

Plant survival and growth in bioretention cells under a cold climate

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ABSTRACT

Urbanization coupled with climate change results in significant stormwater management challenges. In this context, the use of green infrastructures such as bioswales and bioretention systems to intercept, slow down and filter runoff has been increasing in North America in recent years. However, little data is available on the selection of optimal plant species adapted to cold climates, their optimal positioning in the swale and intra and inter-seasonal variation in plant growth. A field experiment was conducted during three growing seasons from July 2020 to August 2022 in a proximal suburb of Québec City, Canada, to monitor the survival rate. Growth (height and plant area), and floridity (number of flower buds and flower stems) of 22 plant species in 48 cold climate bioretention cells located along streets. The study aimed to understand the influence of planting position (margin: upper position, usually dryer; slope; middle position, fluctuating water conditions; bottom: lower position, usually moister) on species development, in order to identify the species most and least adapted to the different moisture conditions. Results showed that survival was generally high (> 86%) and was not affected by position within the bioretention cells. However, for most species, plant area increased, and height decreased at the margin compared to the slope position, while floridity only increased at the margin for four species (*Heliopsis helianthoides* (L.) Sweet, *Coreopsis verticillata* L., *Hemerocallis* ‘Stella Supreme’ L., *Verbena hastata* L.). Seven species (*Campanula carpatica* Jacq ‘Alba’, *Hesperis matronalis* L., *Osmundastrum cinnamomeum* (L.) C. Presl, *Rudbeckia hirta* L., *Verbena hastata* L., *Cerastium tomentosum* L., *Athyrium filix-femina* (L.) Roth ex Mertens) exhibited lower survival and growth rates over time than the others. Overall, 15 out of 22 species performed well in the bioretention cells with minimum maintenance over the course of the experiment. Results also showed that plant area at the end of the growing season was much more influenced by position in the bioretention cells than were height or floridity, while survival was not influenced by this factor. A better knowledge of plant interactions in varying spatial distribution over time can contribute to improving and potentially maximizing bioretention performance.

1. Introduction

In many temperate regions, climate change has been associated with more frequent and intensive rain events (Intergovernmental Panel on Climate Change, 2022). Urban sprawl, driven by population growth, contributes to increased stormwater runoff from impervious surfaces, resulting in the deterioration of water quality in the surrounding environment (LeFevre et al., 2015). Bioretention or biofiltration systems, often called “bioretention cells”, “rain gardens”, “biofilters” or “bioswales”, represent one example of low-impact technology used to manage stormwater. They are typically small in area and set within parking lots, close to roofs, or along roadways to intercept surface runoff in situ, in order to control large volumes and peak flows (Davis et al.,

2012; James and Dymond, 2012; Pineau et al., 2021), as well as improve the hydrological quality of runoff (Henderson et al., 2007; Hunt et al., 2008; Zhang and Guo, 2014). Bioretention systems characteristically have a moisture gradient with three distinct zones: an often moist to waterlogged bottom in the form of a depression, an occasionally flooded side-slope characterized by a moderately moist soil, and a dryish upper margin (Dunnett and Clayden, 2007). Surprisingly, very few studies performed in bioretention systems have examined plant establishment along this gradient, especially with direct measurement of soil physical conditions (Kratky et al., 2017; Laukli et al., 2022).

Vegetation and growing media have many functions in bioretention systems. Indeed, plants and growing media reduce both the flow and total volume of water (Davis et al., 2009; Hunt et al., 2012) through the

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different processes of interception, infiltration, evaporation, and transpiration (Dunnnett and Clayden, 2007). Processes such as filtration, assimilation, adsorption and degradation/decomposition have been shown to improve water quality (Dunnnett and Clayden, 2007). Vegetation also provides several other benefits besides stormwater management, such as contributing to thermal attenuation of the urban heat island effect (Wadzuk et al., 2015), enhancing local biodiversity (Hoyle et al., 2018), as well as promoting visual aesthetics around impervious urban areas (Muerdter et al., 2018). Attractive flowering displays and flower color diversity are among the keys to gaining social acceptance for designed urban vegetation (Lindemann-Matthies et al., 2010; Hoyle et al., 2018).

Several studies have been published on the function of bioretention systems, focusing especially on hydrological performance (Muthanna et al., 2007; Kratky et al., 2017; Kristvik et al., 2019; Venvik and Boogaard, 2020). However, the role of plants in these systems has not been fully addressed by previous research (Sprakman et al., 2020). Plant species used in bioretention systems must be well adapted to the prevailing extreme growing conditions that can vary alternatively between drought and periodic waterlogging (Dunnnett and Clayden, 2007) and must also be able to tolerate the contaminants concentrated by the bioretention system, notably metals, as well as salts and sand used to de-ice roads during winter (Hanslin et al., 2017). Well established plants improve the hydrological performance of bioretention systems in addition to being more aesthetically pleasing, leading to better social acceptance in urban areas (Lindemann-Matthies et al., 2010; Hoyle et al., 2018). Unfortunately, most plant selection guides used by urban planning professionals or landscape architects are not well adapted to bioretention systems, especially in cold climates (Haraldsen et al., 2019). In addition, while several lists of recommended plants for such use have been published over the years (Dunnnett and Clayden, 2007; Yuan and Dunnnett, 2018; Malaviya et al., 2019), most are not based on

experimental or field studies.

This study aims to understand the survival, growth and floridity of 22 perennial species, at three positions (bottom, slope, margin) within 48 bioretention cells under a temperate cold climate, in order to identify the species most adapted to these growing conditions. We predicted that survival, growth, and floridity among different species will be influenced by their positioning in the bioretention cells. Specifically, we hypothesize that growth and floridity will be higher at the margin position, as interspecific competition is reduced compared to other positions, but that survival will be higher at the slope position, as plants are less exposed to environmental stresses. Results from this research will be helpful to improve plant selection, survival and growth in bioretention systems, thus improving the performance of these infrastructures.

2. Materials and methods

2.1. Site description

A full-scale field study was initiated in bioretention cells along streets in the vicinity of Lake St. Charles, located 20 km north of Québec City (46°48'N 71°14'W), Eastern Canada (Fig. 1). Lake St. Charles is the main drinking water reservoir for Québec City, supplying nearly 300,000 residents (53% of the total population). Its watershed has experienced rapid urbanization recently, which has been identified as a threat to the water quality of the lake (Association pour la protection de l'environnement du lac Saint-Charles, 2014).

