



## Original article

# Soil and plant selection for rain gardens along streets and roads in cold climates: Simulated cyclic flooding and real-scale studies of five herbaceous perennial species



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## ABSTRACT

This paper presents results from a container experiment and a real-scale study in road environments for evaluating the performance of soil mixtures and herbaceous perennials for use in rain gardens. The container experiment included 12 soil mixtures and 4 perennial species. The plants were exposed to three flooding events and one drought period, and their overall vitality was recorded after the floodings. The containers were stored outdoors the following winter and plant survival was observed in spring. *Amsonia orientalis* did not survive the winter after being exposed to flooding in the growing season and was replaced by *Hosta* 'Francee' in the real-scale study, which was established in Drammen (Norway) in a soil mixture based on optimisation of the best mixtures in the container experiment. *Luzula sylvatica* performed well in the container study and survived the winter; however, in the field study, individuals of this species that were located close to the road died due to de-icing salt. *Eurybia divaricata* showed some mortality in both studies, and total mortality occurred in individuals that were close to the road, due to de-icing salt. *Hemerocallis* cv. performed well in both experiments and appeared to be useful in all rain garden positions in the cold climate road environment. *H.* 'Francee' developed well in the road environment, except when exposed to splashes of road water. The study highlights considerable differences between species' adaption to roadside rain gardens in cold climates, and the need for further field investigations.

## 1. Introduction

Climate change has led to more intense rain than in previous years (NOU, 2010:10). Densification has also occurred in cities, and an increasing area of impervious surfaces has replaced green areas that can naturally infiltrate water. Consequently, the volume of surface water has increased to a level that traditional stormwater systems do not have sufficient capacity to treat. This results in flooding, which entails high costs for society (NOU, 2010:10; NOU, 2015:16; Lindholm et al., 2008).

Green infrastructure, such as rain gardens, can reduce the volume of rainwater runoff and flow. Rain gardens are shallow, vegetated depressions in land that receive and infiltrate stormwater and thus relieve the stormwater network (Paus and Braskerud, 2013; Sharma and Malaviya, 2021).

Urban stormwater also contains pollution, especially from roads, and

the pollution load is expected to increase due to a growing population (Malaviya and Singh, 2012; Malaviya et al., 2019). Rain gardens effectively reduce stormwater pollution and thereby protect natural ecosystems. There are many mechanisms involved in the pollutant removal processes in rain gardens, where both soil media and plants play a vital role (Sharma and Malaviya, 2021; Sharma et al., 2021; Wadzuk et al., 2021). There is an increasing focus on the function of rain gardens in cold climates. However, studies of rain gardens in cold climates have so far mainly focused on hydrological function and the ability of rain gardens to bind toxic metals and remove plant nutrients (Muthanna et al., 2007, 2008; Paus et al., 2014a, b; Paus et al., 2016; Kristvik et al., 2018; Venvik and Boogard, 2020; Kratky et al., 2021; Li et al., 2021).

Plants also remove surplus water by evaporation in the growing season, and their roots create pathways that are important for infiltration (Malaviya et al., 2019). Thus, they are crucial if a rain garden is to

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function over time. Without roots working through the soil, a surface crust will eventually form, which will reduce the infiltration capacity (Gonzales-Merchan et al., 2014; Yuan et al., 2017).

The problem is that the growing conditions in cold climate rain gardens in road environments are extremely difficult. Rain garden plants must tolerate growing conditions that vary from drought to periodic inundation (Dunnnett and Clayden, 2007). In cold climates they are also exposed to freeze-thaw cycles and ice covers, which are also occurring 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 the effects of splashes, salt, and other pollution (Shaw and Schmidt, 2003; Norwegian Public Roads Administration, 2008). The correct choice of plant species is, therefore, crucial.

Several lists of suitable plants for rain gardens have been published (Dunnnett and Clayden, 2007; Schmidt et al., 2007; Steiner and Domm, 2012; Malaviya et al., 2019), and some research has also been conducted on plant selection for rain gardens. Yuan and Dunnnett (2018) studied the response of 15 perennial species treated with simulated cyclic flooding in Sheffield, and 9 perennial species were tested in different rain garden zones in north-eastern Italy (Bortolini and Zanin, 2019). This knowledge can be used to some extent in Norway and other countries with similar climate; however, it is not necessarily always relevant because of lower temperatures, more humid conditions, and winter conditions with snow and frozen soil (Haraldsen et al., 2019). This means that all the same plant species may not be successful in a Nordic climate, but also that the soil must have slightly different properties to function well throughout the entire year. In addition, salt is used for de-icing along Norwegian roads in winter, which also has an impact on which plant species can be used.

Vike and Søyland (2011) examined perennials along Norwegian roads in both field and controlled studies and tested their salt tolerance. Their study identified species that are suitable for planting along roads in cold climates; however, whether these species also will thrive in rain gardens along roads remains uncertain.

Kratky et al. (2017) summarised the status of research on cold-climate rain gardens and provided future research recommendations. This article concludes that much research has been done on bio-retention (rain gardens) in hot climates, but that data for cold climates are lacking, especially studies that determine drought, water, and contaminant-tolerant vegetation. Kratky et al. (2017) also highlight several other research gaps, including the need for further research on soil (media) and the long-term effects of contaminants and salt.

As argued above, more research is needed into what kinds of soils and plants will function in rain gardens in cold-climate streets. The aim of this paper was to contribute to identifying:

- 1 Which soil mixtures are suitable both for handling surface water and as a growth medium for perennials? That is, soil mixtures with high permeability, satisfactory water storage capacity, and necessary plant nutrients.
- 2 Which plant species withstand the special growing conditions in rain gardens along streets and roads in cold climates?

To answer these questions, two studies were conducted. The first study was conducted as a container study with 12 soil mixtures and 4 herbaceous perennial species. The second was a real-scale field study to examine how these species responded to combined stresses in rain gardens along streets and roads in a cold climate. In this study, a modified soil mixture based on results from the container study was used, and one more species was added.

## 2. Materials and methods

### 2.1. Container study

#### 2.1.1. Location and time

The container study was conducted at NMBU in Ås (59°39'49"N; 10°45'49"E), situated in Norwegian climate zone 3 (Det norske hageselskap, undated). The temperature and precipitation during the study in 2017 are shown in Table 1 together with normal values (1991–2020).

The container study was established in June 2017, and the recordings, as described in 2.1.4, were performed during the summer and autumn of 2017. After wintering, plant survival was observed.

