uncover whether these species will thrive in roadside rain gardens. Laukli et al. (2022) evaluated five perennial species with simulated cyclic flooding and real scale in roadside rain gardens in Norway. The study showed large differences between the species' tolerance to this environment and considerable differences between how the plants reacted on a real scale and in controlled studies.

As outlined above, in cold climates, plants in roadside rain gardens are subjected to several stresses. Plant stress can be defined as any factor that reduces growth (Ashraf, 1994). When combined, the total stress level generally negatively impacts plants more than the stresses alone (Choudhury et al., 2017). Mittler (2006) argued that combined stresses should be regarded as a new state of stress in plants, not the sum of different stresses. Therefore, stress testing in a laboratory may not provide the same results as those in a field, and more focus on stress combination on a real scale is needed (Mittler, 2006).

This study aimed to contribute to identify which perennial species can withstand the growing conditions in rain gardens along streets and roads in cold climates where they are exposed to combined stresses, including periodic inundation, de-icing salts, road dust, splashes of water from the road, freezing and thawing of soil, and periods with ice cover during the winter. A further important objective was to determine optimal species placement in roadside rain gardens when these are segregated into three planting zones, namely, roadway, bottom, and walkway. The study included 31 herbaceous perennial species and cultivars planted in rain gardens in an actual street in Norway, thereby representing a realistic environment. To identify the progress of the plants over time, they were recorded in the first, second, and third year after planting.

2. Materials and methods

2.1. Location and time

The research was conducted along Bjørnstjerne Bjørnsons Street in Drammen (centre of project: 59°44′11″N; 10°12′12″), situated in Norwegian climate zone 3 (Det norske hageselskap, undated).

Bjørnstjerne Bjørnsons Street is one of the main roads in Drammen, and the annual mean daily traffic is approximately 21,000 vehicles, of which 9 % are heavy vehicles (Norwegian Public Roads Administration, undated). The street was extended from two to four lanes in 2017–2018, and the stormwater management was rebuilt to be entirely Low Impact, with rain gardens as the main solution. The vehicles in the street are regulated with traffic lights, and the speed limit is 50 km/h. Winter maintenance includes heavy salting.

The rain gardens were established in August 2018, and the recordings and measurements, as described in Section 2.4, were conducted in August 2019, 2020, and 2021. At the end of May 2022 and the beginning of August 2022, final observations were conducted to verify whether there were any changes in mortality and plant growth after the fourth overwintering and growing season, respectively. Monthly temperature and precipitation in Drammen during the study are shown in Table 1, together with normal values (1991–2020).

2.2. Plant material

Table 2 shows the 31 species and cultivars planted in the rain gardens in Bjørnstjerne Bjørnsons Street and the number of plots of each species/cultivar.

Geranium 'Rozanne', *Helenium* 'Pumilum Magnificum', and *Veronicastrum virginicum* 'Apollo' had nearly 100 % mortality after the first winter and were replaced by other species. They were not included in the statistical analyses.

All the plants were sourced in 1-L plastic containers from a commercial source.

2.3. Experimental design

Since the research was carried out in situ, the experimental design had some limitations. The rain gardens were designed based on practical and visual considerations above research perspectives, and the experimental design had to be adapted to the actual situation.

All the stormwater from Bjørnstjerne Bjørnsons Street was treated with bioretention in green areas along the street. Nine rain gardens were built along 700 m of the street (Fig. 1). The rain gardens were located between the roadway and walkway, each 30–34 m long. Drains were installed between the rain gardens and the street to direct surface water from the road into the rain gardens in the growing season (Fig. 2). Given that the distance between the drains was approximately 50 m and the width of the roadway was 6.5 m, each drain received runoff rainwater from an area of approximately 325 m^2. In winter (November–May), the road water runoff was directed away from the rain gardens to prevent the influx of potentially toxic de-icing salt. However, water could still flow freely to the rain gardens from the walkway, which was 3 m wide.

The rain gardens were planted with trees with approximately 9-m spacing (Fig. 2), and perennials, as described in 2.2 were established as a groundcover. Each tree was placed in a 4-m-long tree planter in contact with the underground. A structure was built up between each tree planter, as shown in Fig. 3. All groundcover plants were part of the study, both in the tree planters and in between. The growth media consisted of two layers of rain garden soil, as shown in Fig. 3, and a 5–10 cm thick layer of garden/park waste compost as a mulch, as described by Laukli et al. (2022). Both types of rain garden soil had a medium sand texture [1–3 % clay, 4–8 % silt, 40–43 % fine sand (0.06–0.2 mm), 39–46 % medium sand (0.2–0.6 mm), and 6–12 % coarse sand (0.6–2.0 mm)]. In the raingarden topsoil, compost and

Table 1

Monthly mean temperature (°C) and precipitation (mm) for Drammen during the study and monthly normal values 1991–2020 for Drammen (The Norwegian Meteorological Institute, undated).

MONTH	2018		2019		2020		2021		2022		NORMAL	
	TEMP. (°C)	PRECIP. (mm)	TEMP. (°C)	PRECIP. (mm)	TEMP. (°C)	PRECIP. (mm)	TEMP. (°C)	PRECIP. (mm)	TEMP. (°C)	PRECIP. (mm)	TEMP. (°C)	PRECIP. (mm)
JAN.			-3.9	41.6	1.8	47.9	-7.2	72.6	-1.7	11.3	-3.3	59.4
FEB.			-0.6	76.9	2	40.5	-5.0	25.6	0.3	36.4	-2.4	45.7
MAR.			1.8	93.5	3.2	40.5	3.1	36.4	2.1	6.6	1.3	43.2
APR.			7.4	34.3	7.2	25.7	5.5	11.7	6.4	10.9	6.1	46.4
MAY			10.5	109.1	10.4	34.2	10.4	135.8	11.8	22.3	11.2	64.9
JUN.			15.7	81.8	18.5	75.8	17.4	83.9	17.2	67.9	15.3	73.3
JUL.			18.2	50.3	15.5	125.5	19.9	123.3	18.2	26.3	18.0	72.4
AUG.	1.6	42.9	17.0	119.6	17.3	38.6	16.3	25.9			16.4	89.4
SEP.	12.9	98.6	11.6	90.6	12.8	82.7	13.6	88.1			11.9	78.1
OCT.	7.4	31.1	5.3	137.5	7.4	170.6	8.7	106.9			5.8	89.1
NOV.	3.0	106.9	0.2	142.7	4.7	65.1	2.3	43.8			1.7	82.7
DEC.	-2.2	75.2	-0.9	58.1	1.6	214.1	-4.2	22.9			-2.6	64.1
MEAN/ TOTAL PR. YEAR	6.9	595	6.9	1036	8.5	961	6.7	777			6.6	811

Table 2

Number of plots of 31 species/cultivars within different growth environments in rain gardens along Bjørnstjerne Bjørnsons Street, Drammen, Norway.

SPECIES/CULTIVAR	ENVIRONMENT			
	WALKWAY	BOTTOM	ROADWAY	REFERENCE
Amsonia orientalis Decne.	2	2	2	8
Amsonia tabernaemontana Walter	2	2	2	4
Aster incisus Fisch. 'Madiva'	3	5	2	4
Astilbe chinensis var. taquetii (H.Lév.) Vilm 'Purpurlanze'*	4	4	4	4
Baptisia australis (L.) R.Br.	4	4	4	4
Calamagrostis × *acutiflora* (Schrad.) DC. 'Overdam'	4	4	4	4
Calamagrostis brachytricha Steud.	5	10	9	4
Carex muskingumensis Schwein.	5	5	5	8
Chelone obliqua L.	3	3	2	4
Dryopteris filix-mas (L.) Schott*	6	6	3	4
Eurybia divaricata (L.) G.L.Nesom	12	24	12	4
Eurybia × *herveyi* (A.Gray) G.L.Nesom 'Twilight'	2	3	5	4
Geranium L. ROZANNE ('Gerwat')	2	2	2	4
Hakonechloa macra (Munro) Honda	2	2	2	4
Helenium L. 'Pumilum Magnificum'	4	4	4	4
Hemerocallis L. 'Camden Gold Dollar'	12	24	12	2
Hemerocallis L. 'Sovereign'	2	5	3	4
Hemerocallis lilioasphodelus L.	4	4	4	4
Hosta Tratt. 'Francee'	15	26	14	4
Hosta Tratt. 'Striptease'	7	8	6	4
Hosta Tratt. 'Sum & Substance'	4	4	4	2
Iris pseudacorus L.	4	4	4	4
Liatris spicata (L.) Willd. 'Alba'	4	2	2	2
Liatris spicata (L.) Willd. 'Floristan Weiss'	3	6	17	2
Luzula sylvatica (Huds.) Gaudin	16	33	19	4
Lythrum salicaria L. 'Ziegeunerblut'	5	7	2	4
Molinia caerulea (L.) Moench 'Moorhexe'	6	8	4	4
Molinia caerulea (L.) Moench 'Overdam'	3	3	3	4
Polygonatum multiflorum (L.) All.*	2	4	4	4
Sesleria autumnalis (Scop.) F.W.Schultz	3	4	2	4
Veronicastrum virginicum (L.) Farw. 'Apollo'	2	4	4	2

[*] Plant species planted in shade.

fertilizer were mixed in [0.3 m^3 m^{-3} garden/park waste compost and 4 L m^{-3} chicken manure (Grønn 8K (8-3-5), previously named Øko 8K, from Grønn Gjødsel AS)]. The raingarden subsoil had the same texture as the raingarden topsoil, but without compost or fertilizer. The start values for the compost and rain garden topsoil shown in Table 3 represent the mean values for three different batches used in all nine rain gardens sampled after delivery in 2018, and are therefore slightly different from the values described by Laukli et al. (2022). The latter study reported results only from the three rain gardens designed as research fields.

