EVALUATING ORNAMENTAL GRASSES FOR THE CHALLENGING RAIN GARDEN ENVIRONMENT

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DOCTOR OF PHILOSOPHY

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ABSTRACT

Four experiments were conducted to determine the growth and survival of seven species of perennial ornamental grasses, tufted hairgrass [*Deschampsia cespitosa* (L.) P. Beauv.], switchgrass (*Panicum virgatum* L.), big bluestem (*Andropogan gerardii* Vitman), Chinese silvergrass (*Miscanthus sinensis* Andersson), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], blue grama grass [*Bouteloua gracilis* (Kunth) Lag. ex Griffiths], and feather reed grass [*Calamagrostis* x *acutiflora* (Schrad.) Rchb.], when subjected to cyclical flood and drought, varying submergence depths and durations, NaCl, and NaCl with petroleum hydrocarbons. Chinese silvergrass and switchgrass survived cyclical soil flooding and drought and submergence for 7-d at a depth of 30 cm while maintaining an acceptable amount of foliar damage. All grasses survived cyclical flood and drought when the soil VWC was maintained at 14% suggesting all seven grasses can withstand periodic soil flooding as long as the water is not too deep. As water depth and duration increased from 4-d to 7-d, little bluestem, blue grama grass, and feather reed grass suffered significant foliar damage. Tufted hair grass and big bluestem suffered significant foliar damage when submerged for 2-d. Switchgrass and feather reed grass survived NaCl loads of up to 6.7 $Mg \cdot ha^{-1}$ and maintained a visual damage rating less than three making them suitable for planting in rain gardens or bioretention systems receiving NaCl runoff. Switchgrass also tolerated motor oil at rates up to 5% in combination with NaCl at rates up to 6.7 $Mg \cdot ha^{-1}$. Switchgrass would be an ideal grass for planting in areas receiving both contaminates. Tufted hair grass has limited tolerance to NaCl or motor oil and should not be planted in areas that may receive those contaminates in stormwater runoff. Big bluestem and little bluestem have limited tolerance to NaCl but some tolerance to motor oil and may be candidates for planting in areas receiving only motor oil in stormwater runoff. Chinese

silvergrass and blue grama grass can tolerate moderate levels of NaCl and motor oil while maintaining a visual damage rating of four or less and would be candidates for planting in areas that receive moderate amounts of both pollutants in stormwater runoff.

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DEDICATION

In loving memory of my parents, Roger Elmer Nelson, and Jane Marie Jenkins Nelson.

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CHAPTER I. LITERATURE REVIEW

Stormwater

From 2000-2010, the urban population in the United States (U.S.) grew over 12% resulting in over 80% of the U.S. population living in urban areas (U.S. Census Bureau, 2010). As urban areas expand, so does the amount of area covered by impervious surfaces (i.e. buildings, driveways, roads, and parking lots) making stormwater management an increasing priority. Impervious surfaces prevent rainfall from naturally soaking into the soil creating large volumes of stormwater runoff.

Stormwater runoff that enters directly into waterways such as, lakes, rivers, and streams, causes an increase in water temperature, bank erosion, flooding, and pollutant levels leading to a reduction in water quality [U.S. Environmental Protection Agency (U.S. EPA), 2008]. Pollutants that are often found in stormwater runoff include road salts, petroleum hydrocarbons, nitrogen, phosphorous, and sediment (Dietz and Clausen, 2005; U.S. EPA, 2005). Holding stormwater in the urban landscape by using a rain garden, will reduce runoff volume and decrease pollutants entering water bodies.

Rain gardens

Rain gardens have gained favor for commercial and residential development to reduce potential flooding, increase water infiltration, and improve stormwater quality by removing pollutants (Asleson et al., 2009; Hunt et al., 2008). A rain garden is a shallow basin in the landscape that is planted with herbaceous and sometimes woody perennial plants and often covered with shredded wood mulch. Most rain gardens are designed to hold 2.5 cm of rainfall from an impervious surface. The ponding depth may vary from 15 – 46 cm depending on the area of impervious surface that drains into the rain garden and the hydraulic conductivity of the soil [Davis et al. 2009; Minnesota Pollution Control Agency (MPCA), 2015]. To prevent mosquito breeding, ponded water should drain within 24 hours and the soil pore space within 48-96 hours (MPCA, 2015).

Rain garden plants depend on seasonal rainfall and at times will be subject to flooding and drought. Frequent rainfall or soil pore clogging may extend the flooding period experienced by rain garden plants beyond 24 hours and roots maybe subjected to water-logged soil for longer than 48-96 hours. At times, rain garden plants will be partially or completely submerged by water. Rain gardens are seldom irrigated and plants may experience drought depending on the length of time between periods of rainfall. It is critical that plants used in the rain garden are tolerant to periodic flooding and drought and stormwater pollutants.

Perennial ornamental grasses are often recommended for rain gardens (Hausken and Thompson, 2018). However, few scientific studies exist to support their recommendation and only the species is recommended. Several improved cultivars of perennial ornamental grasses are currently available that offer improved tolerance to lodging and foliage coloration when compared to the species (i.e., native little bluestem compared with 'Blue Heaven' little bluestem).