#### 2.1.2. Soil and plant material

Twelve different soil mixtures were used, which were based on sandy materials and different types of composts (ordinary garden waste compost, acidified garden waste compost, horse manure compost, vermicomposted solid digestate of food waste, and bark compost), and sphagnum peat from two soil producers in Norway, Lindum AS (L1–L6) and Skaaret landskap AS (S1–S6). The texture of the sandy mixtures ranged from medium sand to loamy medium sand (dominant fraction 0.2–0.6 mm) (Table 2). The pH of the soil mixtures L1–6 were approximately one unit higher than that of the soil mixtures S1–S6, which appeared to be correlated with the amount of readily available calcium (Ca-AL) (Table 3). The mineral N content in the soil mixtures was calculated based on the concentrations of ammonium N and nitrate N in the composts and the rate of compost used in the soil mixtures. The calculations were based on a topsoil with a depth of 20 cm and showed that almost all mixtures had a low mineral N content at the start of the experiment (3–10 kg mineral N ha<sup>-1</sup>). The L6 mixture, which contained vermicomposted solid digestate of food waste, contained 268 kg mineral N ha<sup>-1</sup> (data not shown). The L6 mixture also contained much higher amounts of readily available P than the other soil mixtures (Table 3), where concentrations < 5 mg 100 g<sup>-1</sup> are classified as low (Krogstad et al., 2008). The amount of readily available K was uniform and low in 10 of the 12 mixtures, whereas the S2 and S6 mixtures had moderately high levels of readily available K (K-AL) due to the addition of horse manure compost (Table 3).

Soil cores (100 cm<sup>3</sup>) were taken in triplicate from each of the soil mixtures for soil moisture retention measurements. The soil was compacted under slightly moist conditions before sampling to avoid volume changes in the cores after saturation with water. Total porosity was set equal to the saturated samples. Water retention was measured at -10, -50, -100, -1000, and -15,000 hPa water potential using a sandbox (Eijkelkamp, 2019) and ceramic plates (Richards, 1947, 1948).

The candidate species were three forbs and one woodrush that were predicted to be capable of withstanding both wet and dry periods (Hansen and Stahl, 1993); *Amsonia orientalis* Decne., *Eurybia divaricata* (L.) G.L.Nesom, *Hemerocallis* L. 'Golden Chimes', and *Luzula sylvatica* (Huds.) Gaudin.

**Table 1**

Monthly mean temperature (°C) and precipitation (mm) for Ås during the container study (Grinde et al., 2018) and monthly normal values 1991–2020 for Ås (The Norwegian Meteorological Institute, undated).

Month	Mean temperature (°C) 2017	Precipitation (mm) 2017	Normal monthly temperature (°C)	Normal monthly precipitation (mm)
June	14.5	94.9	14.5	76.9
July	16.7	40.9	16.8	82.1
August	14.6	133.3	15.7	96.3
September	11.6	121.5	11.5	89.8
October	6.7	138.8	6.1	104.5
Mean/total	6.4	973.5	6.3	891.9

**Table 2**  
Particle size distribution of the soil mixtures used in the container study.

Soil mixture	% of material < 2 mm						
	Sand			Silt			Clay
	2–0.6 mm	0.6–0.2 mm	0.2–0.06 mm	0.06–0.02 mm	0.02–0.006mm	0.006–0.002 mm	< 0.002 mm
S1	25	37	28	5	2	1	2
S2	18	38	27	12	2	1	2
S3	20	44	22	10	2	1	2
S4	20	47	19	9	1	2	3
S5	14	28	35	17	3	1	3
S6	15	34	36	9	3	1	3
L1	21	49	24	4	0	1	0
L2	15	47	25	11	1	1	0
L3	12	46	33	7	1	1	1
L4	23	47	21	5	1	1	1
L5	14	47	30	5	1	1	1
L6	17	42	27	10	2	1	1

**Table 3**  
pH, loss on ignition, and readily available major plant nutrients in the soil mixtures according to Egnér et al. (1960).

Soil mixture	pH (H <sub>2</sub> O)	Phosphorus (P-AL) (mg 100 g <sup>-1</sup> )	Potassium (K-AL) (mg 100 g <sup>-1</sup> )	Magnesium (Mg-AL) (mg 100 g <sup>-1</sup> )	Calcium (Ca-AL) (mg 100 g <sup>-1</sup> )	Loss on ign. % DM
S1	6.5	2.3	7.9	4.8	49	2.2
S2	6.7	2.7	12.0	4.5	40	2.0
S3	6.5	2.1	6.3	4.2	46	1.8
S4	6.2	<2.0	7.1	5.2	55	2.8
S5	6.4	2.4	7.5	4.7	46	2.3
S6	6.4	3.2	14.0	5.7	54	2.4
L1	7.6	4.4	7.4	5.2	89	1.5
L2	7.7	4.2	7.8	5.8	110	1.4
L3	7.7	4.5	7.3	6.3	130	1.6
L4	8.6	4.7	7.5	16.0	1100	1.3
L5	7.9	4.0	7.4	14.0	860	1.4
L6	8.3	10.0	7.2	10.0	350	2.0
BB	7.7	10.0	17.0	9.0	125	2.7
Reference	7.4	6.0	4.5	10.0	295	2.7
Compost	7.7	63.0	186.7	87.3	493	35.2

The plants were supplied in 0.56-L containers for all species except *H. 'Golden Chimes'*, which were supplied in 0.78-L containers. *H. 'Golden Chimes'* plants were more developed than the other species.

### 2.1.3. Experimental design

*A. orientalis*, *E. divaricata*, and *L. sylvatica* were planted in 3.5-L plastic containers and *H. 'Golden Chimes'* in 5-L plastic containers on June 26, 2017. For each soil mixture, there were four replicates for each species, with a total of 48 containers for each plant species (4 replicates x 12 soil mixtures). To study the effect of overwintering, limited controls (soil mixtures S5 and S6) with four replicates of each soil for each species were established and treated with normal irrigation throughout the entire study.

The plants were placed outdoors under a transparent roof with open sides. During the 5-week establishment period, the plants were grouped by species. The plants within the species were randomised. During the first month, the plants were treated with normal irrigation with optimal moisture of 0.30 m<sup>3</sup> m<sup>-3</sup>.

To recreate rain garden conditions, the plants were subjected to repeated flood simulations of varying degrees as well as periods of drought. The first flood simulation was commenced on 1 August 2017. The containers received water equivalent to 50 mm of rain, i.e., 1.1 L for the smallest and 1.6 L for the largest container. The excess water that drained from the soil filled most of the bowls to the top (approximately 4 cm). The plants were in the water for 2 days before the dishes were emptied.