Three rain gardens were established as research fields and divided into squares (plots) where four candidate species were repeated 12 times along the walkway, 12 times along the roadway, and 24 times at the bottom of the rain gardens. The remaining six rain gardens had different designs. However, the analysed species were repeated in at least two plots in each growth environment (Table 2).

One of the rain gardens (RG 7, Fig. 1) was located next to a building that produced shade in the afternoon. Here, shade tolerant plants were used (*Astilbe chinensis* var. *tacquettii* 'Purpurlanze', *Dryopteris filix-mas*, and *Polygonatum multiflorum*). The rest of the rain gardens were in open areas with full sun exposure, except for the limited shade from the newly planted trees.

The candidate species were also planted in reference fields nearby, without the impact of surface water, splashes, salt, and road contaminants. The reference fields were characterized by soil layers similar to those established in the rain gardens, namely, a 5–10-cm layer of

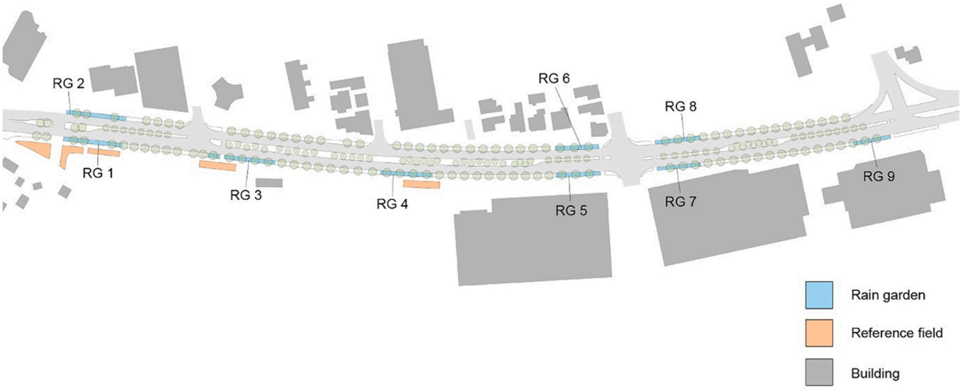

Fig. 1. Location of nine rain gardens and reference fields in Bjørnstjerne Bjørnsons Street, Drammen, Norway.

Fig. 2. A rain garden (RG 1) with a drain that directs surface water from the road into the rain gardens during the growing season. In winter, the road water is directed away from the rain gardens to prevent the influx of de-icing salt. The trees are growing in tree planters (not visible on the surface). Photo: Kirstine Laukli.

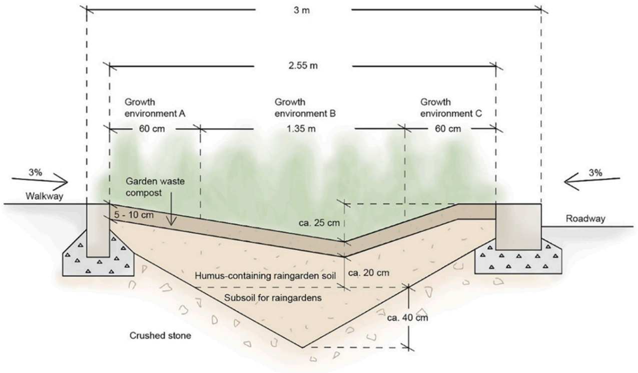

Fig. 3. Structure of the rain gardens in Bjørnstjerne Bjørnsons Street, Drammen, Norway (From: Laukli et al., 2022).

garden/park compost as mulch, topsoil with an admixture of 0.3 m^3 m^{-3} garden/park waste compost, and subsoil without compost. Soil analyses indicated that there was used soil from two different batches. In the northern reference field, a medium sand construction soil was used (4 % silt, 29 % fine sand, 45 % medium sand, 22 % coarse sand), which was similar to the raingarden topsoil. In the southern reference field, loamy medium sand textured construction soil was used (4 % clay, 19 % silt, 27 % fine sand, 35 % medium sand, 13 % coarse sand). There were no significant differences between the rain garden and the reference field topsoils with respect to organic matter content and readily available plant nutrients (Table 3). The reference fields were established at the same time as the rain gardens. The shade-tolerant species in RG 7 were also placed in shady environment in the reference fields.

A total of 6565 individual perennials were planted in the rain gardens and reference fields. The total number of each studied species and cultivars in the different growing environments is shown in Table 4. In addition, 238 *Geranium* 'Rozanne', 204 *Helenium* 'Pumilum Magnificum', and 69 *Veronicastrum virginicum* 'Apollo' were planted. Owing to a very high mortality rate, these were removed before the species distribution in different growing environments was recorded. The mortality at varying distances from the road was therefore impossible to identify.

The planting was done in August 2018, except for *Calamagrostis acutiflora* 'Overdam' that was planted in May 2019, and *Liatris spicata* 'Floristan Weiss', *Liatris spicata* 'Alba', and *Veronicastrum virginicum* 'Apollo' that were established in May 2020.

To ensure a sufficient water supply during the establishment period, a drip irrigation system with 0.5-m spacing was installed, mounted with rain sensors (type Rain Bird RSD) and automatic controllers (type RainBird T-Bos-II), which remained operational through the entire study. The rain sensors, which were 14 in total, were mounted on light poles in the rain gardens, with each sensor having a single automatic controller. During dry periods, the system was set to run for 1.5–2 h every alternative night and remained operational from mid-May to mid-October. Given that the irrigation system also provided irrigation water for the trees that were planted beyond the boundaries of the rain gardens, it was not possible to record or calculate the volume of water each rain garden received from the irrigation system. Neither did we monitor rain garden soil moisture content.

In 2018, base fertilization with chicken manure and compost mixed in the topsoil was found to be sufficient for the normal growth of perennials. Based on soil analyses and the nutrient content of the garden/park compost used as mulch, it was decided that fertilization was not necessary in 2019, 2020, and 2021.

2.4. Recordings and measurements

For recording, the rain gardens were divided into growth environments according to where the plants grew, i.e., the edge by the walkway, bottom, or edge along the roadway (Fig. 3). The edge was defined as the area from the inner side of the curb to 60 cm into the rain garden. In addition, the reference fields were defined as the fourth growth environment.

Table 3
Mean chemical properties of the compost and rain garden topsoil at start of the study in 2018 and in spring 2019 (AL-method according to Egnér et al. 1960).

	Location	pH	P-AL mg 100 g^{-1}	K-AL	Mg-AL	Ca-AL	Na-AL	LOI g 100 g^{-1} DM
Compost	Start	7.6b	67.8a	182.5a	93.0a	505a	12.3c	35.4a
Compost	Roadway	8.7a	28.5b	8.5b	46.0b	560a	200.0a	19.2b
Compost	Bottom	8.4a	22.0b	9.0b	44.5b	440a	175.0a	18.7b
Compost	Walkway	8.3a	35.5b	13.0b	32.0b	415a	91.5b	18.4b
Topsoil	Start	8.12a	12.2a	19.0a	10.0a	133a	7.7a	2.6a
Topsoil	Roadway	8.65a	10.0a	3.5b	6.5ab	105a	13.0a	2.1a
Topsoil	Bottom	8.10ab	9.0a	3.0b	4.5b	75a	8.5a	2.1a
Topsoil	Walkway	7.90ab	11.0a	4.0b	6.0ab	125a	4.5a	2.5a
Topsoil	Reference[a]	6.90b	11.6a	6.5b	8.1ab	162a	4.4a	2.8a
Road dust	Crust	8.3	4.0	6.3	68.0	667	57.7	6.3

Mean values within columns for compost and topsoil with different letters are significantly different ($p < 0.05$).

[a] Sampled in April 2022.

Table 4
Cumulative mortality (%) of 28 perennial species/cultivars grown at different distances from the road (growth environments) in rain gardens along Bjørnstjerne Bjørnsons Street (Norway) 1, 2, and 3 years after planting. Statistical analyses were only performed in the third year. N = Total number of planted individuals of the species within the growth environment.