The region has a cold temperate sub-humid climate with average total annual rainfall of 568 mm and snowfall of 3 m (Environment Canada, 2012). The snow cover persists for an average of 140 days each year and the estimated vegetation growth period is about 165 days (Gerardin and McKenney, 2001). Meteorological temperature and precipitation data for 2020, 2021 and 2022 are presented in Table S1 in

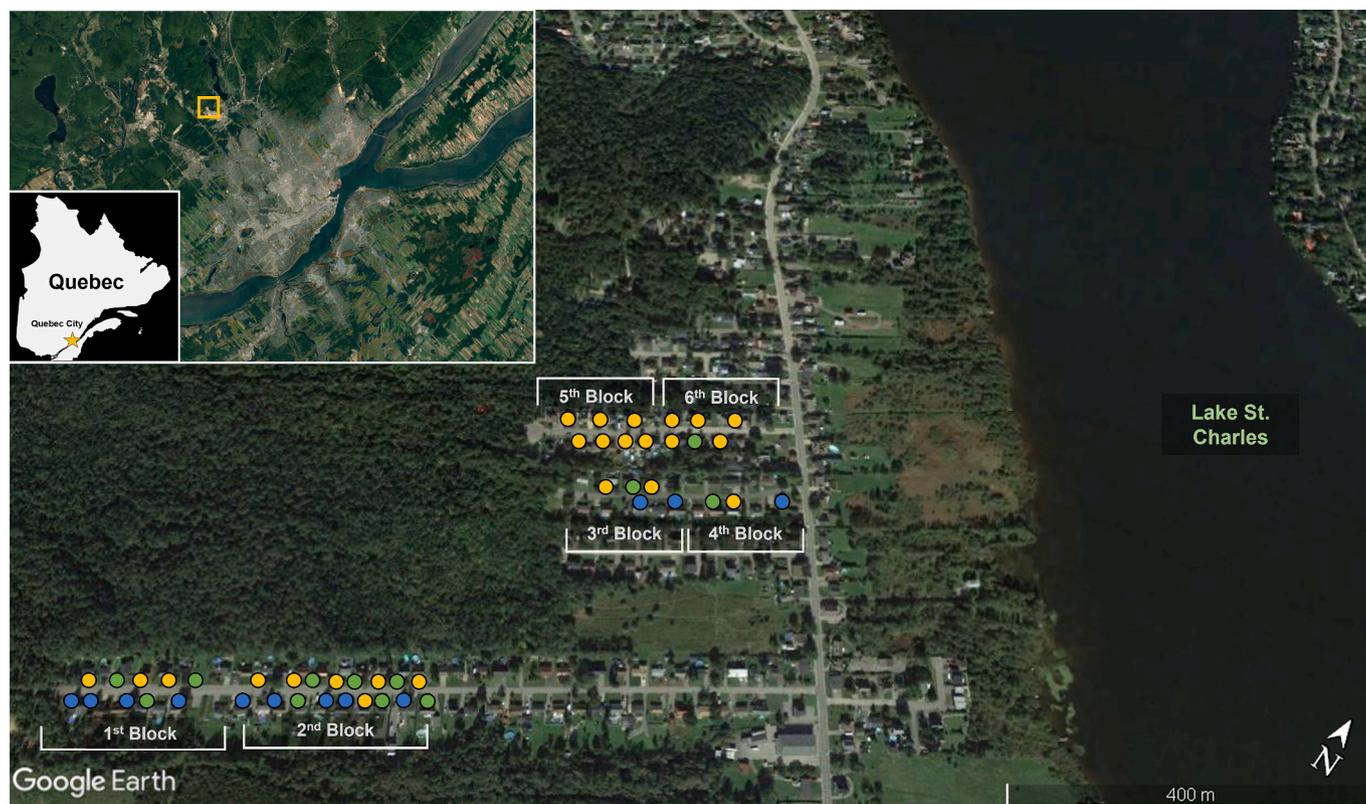


Fig. 1. Location of the bioretention cells sampled in the vicinity of Lake St. Charles. Bioretention cells (green circles = arrangement A, yellow circles = arrangement B, blue circles = arrangement C) were sampled from 2020 to 2022 in a residential sector located 20 km north of Québec City (yellow square). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Supplementary Materials.

2.2. Bioretention design and media characteristics

A total of 48 bioretention cells were designed, constructed, and planted in July 2020 on three residential streets located southwest of Lake St. Charles (Fig. 1). The average slope across the streets was 3.8%, and was directed eastward, towards the lake.

Bioretention cells had a constant width of 1.7 m, and a length between 5 and 15 m. They were filled from the bottom to the top of the cell with a layer of 0.55 to 0.80 m of clean stones (20 mm diameter), a high-density polyethylene (HDPE) perforated pipe (250–600 mm diameter) covered with a Type 4 approved geotextile membrane, then filled with a 0.45 m layer of mixed sand and crushed stone CG-14 (0–3/8”) and a 0.3 m layer of growing media mix recommended for bioretention systems, obtained from a local distributor (Natureausol®, Les Matériaux paysagers Savaria, Boucherville, QC, Canada) (Fig. 2). This media contains 87.2% sand, 10.8% clay and 2.0% silt by mass and has a hydraulic conductivity of 1800 cm / h, an estimated porosity of 54.6% and an estimated density of 1.19 g/cm³ (Supplementary Table S2). The available water capacity (AWC) was 8.5 ml of water / 100 g of substrate.

2.3. Experimental design

Twenty-two perennial species, including 20 forbs and two ferns (Table 1), were planted in July 2020 (year 1) in three types of planting arrangements (A-B-C), each with eight different plant species (Supplementary Fig. S1). Each type of arrangement had five rows of plants longitudinally aligned in the bioretention cell, in three defined positions: bottom (3rd row), slope (2nd and 4th rows) and margin (1st and 5th rows) of the bioretention cells (Figs. 2 and 3). A moisture gradient is present along these three positions, with the difference between positions varying between 2.5% and 5% for at least three days following rain events (Supplementary Fig. S2). On the slope and margin positions, there were three longitudinal divisions, each containing a single species for a total of six different species. At the bottom position, two species were planted alternately per batch of individuals (three to five) along the length of the bioretention cell (Fig. 3).

Bioretention layout, plant selection and planting arrangements were

all planned and implemented by the city before the start of the project, which resulted in an unbalanced experimental design. The factorial experiment was a split split plot design: main plots were planting arrangements (A, B, C) applied in six randomized incomplete blocks (two blocks per street to control for the slope effect) (Fig. 3), subplots were species, and sub-subplots were the position of the species (margin and slope), for a total of 576 units. Planting arrangements A and C each had 12 replicates, while arrangement B had 24 (Fig. 1).