After the first flood simulation, the plants were exposed to drought stress. When the moisture level had dropped to 0.05–0.10 m<sup>3</sup> m<sup>-3</sup> in most containers, normal irrigation regimes were resumed and used until

the next flood simulation. This started on 29 August 2017 and was intended to correspond to an extreme flood event. The containers were placed in buckets filled with 1.0–1.5 L of water. As the water soaked up into the soil, it was replenished with more water until the water level reached up to the soil surface. After 1 day, the containers were moved from the buckets and to the bowls where they were stored in drained water for an additional day. Then, the dishes were emptied.

Due to low evapotranspiration because of low temperatures and high humidity in late summer and autumn, it was not possible to simulate a second drought period. However, a new extreme flood simulation was undertaken after 3.5 weeks with the same method as in the second flood simulation. To avoid loss of growth medium, the containers were placed in a second plastic container with geotextile in between them (Fibertex PPR 433, 150 g m<sup>-2</sup>).

After the first flood simulation and drought stress, it was decided that plants would be irrigated only when the moisture was between 0.20 and 0.25 m<sup>3</sup> m<sup>-3</sup>, because the plants did not dry the soil sufficiently between irrigations.

The container study was completed on 11 October 2017, and the above-ground plant parts were harvested from each plant except from two of the *L. sylvatica* replicates that were intended to overwinter outdoors. All harvested material was dried in a drying cabinet at 85 °C for 2.5 days and then weighed. After harvest, two replicates of each species and soil mixtures were placed outdoors to overwinter at the nursery at NMBU Ås.

### 2.1.4. Recordings and measurements

**Overall vitality** was assessed after the establishment period (T1) and after the second (T2) and third (T3) flood simulations. A scale from

0 to 9 was used whereby 0 was a dead plant, 1 - barely alive, 2 - very poor, 3 - poor, little potential for improvement, 4 - poor, with potential for improvement, 5 - acceptable plant, 6 - fairly good, 7 - good, 8 - very good, and 9 - especially good, lush, and well-developed plant.

**Dry weight** (g) of the aboveground parts of each plant was measured at the end of the experiment.

**Winter survival** was determined in the spring after the flooding and drought treatments.

## 2.2. Real-scale field study

### 2.2.1. Location and time

The real-scale field study was conducted along Bjørnstjerne Bjørnsons Street, a rebuilt street in Drammen (centre of project: 59°44'11"N; 10°12'12"). Drammen is situated in Norwegian climate zone 3 ([Det norske hageselskap, undated](#)), and monthly temperature and precipitation during the study (2018–2020) are shown in [Table 4](#) together with normal values (1991–2020).

Bjørnstjerne Bjørnsons Street has four lanes, is regulated with traffic lights, and has a speed limit of 50 km/h. The annual mean daily traffic is approximately 21,000 vehicles, of which 9 % are heavy vehicles ([Norwegian Public Roads Administration, undated](#)). Winter maintenance includes heavy salting.

The field study was established in August 2018, and the recordings, as described in [2.2.4](#), were conducted in August 2019 and August 2020.

### 2.2.2. Soil and plant material

Based on the results from the container study, a modified soil mixture of the L2 mixture was used as topsoil in the rain garden. In this soil mixture (BB in [Table 3](#)), the amount of garden/park compost was increased from 0.2 to 0.3 m<sup>3</sup> m<sup>-3</sup>, and 4 L m<sup>-3</sup> chicken manure (Øko 8 K (8-3-5) from Grønn Gjødelse AS) was mixed in. This resulted in a higher amount of readily available P and K compared to the original L2 mixture ([Table 3](#)). In addition, a 5–10 cm mulch layer with garden/park compost was placed on top of the soil mixture ([Fig. 1](#)). The compost layer represented high levels of readily available plant nutrients ([Table 3](#)) and low heavy metal concentrations (Cd 0.7 mg kg<sup>-1</sup> DM, Cu 25 mg kg<sup>-1</sup> DM, Cr 21 mg kg<sup>-1</sup> DM, Ni 8 mg kg<sup>-1</sup> DM, and Zn 137 mg kg<sup>-1</sup> DM), determined according to EN 13650 ([CEN, 2001](#)). The compost had a low C/N ratio (10–16) and nitrate-N (2.5–10 mg kg<sup>-1</sup> DM), determined according to EN ISO 10304 ([CEN, 2007](#)). A sand with the same texture as the L2 mixture was used as subsoil ([Fig. 1](#)). In the reference field, a soil with medium sand texture was used with similar pH and organic matter content, but lower content of readily available P and K, as for the rain garden soil (BB) ([Table 3](#)).

The same candidate species as in the container study were used; however, because many flooding-exposed *Amsonia orientalis* died during winter in the container study, this species was replaced with *Hosta* Tratt.

**Table 4**

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

MONTH	2018		2019		2020		NORMAL	
	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	3.4	55.3
FEB.			-0.6	76.9	2	40.5	-2.6	44.8
MAR.			1.8	93.5	3.2	40.5	1	43.7
APR.			7.4	34.3	7.2	25.7	6.2	44.9
MAY			10.5	109.1	10.4	34.2	11.5	64.9
JUN.			15.7	81.8	18.5	75.8	15.5	78.2
JUL.			18.2	50.3	15.5	125.5	17.8	78.3
AUG.	1.6	42.9	17.0	119.6	17.3	38.6	16.3	96.3
SEP.	12.9	98.6	11.6	90.6			12.0	78.1
OCT.	7.4	31.1	5.3	137.5			6.3	88.0
NOV.	3.0	106.9	0.2	142.7			1.3	73.3
DEC.	-2.2	75.2	-0.9	58.1			-2.7	63.9
MEAN /TOTAL PR. YEAR	6.9	595	6.9	1036	8.5	961	6.6	811

'Francee'. Also, another cultivar of *Hemerocallis*, 'Camden Gold Dollar', was used. All plants were supplied in 1-L plastic containers.

### 2.2.3. Experimental design

Because the field study was adapted to an actual street, there were some limitations compared to the design of a purely experimental field.

Nine rain gardens were built along a stretch of 700 m, of which three were established as research fields and were included in this study. The rain gardens were located between the roadway and the walkway and were designed as shown in [Fig. 2](#). Each rain garden was 30–34 m long in total and was divided by trees with approximately 9-m spacing. Each tree was placed in a 4-m-long tree planter, and the perennials used as a ground cover in the tree planters were not included in the study. Between each tree planter, a research field with a length of approximately 5 m was built up, as shown in [Fig. 1](#).