SPECIES/CULTIVAR	ENVIRONMENT AND YEAR															
	Walkway				Bottom				Roadway				Reference			
	N	2019	2020	2021	N	2019	2020	2021	N	2019	2020	2021	N	2019	2020	2021
Amsonia orientalis	55	13	24	29b	56	30	30	30b	46	20	70	83a	117	8	8	8c
Amsonia tabernaemontana	48	0	0	0ab	89	0	0	0ab	45	7	7	9a	300	1	1	1b
Aster incisus 'Madiva'	25	56	56	76a	18	11	11	39a	12	75	75	75a	169	0	0	0b
Astilbe chinensis var. tacquettii 'Purpurla.'	40	50	63	68a	56	64	75	84a	10	100	100	100a	130	1	1	1b
Baptisia australis	14	0	0	0a	35	0	0	0a	15	7	7	7a	52	15	15	15a
Calamagrostis acutiflora 'Overdam'	24	0	0	0a	79	0	0	0a	18	0	0	6a	25	0	0	0a
Calamagrostis brachytricha	21	0	0	0c	94	22	23	32b	38	55	55	92a	95	2	2	2c
Carex muskingumensis	45	18	20	27b	123	15	38	47b	54	81	100	100a	205	0	0	0c
Chelone obliqua	16	6	6	38b	37	14	19	54b	10	30	80	100a	35	0	0	0c
Dryopteris filix-mas	32	3	3	38b	57	35	54	88a	12	100	100	100a	66	0	0	0c
Eurybia divaricata	54	13	28	44c	130	16	44	68b	60	75	100	100a	125	20	20	20d
Eurybia × *herveyi* 'Twilight'	42	2	2	2b	47	0	0	0b	51	29	29	29a	38	0	0	0b
Hakonechloa macra	16	0	13	19b	19	5	21	26b	18	28	44	83a	30	3	3	3b
Hemerocallis 'Camden Gold Dollar'	31	0	0	0a	111	0	3	5a	25	0	8	8a	10	0	0	0a
Hemerocallis 'Sovereign'	17	0	0	0a	45	0	0	0a	16	0	0	0a	100	0	0	0a
Hemerocallis lilioasphodelus	17	0	0	0ab	86	1	1	1b	19	21	21	21a	95	0	0	0b
Hosta 'Francee'	51	2	2	2b	178	1	4	5b	51	4	25	29a	100	0	0	0b
Hosta 'Striptease'	37	0	0	27b	86	0	0	22b	35	11	31	69a	60	2	2	5c
Hosta 'Sum & Substance'	13	0	0	0a	11	0	0	0a	12	0	0	0a	10	0	0	0a
Iris pseudacorus	25	0	0	0a	99	0	0	0a	25	4	4	8a	54	0	0	0a
Liatris spicata 'Alba'	19	–	5	26a	17	–	6	6a	14	–	14	21a	10	–	0	20a
Liatris spicata 'Floristan Weiss'	25	–	0	0a	37	–	0	11a	93	–	1	5a	10	–	0	0a
Luzula sylvatica	122	16	16	92b	188	24	30	88b	117	87	90	100a	59	3	12	80b
Lythrum salicaria 'Ziegeunerblut'	15	27	27	27a	43	23	26	26a	14	29	36	36a	300	13	13	13a
Molinia caerulea 'Moorhexe'	75	0	0	0b	74	7	8	14a	58	3	12	21a	70	0	0	0b
Molinia caerulea 'Overdam'	56	0	5	7a	104	1	7	13a	54	2	15	22a	27	7	7	7a
Polygonatum multiflorum	24	17	21	33b	55	18	22	35a	69	41	48	74a	26	0	0	0b
Sesleria autumnalis	65	9	11	12c	141	9	11	51b	77	64	64	88a	40	0	0	13c

Mean values within each species in 2021 (end of study) with different letters are significantly different ($p < 0.05$).

In the rain gardens, overall vitality, coverage, and height were evaluated separately for five random representative individuals of the surviving plants in each growth environment in every plot. The selection of individuals was random every year. Five representative individuals in four random squares were evaluated in the reference fields. This gave 20 observations (N) in the reference fields for most species. However, *Amsonia orientalis* and *Carex muskingumensis* were planted in two reference fields and had twice as many data points in this growing environment. *Hemerocallis* 'Camden Gold Dollar' and the cultivars of *Liatris spicata* had only 10 individuals in the reference fields, which limited the number of observations.

The following recordings and measurements were performed:

The total number of planted individuals and dead individuals within each species and growth environment.

Overall vitality was determined on a scale from 0 to 9, whereby:

0 = dead plant.

1 = barely alive; all plant tissue dead or dying.

2 = very poor; although some healthy tissue is visible, this is inadequate to maintain healthy plant functions and the plant is dying.

3 = poor with little potential for improvement; significant leaf senescence; some healthy tissue visible, but inadequate to maintain healthy plant functions.

4 = poor with potential for improvement; some leaf senescence and/or dying leaf tissue; however, there is sufficient healthy tissue visible to assume potential improvement.

5 = acceptable plant; development as expected for a healthy plant of the species, but the plant is slightly smaller and/or has some leaf damage/necrosis or chlorosis.

6 = fairly good; development as expected for a healthy plant of the species.

7 = good; healthy tissue without signs of leaf damage/necrosis or chlorosis; Plant with slightly better development than expected for the species.

8 = very good; notably healthy tissue, larger and better developed plant than expected for the species.

9 = particularly good; lush, well-developed plant, considered the best possible performance for the species at this stage.

Coverage was rated on a scale from 0 to 5, whereby 0 was no coverage/dead plants, 1 – low coverage, 2 – some coverage, 3 – medium coverage, 4 – good coverage, and 5 – very good coverage. Coverage was assessed in relation to the space each plant had been given and thus varied with the planting distance. Plants that were considered to have a coverage of 5 had filled their entire space.

Height of each plant was measured. The measurement method varied depending on the growth form of the species. *Aster incisus* 'Madiva', *Eurybia divaricata,* and *Eurybia* × *herveyi* 'Twilight' were measured at the highest point of the tuft when a measuring stick was inserted in the middle without stretching the leaves. The rest of the species were determined as the mean of the three longest shoots in a stretched state.

Leaf damage was recorded when there were signs of damage.

2.4.1. *Soil sampling and analyses*

Composite soil samples from the different batches of rain garden topsoil were taken at the start of the experiment in 2018. Soil delivered in December 2017 was sampled on 9 May 2018, and soil from another batch used for refilling after subsiding was tested on 1 June 2018. The third batch of rain garden soil was sampled after delivery on 28 August 2018. The compost layer was sampled as composite samples at four rain gardens on 6 November 2018.

After the first winter, a crust layer of road dust was found over the compost layer. The thickness of this crust varied from a few millimetres to approximately 1 cm. Three random samples were collected on 28 March 2019, the mean values of which are presented in Table 3. The compost layer was sampled from the roadway, bottom, and walkway zones of one rain garden on 12 April 2019. The compost samples were extracted down to the surface of the topsoil. Soil samples were also collected from the same rain garden as the compost samples on 26 June 2019 from the roadway, bottom, and walkway zones. When collecting soil samples, the compost layer was pushed aside, and samples of the topsoil were extracted down to a depth of 20 cm. Although no soil samples were collected from the reference field in 2019, soil from this area was collected on 30 April 2022.

All compost and soil samples were collected in duplicates, each of which was a composite of 10–15 subsamples. The samples were collected with a small hand garden spade and mixed in a container prior to sampling. For each sample, 1 L rain garden topsoil and 4 L compost were sent for laboratory analysis at Eurofins Agro Testing.

The topsoil and compost samples were analysed for readily available P, K, Mg, Ca, and Na according to the AL method (Egnér et al. 1960). pH was determined in H_2O according to ISO 10390 (ISO, 2021), and loss on ignition was determined according to EN 13039 (CEN, 2011). The soil analyses results are given in Table 3.

2.5. *Statistical analyses*

Fisher's exact test was conducted on all the pairwise differences between locations, for every species separately to investigate the differences in mortality for the different locations. After the three-year trial, the input was the count of dead and remaining plants. Fisher's exact test is beneficial for a small sample size, which is the case for many plant species with zero or all dead for different locations after three years. The test was conducted using the fisher.test function in RStudio (RStudio Team, 2022). Bonferroni correction was conducted to cope with the problem of multiple testing within plant species.

To study differences in overall vitality, coverage and height for the different species and environments analyses of variance (F-test, GLM procedure) were performed using the SAS software system. Multiple comparisons were carried out on all main effects using the Ryan-Einot-Gabriel-Welsch Multiple Range Test. Response variables were overall vitality, coverage, and height. Firstly, three-factor analyses (year, plant species, and environment) were carried out with all possible two-factor interactions. Secondly, a two-factor analysis (with factors year and environment) was carried out separately for each species. Finally, a one-factor analysis (environment) was carried out separately for each species and year.