The selected species, along with their abbreviations, are presented in Table 1. Plant species selection was done by the landscape architects mandated by the city to design the swales before the research project was initiated based on different criteria: visual appeal, prolonged flowering, high filtering potential, preference for indigenous species, tolerance to water stress, rapid growth and spread, resistance to insects and diseases, and resilience to winter conditions. Maximum plant height was also considered, as plants higher than 0.9 m were considered to negatively affect the visibility of the street from the nearby houses' driveways, thus representing a security hazard according to the city. A 75 mm layer of ramial chipped wood mulch (length < 25 mm, Les Matériaux paysagers Savaria, Boucherville, Qc, Canada) was spread on top of the growing media in order to conserve moisture and control weeds. Irrigation was only provided during planting to ensure adequate plant establishment. Plants were cut to the ground each year in late October as part of the maintenance plan required by the city and leaf biomass was removed. Geotextile membranes were installed and anchored on all the surfaces of the bioretention cells in early November, before the first snowfall, and removed in early spring as soon as the snow had melted, each year. As this study site is located near a potable water source, the use of abrasives (sand and crushed stone) to improve traction on adjacent roads is favored by the city during winter, and the use of de-icing salt is very limited. No fertilizer or compost were added during the experiment. Weeds were controlled by hand-weeding in mid-July 2021 (year 2), early June, and late July 2022 (year 3) by a contractor; no weed control was performed in year 1.

2.4. Plant monitoring

The baseline number of plants was determined one week after planting in July 2020 (year 1) and was subsequently used to calculate

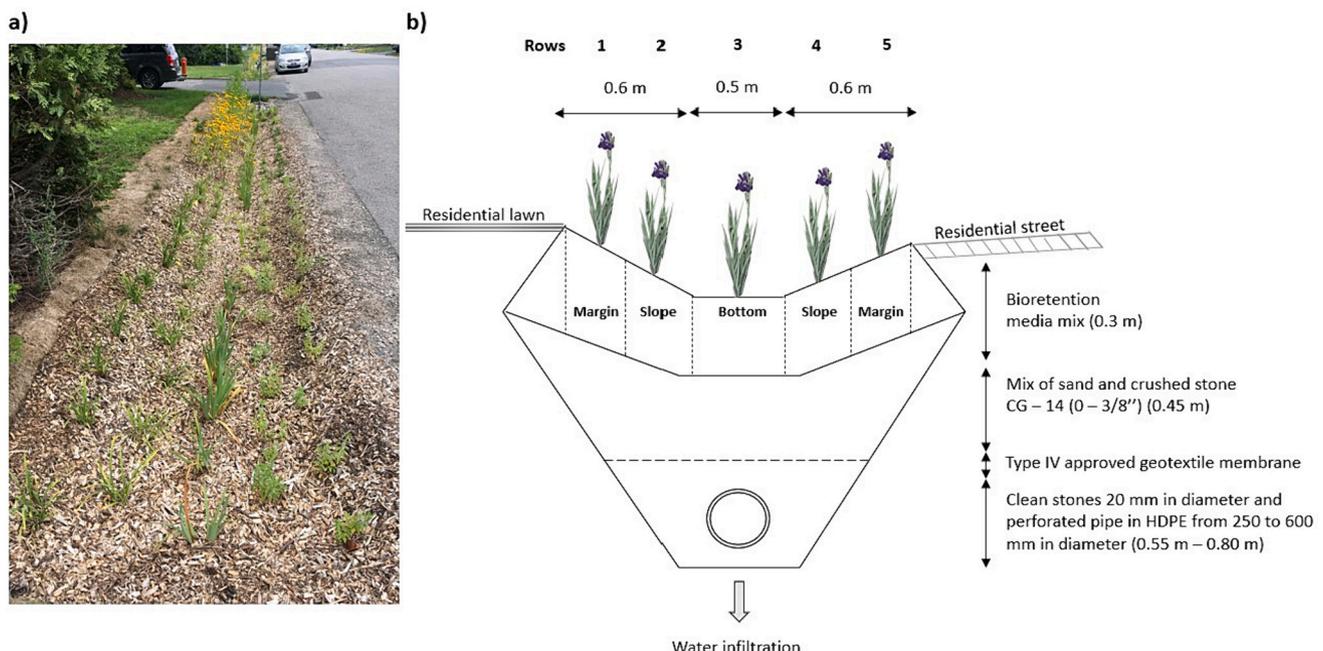


Fig. 2. Actual bioretention cell (a) and schematic cross-section (b) The average slopes in the bioretention cell of the residential lawn and the residential street side were 46.4% and 42.2% respectively. The average slope for the inflow of runoff from the street was 2.5%.

Table 1
List of species planted in bioretention cells.

Family	Latin Name	Common Name	Local distribution*	Hardiness zone	Abbreviation
Asteraceae	<i>Achillea millefolium</i> L.	Common yarrow	Introduced	2	Ach mil
Ranunculaceae	<i>Anemone canadenses</i> (L.) Mosyakin	Canadian Anemone	Naturalized	3	Ane can
Saxifragaceae	<i>Astilbe x arendsii</i> 'White'	Garden Astilbe	Horticultural variety	3	Ast are
Athyriaceae	<i>Athyrium filix-femina</i> (L.) Roth ex Mertens	Lady Fern	Naturalized	3	Ath fil
Campanulaceae	<i>Campanula carpatica</i> Jacq 'Alba'	Carpathian Bellflower	Horticultural variety	3	Cam car
Caryophyllaceae	<i>Cerastium tomentosum</i> L.	Snow-in-summer	Introduced	4	Cer tom
Plantaginaceae	<i>Chelone glabra</i> L.	Turtlehead	Naturalized		Che gla
Asteraceae	<i>Coreopsis verticillata</i> 'Zagreb' L.	Thread leaf tickseed	Introduced	4	Cor ver
Geraniaceae	<i>Geranium sanguineum</i> L.	Bloody geranium	Introduced	3	Ger san
Asteraceae	<i>Heliopsis helianthoides</i> (L.) Sweet	False Sunflower	Naturalized	4	Hel hel
Xanthorrhoeaceae	<i>Hemerocallis</i> 'Stella Supreme' L.	Daylily	Horticultural variety	3	Hem Ste
Brassicaceae	<i>Hesperis matronalis</i> L.	Dame's rocket	Introduced	3	Hes mat
Iridaceae	<i>Iris sibirica</i> L.	Siberian iris	Introduced	3	Iri sib
Iridaceae	<i>Iris versicolor</i> L.	Blue Flag Iris	Naturalized	3	Iri ver
Lamiaceae	<i>Mentha arvensis</i> L.	Wild Mint	Naturalized	3	Men arv
Osmundaceae	<i>Osmundastrum cinnamomeum</i> (L.) C. Presl	Cinnamon Fern	Naturalized	3	Osm cin
Lamiaceae	<i>Physostegia virginiana</i> (L.) Bentham	Obedient Plant	Naturalized	3	Phy vir
Asteraceae	<i>Rudbeckia hirta</i> L.	Black-eyed Susan	Introduced	3	Rud hir
Rosaceae	<i>Sanguisorba canadensis</i> L.	Canadian Burnet, American Great Burnet	Naturalized	3	San can
Asteraceae	<i>Symphyotrichum novae-angliae</i> (L.) G.L. Nesom	New England Aster	Naturalized	3	Sym nov
Ranunculaceae	<i>Thalictrum aquilegifolium</i> L.	Columbine meadow-rue	Introduced	4	Tha aqu
Verbenaceae	<i>Verbena hastata</i> L.	Blue Vervain	Naturalized	4	Ver has

* Species distribution in Québec (Canada) according to Brouillet et al. (2010+). Horticultural varieties are not included in the database.