Between the rain gardens and the roadway, drains were installed to direct surface water from the road into the rain gardens in the growing season (see [Fig. 2](#)). In winter, the road water was directed away from the rain gardens to avoid de-icing salt entering. Along the walkway, water could flow freely to the rain gardens along the entire profile.

Each rain garden consisted of four parts (fields) that in turn were divided into eight squares (see [Fig. 3](#)). The size of the squares was approximately 1.2m × 1.2m, and each of the four candidate species was planted in one square along the road and one along the walkway in each field. With 3 rain gardens consisting of 4 fields, each with 8 squares, there were a total of 12 squares of each species along the roadway and 12 along the walkway. The number of individuals in each square varied with the planting distance of the different species as well as local variations. On average, 10 *Eurybia divaricata*, 7 *Hemerocallis* 'Camden Gold Dollar', 7 *Hosta* 'Francee', or 12 *Luzula sylvatica* were planted in each square.

The candidate species were also planted in a reference field nearby with a construction soil of medium sand texture and without the impact of surface water, splashes, salt, and road contaminants. The reference field was established at the same time as the experimental fields/rain gardens, and a 50–100 mm-thick top layer of garden compost of the same type as in the rain gardens was used.

A total of 1154 individual plants were used in the experiment. In the rain gardens 243 *E. divaricata*, 167 *Hemerocallis* 'Camden Gold Dollar', 155 *H. 'Francee'*, and 295 *L. sylvatica* were planted, and in the reference field 125 *E. divaricata*, 10 *H. 'Camden Gold Dollar'*, 100 *H. 'Francee'*, and 59 *L. sylvatica* were planted.

All planting was done in August 2018. To ensure water supply during the establishment period, a drip irrigation system with 0.5-m spacing, a humidity meter, and an automatic controller (type RainBird T-Bos-II) were mounted.

Based on soil analyses and the nutrient content of the garden compost, it was determined that fertilisation was not necessary in

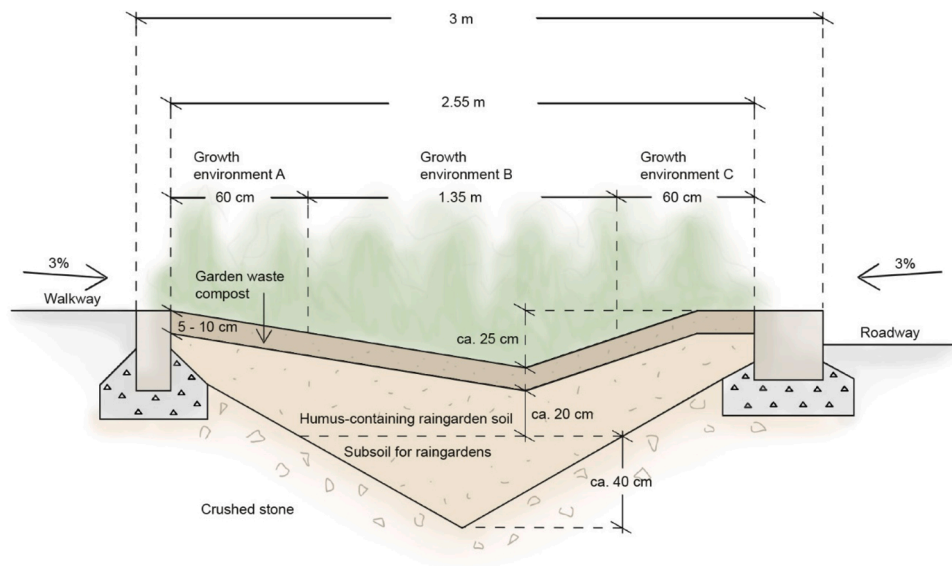


Fig. 1. Structure of the rain gardens in Bjørnstjerne Bjørnsons Street, Drammen.

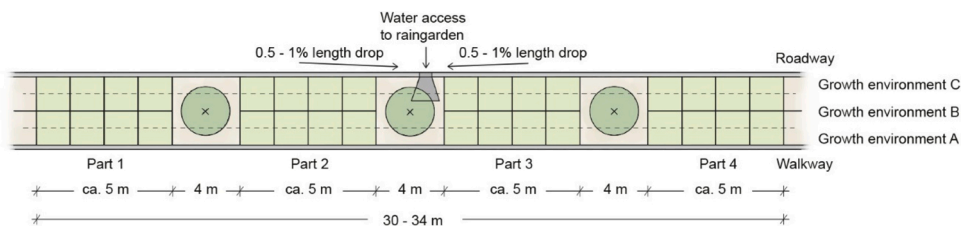


Fig. 2. Three similar rain gardens, each containing four parts, were used in the study. Fig. 3 provides details of the four parts.

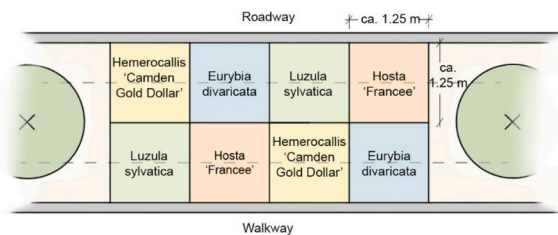


Fig. 3. Each rain garden included four parts which were divided into eight squares and planted with the four candidate species.

neither 2019 nor 2020.

### 2.2.4. Recordings and measurements

Upon recording, each of the squares shown in Fig. 3 was divided into growth environments (Fig. 1). A growth environment was defined according to where the plants were growing; i.e., the edge by the walkway (growth environment A), the bottom (growth environment B), or the edge along the roadway (growth environment C). The edge was defined as the area from the inner side of the curb to 60 cm into the rain garden. For most species this was one row, but there were two rows for some species with a small planting distance. Because all squares included growth environment B (bottom), there were twice as many observations for mortality in growth environment B as in the other environments. For all species, there were thus 12 observations towards each edge and 24 at the bottom. For *Hosta*, one square was not planted; therefore, the number of observations for this species was 11 by the roadway and 23 at the bottom.

When recording overall vitality, coverage, height, and leaf damage,

five random representative individuals of the surviving plants were selected in each growth environment in each of the squares and evaluated separately. In the reference fields, four random squares with five representative individuals were selected and rated in the same way as the plants in the rain gardens.

The following recordings and measurements were performed:

**Total number of planted individuals and number of dead individuals** within each species, square, and growth environment.

**Overall vitality** was determined on a scale from 0 to 9 in the same way as in the container study.

**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. *Hemerocallis*, *Hosta*, and *Luzula* were measured as the mean of the three longest shoots in a stretched state, whereas *Eurybia* was measured at the highest point of the tuft when a measuring stick was inserted in the middle, without stretching the leaves.