Further, analyses of variance (ANOVA) with a posthoc pairwise Tukey's Honest Significant Difference test were carried out for the soil and compost samples. The analysis was done for Compost and Topsoil separately. For this analysis, the functions aov and TukeyHDS were used in R Studio (RStudio Team, 2022). The response variables were pH, P-AL, K-AL, Mg-AL, Ca-AL, Na-AL, and loss on ignition (LOI).

Model assumptions for all models were checked and were found to be adequate.

3. Results and discussion

Among the plants growing for three years, 12 % (regardless of species/cultivar and environment) died after the first year, 16 % died after two years, and 25 % after three years.

Large differences in growth patterns were observed between the species/cultivars. The mortality at the end of the study varied from 0 % for *Hemerocallis* 'Sovereign' and *Hosta* 'Sum & Substance' to 91 % for *Luzula sylvatica*.

In addition to the species/cultivar and year, the growth environment greatly impacted plant survival and development. After three years, regardless of the species/cultivar, plant mortality was 55 % along the roadway, 31 % at the bottom, 27 % along the walkway, and 6 % in the reference fields. The differences were significant except for those between the bottom and walkway. At the end of three years, the overall vitality of the surviving plants (regardless of the species/cultivar) in the reference field and the bottom of the rain gardens was 6.9, followed by the walkway at 6.7. The overall vitality along the road was 5.7, which was significantly lower than that in every other environment, and most likely due to the impacts of salt, pollution, and splashes. For coverage and height, the reference field was significantly better than any other environment, while there were no differences between the bottom and walkway, and the plants along the roadway decreased significantly. Table 5 shows the relationship between the species/cultivar's development and environment.

The weather during the study was not considered to be extreme. It was very wet in May 2019 and the autumn seasons in 2019 and 2020, but the rain occurred evenly and was not intense as it has been on some occasions in recent years. In 2009 (5th July), 90 mm of rainfall occurred in less than two hours on Bjørnstjerne Bjørnsons Street, and the whole area was flooded. During the study, in December 2020, 60 mm of rainfall occurred in one day and night. During the growing season, the maximum was 45 mm of rain in one day and night. There were also some dry periods, but the plants were not subjected to drought because of the irrigation system. However, we did not actively monitor the soil moisture content, which can be considered a major limitation of the study. The first winter had a stable snow cover that protected the plants, but the temperature varied in the second and third winter, and much of the precipitation came as rain. This led to numerous freezing and thawing periods, and the rain gardens were covered with ice for longer periods. In addition, the plants were subjected to road dust, splashes of water from the road, and de-icing salt. These stresses, in combination, were a big challenge to the plants.

At the start of the experiment, the level of Na-AL in the compost layer and the rain garden soil was low (Table 3). The samples taken in spring 2019 showed a significant increase in Na-AL concentration in the compost layer, and the increase was largest along the roadway and at the

Table 5
Mean overall vitality (the first and third year after planting), coverage, and height (the third year after planting) for 28 perennial species/cultivars grown at different distances from the road (growth environments) in rain gardens along Bjørnstjerne Bjørnsons Street, Norway. N = Number of observations.

SPECIES/CULTIVAR	ENVIRONMENT	2019		2021			
		N	OVERALL VITALITY (Scale 0–9)	N	OVERALL VITALITY (Scale 0–9)	COVERAGE (Scale 0–5)	HEIGHT (cm)
Amsonia orientalis	Walkway	10	5.0b	10	6.5ab	4.1b	50b
	Bottom	10	6.3a	10	5.6b	3.2c	44b
	Roadway	10	4.5b	7	4.1c	2.1d	29c
	Reference	40	6.8a	40	7.1a	4.7a	60a
Amsonia tabernaemontana	Walkway	10	6.8bc	10	8.6a	4.9a	79b
	Bottom	10	8.8a	10	9.0a	5.0a	102a
	Roadway	10	6.3c	10	6.6b	4.5b	65c
	Reference	20	7.6b	20	8.3a	4.9a	84b
Aster incisus 'Madiva'	Walkway	11	7.8a	6	7.0b	4.8a	64a
	Bottom	16	8.5a	11	7.0b	4.2a	63a
	Roadway	3	7.7a	3	9.0a	5.0a	80a
	Reference	20	9.0a	20	8.0ab	4.9a	75a
Astilbe chinensis 'Purpurlanze'	Walkway	15	4.7b	11	5.5c	3.2b	59c
	Bottom	12	5.8a	7	7.3b	4.3a	88b
	Roadway	0	0	0	0	0	0
	Reference	20	6.8a	20	8.7a	5.0a	127a
Baptisia australis	Walkway	13	7.1a	13	7.2b	4.7ab	118a
	Bottom	19	6.9a	19	8.4a	5.0a	122a
	Roadway	12	6.4ab	12	7.7ab	5.0a	109a
	Reference	20	5.4b	20	7.0b	4.3b	108a
Calamagrostis × *acutiflora* 'Overdam'	Walkway	19	6.3a	19	7.7a	4.3a	147a
	Bottom	20	6.6a	20	6.3b	3.7a	148a
	Roadway	15	6.0a	15	5.1c	3.5a	111b
	Reference	20	6.4a	20	6.1bc	3.9a	152a
Calamagrostis brachytricha	Walkway	18	8.3a	18	8.2ab	5.0a	145b
	Bottom	31	6.6bc	31	7.2b	4.6a	137b
	Roadway	17	5.6c	3	4.7c	3.3b	104c
	Reference	20	7.5ab	20	8.7a	5.0a	165a
Carex muskingumensis	Walkway	25	4.6b	22	6.4a	4.3b	71a
	Bottom	25	4.2b	50	6.9a	4.6b	77a
	Roadway	10	2.1c	0	0	0	0
	Reference	40	8.3a	40	6.6a	5.0a	77a
Chelone obliqua	Walkway	15	5.7b	10	7.3a	5.0a	74a
	Bottom	14	4.9b	10	5.2b	3.9b	52b
	Roadway	7	2.9c	0	0	0	0
	Reference	20	7.6a	20	7.9a	5.0a	85a
Dryopteris filix-mas	Walkway	24	4.1b	17	3.8b	2.2b	31b
	Bottom	23	3.4b	6	2.3c	0.8c	19b
	Roadway	0	0	0	0	0	0
	Reference	20	6.7a	20	8.4a	5.0a	89a
Eurybia divaricata	Walkway	45	6.0a	30	6.2b	4.0b	46b
	Bottom	93	5.7a	40	6.3b	3.9b	48b
	Roadway	15	2.9b	0	0	0	0
	Reference	20	6.1a	20	7.2a	4.9a	59a
Eurybia × *herveyi* 'Twilight'	Walkway	10	6.8a	10	6.3a	4.6a	55b
	Bottom	15	7.7a	15	7.0a	4.9a	71a
	Roadway	25	5.5b	25	5.1b	2.8b	58b
	Reference	20	6.6ab	20	6.2a	4.8a	79a
Hakonechloa macra	Walkway	10	4.1b	10	5.6b	3.5b	44b
	Bottom	10	4.1b	10	7.6a	4.9a	66a
	Roadway	10	2.9b	3	6.7ab	4.8a	49ab
	Reference	20	5.8a	20	7.9a	5.0a	62ab
Hemerocallis 'Camden Gold Dollar'	Walkway	28	6.4a	28	8.2a	4.9a	85a
	Bottom	110	6.4a	105	8.1a	4.7a	88a
	Roadway	25	5.5b	23	6.1b	3.5b	66b
	Reference	10	6.9a	10	7.7a	4.9a	91a
Hemerocallis 'Sovereign'	Walkway	10	7.5a	10	8.1a	5.0a	94a
	Bottom	25	7.0ab	35	6.1b	3.9b	68bc
	Roadway	14	5.2c	14	5.0c	3.4b	57c
	Reference	20	6.3b	20	7.0b	4.6a	78b
Hemerocallis lilioasphodelus	Walkway	16	7.4a	16	7.5a	4.6a	91b
	Bottom	20	7.2a	20	7.8a	4.7a	100a
	Roadway	15	6.8a	15	6.2b	3.8b	77c
	Reference	20	7.1a	20	7.9a	4.9a	104a
Hosta 'Francee'	Walkway	41	6.3ab	41	7.9a	4.8a	50b
	Bottom	116	6.0b	108	7.9a	4.8a	48b
	Roadway	37	4.9c	24	6.8b	4.2b	31c
	Reference	20	6.9a	20	7.9a	5.0a	62a
Hosta 'Striptease'	Walkway	27	6.8a	19	6.7a	4.6a	50b
	Bottom	38	6.9a	30	6.4a	4.4a	53b
	Roadway	22	5.3b	10	4.5b	2.9b	25c

(*continued on next page*)

Table 5 (*continued*)