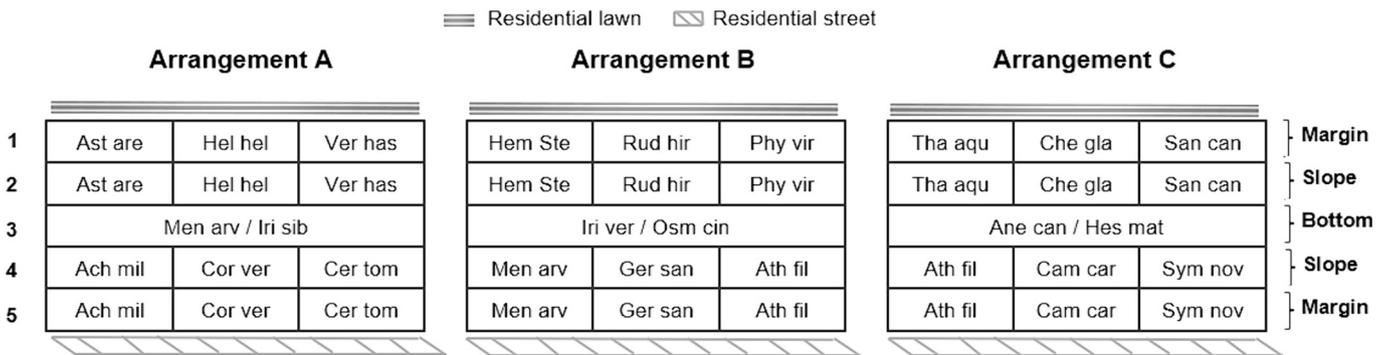


Fig. 3. Three types of systematic planting arrangements used. Rows and Positions are indicated respectively in bold at the left and at the right margins. In the bottom position, two species were planted alternately per batch of individuals (three to five) along the length of the bioretention cell.

the survival rate throughout the experiment. Each plant was recorded as being either alive or dead, according to the presence or absence of green foliage, respectively. Survival of each species was measured once at the end of each season in late August (year 1 to year 3). Spring recovery was measured at each start of the season in late May of years 2 and 3.

Growth was determined by measuring height and lateral area on plants. Growth and floridity were measured on four to six individual plants at each position for each species monthly in year 2 for a total of four surveys (May 23; June 25; July 24; August 25), and twice in year 3, in late May and early August, except for floridity, which was evaluated only in year 2. Plant height was measured vertically from the soil surface to the highest point. Area was calculated by measuring the maximum length and the perpendicular width of each plant and by applying the formula:

$$Area = \frac{maximum\ length \times perpendicular\ width}{2} \times \pi$$

Area was not measured for *M. arvensis*, *A. millefolium* and *P. virginiana* due to their creeping nature, which led to difficulties in sampling individuals. For floridity, the number of flower buds (species: *C. tomentosum*, *C. glabra*, *H. helianthoides*, *C. carpatica* 'Alba', *C. verticillata* 'Zagreb', *G. sanguineum*, *H. 'Stella Supreme'*, *M. arvensis*, *R. hirta*, *S. canadensis*, *V. hastata*) and flower stems (species: *A. millefolium*, *A. x arendsii* 'White', *S. novae-angliae*, *A. filix-femina*,

T. aquilegifolium) were counted.

2.5. Statistical analysis

Each of the evaluated parameters (growth and floridity) was analyzed differently according to the position of the species in the bioretention cells; the species located on the margin and the slope were analyzed separately from those located at the bottom, since the latter were not planted in any other positions (except for *M. arvensis*).

A Binomial Generalized Linear Mixed Model using Penalized Quasi-Likelihood (glmmPQL) with an empirical logit (Agresti, 2003) was used to compare survival and spring recovery rates for all species between each of the two intraspecies positions (Margin – Slope) over time. Fixed effects were species, position, and time (years). Random effects were considered for the street, block, planting arrangement, bioretention cells, and the individual id of each plant.

Growth data was analyzed using a Linear Mixed-Effects Model (lme). Area and height for all species were compared between each of the two intraspecies positions (Margin – Slope) over time. Fixed effects for these models were species, positions, and time (month). Random effects were considered for the street, block, planting arrangement, bioretention cells, individual id and years including a convergence modelizer (control = lmeControl) (Bates et al., 2015), a first order autoregressive covariance structure for repeated measures (taken on repeated

individual id measured over months) and a constant variance structure over species (weight = varIdent). Both models were square root transformed. Floridity was also compared for all species between each of the two intraspecies positions (Margin – Slope) over time. Fixed and random effects for the model were the same as area and height variables, except that we removed the year for the random effect (only one year of

measurements). The model also had a first order autoregressive covariance structure for repeated measures, but only one constant variance structure over months (weight = varIdent). A log transformation was done on the model, and we adjusted the variable ($y + 0.1$) to account for zeros (Sokal and Rohlf, 1994). All the assumptions were respected in each model, with outlier values removed (normality of the