Grasses

Grasses belong to the Poaceae family which contains over 12,000 species, belonging to 771 genera. The 771 genera are divided among 12 subfamilies, 51 tribes, and 80 subtribes (Soreng et al., 2015). Grasses with eye-appealing attributes such as leaf color, unique inflorescences, or upright form are commonly referred to as ornamental grasses. Ornamental grasses are a popular garden and landscape plant because they can provide year-long interest, perform in tough locations (i.e. wet and dry soils and saline soils), and require minimal maintenance as long as the correct species is selected and planted in the proper location (Meyer, 2013; Zuk et al., 2016). In the U.S., sales of ornamental grasses increased from approximately $158 million to $179 million from 2014 to 2019 [U.S. Department of Agriculture (USDA), 2015 and 2020].

The perennial ornamental grasses 'Pixie Fountain' tufted hairgrass [*Deschampsia cespitosa* (L.) P. Beauv.], 'Northwind' switchgrass (*Panicum virgatum* L.), 'Red October' big bluestem (*Andropogan gerardii* Vitman), 'Purpurascens' Chinese silvergrass (*Miscanthus sinensis* Andersson), 'Blue Heaven' little bluestem [*Schizachyrium scoparium* (Michx.) Nash], 'Blonde Ambition' blue grama grass [*Bouteloua gracilis* (Kunth) Lag. ex Griffiths], and 'Karl Foerster' feather reed grass [*Calamagrostis* x *acutiflora* (Schrad.) Rchb.] will be used for the proposed studies because 1) of their wide commercial availability in the U.S., 2) their adaptability to challenging environments, and 3) they are often recommended for rain gardens (Hausken and Thompson, 2018; Meyer, 2004; Meyer 2012; Steiner and Domm, 2012).

Tufted hairgrass, switchgrass, big bluestem, little bluestem, and blue grama grass are native to the north central United States [USDA-Natural Resources Conservation Service (NRCS), 2020]. Chinese silvergrass is native to eastern Asia and was introduced into the U.S. as early as 1893 (Dougherty et al., 2014). Feather reed grass is thought to be a hybrid between two species native to Europe and Asia, *C. arundinacea* [(L.) Roth] and *C. epigejos* [(L.) Roth], first discovered by Karl Foerster in Germany during the 1930's (Missouri Botanical Garden, 2020b). The selected grasses include C_3 and C_4 photosynthetic pathways and represent four of the five wetland indicator categories (Table 1).

Tufted hairgrass is a cool-season, bunch-type grass ranging in height from 20-155 cm (St. John et al., 2011). Leaf blades are narrow, ranging from 1-5 mm, and 10-50 cm long. Tufted hairgrass culms terminate with a panicle ranging in height from 5-50 cm long. Tufted hairgrass is adapted to moist areas with full sun exposure although partial shade can be tolerated. Once established tufted hairgrass can tolerate dry conditions (Meyer, 2012). The cultivar, Pixie Fountain, was introduced in 2010 by Jelitto Perennial Seeds, Louisville, KY for its silver-green foliage and compact form (i.e., flowering height of 60 cm) (Jellito, 2020).

Switchgrass is a warm-season rhizomatous grass with a mature height of 1-2 m. Switchgrass culms are round and terminate in a panicle that is open in appearance (Meyer, 2012 and USDA-NRCS, 2020). Switchgrass is adapted to several soil types and conditions, from sandy to clay loam soils with soil water contents from dry to fully saturated (USDA-NRCS, 2006). The cultivar, Northwind, was introduced by Northwind Perennial Farm (Burlington, WI) and has erect green to bluish green foliage on a compact narrow clump reaching a mature height of approximately 1.5 m. In 2014, 'Northwind' was selected as the Perennial Plant Association's Perennial Plant of the Year® (Missouri Botanical Garden, 2020e; Perennial Plant Association, 2020).

Big bluestem is a warm-season grass with short rhizomes and a mature plant height up to 3 m. Culms have a bluish wax layer and terminate with three to seven spike-like racemes. Leaf blades are flat and range in length from 15-60 cm and 0.5-1 cm wide. Big bluestem is adapted to planting locations with full sun to part shade and moist sandy or clay loam soils (Wennerberg, 2004). The cultivar, Red October, is a seedling of 'Indian Warrior' big bluestem and is described as having deeper green foliage compared to the species and a scarlet red fall color. 'Red October' was introduced in 2013 by Intrinsic Perennial Gardens, Inc. (Hebron, IL) (Missouri Botanical Garden, 2020a).

Chinese silvergrass is a perennial warm season grass with short rhizomes and a mature height ranging from 1-3 m. Leaves are approximately 9-mm wide with serrated edges and have a white to silver midrib. Culms terminate with a panicle 20-25 cm long. Chinese silvergrass tolerates sandy to fine textured soils and full sun to partial shade conditions (Missouri Botanical Garden, 2020d and Quinn et al., 2012). Only cultivated varieties are recommended for landscape planting because the species can self-seed aggressively (Meyer, 2012). The cultivar, Purpurascens, has orange-red fall color and reaches a height of approximately 1 m (Missouri Botanical Garden, 2020d).

Little bluestem is a warm-season bunchgrass, sometimes having short rhizomes, and is widely distributed across the U.S. and Canada with numerous ecotypes. Little bluestem tolerates sandy to clay-loam textured soils and is commonly found on dry upland sites such as ridges. Mature height ranges from 0.3-1 m. Culms are slightly flattened and terminate with a single raceme that is 2.5-7.5 cm long. Leaves range in length from 5-30 cm and 1.5-6 mm in width (Tober and Jensen, 2013). The cultivar Blue Heaven is approximately 1.5 m tall with foliage colors of light purple and light blue, red, pink, burgundy, and orange. 'Blue Heaven' was selected by the University of Minnesota from open-pollinated seed collected in 1995 from a seed production field near Princeton, Minnesota (Meyer, 2006).