SPECIES/CULTIVAR	ENVIRONMENT	2019		2021			
		N	OVERALL VITALITY (Scale 0–9)	N	OVERALL VITALITY (Scale 0–9)	COVERAGE (Scale 0–5)	HEIGHT (cm)
	Reference	20	6.7a	20	7.5a	5.0a	68a
Hosta 'Sum & Substance'	Walkway	13	5.8a	13	6.5a	4.2ab	43bc
	Bottom	11	6.5a	11	6.7a	4.5ab	52b
	Roadway	12	5.5a	12	5.8a	3.8b	38c
	Reference	10	6.6a	10	6.3a	5.0a	68a
Iris pseudacorus	Walkway	18	6.9b	18	7.0b	4.6b	137b
	Bottom	20	7.8a	20	8.8a	5.0a	162a
	Roadway	18	5.9c	17	7.1b	4.5b	135b
	Reference	20	6.0c	20	6.7b	4.6b	114c
Liatris spicata 'Alba'	Walkway	–	–	11	7.2a	3.6a	74a
	Bottom	–	–	10	7.1a	3.5a	77a
	Roadway	–	–	10	6.9a	3.7a	64ab
	Reference	–	–	8	6.8a	2.8a	59b
Liatris spicata 'Floristan Weiss'	Walkway	–	–	18	6.8a	3.4a	84b
	Bottom	–	–	24	7.0a	3.4a	89ab
	Roadway	–	–	76	6.7a	3.5a	82b
	Reference	–	–	10	7.3a	3.5a	99a
Luzula sylvatica	Walkway	70	6.6b	9	2.0b	1.4b	17c
	Bottom	116	6.2b	17	4.2a	2.9a	27b
	Roadway	21	3.9c	0	0	0	0
	Reference	20	7.9a	12	4.2a	2.9a	41a
Lythrum salicaria 'Ziegeunerblut'	Walkway	11	6.0a	11	6.5a	3.5a	118a
	Bottom	26	6.6a	25	7.1a	4.0a	124a
	Roadway	9	6.2a	8	4.8b	2.4b	100b
	Reference	20	7.1a	20	6.5a	3.2a	122a
Molinia caerulea 'Moorhexe'	Walkway	25	6.6a	30	6.9a	3.6a	87a
	Bottom	34	6.2a	35	6.4a	3.2a	86a
	Roadway	20	5.7a	35	4.9b	2.2b	61b
	Reference	20	6.5a	20	6.4a	3.7a	66b
Molinia caerulea 'Overdam'	Walkway	15	7.3a	15	6.7a	3.8a	75ab
	Bottom	15	6.3ab	15	6.4a	3.5a	79a
	Roadway	15	5.5b	15	4.4b	1.6b	51c
	Reference	20	6.5ab	20	6.6a	3.6a	66b
Polygonatum multiflorum	Walkway	10	3.5b	10	3.8b	2.2b	72b
	Bottom	14	2.4b	12	2.1c	0.5c	36c
	Roadway	17	1.2c	13	1.1d	0.5c	23c
	Reference	20	5.6a	20	7.5a	5.0a	116a
Sesleria autumnalis	Walkway	17	6.9a	26	4.7a	3.6a	38a
	Bottom	35	6.1a	32	4.1ab	2.5a	29b
	Roadway	18	4.3b	14	3.0b	0.5b	16c
	Reference	20	7.1a	20	5.7a	3.6a	37a

Mean values within columns for each species with different letters are significantly different ($p < 0.05$).

bottom of the rain gardens. The level of Na-AL in the compost layer was far above 50 mg 100 g^{-1}, which is often quoted as a limit value for salt-sensitive plants (Eurofins, undated). The pH in the compost layer increased significantly in all three environments in spring 2019 compared with the start value. In the rain garden topsoil, a significant increase in pH was found along the roadway compared with the start value and reference field. The effects of de-icing salts on soil alkalinity were also observed by Dmuchowski et al. (2014). Consistent with our observations, Mills et al. (2021) detected similar increases in pH and Na accumulation close to a highway. Compared with the initial levels, the levels of readily available potassium and magnesium (K-AL and Mg-AL) were found to have declined significantly in the compost layer and rain garden topsoil in spring of 2019 (Table 3), which is similar to the pattern reported by Mills et al. (2021). In addition, the amount of readily available P (P-AL) and the loss of ignition in the compost also decreased significantly. When the compost was sampled in spring 2019, the road dust crust on the top was sampled separately, and visible road dust was not included in the compost samples. The most probable reason for the decrease in organic matter and P-AL in the compost may be due to the particles of road dust being flushed into the rain garden with water splashed from the road and mixed with the compost during the winter (Fig. 4, Fig. 5). Although some mineralization of the compost may have occurred, the mineralization of garden/park waste compost has been found to be a slow process as the remaining organic matter in this type of compost is generally recalcitrant to degradation (Haraldsen et al. 2014).

Fig. 4. Splashes from the road in rain garden 1 (RG 1), Bjørnstjerne Bjørnsons Street, Drammen, Norway. Photo: Kirstine Laukli.

Gerhard et al. (2021) detected leaching of P and dissolved organic C (DOC) from forest humus with coarse texture soils. However, although a certain amount of P may have leached from the compost applied in Bjørnstjerne Bjørnsons Street, it is unlikely that the large reduction in P-AL levels can be attributed to plant uptake, as the decline in P-levels was found to be considerably larger than plant P demand. The loss of K and Mg from the compost and rain garden topsoil can probably be ascribed to cation exchange processes and the leaching of these cations together with chloride ions (Cl^-), whereas Na^+ was retained within the

Fig. 5. Grey road dust deposited upon the compost layer is clearly visible, particularly on the roadway side of the rain garden. Photo: Trond Knapp Haraldsen.

compost. In this regard, Blume et al. (2016) have described models for cation exchange, in which there can be exchange of ions with same valence (homovalent), as in the case where Na^+ replaces K^+ on a surface with exchange sites X^-, or exchange of heterovalent ions, such as when Na^+ replaces Mg^{2+} on a surface with exchange sites X^-. By way of confirmation, Kim and Koretsky (2013) have demonstrated that the addition of NaCl to soils stimulates ion exchange and the release of ions such as Mg^{2+} and K^+ to pore waters.

Surprisingly, the effects of de-icing salts were considerable after only one winter with exposure. In a study with eleven bush species, Thompson and Rutter (1986) found that salt added to soil had greater effects on the plants than the same amount sprayed onto the plants. Progressively, the accumulation of Na may also reach the root zone in the rain garden topsoil and lead to salt concentrations which can affect plants deleteriously (Fay and Shi, 2012; Haraldsen and Lundetræ, 2014; Kratky et al., 2017, Mills et al. 2021). However, Munck et al. (2010) found no increasing impact of de-icing salts on roadside conifers over time. The high Na^+ saturation and pH in the moderately alkaline range found in both the compost and the raingarden topsoil (Table 3) are typical for soil materials with high Na^+ saturation in the absence of sodium carbonate formation, whereas a high content of neutral salts, such as NaCl, is normally associated with somewhat lower pH values (Blume et al. 2016). However, a more detailed investigation of the gradual accumulation of salt at different distances from the road is necessary to verify the effects in the rain gardens along Bjørnstjerne Bjørnsons Street.

Together with the adverse effects of salt, pollution, and splashes of water and the intolerance to low temperatures, a high pH may have contributed to the failure of sensitive plant species, particularly those with an already high mortality rate in the entire rain garden profile after the first winter. In this regard, Hann et al. (2012) studied plant establishment during roadside restoration and found that plant survival is largely determined by soil characteristics. Plants are less likely to survive in soils with a high bulk density, high pH, and textures rich in silt or clay. In Bjørnstjerne Bjørnsons Street, although the soil had a low bulk density and low content of silt and clay, the pH of the rain garden topsoil and compost was high (7.6–8.65), whereas that in soil of the reference field was in the normal range (6.9) (Table 3). In addition, an insufficiently well-developed root mass can be a potential factor contributing to early plant death, as demonstrated by Jernigan and Wright (2011), who examined the effects of short-term flooding events on four shrub taxa and concluded that enabling plants to develop a more robust root system prior to flooding treatments conferred a greater tolerance to flooding. As the rain gardens in Bjørnstjerne Bjørnsons Street were established in August, the roots were probably insufficiently developed when flooding events occurred in the following autumn than had they been planted in springtime, and thus we may have obtained differing results had we established plants earlier in the season.

In the following discussion, the candidate species/cultivars are grouped according to how well they appeared to adapt to roadside cold climate rain gardens in this study. The main criteria for grouping were that a maximum of approximately 20 % mortality was accepted in the growing environment in which the species/cultivar was evaluated, and that the development of the surviving plants after three years was favourable. A suggested distribution in different rain garden zones is shown in Table 6.

3.1. *Species adapted to all roadside rain garden positions*

Some candidate species/cultivars had a high survival rate in all growth environments (Table 4) and developed well (Table 5). These included *Amsonia tabernaemontana, Baptisia australis, Calamagrostis* × *acutiflora* 'Overdam', *Iris pseudacorus, Hemerocallis* 'Camden Gold Dollar', *Hemerocallis* 'Sovereign', *Hemerocallis lilioasphodelus, Hosta* 'Sum & Substance', and *Liatris spicata* 'Floristan Weiss'. These species/cultivars are recommended in the rain garden literature (Dunnett and Clayden, 2007; Schmidt et al., 2007; Clasen, 2012; Steiner and Domm, 2012; Malaviya et al., 2019).