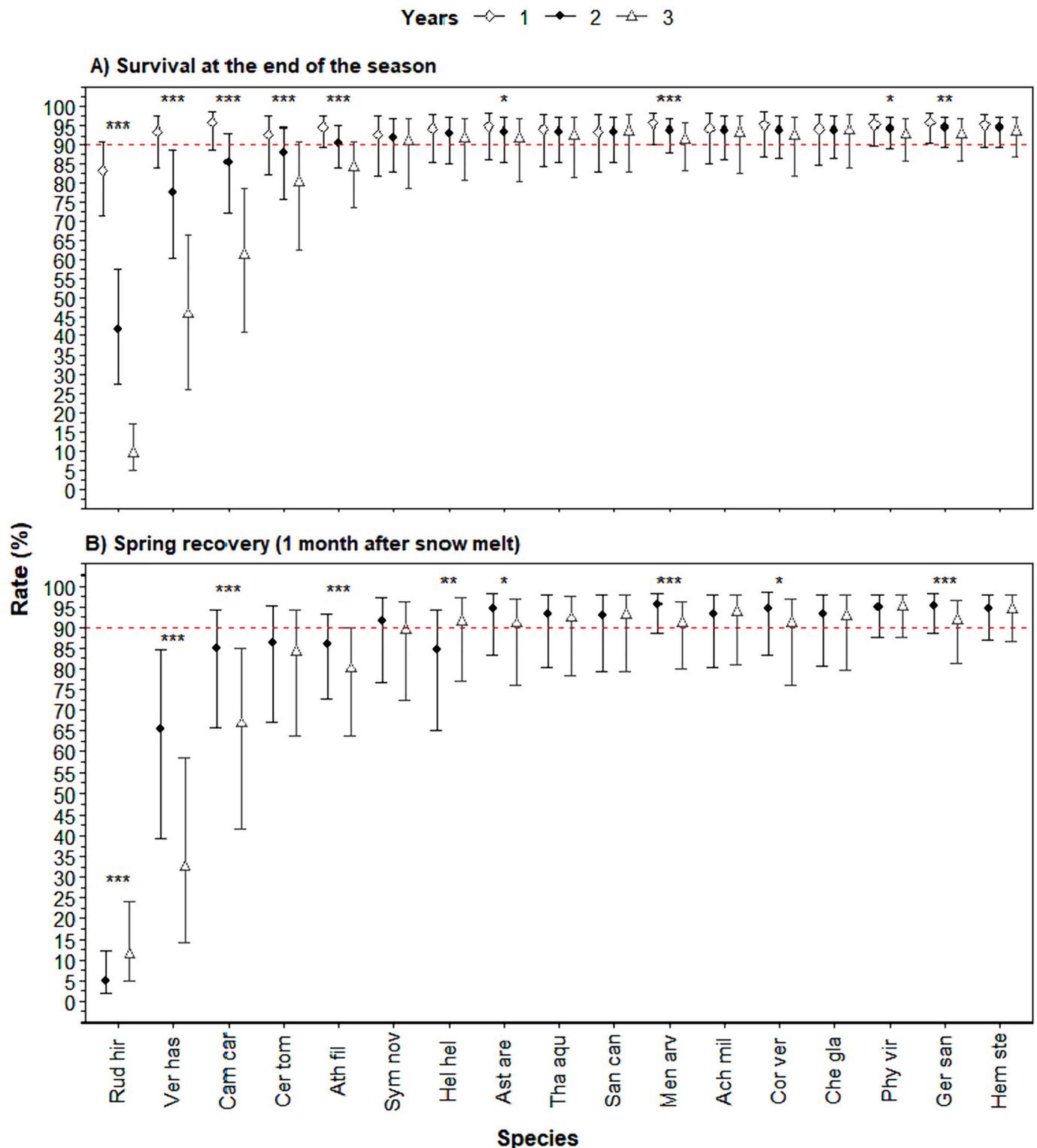


Fig. 4. Survival rate at the end of each growing season (a) and spring recovery rate at the beginning of each growing season (b) without bottom position. Species are placed in ascending order of survival (a). Since the first year included the year of establishment, spring recovery was only evaluated on years 2 and 3. Contrasts between years are presented for each species (***: $P \leq 0.001$; **: $P \leq 0.01$; *: $P \leq 0.05$). Error bars represent lower and upper confidence intervals.

data was not respected, but the data showed very high robustness ($-2 < \text{kurtosis test} < 2$); homogeneity of variances).

The species located in the bottom of the bioretention cells were all analyzed with the same models (survival and spring recovery rates, Growth – Area and Height only) as those used with the species located on the slope and margin positions, except that the fixed effect of position was removed for all models. Random effects were also the same. Log and square root transformations were carried out respectively on the area and height models. All the assumptions were respected in each model (Area and Height), with outlier values removed (normality of the data was not respected, but the data showed very high robustness ($-2 < \text{kurtosis} < 2$); homogeneity of variances). No model was developed for floridity, because the differences in flowering periods between species resulted in a very high data variability.

All statistical analyses were performed using the functions `glmmPQL`, `lme`, `joint_tests` and `emmeans` from the “MASS” (Lenth, 2022), “emmeans” (Venables and Ripley, 2002), “multcomp” (Hothorn et al., 2008) and “nlme” (Pinheiro and Bates, 2000; Pinheiro et al., 2022) packages in Rstudio, version 4.2.1 (RStudio Team, 2020).

3. Results

3.1. Plant survival and spring recovery

Plant survival rate at the end of the season was 94.1% for year 1 and decreased to 90.9% for year 2 and 86.3% for the third year, but this decrease was mostly attributable to certain species (Fig. 4A), as survival significantly varied among species over the years ($p < 0.0001$; Table 2). For most species, survival remained above 90% throughout the experiment, except for 5 species. Specifically, three species (*R. hirta*, *V. hastata* and *C. carpatica* ‘Alba’) had their survival drop to 9%, 46%, 61% respectively at the end of year 3. Two species (*C. tomentosum*, *A. filix-femina*) also showed lower survival rates, with a drop to 80% and 84.2% respectively at the end of year 3. The other species had significant differences between years, but survival constantly remained above 90%.

Overall, most species had a good spring recovery, i.e. $> 95\%$ of individuals recorded as alive in the previous fall were still alive in the following spring on both years. Species with the lowest spring recovery were essentially the same as those with low end-of-season survival (Fig. 4B). *R. hirta*, *V. hastata*, *H. helianthoides* and *A. filix-femina* are the four species that appear to be the slowest to initiate growth in the spring, since their spring recovery rate was lower than their survival rate for year 2, (differences of 37%, 13%, 8% and 5% respectively). *A. x arendsii* ‘White’, *C. verticillata* ‘Zagreb’, *G. sanguineum*, *M. arvensis* and *H. helianthoides* had significant differences between years, but spring recovery was still very high ($> 80\%$).

The impact of position in the bioretention cells on plant survival at the end of the season increased over the years ($p = 0.0215$; Table 2). For a given plant species, planting position (margin vs slope) did not significantly affect survival for years 1 and 2, but survival rate at the end of the season was significantly lower (84.8% vs 87.7%) on the slope compared to the margin in year 3 (Supplementary Fig. S3).