**Leaf damage** was determined on a scale from 0 to 9, whereby 0 was no damage and 9 was where all leaves were completely damaged/necrotic. Only abiotic damage was recorded.

### 2.3. Statistical analyses

For both the container study and field study, 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.

### 2.3.1. Container study

Response variables (plants) were overall vitality and dry weight. Analyses with two factors (plant species and soil mixture and interactions) were carried out for each time (T1, T2, and T3). Response variable (soil) was volume of pores ( $m^3 m^{-3}$ ). Analyses with two factors (soil mixture and water potentials and interactions) were carried out.

### 2.3.2. Field study

Response variables were mortality (%), overall vitality, coverage, height, and leaf damage. First, five-factor analyses (rain garden, part nested in rain garden, year, plant species and environment) with all possible two-factor interactions were carried out. Finally, for the response variable mortality (%) a two-factor analyses (with factors rain garden and environment and their interaction) was carried out for each year and species separately. For the response variables overall vitality, coverage, height, and leaf damage, a three-factor analyses (with factors rain garden, part nested in rain garden, and environment with two-factor interactions) was carried out separately for each year and species.

## 3. Results and discussion

### 3.1. Container study

#### 3.1.1. Soil properties

Although the variation in texture between the different soil mixtures was relatively small, significant differences in water retention properties were found. In rain gardens, it is extremely important that air-filled pores reappear rapidly after periods of waterlogging to ensure oxygen supply to the roots. At  $-10$  hPa water potential, an air-filled porosity of  $0.09 m^3 m^{-3}$  was measured for soil mixtures L2 and L3, which is close to  $0.1 m^3 m^{-3}$ , i.e., the critical limit for air-filled porosity related to root development suggested by Grable and Siemer (1968). At  $-50$  hPa, all soil mixtures had more than sufficient air-filled porosity for root growth. S5 and S6 soil mixtures had the best water retention properties (Table 5). These two soil mixtures had higher contents of fine sand compared to medium sand combined, and S5 had the highest silt and clay content (Table 3). Although it was not exactly measured, it was observed that all 12 soil mixtures had a higher than sufficient infiltration rate to be used in a rain garden receiving an intensity of precipitation of  $100 mm h^{-1}$  causing waterlogged conditions for  $< 24 h$ .

**Table 5**

Volume of pores ( $m^3 m^{-3}$ ) at different water potentials in the soil mixtures used in the container study.

Soil mixture	N	Saturation	-10	-50 hPa	-100	-1000
		-10 hPa	-50 hPa	-100 hPa	-1000 hPa	-15,000 hPa
		$m^3 m^{-3}$	$m^3 m^{-3}$	$m^3 m^{-3}$	$m^3 m^{-3}$	$m^3 m^{-3}$
S1	3	0.075ab	0.176cd	0.037de	0.053ab	0.096cd
S2	3	0.080ab	0.177cd	0.039de	0.063ab	0.091cde
S3	3	0.054b	0.215a	0.033e	0.052ab	0.069cde
S4	3	0.062ab	0.214a	0.035de	0.056ab	0.100bc
S5	3	0.073ab	0.141e	0.040cde	0.070ab	0.133ab
S6	3	0.076ab	0.155de	0.048abcde	0.075a	0.150a
L1	3	0.072ab	0.220a	0.047bcde	0.043b	0.061cde
L2	3	0.086a	0.205ab	0.057abc	0.041b	0.058de
L3	3	0.093a	0.189bc	0.065a	0.053ab	0.074cde
L4	3	0.075ab	0.186bc	0.034de	0.052ab	0.053e
L5	3	0.070ab	0.171cd	0.051abcd	0.057ab	0.068cde
L6	3	0.075ab	0.160de	0.062ab	0.065ab	0.058de

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

### 3.1.2. Plant response to flooding

After the 5-week establishment period, before the flooding and drought treatments, the mean overall vitality of the different species was 7.2 for *A. orientalis*, 6.3 for *E. divaricata*, 7.1 for *H. 'Golden Chimes'*, and 7.7 for *L. sylvatica*. At this stage of the experiment, there were no significant differences between the plants grown in the different soil mixtures.

Although all species tolerated the flooding and drought treatment well, there was a reduction in the mean overall vitality of plants (Table 6) in all soil mixtures except L6 after two and three flooding events; this was most likely because L6 had a high mineral N content whereas the other mixtures had a deficit. Plants grown in S5 and S6 had significantly lower overall vitality after the second flooding event. After the third flooding event, S5 had the lowest overall vitality; however, at this time the plants also started to be affected by autumn senescence. S5 and S6 were the soil mixtures with the highest fine particle content (Table 2), which most likely caused a reduced oxygen supply to the roots during the experiment.

To some extent, the species reacted differently to the treatment and soil mixtures (Table 6). Mean overall vitality was highest for *L. sylvatica* and lowest for *E. divaricata* after both the second and third flooding simulations. For *A. orientalis* there were no significant differences in overall vitality between plants grown in the different soil mixtures. *E. divaricata* grew significantly better in L soil mixtures compared to this in S soil mixtures. The overall vitality was poorest when grown in S3, S4, S5, and S6 soil mixtures. *H. 'Golden Chimes'* had the best overall vitality in L6. For *L. sylvatica*, there were no significant differences in overall vitality; however, there was a tendency towards improved vitality in S soil mixtures, which was most likely due to the lower pH in these mixtures.

The dry weight of the plants that had grown in soil mixtures L1–L6 was generally higher than that of plants grown in S1–S6. Table 6 shows that there was a tendency towards the highest dry weight of the above-ground plant parts in soil mixture L6 and the lowest dry weight in S3, S4, S5, and S6, calculated as the mean of all species. The difference was significant for *E. divaricata* and *H. 'Golden Chimes'*, whereas *A. orientalis* showed a tendency towards a higher dry weight in L6. There were no clear tendencies for *L. sylvatica*.

There were large differences in survival of different species after overwintering. *L. sylvatica* and *H. 'Golden Chimes'* survival was 100 % and 90 %, respectively, whereas only 35 % of *E. divaricata* survived; however, there were no differences from the control plants. For *A. orientalis*, all control plants survived; however, only 50 % of the flooding and drought-exposed replicates survived and the surviving plants were weak.