After three years, no individuals of *A. tabernaemontana, B. australis, C.* × *acutiflora* 'Overdam' and *I. pseudacorus* had died along the walkway or at the bottom, while the mortality rate along the roadway was less than 10 % for these species (Table 4). However, in spring 2022, a few dead individuals of *B. australis* were observed for the first time. The overall vitality of the surviving plants increased every year in all the growing environments, except for *C.* × *acutiflora* 'Overdam', which was slightly lower each year at the bottom and along the roadway (Table 5). However, this also occurred in the reference field. *Amsonia tabernaemontana* and *B. australis* are native to the prairies in North America and are well adapted to the dry, stony steppes (Hansen and Stahl, 1993), where *C.* × *acutiflora* is also recommended (Hansen and Stahl, 1993). *Baptisia australis and C.* × *acutiflora* are not known from any rain garden studies, but *A. tabernaemontana* was treated with simulated cyclic flooding in Sheffield, where it was found useful for the margin and slope of a rain garden, but not at the bottom (Yuan and Dunnett, 2018). *Iris pseudacorus* grows naturally in Norway in moist, nutrient-rich soil on coastal beaches exposed to salt from sea spray, and was found to be well adapted to rain gardens in north-eastern Italy (Bortolini and Zanin, 2019). The study in Bjørnstjerne Bjørnsons Street shows that *A. tabernaemontana, B. australis,* and *I. pseudacorus* thrived well in all rain garden positions after three years. However, since some individuals of *B. australis* died in the bottom of the rain gardens during the fourth winter, this growing environment may be less suitable for this species. Also, *C.* × *acutiflora* 'Overdam' performed well but showed slightly decreased development in the bottom and when closest to the roadway. Further investigations are needed to determine the performance of this species in the longer term.

The mortality rate was very low for the three species/cultivars of *Hemerocallis*, and there were no significant differences between the growing environments except for *H. lilioasphodelus* along the roadway, which had 21 % mortality (Table 4). However, no individuals died after the first year; this species seems stable once established. The overall vitality of the surviving plants increased over time for all *Hemerocallis* cvv. along the walkway and in the reference fields (Table 5). In the bottom and along the roadway, the development between the species/cultivars differed, especially along the roadway where the overall vitality increased for *H.* 'Camden Gold Dollar', while it decreased for *H. lilioasphodelus* due to smaller individuals, and for *H.* 'Sovereign' due to necrosis probably caused by de-icing salt. However, in the final observation in August 2022, the leaves of *H.* 'Camden Gold Dollar' had developed a certain degree of necrosis, whereas we detected no evidence of necrosis on the leaves of *H. lilioasphodelus*. In July 2022, levels of

Table 6
Suggestion of species distribution in different rain garden zones along streets and roads in cold climates.

SPECIES/CULTIVAR	ENVIRONMENT			
	WALKWAY	BOTTOM	ROADWAY	NOTE
Amsonia orientalis				Not recommended
Amsonia tabernaemontana	X	X	X	
Aster incisus ‘Madiva’				Not recommended
Astilbe chinensis var. taquetii ‘Purpurlanze’				Not recommended
Baptisia australis	X	X	X	Some mortality in the bottom after the fourth overwintering
Calamagrostis × *acutiflora* ‘Overdam’	X	X	X	
Calamagrostis brachytricha	X			
Carex muskingumensis	X			
Chelone obliqua				Not recommended
Dryopteris filix-mas				Not recommended
Eurybia divaricata				Not recommended
Eurybia × *herveyi* ‘Twilight’	X	X		Spreads via rhizomes
Geranium ‘Rozanne’				Not recommended
Hakonechloa macra	X			
Helenium ‘Pumilum Magnificum’				Not recommended
Hemerocallis ‘Camden Gold Dollar’	X	X	X	Shows necrosis closest to the road. Uncertain salt-tolerance
Hemerocallis ‘Sovereign’	X	X	X	Shows necrosis closest to the road. Uncertain salt-tolerance
Hemerocallis lilioasphodelus	X	X	X	
Hosta ‘Francee’	X	X		Vulnerable to splashes of water from the road
Hosta ‘Striptease’	X	X		
Hosta ‘Sum & Substance’	X	X	X	
Iris pseudacorus	X	X	X	
Liatris spicata ‘Alba’		X		
Liatris spicata ‘Floristan Weiss’	X	X	X	
Luzula sylvatica				Not recommended
Lythrum salicaria ‘Ziegeunerblut’	X	X		
Molinia caerulea ‘Moorhexe’	X	X		Poor coverage => maintenance problem
Molinia caerulea ‘Overdam’	X	X		Poor coverage => maintenance problem
Polygonatum multiflorum				Not recommended
Sesleria autumnalis	X			
Veronicastrum virginicum ‘Apollo’				Not recommended

X = Possible placement of species in different roadside rain garden environments.

precipitation were very low, which may have exacerbated the detrimental effects of salinity, in addition to a probably higher concentration of salt after the fourth winter. Furthermore, we observed that *H.* ‘Happy Returns’, a cultivar that was planted in the raingardens although not in the reference field, and was thus not included in the study, showed no signs of necrosis, even at the time of the final observation. The findings tend to indicate that the salinity tolerance of this species can vary to a large extent and that the accumulation of salt and pollution warrants long-term observations to determine tolerance patterns over time. *Hemerocallis* thrives on moist to damp soil but can also tolerate drought (Hansen and Stahl, 1993) and is known to be well adapted to rain gardens (Schmidt et al., 2007; Clasen, 2012; Malaviya et al., 2019). In rain garden studies, the species developed well (Bortolini and Zanin, 2019; Yuan and Dunnett, 2018), and studies from road environments indicate tolerance to salt and pollution (Vike and Søyland, 2011). The study in Bjørnstjerne Bjørnsons Street shows that *Hemerocallis* generally is well adapted to roadside rain gardens in cold climates, but there are differences between both species and cultivars. Thus, more investigation is needed to identify the species and cultivars best suited to these conditions, especially with respect to tolerance of de-icing salt.

The three *Hostas* acted very differently. While *H.* ‘Sum & Substance’ showed no mortality in any growing environment after three years (Table 4), 28 % of all the *H.* ‘Striptease’ and 18 % of all the *H.* ‘Francee’ in the rain gardens were dead and therefore considered less suitable. For *H.* ‘Sum & Substance’, no significant differences were noted in the overall vitality of the surviving plants after three years, but the coverage and height decreased significantly along the roadway (Table 5). *Hosta* is adapted to woodlands but can also grow in limited shade. The species tolerates strong fluctuations in soil moisture (Hansen and Stahl, 1993) and is recommended in all rain garden positions (Schmidt et al., 2007) but has not been included in any known rain garden studies. Vike and Søyland (2011) found that *Hosta* performed well in perennial borders along roads in Norway, and in a container study, they concluded that *H.* × *fortunei* tolerates salt polluted soil to some extent. Laukli et al. (2022) found that *H.* ‘Francee’ can withstand a combination of rain gardens and road environments in cold climates, except when treated with heavy splashes. The results after three years in Bjørnstjerne Bjørnsons Street indicate that there can be large differences between the cultivars, and more investigation is needed to determine which *Hosta* cvv. are best adapted to roadside rain gardens in cold climates.

Liatris spicata ‘Alba’ and *L. spicata* ‘Floristan Weiss’ were planted later and only recorded for two years. However, the salt and pollution build-up from the road affected the soil for three years. The two cultivars acted quite differently as *L. spicata* ‘Floristan Weiss’ had a lower mortality rate than *L. spicata* ‘Alba’ and thus seemed more adapted to roadside rain gardens. For *L. spicata* ‘Floristan Weiss’, the highest mortality rate was in the bottom (11 %), followed by the roadway (5 %), while no plants had died along the walkway or in the reference field during the study. The surviving plants developed well, and there were no significant differences between the overall vitality or coverage in any growing environment except for small height differences (Table 5). *Liatris spicata* is a prairie plant native to North America and prefers moist soils but is also very drought tolerant (Schmidt et al., 2007). Even though *L. spicata* ‘Floristan Weiss’ was only recorded for two years, it seemed very stable in all rain garden positions and was still growing well in spring and late summer 2022. It will most likely develop well in the longer term, but more investigation over time is needed.

3.2. *Species with medium tolerance to roadside rain gardens*

Some species seemed to be adapted to parts of the rain gardens or had medium tolerance. These were: *Hosta* ‘Francee’, *Hosta* ‘Striptease’, *Liatris spicata* ‘Alba’, *Calamagrostis brachytricha, Carex muskingumensis, Hakonechloa macra, Sesleria autumnalis, Lythrum salicaria*

'Ziegeunerblut', *Molinia caerulea* 'Moorhexe', *Molinia caerulea* 'Overdam', and *Eurybia* × *herveyi* 'Twilight'.