Blue grama is a warm-season bunchgrass, although some ecotypes may have short rhizomes, reaching a mature height of 20-60 cm. Leaves are blue-gray, approximately 6 mm wide and range in length from 7.5-15 cm. The culms terminate with an inflorescence that look similar to a human eyebrow. Blue grama is tolerant of soils ranging from sandy to clayey and has good drought tolerance but is not adapted to frequent flooding, submergence, shade, and acid soils (Wynia, 2007 and Missouri Botanical Garden, 2020c). The cultivar, Blonde Ambition, has an inflorescence that emerges with a chartreuse color and ages to blonde which is unique compared with ‘Hachita,’ a commercially available cultivar, with blue-green inflorescences that age to a brown color. ‘Blonde Ambition’ was the result of a whole plant mutation from a ‘Hachita’ blue grama plant found in 2007 in Santa Fe, NM in a residential yard (Salman, 2011).

Feather reed grass is a cool-season clump grass with a mature height of approximately 1.5 m. Leaves are bright green and upright. Culms terminate with a raceme. Feather reed grass is best adapted to full sun planting locations and is tolerant of moist to wet soils. The cultivar, Karl Foerster, is named after the nurseryman that discovered the plant in Germany and produces no seed (Meyer, 2012 and Missouri Botanical Garden, 2020b). In 2001, ‘Karl Foerster’ won the Perennial Plant Association’s Perennial Plant of the Year® award (Perennial Plant Association, 2020).

Cyclical flooding and drought

Plants growing in a rain garden rely on precipitation to satisfy water requirements. Depending on the frequency of rainfall, water may be in excess or limited. As the rain garden fills with stormwater, plants within the rain garden will experience partial or complete submergence. Subsequently, additional water is limited until the next stormwater event since rain gardens typically receive minimum maintenance and no irrigation.

During periods of frequent rainfall, a rain garden may experience waterlogged soil for several days. In some cases, plants may be partially or completely submerged for several days. Waterlogged soils quickly become deficient in oxygen as plant roots and soil microbes use the available soil oxygen while oxygen slowly replenishes from the atmosphere by diffusion through water (i.e., is 10^4 fold slower through water than air; Armstrong and Drew, 2002). Low soil oxygen levels reduce carbohydrate reserves in the root resulting in reduced root growth and root function and ultimately plant death if low soil oxygen levels persist long enough. Some plants have the ability to survive waterlogged soil conditions by reducing radial oxygen loss from roots, aerenchyma formation, and the formation of adventitious roots (Sauter, 2013).

Following stormwater events, the available soil water level may drop below a plant's threshold for drought stress. A common response to drought stress is stomatal closure (Farooq et al., 2012). Closing stomata reduces the amount of water vapor leaving the plant but at the same time photosynthesis is reduced because carbon dioxide is not able to enter the plant. Plants that utilize the C_3 photosynthetic pathway are more susceptible to drought stress compared with plants that utilize the C_4 photosynthetic pathway because the C_4 pathway is more efficient and uses less water to produce a gram of biomass. For example, C_3 grasses require approximately three times more water to produce a gram of dry matter compared with C_4 grasses (Christians et al., 2017). Prolonged drought results in reduced dry matter accumulation which is attributed to reduced cell elongation and division (Farooq et al., 2012). Plants use a variety of strategies to survive drought such as adapting physiological and biochemical reactions and altering plant morphology.

Available literature evaluating the flooding tolerance of the seven ornamental grass species listed in Table 1 is limited. A study by Yuan and Dunnett (2018) evaluated the flooding tolerance of Chinese silvergrass. Plants were grown in 2-L containers and flooded with water to the level of the substrate for one or four days and then allowed to freely drain for a period of four days. After draining, the flood treatment was repeated. The one-day and four-day treatments went through seven and four flooding cycles, respectively. At the end of the trial, there was no significant difference between the flooding treatments or the control for shoot and root dry

Table 1-1. Ornamental grass species and cultivar, common name, photosynthetic pathway, wetland indicator status, and origin of plant material. Wetland indicator status, description, and designation are from Lichvar et al. (2016) and the U.S. Army Corps of Engineers (2022).

Scientific name and cultivar	Common name	Origin of plant material	Photosynthetic pathway	Wetland indicator status (Great Plains)	Wetland indicator description and designation
Deschampsia cespitosa (L.) P. Beauv. ‘Pixie Fountain’	Tufted hairgrass	Emerald Coast Growers, Pensacola, FL	C_3	Facultative wetland (FACW)	Usually occur in wetland, but may occur in non-wetland (hydrophyte)
Panicum virgatum L. ‘Northwind’	Switchgrass	Emerald Coast Growers, Pensacola, FL	C_4	Facultative (FAC)	Occur in wetland and non-wetland (hydrophyte)
Andropogon gerardii Vitman ‘Red October’	Big bluestem	Emerald Coast Growers, Pensacola, FL Hoffman Nursery, Rougemont, NC Paul Bunyan Nurseries, West Fargo, ND	C_4	Facultative Upland (FACU)	Usually occur in non-wetland, but may occur in wetland. (non-hydrophyte)
Miscanthus sinensis Andersson ‘Purpurascens’	Chinese silvergrass	Emerald Coast Growers, Pensacola, FL Hoffman Nursery, Rougemont, NC Walters Gardens, Zeeland, MI	C_4	Facultative Upland (FACU)	Usually occur in non-wetland, but may occur in wetland. (non-hydrophyte)
Schizachyrium scoparium (Michx.) Nash ‘Blue Heaven’	Little bluestem	Hoffman Nursery, Rougemont, NC Walters Gardens, Zeeland, MI	C_4	Facultative Upland (FACU)	Usually occur in non-wetland, but may occur in wetland. (non-hydrophyte)
Bouteloua gracilis (Kunth) Lag. ex Griffiths ‘Blonde Ambition’	Blue grama grass	Emerald Coast Growers, Pensacola, FL Hoffman Nursery, Rougemont, NC	C_4	Upland*	Almost never occur in wetland (non-hydrophyte)
Calamagrostis x *acutiflora* (Schrad.) Rchb. ‘Karl Foerster’	Feather reed grass	Emerald Coast Growers, Pensacola, FL	C_3	Upland*	Almost never occur in wetland (non-hydrophyte)