### 3.1.3. Directions for further field investigation

The container experiment showed small differences between the different soil mixtures. This was expected because all were constructed to be suitable for use in rain gardens. However, the vitality and growth of the perennials in soil mixtures S5 and S6 was significantly poorer than in the other soil mixtures. Because the growth of the perennials in all mixtures except L6 had N-limited growth combined with a low content of readily available P, more available plant nutrients in the soil mixture for Bjørnstjerne Bjørnsons Street were required. The L2 mixture, which rapidly released air-filled pores after drainage, was found to have suitable physical properties. By increasing the amount of compost that was mixed in and adding a mulch layer of compost on top, it was assumed that both the physical and chemical properties of the soil should be suitable for good growth and performance of the selected perennials.

### 3.2. Real-scale field study

After the first year, 19 % of all plants had died, and after 2 years 31 % were dead. There were large differences between the species ( $p < 0,0001$ ). *H. 'Camden Gold Dollar'* had 3 % mortality after 2 years, and

**Table 6**

Mean overall vitality (OV) (scale 0–9) after the second (T2) and third (T3) flood simulation and the mean aboveground dry weight (DW) (g) at the end of the experiment for four perennial species grown in six soil mixtures from Skaaret Landskap (S) and six soil mixtures from Lindum (L). Values are the means of four replicates, except for the dry weight *L. sylvatica* where N = 2.

SOIL	<i>Amsonia orientalis</i>			<i>Eurybia divaricata</i>			<i>Hemerocallis</i> ‘Camden Gold Dollar’			<i>Luzula sylvatica</i>			MEAN		
	OV	OV	DW	OV	OV	DW	OV	OV	DW	OV	OV	DW	OV	OV	DW
	T2	T3		T2	T3		T2	T3		T2	T3		T2	T3	
S1	7.3a	6.0a	6.8a	5.3b	5.0bc	3.0bc	6.8b	5.3ab	11.9ab	8.0a	7.5a	23.8a	6.8ab	5.9ab	9.6a
S2	7.0a	6.0a	5.1a	6.0ab	5.0bc	3.0bc	6.3b	5.5ab	12.5ab	8.0a	7.8a	26.6a	6.8ab	6.1ab	9.7a
S3	7.3a	6.5a	6.8a	5.5ab	4.8c	2.2c	5.8b	4.5b	9.1b	8.3a	8.0a	20.7a	6.7ab	5.9ab	8.1a
S4	7.3a	6.3a	6.5a	5.3b	4.3c	2.2c	6.3b	5.3ab	9.9b	7.8a	8.3a	24.0a	6.6ab	6.0ab	8.8a
S5	6.8a	6.0a	4.5a	5.3b	5.0bc	2.9bc	6.3b	4.3b	11.3ab	7.0a	6.8a	17.1a	6.3b	5.5b	7.8a
S6	7.0a	6.3a	5.1a	5.3b	4.8c	2.8bc	6.5b	5.5ab	10.6ab	7.0a	7.0a	20.3a	6.4b	5.9ab	8.2a
L1	7.8a	7.0a	5.0a	7.3ab	7.5a	5.9ab	6.5b	4.8b	10.9ab	7.0a	6.8a	25.8a	7.1ab	6.5ab	9.9a
L2	7.3a	6.3a	5.3a	7.0ab	7.0ab	4.9abc	6.5b	5.8ab	11.8ab	7.3a	7.5a	19.5a	7.0ab	6.6ab	9.1a
L3	7.5a	6.5a	6.2a	7.3ab	7.3a	5.1abc	6.5b	4.8b	11.6ab	7.8a	7.8a	19.2a	7.3ab	6.6ab	9.3a
L4	7.8a	6.8a	6.3a	6.8ab	7.0ab	3.7abc	6.5b	5.3ab	11.9ab	7.0a	7.0a	26.9a	7.0ab	6.5ab	10.1a
L5	6.8a	6.0a	4.9a	6.8ab	7.0ab	4.9abc	6.8b	5.8ab	12.4ab	7.3a	7.5a	23.1a	6.9ab	6.6ab	9.7a
L6	7.8a	7.0a	7.9a	7.5a	7.8a	6.8a	8.5a	7.3a	16.0a	7.3a	7.0a	23.3a	7.8a	7.3a	12.1a
MEAN	7.3	6.4	5.9	6.3	6.0	4.0	6.6	5.4	11.7	7.5	7.4	22.5	6.9	6.3	9.4

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

mortality was 19 % for *H. ‘Francee’*, 55 % for *E. divaricata*, and 45 % for *L. sylvatica*.

In addition to the species, the growth environment ( $p < 0.0001$ ) and year ( $p < 0.0001$ ) were the most important factors influencing plant survival and development. Mortality for all plants (regardless of the species) was 64 % after 2 years along the roadway, 25 % at the bottom, 11 % along the walkway, and 8 % in the reference fields. The overall vitality of surviving plants was significantly improved along the walkway, followed by the reference fields and the bottom. Along the road, the overall vitality was significantly lower than in every other environment, which was most likely due to the impacts of salt, pollution,

and splashes. Coverage and height showed the same tendency, and plants were larger and had greater coverage farther away from the road. There was also more leaf damage near the road, most likely due to salt. Table 7 shows the relationship between the species and environment in the two survey years.

De-icing salt may cause serious damage to plants through uptake from soil and/or deposition on leaves from salt spray (Fostad and Pedersen, 2000; Norwegian Public Roads Administration, 2008; Munck et al., 2010) and may affect plants by disrupting nutrient and water uptake and eventually increase the Na and Cl contents to toxic levels in susceptible plants (Fay and Shi, 2012; Kratky et al., 2017). On 28 March

**Table 7**

Mean overall vitality, coverage, height, and leaf damage for four perennial species grown in different distances from the road (growth environments) in rain gardens along Bjørnstjerne Bjørnsons Street the first and second year after planting. N = Number of observations.