Table 2

Effects of species (without bottom position), positions (Margin, Slope) and years from planting on a) Survival (2020: year 1; 2021: year 2; 2022: year 3) b) Spring recovery (year 2 and year 3) as well as their interaction on species survival. Significant p -values (< 0.05) are indicated in bold.

	a. Survival				b. Spring recovery			
	Df	SS	F.ratio	P.value	Df	SS	F.ratio	P.value
Species	16	494	63.763	<0.0001	16	494	113.862	<0.0001
Position	1	494	3.241	0.0724	1	494	3.445	0.0640
Year	1	1114	299.909	<0.0001	1	539	30.337	<0.0001
Species: Position	16	494	0.171	0.9999	16	494	0.214	0.9996
Species: Year	16	1114	44.373	<0.0001	16	539	12.886	<0.0001
Position: Year	1	1114	5.297	0.0215	1	539	0.022	0.8829
Species: Position: Year	16	1114	0.835	0.6456	16	539	0.903	0.5657

3.2. Plant growth and floridity

Plant area, height and floridity of each species were affected differently by position and month (Table 3). Four species (*C. carpatica* ‘Alba’, *R. hirta*, *V. hastata*, *A. filix-femina*) had a lower area at the start of each growing season; they also turned out to be the least developed at the end of the season. Five species (*S. canadensis*, *H. ‘Stella Supreme’*, *G. sanguineum*, *H. helianthoides* and *S. novae-angliae*) had a greater area during the growing season compared to the rest of the species. *T. aquilegifolium* was the species with the largest area in May, but its growth during the rest of the season was lower than other species. For a given species, individuals planted at the margin of the bioretention cells generally had a larger area at the end of the season compared to those planted on the slope, except for *R. hirta* (Fig. 5A).

At the start of the growing season, *T. aquilegifolium* not only had the largest area, it was also the fastest vertical growing species, while *R. hirta* had the lowest height. Eight species (*V. hastata*, *C. glabra*, *M. arvensis*, *A. millefolium*, *P. virginiana*, *S. canadensis*, *H. helianthoides* and *S. novae-angliae*) had the largest increase in height during the growing season. Overall, height was affected differently between positions among species over time. At the beginning of the season, six species (*C. tomentosum*, *C. verticillata* ‘Zagreb’, *H. helianthoides*, *G. sanguineum*, *H. ‘Stella Supreme’*, *P. virginiana*) were significantly taller in the margin position compared to the slope position. However, at the end of the growing season, individuals planted on the slope were significantly taller than those planted at the margin for six species (*T. aquilegifolium*, *S. novae-angliae*, *S. canadensis*, *G. sanguineum*, *M. arvensis* and *P. virginiana*) (Fig. 5B). Overall, species position had a greater effect on area than on height for most species.

For the few species flowering from late May to late June, floridity (*G. sanguineum*, *T. aquilegifolium*) was relatively low. Most species started flowering between late June and late July. High floridity was also associated with a higher variability between individuals, which reduced the accuracy of the model. Floridity for four species (*H. helianthoides*, *C. verticillata* ‘Zagreb’, *H. ‘Stella Supreme’*, and particularly *V. hastata*), was significantly increased at the margin compared to the slope position. *R. hirta* was the only species for which floridity was higher on the slope compared to the margin from late July to late August (Supplementary Fig. S4).

At the bottom position, plant survival differed significantly among species and years ($p < 0.0001$, Table 4). Survival remained above 80% throughout the experiment for most species, except for *H. matronalis* and *O. cinnamomeum*, for which the survival rate dropped significantly, to 12% and 61%, respectively, at the end of year 3. *M. arvensis* experienced a significant decrease in survival rate over time (Fig. 6), down to below 85%, which is lower than the survival rate observed for this species at the other positions (Fig. 4).

As for plant area, *H. matronalis* and *O. cinnamomeum* were the two species with the lowest values at the end of both seasons, with 0.04 and 0.06 m² compared to *I. versicolor* and *I. sibirica* with 0.28 and 0.46 m², respectively (Supplementary Fig. S5). *O. cinnamomeum* and *A. canadenses* were the two species with the lowest height at the

Table 3

Effects of species, positions (Margin, Slope) and months (May, June, July, August) as well as their interaction on a) Area, b) Height and c) Floridity, obtained from linear mixed models.

	a. Area				b. Height				c. Floridity			
	Df	SS	F.ratio	P.value	Df	SS	F.ratio	P.value	Df	SS	F.ratio	P.value
Species	14	3655	520.901	<0.0001	16	4214	1457.685	<0.0001	13	2688	157.572	<0.0001
Position	1	3655	31.682	<0.0001	1	4214	0.002	0.9685	1	2688	16.010	<0.0001
Month	1	5599	4284.934	<0.0001	1	7147	19,435.087	<0.0001	1	4319	5643.080	<0.0001
Species: Position	14	3655	7.736	<0.0001	16	4214	5.533	<0.0001	13	2688	3.909	<0.0001
Species: Month	14	5599	141.876	<0.0001	16	7147	688.670	<0.0001	13	4319	222.889	<0.0001
Position: Month	1	5599	2.506	<0.0001	1	7147	27.349	<0.0001	1	4319	10.775	0.0015
Species: Position: Month	14	5599	4.714	<0.0001	16	7147	4.034	<0.0001	13	4319	4.541	<0.0001