*Plant is not listed on National Wetland Plant List and therefore considered an upland plant.

weight. Plant height was increased by flooding for one and four days when compared with the control but only significantly for the one-day flood treatment. Chinese silvergrass may have experienced drought stress during the study given that plants were allowed to dry for four days between flooding treatments. However, that is unknown because soil water content and matric potential were not presented in the study.

Scientific studies evaluating the flooding tolerance of the other six species do not exist. Using the wetland indicator status as a guide (Table 1), tufted hairgrass and switchgrass are facultative wetland and facultative, respectively, and are likely able to tolerate flooded conditions. Big bluestem and little bluestem are facultative upland plants and are likely able to tolerate some flooding while blue grama grass and feather reed grass are upland plants and are less adapted to flooding. A study by Nelson et al. (2018) evaluated seven sedge species with a wetland indicator status of obligate, facultative wetland, facultative, facultative upland, or upland to cyclical flood and drought stress. Sedges with a wetland indicator status of facultative upland, facultative, or facultative wetland were best able to handle repeated stress from flooding and drought.

Few scientific studies exist that evaluate the effect of flood depth and duration on the growth and survival of grasses. A study evaluating survival and biomass production of 14 wetland plants subjected to seven different water depths ranging from 6 cm below the soil surface to 6 cm above the soil surface found that as flooding depth increased the percent survival decreased as well as total biomass. Three of the 14 species were perennial grasses; blue-joint grass [*Calamagrostis canadensis* (Michx.) Beauv.], Virginia wildrye (*Elymus virginicus* L.), and rattlesnake mannagrass [*Glyceria canadensis* (Michx.) Trin.]. It is important to note that flooding lasted six months and at the start of flooding the grasses were only two weeks old (Fraser and

Karnezis, 2005). Studies evaluating flood depth and duration of the seven grass species in the proposed study do not exist.

To our knowledge, no scientific studies have evaluated the drought tolerance of the seven grass species selected for the present sequence of experiments. Given that C_4 plants are more tolerant of drought compared with C_3 plants, the C_4 grasses; switchgrass, big bluestem, Chinese silvergrass, little bluestem, and blue grama grass should be more tolerant than the C_3 grasses, tufted hair grass and feather reed grass. Additionally, tufted hairgrass is a facultative wetland plant and should be less adapted to drought compared with the other six grass species that have a wetland indicator status of facultative, facultative upland, and upland.

In general, for the seven grass species selected for this trial, there appears to be no existing scientific literature reporting on their tolerances to the individual effects of flood duration, submergence, and drought. The only exception is that of flood duration on Chinese silvergrass by Yuan and Dunnett (2018). Moreover, there appears to be no existing scientific literature on the evaluation of real-world combination of flooding and drought on the growth and survival of the seven grass species.

Salinity stress

In the U.S. and Canada, NaCl is commonly used to control ice and snow on roadways, parking lots, and sidewalks. The U.S. in 2005 applied an estimated 21 million Mg of NaCl to roadways while Canada in 2001 applied an estimated 5 million Mg to combat snow and ice (Sander et al., 2007 and Howard and Maier, 2007). Sodium chloride is readily available and inexpensive compared with other products such as CaCl and MgCl (Kelting and Laxson, 2010). Sodium chloride has a high solubility and readily dissolves in water. Once applied to an impervious surface, snowmelt and rainfall will transport the salt to stormwater catchment basins such as retention ponds and rain gardens, a receiving body of water, or groundwater (Sander et al., 2007). Rain gardens that collect runoff from parking lots or streets are likely to receive and accumulate significant quantities of NaCl during spring melt that could increase to harmful levels in some plants.

As salt levels increase in the soil, plants will become stressed once a certain threshold is reached. The first to occur is osmotic stress followed by ion toxicity. Osmotic stress occurs once the salt concentration around the roots reaches a certain threshold resulting in reduced shoot growth and growth rate. If plants survive osmotic stress, then over time, ions could accumulate in plant tissues to toxic levels resulting in senescence (Munns and Tester, 2008). The threshold levels needed to induce osmotic stress and ion toxicity will vary based on plant species and their ability to tolerate soil salinity.

Plant mechanisms to tolerate soil salinity may include reduced salt uptake into the plant (i.e., by exclusion from the root system and reduced leaf and shoot growth) and reducing salt concentration in the cytoplasm (i.e., compartmentalizing salt into the vacuole and excretion by salt glands) (Munns and Tester, 2008). Plants with a low soil salinity threshold will have reduced shoot growth and increased leaf senescence and over time will result in plant death while plants with a higher threshold will be able to tolerate the saline soil conditions.