SPECIES	ENVIRONMENT	YEAR	N	OVERALL VITALITY (Scale 0–9)	COVERAGE (Scale 0–5)	HEIGHT (cm)	LEAF DAMAGE (Scale 0–9)
<i>Eurybia divaricata</i>	Walkway (A)	1	45	6.0a	2.9ab	38a	1.1b
	Bottom (B)	1	93	5.7a	2.4b	38a	1.0b
	Roadway (C)	1	15	2.9b	0.9c	17b	2.6a
	Reference field	1	20	6.1a	3.2a	42a	0.9b
	Walkway (A)	2	37	6.6a	4.4a	52b	1.1a
	Bottom (B)	2	60	6.8a	4.3a	55b	1.1a
	Roadway (C)	2	0	–	–	–	–
	Reference field	2	20	6.7a	4.4a	69a	1.4a
	Walkway (A)	1	28	6.4a	1.3ab	46c	1.2ab
	Bottom (B)	1	110	6.4a	1.3ab	51b	0.8bc
<i>Hemerocallis</i> ‘Camden Gold Dollar’	Roadway (C)	1	25	5.5b	1.0b	44c	1.5a
	Reference field	1	10	6.9a	1.4a	58a	0.4c
	Walkway (A)	2	28	7.3a	3.6a	73b	0.5bc
	Bottom (B)	2	107	6.6b	3.2a	75b	0.9b
	Roadway (C)	2	23	4.6c	2.1b	57c	1.6a
	Reference field	2	10	7.7a	3.5a	84a	0.3c
	Walkway (A)	1	27	6.1b	2.7b	33b	1.4b
	Bottom (B)	1	101	6.1b	2.7b	33b	1.3b
	Roadway (C)	1	22	4.9c	2.1c	23c	1.9a
	Reference field	1	20	6.9a	3.8a	41a	0.9c
<i>Hosta</i> ‘Francee’	Walkway (A)	2	27	6.7a	4.5a	45ab	1.0b
	Bottom (B)	2	94	6.0b	4.4a	43b	0.9b
	Roadway (C)	2	11	4.1c	3.1c	22c	0.7b
	Reference field	2	20	5.5b	3.7b	49a	2.7a
	Walkway (A)	1	50	6.5b	3.5b	36b	1.3ab
	Bottom (B)	1	79	5.8b	2.8b	37b	1.1b
	Roadway (C)	1	7	2.4c	0.6c	21c	1.0b
	Reference field	1	20	7.9a	4.8a	55a	1.8a
	Walkway (A)	2	50	7.7a	4.7a	41b	0.7b
	Bottom (B)	2	76	6.0b	4.1b	36c	1.4a
<i>Luzula sylvatica</i>	Roadway (C)	2	5	3.2c	3.0c	27d	1.2ab
	Reference field	2	20	7.4a	4.9a	58a	1.2ab

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

2019, a layer of road dust overlying the compost layer and grass vegetation close to the roadway was observed, varying from a few millimetres up to approximately 1 cm thickness. Analysis of this material showed high concentrations of readily available Na (Na-AL, according to Egnér et al., 1960). The mean Na-AL concentration in this material was  $57.7 \text{ mg } 100 \text{ g}^{-1}$  ( $n = 3$ ), which is higher than the concentration of  $50 \text{ mg } 100 \text{ g}^{-1}$  which is often quoted as a limit for risk of salt damage on susceptible plants (Eurofins, undated). This analysis supported that the use of de-icing salts could lead to salt concentrations which could deleteriously affect plants (Haraldsen and Lundetrae, 2014); however, a more detailed investigation of salt accumulation in the soil is needed to verify the effects.

There were also differences between the three rain gardens, most likely due to different amounts of splashes from the road, especially during autumn in the second year when the drain to rain garden 3 was clogged (Fig. 4). All species had higher mortality in this rain garden, however, the difference was only significant for *H. 'Francee'*. Vulnerability to splashes during the growing season thus appeared to vary among the species used in this study.

### 3.2.1. *Hemerocallis 'Camden Gold Dollar'*

*H. 'Camden Gold Dollar'* had the highest survival, both in terms of total survival and survival in the various growth environments (Fig. 5). None of the individuals of this species died in the first year. In the second year, all the plants were alive along the walkway, whereas 3 % at the bottom and 8 % by the roadway were dead. Mortality was higher in the rain garden exposed to heavy splashes; however, the difference was not significant and the tested cultivar appeared to tolerate this.

In the first year, there was little difference in overall vitality between the growth environments (Table 7). In the second year, the value for overall vitality was 7.3 along the walkway, 6.6 at the bottom, and 4.6 along the roadway, and there was no significant difference between the value along the walkway and the reference fields. The height, coverage, and leaf damage followed the same pattern, and the difference between the growing environments became clearer in the second year, most likely due to accumulation of salt and pollution.

*Hemerocallis* thrives on moist to damp, nutrient-rich soil in full sun; however, some cultivars also tolerate heat and drought in summer (Hansen and Stahl, 1993). *Hemerocallis* is recommended in rain garden literature (Schmidt et al., 2007; Clasen, 2012; Malaviya et al., 2019) and has been used in previous rain garden studies. Yuan and Dunnett (2018) treated *H. 'Golden Chimes'* with simulated cyclic flooding and found that plants adapted to infrequent inundation and that the species was useful in all rain garden positions in Sheffield. Bortolini and Zanin (2019) found high adaptability of *H. 'Glittering Treasure'* in all rain garden zones in north-eastern Italy. The species has also been studied in perennial borders along Norwegian roads (Vike and Søyland, 2011). They found that *H. 'Golden Specter'* performed well, even closest to the

road where many species had high mortality. The results in Bjørnstjerne Bjørnsons Street indicate that *Hemerocallis* can withstand the stress factors in rain gardens even when combined with road environments in cold climates.

### 3.2.2. *Hosta 'Francee'*

For *H. 'Francee'*, the environment had a clear effect after 2 years, when mortality was 53 % closest to the road, 12 % at the bottom, 3 % along the walkway, and 0 % in the reference field (Fig. 5). There was also a significant difference between the rain gardens. In rain garden 3, which was exposed to heavy splashes, the mortality rate was 42 %, and in rain gardens 1 and 2 it was 2 % and 13 %, respectively.

This species had the lowest overall vitality, coverage, and height along the roadway, and this tendency became clearer in the second year (Table 7). However, all growth parameters except height showed improved results along the walkway and at the bottom than in the reference fields. This may indicate that *H. 'Francee'* thrives better with the water supply in rain gardens; however, differences in soil properties may also be an explanation. In the second year *Botrytis* sp. was detected, which explained the leaf damage.

*Hosta* is adapted to woodlands but is also useful when shade is limited and in growing media with little woodland humus. The species tolerates strong fluctuations in soil moisture (Hansen and Stahl, 1993) and is recommended in rain garden literature (Schmidt et al., 2007; Clasen, 2012; Steiner and Domm, 2012); however, it has not been included in any known rain garden studies. Vike and Søyland (2011) examined *Hosta* in perennial borders along Norwegian roads and found that it performed well, even close to the road and after 10–20 years. The salt tolerance of nine species was also studied in a container experiment with polluted soil, and *Hosta x fortunei* exhibited the best performance (Vike and Søyland, 2011). The results in Bjørnstjerne Bjørnsons Street indicated that *Hosta* can withstand the combination of rain gardens and road environments in cold climates but is vulnerable to heavy splashes.