Among the *Hostas*, *H.* 'Francee' and *Hosta* 'Striptease' had higher mortality rates than *H.* 'Sum and Substance'. Also, *Liatris spicata* 'Alba' showed poorer survival than *L. spicata* 'Foristan Weiss' (Table 4), and these cultivars were therefore considered less suitable in cold climate roadside rain gardens. *Hosta* 'Francee' was very stable except along the roadway, where the mortality rate increased every year and was 29 % at the end of the study. *Hosta* 'Striptease' had a 27 % mortality along the walkway, 22 % in the bottom, 69 % along the roadway, and 5 % in the reference field after three years (Table 4). However, some *H.* 'Striptease' were subjected to major erosion due to system failure in the third year, and the mortality rate increased. Planting *H.* 'Francee' and *H.* 'Striptease' should be avoided closest to the roadway but can be useful in other rain garden positions in road environments. The mortality rate of *L. spicata* 'Alba' was 26 %, 6 %, 21 %, and 20 % at the walkway, bottom, along the roadway, and in the reference field, respectively, at the end of the study (Table 4). If used, this cultivar should only be planted at the bottom of roadside rain gardens in cold climates.

Calamagrosis brachytricha, *Carex muskingumensis, Hakonechloa macra,* and *Sesleria autumnalis* showed an increased mortality rate over time in most rain garden positions, while very few individuals died in the reference fields (Table 4). *Calamagrosis brachytricha* had 92 % mortality along the roadway at the end of the study, while 100 % of *C. muskingumensis*, 83 % of *H. macra,* and 88 % of *S. autumnalis* were dead. At the bottom, the mortality rate increased every year, and at the end of the study, it was higher than what was considered acceptable. *Calamagrosis brachytricha, C. muskingumensis,* and *S. autumnalis* performed better when they were further away from the road (Table 5), while *H. macra* showed the best development at the bottom and reference fields, followed by the walkway and roadway, probably due to more humid conditions in the bottom. *Calamagrosis brachytricha* grows naturally in moist open woods and at the woodland's edge in central and eastern Asia (Hortipedia, undated) and was found to develop well in a rain garden study in Sheffield, especially at the bottom (Yuan and Dunnett, 2018). *Carex muskingumensis* grows naturally in humid to wet forests and floodplains in North America (Flora of North America, undated), and is recommended for all rain garden positions (Schmidt et al., 2007). *Hakonechloa macra* is native to woodland in Japan, while *S. autumnalis* is a steppe plant from south-eastern Europe (Hansen and Stahl, 1993), and they are not known as rain garden plants. This study indicated that *C. brachytricha, C. muskingumensis, H. macra,* and *S. autumnalis* are useful along the walkway in roadside rain gardens in cold climates, but they do not tolerate the growing conditions closest to the roadway or at the bottom, most likely due to salt exposure which increases when closer to the road (Table 3).

Lythrum salicaria 'Ziegeunerblut' had a rather high mortality rate already after the first winter, also in the reference fields; however, after that, very few individuals died (Table 4). The development of the surviving plants was good except for those closest to the road, where it was significantly decreased (Table 5). The plants of this species were considered weak when delivered, which most likely caused mortality during the first winter. The mortality of *Molinia caerulea* 'Overdam' and *M. caerulea* 'Moorhexe' increased slightly at the bottom and along the roadway each year and was 13–14 % at the bottom and 21–22 % along the roadway at the end of the study, while very few individuals died along the walkway and in the reference field (Table 4). The overall vitality, coverage, and height of the surviving plants decreased significantly along the roadway, while small differences were observed between the other environments. Yuan and Dunnett (2018) and Bortolini and Zanin (2019) found *M. caerulea* well adapted to all rain garden positions in Sheffield and north-eastern Italy. The species also performed well on the slope of the rain garden at Campus Ås (Vike and Clewing, 2020). *Lythrum salicaria* was found unsuitable in rain gardens in north-eastern Italy due to yearly insect attacks (Bortolini and Zanin, 2019), probably because of the warm climate. Both *L. salicaria* and *M. caerulea* grow naturally on moist soils along beaches, beach meadows, and moors in Norway (Mossberg and Stenberg, 2012), which means that they occur naturally in places with high concentration of sea salt, but they are also found further away from the coast. Thus, large differences between salt tolerance in different populations of these species are likely. The cultivars in Bjørnstjerne Bjørnsons Street showed a higher mortality rate than acceptable closest to the road, and more studies are required to identify salt-tolerant cultivars.

Eurybia × *herveyi* 'Twilight' was very stable, and once established, no dead plants were recorded (Table 4). The mortality rate was close to zero, except for those closest to the road, where 29 % of the plants were dead at the end of the study. However, this species spreads via rhizomes and was difficult to count as the plants grew into one mass after some time. The overall vitality and coverage of the surviving plants significantly decreased along the roadway after three years, while the differences between the other growing environments were small (Table 5). *Eurybia* × *herveyi* (syn. *Aster macrophyllus*) is native to North America and is recommended for the edges of rain gardens (Schmidt et al., 2007). The species is invasive, which makes it a potential problem, but if planted alone or in a natural planting system where it is allowed to spread, it appears to have a high potential along the walkway and at the bottom of roadside rain gardens.

3.3. Species vulnerable to roadside rain garden environment

Geranium 'Rozanne', *Helenium* 'Pumilum Magnificum', *Veronicastrum virginicum* 'Apollo', *Luzula sylvatica*, *Astilbe chinensis* var. *tacquettii* 'Purpurlanze', *Dryopteris filix-mas, Polygonatum multiflorum, Amsonia orientalis, Chelone obliqua, Eurybia divaricate, and Aster incisus* 'Madiva' showed high mortality (Table 4) and poor development (Table 5) in all the rain garden positions. The study indicates that these species are not adapted to roadside rain gardens in cold climates and should be avoided.

Some species had a high mortality rate after the first winter; 93 % of *Helenium* 'Pumilum Magnificum', 88 % of *Geranium* 'Rozanne', and 86 % of *Veronicastrum virginicum* 'Apollo' in the rain gardens were dead in spring the first year, while most of the individuals from these species survived in the reference fields. These species were replaced after the first winter and were not recorded. Both *H. autumnale* and *V. virginicum* are recommended widely for rain gardens, especially in the moist part at the bottom (Shaw and Schmidt, 2003; Dunnett and Clayden, 2007; Schmidt et al., 2007; Steiner and Domm, 2012). *Veronicastrum virginicum* performed well in all rain garden positions in a study in Sheffield (Yuan and Dunnett, 2018) and on the slope of the rain garden at Campus Ås (Vike and Clewing, 2020). *Helenium* 'Pumilum Magnificum' is a cultivar of *H. autumnale,* which is common on roadsides, fields, along streams, ditches, ponds, and lakes in North America, while *V. virginicum* grows naturally in dry to mesic forests, tallgrass prairies, thickets, and oak savannas in North America (Flora of North America Association, undated). *Geranium* 'Rozanne' is a hybrid of *G. himalayense* × *G. wallichianum* 'Buxton's Variety' (Ballyrobert Gardens, undated). Many geraniums are well adapted to rain gardens; however, this cultivar is vulnerable to waterlogging soils (RHS, undated), which could explain why most of the individuals had already died after the first winter. Furthermore, the high pH of the rain garden topsoil and compost may have contributed to the rapid failure of *G.* 'Rozanne', *H.* 'Pumilum Magnificum' and *V. virginicum* 'Apollo', as soil in the reference fields in which most of the plants survived, was characterized by a mean pH within the normal range (Table 3). However, all of these species are known to tolerate mildly alkaline soils (Plants for a future; RHS, undated). A further conceivable contributory factor is an insufficiently well-developed root mass, as the roots of most plants were probably small and thus less tolerant to flooding events that occurred during the first autumn (Jernigan and Wright, 2011). However, this does not explain the high mortality of *V. virginicum*, which was planted in May 2020. The chemical analyses of the compost layer in Bjørnstjerne Bjørnsons Street showed that salt had also affected the area closest to the walkway after the first winter (Table 3), which can probably be attributed to road splashes containing salt water, and this could be the main factor contributing to the failure of these species. More studies are needed to verify if *H.* 'Pumilum Magnificum', *V. virginicum* 'Apollo', and *G.* 'Rozanne' are useful to cold climate rain gardens that are unaffected by salt.

After two years, *Luzula sylvatica* appeared to thrive well along the walkway and to some extent at the bottom of the rain gardens, while the individuals closest to the road had died due to salt exposure (Laukli et al., 2022). However, after three years, 92 % of the plants in the entire rain garden were dead, and the mortality in the reference field was also high (80 %) (Table 4). Most of this species died after three years because bare frost combined with sun exposure occurred during the third winter, to which evergreens like *L. sylvatica* are susceptible. Vike and Clewing (2020) found that this species developed well on the slope of a rain garden in a shady site at Campus Ås but froze back during some winters. However, at Campus Ås, this species recovered after freezing, whereas the individuals in Bjørnstjerne Bjørnsons Street died. This indicates that *L. sylvatica* is unstable and may not be suitable for cold climate rain gardens.