Scientific studies evaluating sodium chloride tolerance of ornamental grasses is limited. A study by Sun and Palmer (2018) evaluated the salt tolerance of blue grama grass as well as seven other species. Grasses were greenhouse grown in 3.8-L containers and watered weekly with saline solutions with an electrical conductivity (EC) of 1.2 $dS{\cdot}m^{-1}$ (control), 5.0 $dS{\cdot}m^{-1}$, and 10 $dS{\cdot}m^{-1}$. The 5.0 and 10 $dS{\cdot}m^{-1}$ saline solutions were prepared using NaCl and CaCl. After nine weeks, blue grama grass irrigated with saline solutions with an EC of 5.0 $dS{\cdot}m^{-1}$ and 10

$dS{\cdot}m^{-1}$ had a significantly lower visual score rating (3.8) when compared with the control (5.0) when using a 0-5 rating scale [0 = dead, 3 = slight foliar damage (<50%), 5= no foliar salt damage]. Plant height was also reduced, approximately 13%, for blue grama plants irrigated with the saline solution with an EC of 10 $dS{\cdot}m^{-1}$ compared with the other two treatments. After 19 weeks, blue grama plant height was significantly reduced by 18% and 22% when compared with the control for plants irrigated with saline solutions with an EC of 5.0 and 10 $dS{\cdot}m^{-1}$. Although height was reduced, there were no significant differences among treatments for the number of inflorescences, number of tillers, leaf area, or dry weight of shoots and roots indicating that the grasses were still growing. A study by Miyamoto (2008) found two cultivars of blue grama grass, 'Alamo' and 'Bad River' continued to produce top growth when irrigated with a saline solution at an EC of 9.4 $dS{\cdot}m^{-1}$ but top growth stopped when the saline solution increased to an EC of 13.7 $dS{\cdot}m^{-1}$.

A similar study by Wang et al. (2019) evaluated the salt tolerance of 'Gracillimus' Chinese silvergrass, 'Northwind' switchgrass, little bluestem, and purple love grass by watering greenhouse grown plants (7.6-L containers) every four days using saline solutions with an EC of 1.2 (control), 5.0, or 10 $dS{\cdot}m^{-1}$ over the course of 65 days. Saline solutions with an EC of 5.0 and 10 $dS{\cdot}m^{-1}$ were prepared using NaCl and CaCl. Saline solutions with an EC of 5.0 and 10 $dS{\cdot}m^{-1}$ did not reduce the visual score (0 – 5 scale; Sun and Palmer, 2018) for little bluestem or switchgrass when compared to their respective control. The visual score for Chinese silvergrass was significantly reduced for the 5.0 and 10 $dS{\cdot}m^{-1}$ saline solutions when compared to the control but the scores were 3.3 and 3.7, respectively, indicating only slight foliar salt damage. Plant height was significantly reduced by 15% for all grass species irrigated with the saline solution with an EC of 10 $dS{\cdot}m^{-1}$ when compared with the control while plants irrigated with the saline solution at an EC of 5.0 $dS \cdot m^{-1}$ were similar to the control. The leaf area of all grasses were reduced when irrigated with solutions with an EC of 5.0 or 10 $dS \cdot m^{-1}$ by 22% and 47%, respectively, and shoot dry weight was reduced by 25% and 46%, respectively, when compared with the control.

The salt tolerance of tufted hairgrass was evaluated by Henschke (2016) using different concentrations of NaCl to give the following EC values of the soil saturation extract (EC_e); 2.0 (control), 2.5, 3.5, 4.0, and 5.7 $dS \cdot m^{-1}$. Salt solutions were applied only once to plants growing in 750 cc pots. After 56 days of growth, all saline solutions significantly reduced the number of mature shoots from 21% - 47% when compared with the control. The length of shoots and leaves were similar to the control for solutions with an EC_e of 2.5 and 3.5 $dS \cdot m^{-1}$ while plants irrigated with solutions with an EC_e of 4.0, and 5.7 $dS \cdot m^{-1}$ were significantly reduced when compared with the control.

Although previous research has been conducted with blue grama grass, Chinese silvergrass, little bluestem, tufted hairgrass, and switchgrass, the cultivars that were used are different than the cultivars being used in this research with the exception of 'Northwind' switchgrass. It is possible that cultivars of the same species differ in their level of salt tolerance. Therefore, it is critical to evaluate specific cultivars of the species if those cultivars are to be grown in areas receiving salts or prone to salinization.

Hydrocarbon stress

Petroleum hydrocarbons are a common pollutant detected in stormwater runoff (Davis et al., 2009). Petroleum hydrocarbons found in stormwater may come from impervious surfaces such as parking lots and streets, as a result of motor vehicle use, or from the erosion of tar-based seal coats used on driveways and parking lots (LeFevre et al., 2012). Some petroleum hydrocarbons such as, coal tar-based seal coats, are of special concern because they contain high concentrations of polycyclic aromatic hydrocarbons (PAHs) which are known human carcinogens and are known to cause harm to aquatic environments (Mahler et al., 2016).