### 3.2.3. *Eurybia divaricata*

*E. divaricata* had very high mortality along the roadway, i.e., 79 % the first year and 100 % the second. Along the walkway and in the reference field, 20 % of the plants had died after 2 years, and at the bottom 18 % were dead after 1 year and 52 % were dead after two years (Fig. 5). Thus, the species showed a clear tendency for higher mortality closer to the road and increased mortality over time. There were no significant differences in mortality in the different rain gardens; however, because all of the individuals along the road had died the second year, the effect of direct splashes from the road could not be determined (rain garden 3).

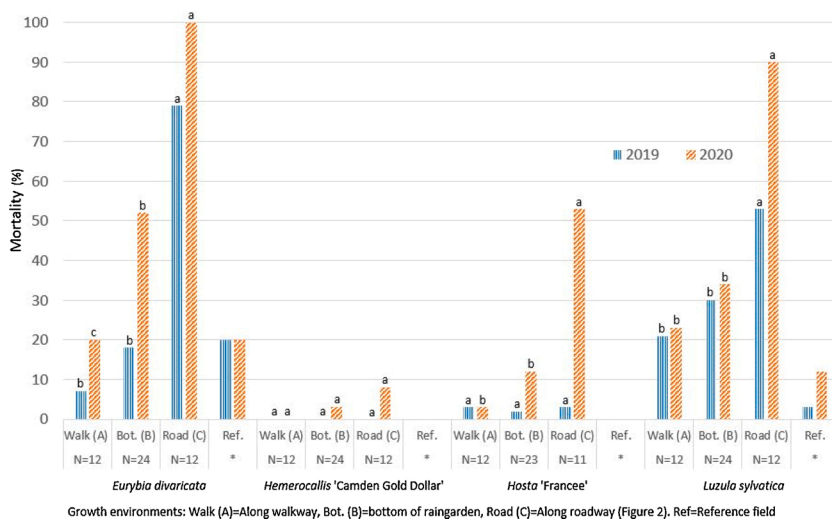
For *E. divaricata*, there were no significant differences in overall vitality, coverage, or leaf damage between the different growing environments the second year; therefore, even though high mortality occurred at the bottom, the plants that did survive thrived well (Table 7). After 2 years, the plants were significantly taller in the reference field, which may have been due to differences in soil depth, flooding, or impact from the road.

*E. divaricata* grows naturally in dry to moderately moist places in deciduous forests, in clearings, and along roadsides in the eastern part of North America (Flora of North America, undated). The species prefers a nutritious growing place, but also tolerates dry, sandy soil (Hansen and Stahl, 1993). *E. divaricata* is not known from the rain garden literature or relevant studies. The experiment in Bjørnstjerne Bjørnsons Street showed that this species should not be planted near the roadway but is useful farther away. Because only half the plants survived in the bottom and it is unknown whether the cause was standing water, freezing and thawing cycles, direct splashes, or salt and pollution, it is uncertain whether this species can be useful in the wet zone in normal rain gardens, and further investigations are needed.



Fig. 4. Splashes from the road, rain garden 3 Bjørnstjerne Bjørnsons street, Drammen (Photograph: Trond K. Haraldsen).





**Fig. 5.** Mean mortality (%) of four perennial species grown at different distances from the road (growth environments) in rain gardens along Bjørnstjerne Bjørnsons Street 1 and 2 years after planting. Growth environments: Walk (A) = Along walkway, Bot. (B) = Bottom of rain garden, Road (C) = Along roadway, Ref = Reference field. N = Number of observations. \*For reference fields, % mortality was calculated in relation to the total number of plants of each species in the field. Mean values for each species and year with different letters are significantly different ( $p < 0.05$ ).

### 3.2.4. *Luzula sylvatica*

For *L. sylvatica*, mortality after 2 years was 94 % along the roadway, 34 % at the bottom, 23 % by the walkway, and 12 % in the reference fields (Fig. 5). There were no significant differences between the rain gardens; however, because most individuals along the road died during the first year, there was little plant material left to record possible effects of direct splashes in rain garden 3. Nevertheless, it was clear that this species was strongly influenced by the road environment.

*L. sylvatica* showed good overall vitality along the walkway both years, and there was no significant difference from the reference fields (Table 7). The plants at the bottom were not equally vital as those along the walkway, and those along the roadway were clearly less vital. Coverage showed the same tendency. There were only small differences in leaf damage, and the most damage was recorded closest to the road. The plants were tallest in the reference field.

*L. sylvatica* is an evergreen species and is common in most of Europe. In Norway, the species thrives on moist, nutrient-poor soil along the coast, in forests, and on heather moors (Mossberg and Stenberg, 2012). According to Hansen and Stahl (1993), it can also withstand dry soil and low pH, but prefers humus-rich soil. The species was used in a rain garden at Campus Ås where it performed well (Vike and Clewing, 2020). In the container study, *L. sylvatica* showed good tolerance for flood and drought, and in Bjørnstjerne Bjørnsons Street it developed well where it was least affected by the road environment, whereas direct salt spray caused mortality. Evergreen plants generally do not tolerate direct salt spray; however, there are differences between species and genotypes, and small individuals are more exposed than large trees (Norwegian Public Roads Administration, 2008). This may explain why individuals of this species died along the road in Bjørnstjerne Bjørnsons Street but survived farther away.

## 4. Conclusion

This paper shows that the growing conditions closest to the roadway in cold climate rain gardens are challenging. Salt and splashes from the road appeared to be the greatest problem, and there were large differences in the tolerance for these factors in different species. *H. 'Camden Gold Dollar'* appeared to tolerate the road environment well, whereas *L. sylvatica* and *E. divaricata* showed high mortality closest to the road. *H. 'Francee'* developed well, except when exposed to splashes of road water. *A. orientalis* was not part of the real-scale study; however, it did not survive the winter in the container study and was therefore considered not suitable for use in rain gardens. Further studies are needed to identify species that are able to withstand salt exposure and survive close to the road.

The selected soil mixture in the real-scale study functioned well, and showed that the adjustments of the recipe used in the container study had the expected effect.

*L. sylvatica* performed well during the controlled studies in the container experiment; however, this species died in the real-scale study, especially closest to the road. This shows the necessity of investigating plant responses under relevant environmental conditions.

## Author statement

Kirstine Laukli: Conceptualization, investigation (real-scale field study), formal analysis, validation, writing, visualization, project administration, funding acquisition.

Marina Gamborg: Investigation (container study).

Trond Haraldsen: Methodology (container study), writing, visualization, supervision.

Eva Vike: Methodology (container study & real-scale field study), formal analysis, supervision.

## 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.

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