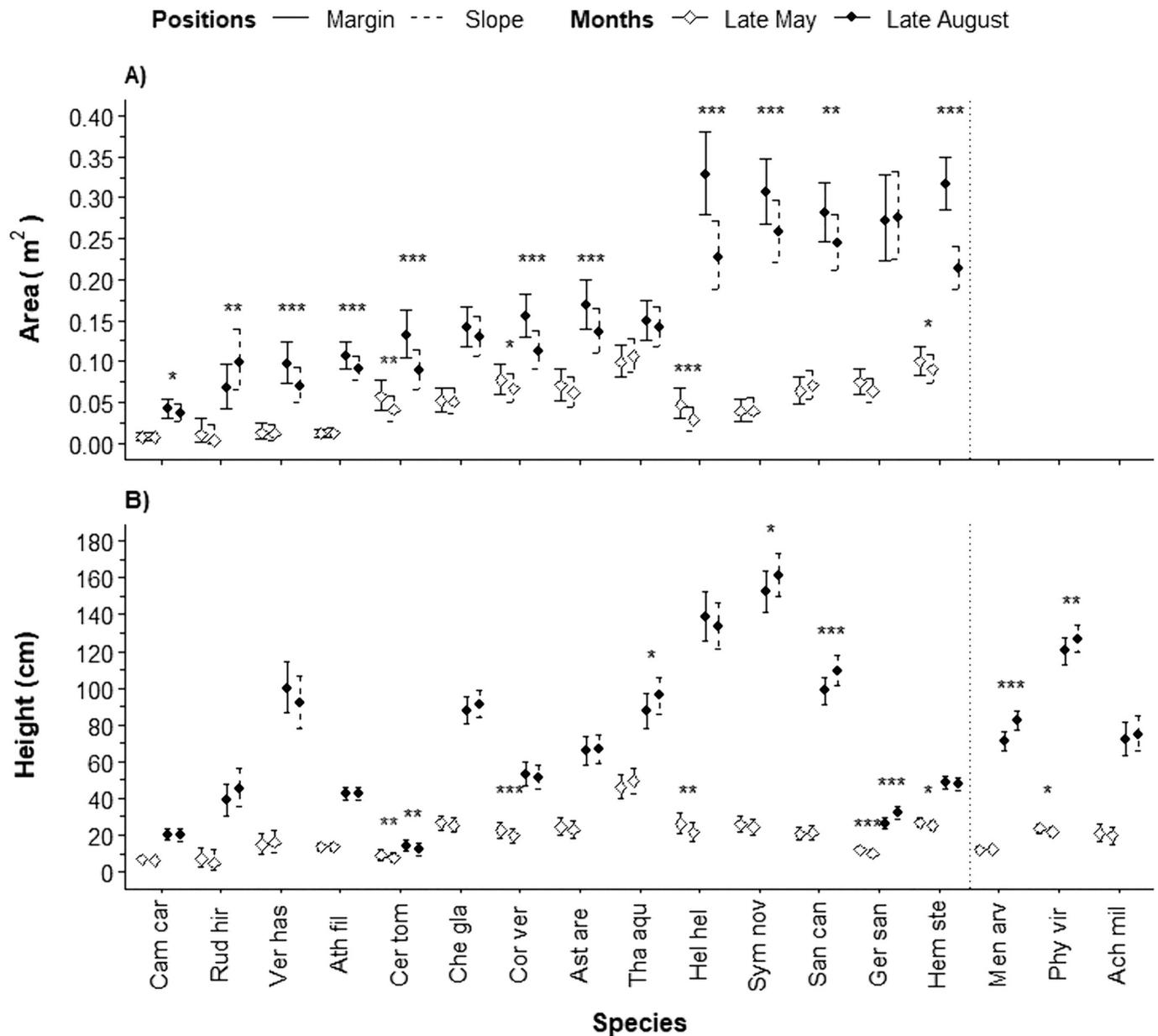


Fig. 5. Plant area (a) and Height (b) at two positions in May and August. Floridity is not presented due to the different flowering periods, which resulted in large differences in confidence intervals between species. Year 2 and year 3 were pooled for area and height. Area was not measured for the species after the vertical dotted line due to difficulties for these species. Species are placed in ascending order according to the area variable between species. Contrasts between positions for each month are presented (***: $P \leq 0.001$; **: $P \leq 0.01$; *: $P \leq 0.05$; no asterisk: nonsignificant). Error bars represent lower and upper confidence intervals.

Table 4
Effects of species, and time as well as their interaction on a) Survival, b) Area and c) Height, obtained from linear mixed models.

	a. Survival					b. Area			c. Height				
	Df	SS	F.ratio	P.value		Df	SS	F.ratio	P.value	Df	SS	F.ratio	P.value
Species	5	43	39.859	<0.0001	Species	3	604	434.497	<0.0001	5	800	379.199	<0.0001
Years	1	182	158.635	<0.0001	Months	1	1069	1737.970	<0.0001	1	1671	4581.818	<0.0001
Species: Years	5	182	35.059	<0.0001	Species: Months	3	1069	52.596	<0.0001	5	1671	210.388	<0.0001

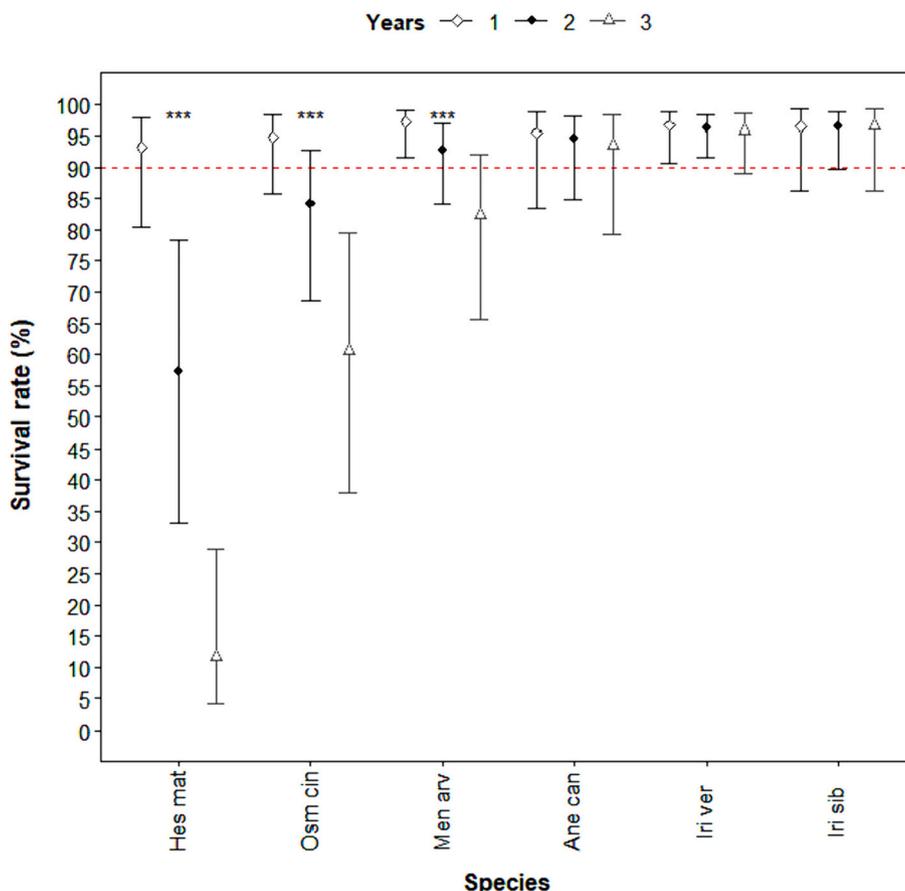


Fig. 6. Survival of species at the bottom position. Contrasts between years are presented (***: $P \leq 0.001$; **: $P \leq 0.01$; *: $P \leq 0.05$).

beginning and end of the season, reaching a maximum of 44.5 and 39.7 cm respectively. *H. matronalis* and *I. sibirica* were the two tallest species, with a similar height of 100 cm at the end of the seasons. Most species started flowering in June 2021, except *M. arvensis*, which began flowering in July that year. Overall, *I. sibirica*, *I. versicolor* as well as *A. canadenses* and *M. arvensis* showed a good capacity for survival and growth over time (Supplementary Fig. S5).