Rain gardens that collect stormwater from driveways, parking lots, and streets are likely to have higher amounts of petroleum hydrocarbons in the soil compared with sites not collecting stormwater runoff. For example, Lefevre et al. (2012) sampled 58 rain gardens in Minneapolis, Minnesota and quantified the total petroleum hydrocarbon (TPH) concentrations and compared the value with four upland sites that did not collect stormwater runoff. Rain gardens collecting stormwater from commercial parking lots had higher median TPH concentrations of approximately 1.1 $\mu g \cdot kg^{-1}$ of dry soil compared with rain gardens collecting stormwater from residential streets and roofs (approximately 0.3 $\mu g \cdot kg^{-1}$ of dry soil). It is important to note the values were not significantly different from one another and all TPH concentrations were well below limits requiring corrective action. For example, the MPCA requires corrective action when surface soils are contaminated with petroleum in excess of 10,000 $\mu g \cdot kg^{-1}$. The TPH levels in the rain garden soils were significantly greater than the TPH levels found in the upland sites. Levels of TPH were far less than expected in rain garden soils given TPH concentrations in stormwater suggesting that rain gardens are able to biodegrade petroleum hydrocarbons.

LeFevre et al. (2012) also found that rain gardens planted with deep rooted vegetation (deeper than 15 cm) had more soil bacteria compared with rain gardens covered with turfgrass or mulch suggesting that rain gardens with deep rooted plants are better able to assimilate petroleum hydrocarbons. Plant roots increase microbial populations due to the release of root exudates and oxygen used by soil microbes (Chaudhry et al., 2005). Grasses have a fibrous root system allowing for ample surface area for soil microorganisms. As the soil microbial population increases, so does the breakdown of petroleum hydrocarbons. A study evaluating nine Australian native grass species found that all the grass species increased the soil microbial population when seeded into a soil contaminated with a diesel and oil mixture at concentrations of 1% (w/w), 0.5% (w/w), and 0% (control). Three of the species had increased root biomass in contaminated soil compared with the control (Gaskin et al., 2008).

Currently, there is no research reported in the scientific literature on the ability of the seven cultivars of grasses used in this study to grow when subjected to petroleum hydrocarbon contamination or their ability to promote phytoremediation of contaminated stormwater and soils. It is likely that rain gardens in northern climates receiving runoff from parking lots will also have higher concentrations of sodium chloride as well as TPH. Therefore determining the ability of the seven cultivars of grasses to breakdown petroleum hydrocarbons while enduring salt stress is essential for making recommendations for rain gardens to provide multiple services.

Research objectives

Currently, there is essentially no scientific literature on a large quantity of ornamental grass species and cultivars to help build recommendations for their use, performance, and expected outcomes in urban rain gardens. Therefore, the objectives of this research are as follows:

1) Determine the effect of cyclical flood and drought on the growth and survival of seven species of ornamental grass using one commercially available cultivar for each species.
2) Determine the effect of flood depth and duration on the growth and survival of seven species of ornamental grass using one commercially available cultivar for each species.

3) Determine the salt tolerance, using sodium chloride, of seven species of ornamental grass using one commercially available cultivar for each species.
4) Determine the ability of ornamental grasses to degrade hydrocarbons while enduring salt stress. Grasses with sufficient salt tolerance will be subjected to two petroleum hydrocarbon levels and three levels of sodium chloride (including a control).

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CHAPTER II. EVALUATION OF SEVEN ORNAMENTAL GRASS CULTIVARS TO CYCLICAL FLOOD, DROUGHT AND SUBMERGENCE

Introduction

Prior to 2008, a majority of the world population lived in rural areas. By 2018, 55% of the world population lived in urban areas and this number is projected to increase to over 67% by 2050 (United Nations, 2019). Urban settlements with fewer than 500,000 people are estimated to be home for 45% of the world's urban population by 2030 (United Nations, 2014). In the U.S., the urban population grew 12% from 2000-2010 making the U.S. one of the most urbanized countries in the world with over 80% of the population living in urban areas (U.S. Census Bureau, 2010). As urban areas expand, so does the amount of area covered by impervious surfaces (i.e. buildings, driveways, roads, and parking lots) making stormwater management an increasing priority. Stormwater runoff entering directly into waterways (e.g., lakes, rivers, and streams) can increase water temperature, bank erosion, flooding, and pollutant levels, compromising water quality [U.S. Environmental Protection Agency (U.S. EPA), 2008]. However, holding stormwater in the urban landscape by using bioretention structures, such as rain gardens, aid in reducing runoff and pollutant loads entering waterways.

Rain gardens have gained favor for commercial and residential development to reduce potential flooding, increase water infiltration, and improve stormwater quality by removing pollutants (Asleson et al., 2009; Hunt et al., 2008). A rain garden is a shallow basin in the landscape that is planted with herbaceous and sometimes woody perennial plants and often covered with shredded wood mulch. Rain gardens collect stormwater from impervious surfaces such as a roof, road, or parking lot. Rain gardens vary in size and are commonly 20-30% of the impervious surface area (Jennings et al., 2015). The ponding depth may vary from 15 – 46 cm depending on the area of impervious surface that drains into the rain garden and the hydraulic conductivity of the soil [Davis et al., 2009; Minnesota Pollution Control Agency (MPCA), 2021]. To prevent mosquito breeding, ponded water should drain within 24 hours and the soil pore space become unsaturated within 48-96 hours (Davis et al., 2009; MPCA, 2021).

Plants growing in a rain garden rely on precipitation to satisfy water requirements. Depending on the frequency of rainfall, water may be in excess or scarce. As the rain garden fills with stormwater, plants experience partial or complete submergence. Subsequently, additional water is limited until the next stormwater event since rain gardens typically receive minimum maintenance and no irrigation. It is critical that plants used in rain gardens are tolerant to periodic flooding and drought and stormwater pollutants.