The mortality rate for *Astilbe chinensis* var. *tacquettii* 'Purpurlanze' and *Dryopteris filix-mas* in the rain gardens after three years was 79 % and 73 %, respectively, while in the reference field, it was 1 % and 0 % (Table 4). All plants of both species were dead along the roadway after one winter. At the bottom, all surviving plants were located closest to the walkway. *Astilbe chinensis* grows naturally in forests, forest margins, meadows, valleys, and riversides in China, Japan, Korea, and Russia (Flora of China, undated) and cultivars of *Astilbe* are recommended for rain gardens (Dunnett and Clayden, 2007; Schmidt et al., 2007; Clasen, 2012), especially at the sides. *Astilbe* 'Purpur Lanze' performed well in the margin and slope but not in the bottom in rain gardens in Sheffield (Yuan and Dunnett, 2018). *Dryopteris filix-mas* is a native species in Norway and northern Europe found on rocky soils in woodlands (Mossberg and Stenberg, 2012) and is also recommended for rain gardens (Malaviya et al., 2019). Both species prefer moist soils and shade or semi-shade (Hansen and Stahl, 1993). The high mortality indicates that *A. chinensis* var. *tacquettii* 'Purpurlanze' and *D. filix-mas* do not tolerate the conditions in cold climate roadside rain gardens, most likely due to salt exposure along the roadside and in the bottom and drought along the walkway.

The mortality rate of *Polygonatum multiflorum* in the rain gardens after three years was 33 % along the walkway, 35 % on the bottom, and 74 % along the roadway, while all individuals in the reference fields had survived (Table 4). The plants in the rain gardens were strongly affected by necrosis after the first winter, and the effect grew stronger with proximity to the roadway, where the entire plants appeared to be withered and barely alive. The necrosis increased during the growing season, indicating that the plants were affected by de-icing salt accumulated in the soil. After three years, the overall vitality was 3.8 along the walkway, 2.1 in the bottom, 1.1 along the roadway, and 7.5 in the reference fields, and coverage and height followed the same pattern (Table 5). *Polygonatum multiflorum* is native to Europe and temperate Asia and prefers moist or moderately damp soil in the bright shade (Hansen and Stahl, 1993). The species is recommended for rain gardens (Steiner and Domm, 2012) and performed well on the slope at Campus Ås rain garden (Vike and Clewing, 2020). However, this species appears extremely vulnerable to salt exposure and should be avoided in rain gardens along streets and roads in cold climates.

Amsonia orientalis, Chelone obliqua, and *Eurybia divaricata* showed increasing and unacceptable mortality in all rain garden positions after three years, while none or few individuals died in the reference fields (Table 4). *Chelone obliqua* is found on riverside floodplains or small depressions subjected to annual flooding in North America (Penskar and Crispin, 2010) and is recommended for all rain garden positions (Schmidt et al., 2007). *Amsonia orientalis* grows naturally in humid places, often near the seacoast, in a small area in Turkey (The UICN Red List of Threatened Species, 2017). The species is not known for use in rain gardens but was part of a container study (Laukli et al., 2022) where half of the individuals exposed to simulated cyclic flooding died after overwintering and was considered unsuitable for rain gardens. The results from the Bjørnstjerne Bjørnsons Street confirm this supposition. Laukli et al. (2022) also evaluated *E. divaricata* with simulated cyclic flooding and on a real scale in Bjørnstjerne Bjørnsons Street for two growing seasons and concluded that the species should not be planted near the roadway but could be useful in normal rain gardens or farther away from the road and further investigations were needed. After three years in Bjørnstjerne Bjørnsons Street, the mortality of *E. divaricata* in the rain gardens increased (Table 4), and this species is not suitable in roadside cold climate rain gardens. Whether *E. divaricata* is useful in normal rain gardens needs to be investigated.

Aster incisus 'Madiva' was different than any other species in the study. The mortality rate was very high along the roadway after the first year (75 %), but in the following years, no individuals died (Table 4). Along the walkway and at the bottom, the mortality increased over time, and after three years, it was 76 % and 39 %, respectively, while no individuals died in the reference fields. The overall vitality of the surviving plants was extremely high and was significantly improved along the roadway (9.0), followed by the reference field (8.0), while no difference appeared between the bottom and walkway (7.0) (Table 5). No significant differences were observed in the different growing environments after three years for coverage and height. *Aster incisus* originates from Siberia, Japan and North China and is adapted to the woodland edge (Hansen and Stahl, 1993) but is not known as a rain garden plant. The mortality of this species during the first year could be attributed to weather-related factors, as 2018 was drier than normal, and even with irrigation, the plants may have succumbed to the dry conditions. However, we speculate that an insufficient well-developed root mass may have caused the high first-year mortality rate, as Jernigan and Wright (2011) found that plants that had developed a more robust root system prior to flooding treatments had greater tolerance. Owing to the high mortality rate observed in Bjørnstjerne Bjørnsons Street, the species cannot be recommended in cold-climate rain gardens. However, we suspect that survival during the first winter may have been higher, had planting been conducted in the springtime, which would have given more time for plants to develop sufficiently robust root systems by autumn when most flooding events occur. However, further studies are needed in this regard. Moreover, if planted in a natural system where the initial mortality is acceptable, *A. incisus* 'Madiva' could be promising because of the outstanding development of the surviving plants.

4. Conclusion

Healthy plants are vital for maintaining the functionality and aesthetics of rain gardens, and proper species choice is therefore crucial. In this study thirty-one herbaceous perennial species and cultivars were tested in real-scale rain gardens which received supplemental irrigation in a street in Norway, and the results showed large differences in tolerance to the growing conditions in roadside cold climate rain gardens, especially closest to the road, where the exposure to salt, pollution, and water splashes is the largest. De-icing salt appeared to be the most important factor influencing plant survival and development. Plants like *Iris pseudacorus* that grow naturally on coastal beaches showed high tolerance to de-icing salt, while some, but not all, inland plants like *Astilbe chinensis* and *Dryopteris filix-mas* failed. Evergreens, like *Luzula sylvatica*, were vulnerable to the deposition of salt spray on foliage, which caused serious damage and death.

Some species, such as *Amsonia tabernaemontana*, *Baptisia australis,* and *Iris pseudacorus* that are recommended in the rain garden literature, had a high survival rate and developed well in the entire rain garden profile. While others, like *Polygonatum multiflorum, Helenium* 'Pumilum Magnificum' and *Veronicastrum viginicum,* died or performed poorly in every position. Still others, like *Calamagrosis brachytricha*, only survived and showed satisfactory development at increasing distances from the road. The results show that species considered to be suitable to rain garden environments may not survive or perform well when planted along the roadside in cold climates and further studies in relevant settings are required.

There were also considerable differences between cultivars of the same species. While no *Hosta* 'Sum & Substance' individuals died during the study, *H.* 'Francee' and *H.* 'Striptease' mortality was high along the roadway after three years. All the cultivars of *Hemerocallis* had a high survival rate, but the overall vitality closest to the road differed due to increasing necrosis in *H.* 'Sovereign' and *H.* 'Camden Gold Dollar', while *H. lilioasphodelus* showed no such signs. *Liatris spicata* 'Floristan Weiss' had a low mortality rate in every rain garden position, while the cultivar *L. spicata* 'Alba' showed acceptability at the bottom. Further investigation is needed to identify the cultivars with the greatest adaption to this environment. The cultivars of *Lythrum salicaria* and *Molina caerulea* were not optimal, but because of their natural habitat, these species most likely include populations suitable for roadside rain gardens in cold climates.

The main outcome of this study is a suggestion of species distribution in different rain garden zones along streets and roads in cold climates. However, further research is required to ascertain the recommendations. The suitability of the plants selected in this study for inclusion in roadside raingardens cannot be fully assessed until the responses of these plants have been evaluated when irrigation is withheld. Furthermore, studies of the same species in rain gardens in other areas with different winter climatic conditions would be useful, as would the effects of planting time. Planting in springtime may potentially increase the rate of plants survival in the first year, as this would permit sufficient time for plants to develop a sufficiently robust root system prior to the occurrence of autumn flooding and winter frosts. However, given that flooding can also occur during the summer season, the optimal time for establishing plants in rain gardens may depend on the climatic conditions in the year of establishment. Furthermore, avoiding planting in the zone closest to the road in this environment should be considered, and use of other materials may be a better choice.

The study showed considerable effects of de-icing salt on the chemical properties of the compost layer and rain garden topsoil after the first winter. Further investigation into the progressive development of the plants and how the de-icing salt affects the chemical properties of the growing medium for the plants is required.

CRediT authorship contribution statement

Kirstine Laukli: Conceptualization, Investigation, Formal analysis, Validation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Hilde Vinje:** Statistical analysis. **Trond Haraldsen:** Writing – original draft, Writing – review & editing, Formal analysis, Supervision. **Eva Vike:** Methodology, Formal analysis, Supervision.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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