4. Discussion

4.1. Factors affecting plant survival

Most of the plant species evaluated in this experiment had very good survival rate (>80%) and exhibited adequate growth, and thus would be good choices for future bioretention systems under similar climatic conditions. In fact, fifteen out of twenty-two species (*A. millefolium*, *A. canadenses*, *A. x arendsii* ‘White’, *C. glabra*, *C. verticillata* ‘Zagreb’, *H. helianthoides*, *G. sanguineum*, *H. ‘Stella Supreme’*, *I. sibirica*, *I. versicolor*, *M. arvensis*, *P. virginiana*, *S. novae-angliae*, *S. canadensis*, *T. aquilegifolium*) were found to be well adapted to cold climate bioretention cells. Two other species (*C. tomentosum*, *A. filix-femina*)

showed lower survival rates, but they were still above 80%. In contrast, five species (*O. cinnamomeum*, *V. hastata*, *C. carpatica* ‘Alba’, *H. matronalis*, *R. hirta*) had low survival and slow growth rates and should be avoided in future projects.

In nature, *O. cinnamomeum* is considered an indicator of wet acidic soils (Meilleur et al., 1992). In our experiment, the soil pH was mostly alkaline, which could have negatively affected its growth. In addition, this species was prone to encroachment by other plant species, such as *P. virginiana* and *M. arvensis*, and has been previously described as a weak competitor (Komarek, 1973).

V. hastata is a perennial forb that is recommended in several technical documents, for both riparian strips (Federation interdisciplinary of ornamental horticulture of Québec, 2008) and wetlands (Shaw, 2003), and has previously been used in bioretention systems in the province of Québec (Carbonneau and Methot, 2017). In our study, this species was significantly affected by powdery mildew, a fungus that thrives in hot, dry weather with cool, damp nights. It is possible that this disease was partially responsible for the low survival rate observed during the experiment, since it has been previously shown that this species is particularly sensitive to foliar damage (Rachich and Reader, 1999).

C. carpatica ‘Alba’ was another one of the few species with a lower

growth and survival rate in this experiment. While this species is generally known to be a poor competitor (Hitchmough and Wagner, 2013), it is also possible that it was significantly affected by mulch and other sediments accumulating on its basal rosette, as it was planted along the street and therefore received runoff water directly. Laukli et al. (2022) reported that mortality was 50% higher and growth was reduced for species positioned beside the street compared to other positions in the bioretention cells (e.g. bottom and along the sidewalk).

H. matronalis is an introduced species widely distributed and found in thickets, open woodlands, forest margins and along stream banks. A common invasive plant across Canada and the United States (Murphy et al., 2007), it can crowd out native vegetation and thus reduce biodiversity (White et al., 1993). It is considered a biennial or short-lived perennial species (Francis et al., 2009), which may explain its low survival rate during the experiment.

R. hirta is a species with a variable life cycle (annual, biennial or short-lived perennial) (Gleason and Cronquist, 1991) that can be influenced by growing conditions (Harkess and Lyons, 1994). In the current experiment, species were planted relatively late in the season (July) and soon experienced a period of high temperatures and low precipitation. Considering this species was in full bloom at this time, it is possible that it was negatively affected by these conditions at a particularly sensitive growth stage, explaining its low survival rate. Coletta (2014) also observed a low survival rate for this species in bioretention cells in a similar climate.

Water availability in the surrounding environment is another important factor in plant survival. The timing and amount of rainfall during the season, competition with other plants (weeds, lawns, nearby trees, etc.) and volume of runoff channelled into the swale are some of the factors that can affect water availability in the substrate and therefore plant survival. Each species also has its own specific water requirements, highlighting the importance of selecting less demanding ones that are more resistant to drought.

4.2. Effects of plant position (Margin, Slope)

While few studies have investigated the impact of the position of species in bioretention systems over time, this experiment showed that this deserves attention. Our results showed that, for most species, plant area was greatly increased at the margin compared to the slope position, while the opposite was true for plant height. In this experiment, the individuals on the slope faced competition from two rows of plants, compared to one row for individuals at the margin, which can increase competition for light (Givnish, 1982; Díaz et al., 2016) and stimulate vertical growth (Muller-Landau et al., 2008; Moles et al., 2009). This resource investment in vertical growth can, in turn, decrease allocation to lateral growth, thus resulting in a smaller plant area (Givnish, 1982), as was observed for some species in the current experiment (*T. aquilegifolium*, *S. novae-angliae*, *S. canadensis*). Plants at the margin also had much more room to expand, and faced competition from only the slope side, which may also have influenced biomass accumulation (Pant, 1979), and thus area. Species vary in their physiological ability to adapt to different levels of light, water, and nutrients (Givnish, 1982), which may explain why the growth of some species did not seem affected by position in this experiment.

5. Conclusion

Plant selection plays a major role in both the functionality and the visual aspects of bioretention systems, thus survival, spring recovery, area and aesthetics are important factors to consider for optimal plant choice. While some species such as *Campanula carpatica*, *Hesperis matronalis*, *Osmundastrum cinnamomeum*, *Rudbeckia hirta*, *Verbena hastata*, *Cerastium tomentosum*, and *Athyrium filix-femina* showed poorer survival and growth rates than others in the systems set up in this study, fifteen out of the twenty-two species (*Achillea millefolium*, *Anemone*

canadenses, *Astilbe x arendsii* 'White', *Chelone glabra*, *Coreopsis verticillata* 'Zagreb', *Heliopsis helianthoides*, *Geranium sanguineum*, *Hemerocallis* 'Stella Supreme', *Iris sibirica*, *Iris versicolor*, *Mentha arvensis*, *Physostegia virginiana*, *Symphotrichum novae-angliae*, *Sanguisorba canadensis*, *Thalictrum aquilegifolium*) were found to be well adapted to cold climate bioretention cells. For most species, area at the end of the growing season was much strongly influenced by position in the bioretention cells than height or floridity, while survival was not influenced by plant position. However, a better knowledge of plant growth and interactions can contribute to improving future planting arrangements and potentially maximize bioretention performance. In addition to survival and growth, species selection for bioretention systems should also consider other important criteria, such as their ability to treat stormwater and reduce water volumes and peak flows as well as their impact on biodiversity. While most studies have been carried out on the depolluting effectiveness of plants in bioretention systems, other aspects such as social acceptability, pollinator attraction and maintenance practices should be investigated in future research.

CRedit authorship contribution statement

Jessica Champagne-Caron: Formal analysis, Investigation, Methodology, Writing – original draft. **Chloé Frédette:** Writing – review & editing. **Monique Poulin:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Guillaume Grégoire:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Guillaume Grégoire reports financial support was provided by Mitacs Canada.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoleng.2024.107239>.

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