Perennial ornamental grasses are often recommended for rain gardens, but few scientific studies exist to support their recommendation and often times only the species is recommended (Hausken and Thompson, 2018; Meyer, 2004; Meyer, 2012; Steiner and Domm, 2012). Several ornamental cultivars of perennial grasses are currently available that offer improved tolerance to lodging and foliage coloration when compared to the species (e.g., native little bluestem compared with 'Blue Heaven' little bluestem). These ornamental grasses include 'Pixie Fountain' tufted hairgrass [*Deschampsia cespitosa* (L.) P. Beauv.], 'Northwind' switchgrass (*Panicum virgatum* L.), 'Red October' big bluestem (*Andropogon gerardii* Vitman), 'Purpurascens' Chinese silvergrass (*Miscanthus sinensis* Andersson), 'Blue Heaven' little bluestem [*Schizachyrium scoparium* (Michx.) Nash], 'Blonde Ambition' blue grama grass [*Bouteloua gracilis* (Kunth) Lag. ex Griffiths], and 'Karl Foerster' feather reed grass [*Calamagrostis* x *acutiflora* (Schrad.) DC] (Thetford et al., 2009). Note that Chinese silvergrass has the synonym *Miscanthus sinensis* var. *purpurascens* and is frequently sold in the horticultural trade under this name (Integrated Taxonomic Information System, 2022).

Available literature evaluating flooding, drought, and submergence tolerance of the seven ornamental grass species previously listed is severely limited and virtually nonexistent for the cultivars. Yuan and Dunnett (2018) repeatedly flooded Chinese silvergrass with water to the level of the substrate for one or four days and then allowed to freely drain for a period of four days. They observed flooding to significantly increase plant height for the one-day flood compared with the control, but no significant effects on shoot and root dry weight. Barney et al. (2009) flooded four cultivars of switchgrass, two from lowland environments ‘Alamo’ and ‘Kanlow’ and two from upland environments ‘Cave-In-Rock’ and ‘Blackwell,’ for 11 weeks (2-5 cm above the soil surface). All grasses survived continuous flooding. Plant height, shoot count, and shoot and root weights were similar for grasses in the flooded treatment compared with their respective controls. However, the lowland cultivars had higher values for the measured parameters when compared with the upland cultivars.

Using the wetland indicator status [Lichvar et. al., 2016; US Army Corps of Engineers (USACE) 2022] for the species as a guide (Table 1), tufted hairgrass and switchgrass are facultative wetland and facultative, respectively, and are likely able to tolerate flooded conditions. Big bluestem and little bluestem are facultative upland plants and are likely able to tolerate some flooding, while blue grama grass and feather reed grass are upland plants and less adapted to flooding. Nelson et al. (2018) evaluated seven sedge species with a wetland indicator status of obligate, facultative wetland, facultative, facultative upland, or upland to cyclical flood and drought stress. Sedges with an intermediate wetland indicator status of facultative upland, facultative, or facultative wetland were best able to handle repeated stress from flooding and drought that simulated rain garden environments.

Few scientific studies exist that evaluate the effect of flood depth and duration on the growth and survival of grasses. For instance, Fraser and Karnezis (2005) evaluated 14 wetland species to seven different water depths (i.e., ranging from 6 cm below to 6 cm above the soil surface) found the total biomass and percent survival to decrease with increasing flooding depth (Fraser and Karnezis, 2005). Three of the 14 species were perennial grasses; blue-joint grass [*Calamagrostis canadensis* (Michx.) Beauv.], Virginia wildrye (*Elymus virginicus* L.), and rattlesnake mannagrass [*Glyceria canadensis* (Michx.) Trin.] (Fraser and Karnezis, 2005). To our knowledge, studies evaluating flood depth and duration of the seven ornamental grass cultivars previously listed do not exist.

Similarly, few to no scientific studies have evaluated the drought tolerance of the seven grass species previously listed and no studies have evaluated the cultivars. Stavridou et al. (2019) found no difference in shoot or root biomass for two genotypes of Chinese silvergrass when grown under 80% of soil field capacity measured gravimetrically compared with 15% of soil field capacity. Similar results were found by Clifton-Brown and Lewandowski (2000) when Chinese silvergrass was grown at 16-18% soil gravimetric water content (GWC) (0.0 MPa; no drought), 9% soil GWC (moderate drought; about -0.5 MPa), and 6% soil GWC (severe drought; about -0.8 MPa). The authors noted that no leaf senescence was observed on Chinese silvergrass regardless of soil GWC. Dougherty et al. (2015) found similar gains in plant height and shoot count within each of seven cultivars of Chinese silvergrass 'Adagio,' 'Autumn Light,' 'Dixieland,' 'Gracillimus,' 'Graziella,' Variegatus,' and 'Zebrinus' grown for 16 weeks under four soil matric potential treatments ranging from -0.02 MPa to -4.05 MPa. Barney et al. (2009)

also evaluated drought stress of four switchgrass cultivars. Grasses maintained at 25-30% soil VWC (0.0 MPa; saturated) and 5% soil VWC (-4.2 MPa) all survived the 11-week experiment. Grasses maintained at 5% soil VWC had reduced plant height, shoot count, and shoot and root weights when compared with plants kept at 25-30% soil VWC. Interestingly, no differences occurred between the lowland and upland cultivars. Similar results were found by Mann et al. (2013) when shoot and root mass of 'Alamo' switchgrass was reduced under drought conditions (≤ -1.0 MPa at a depth of 30 cm) when compared with a well-watered control (≥ -0.01 MPa). Given that C_4 plants are more tolerant of drought compared with C_3 plants, the C_4 grasses (switchgrass, big bluestem, Chinese silvergrass, little bluestem, and blue grama) should be more tolerant than the C_3 grasses (tufted hair grass and feather reed grass) (Taylor et. al., 2014). Additionally, tufted hairgrass is a facultative wetland plant and should be less adapted to drought compared with the other seven grass species that have a wetland indicator status of facultative, facultative upland, and upland.

For the cultivars of the seven grass species previously identified, there appears to be no existing scientific literature reporting on the evaluation of real-world combination of flooding and drought or submergence depth and duration. Therefore, two experiments were conducted to answer our research objectives: Experiment 1) determine the effect of cyclical flood and drought on the growth and survival of the listed grasses. Experiment 2) determine the effect of submergence depth and duration on the growth and survival of the listed grasses.

Materials and methods

Plant material. For both experiments, grasses were purchased, as plugs, from commercial greenhouses (Table 2-1) and represent four of the five wetland indicator categories in the National Wetland Plant List for the Great Plains region [Lichvar et. al., 2016; US Army

Corps of Engineers (USACE) 2022]. Grasses were transplanted into 1.07 L (10.7 cm wide x 8.7 cm tall) square pots (T.O. Plastic, Clearwater, MN) filled with Pro Mix BRK (Premier Tech Horticulture, Quakertown, PA) containing 45-55% sphagnum peat moss, processed pine bark, perlite, and limestone (to adjust pH). The potting medium was amended with five grams of Multicote 14-14-16 (Haifa North America, Savannah, GA) per 1.07 L pot. Grasses were kept in a greenhouse located on the North Dakota State University Campus, Fargo, ND, U.S.A. (latitude 46° 52' 38" N and longitude 96° 48' 18" W) maintained at a minimum of 21 °C with a 14-h photoperiod until needed for experiments.

Grasses were cut to a height of 25 cm, roots washed free of potting media, and planted into 2.9 L (16.5 cm wide x 17.8 cm tall) nursery containers (Meyers Industries, Akron, Ohio) filled with a mixture of all-purpose play sand, topsoil from a Barnes soil series (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) (Soil Survey Staff, 2011), and peat moss (5:4:1 by volume). Shoot counts at planting for tufted hair grass, switchgrass, big bluestem, Chinese silvergrass, little bluestem, blue grama grass, and feather reed grass were 40, 15, 10, 25, 15, 25, and 20, respectively (experiment 1) and 40, 10, 7, 12, 15, 25, and 20, respectively (experiment 2). Grasses were placed in a greenhouse, fertilized every two weeks with a water-soluble fertilizer (20N-8.7P-16.6K; JR Peters Inc., Allentown, PA) with each pot receiving 200 $mg \cdot L^{-1}$ (N), 87 $mg \cdot L^{-1}$ (P), and 166 $mg \cdot L^{-1}$ (K) and allowed to establish for at least three months before starting the experiment. During establishment, grasses were treated with a onetime application of 1.0 g FeDTPA (Sprint 330, BASF Corporation, Triangle Park, NC) applied to each container to correct iron deficiency chlorosis (IDC). For experiment 2, a onetime application of 5.3 g of imidacloprid (Marathon 1% G, OHP, Inc., Bluffton, SC) was applied to each pot of run 2 for mealybug control. Supplemental heat was provided when temperatures dropped below 18 °C and the air cooled when temperatures reached 25 ˚C. Experiment 1 was started in 2019 on 6 Oct. (run 1, 124 d), and in 2020 on 6 Jan. (run 2, 111 d), and 10 Apr. (run 3, 106 d). The average temperature during the study was 24.7 ˚C. Experiment 2 was started in 2020 on 20 Dec. (run 1) and in 2021 on 6 Feb. (run 2) with each run lasting 34 d. The average temperature during the study was 24.2 ˚C.

Preliminary study for drought set points. A preliminary study using tufted hair grass, switchgrass, Chinese silvergrass, little bluestem, and feather reed grass, was conducted to determine drought set points for the cyclical flood and drought study using three soil mixes. Grasses were cut to a height of 15 cm, potting medium was washed from roots, and plants were potted into 2.8 L (16.5 cm wide x 17.8 cm tall) nursery containers (Meyers Industries, Akron, Ohio). Nursery containers were filled with a mixture of topsoil from a Delamere soil series (coarse-loamy, mixed, superactive, frigid Typic Endoaquolls) (Soil Survey Staff, 2005), all-purpose play sand (TCC Materials, Mendota Heights, MN), and peat moss (Premier Tech Horticulture, Quakertown, PA) mixed 4:5:1 or 1:8.5:0.5 (by volume) or a soil mixture containing topsoil from a Barnes soil series (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) (Soil Survey Staff, 2011), all-purpose play sand, and peat moss mixed 4:5:1 (by volume). Grasses were allowed to establish for three months. During establishment, grasses were fertilized every two weeks as previously described. After establishment, plants were allowed to dry down over the course of 10 days with soil volumetric water content (VWC) readings taken daily using a handheld GS3 volumetric water content sensor connected to a ProCheck sensor readout storage system (Decagon Devices, Pullman, WA). After 10 days of dry down, grasses were watered and allowed to dry down for another 10 days with soil VWC readings taken daily. Daily visual observations were made of the foliage to note leaf roll, leaf wilt, and leaf dieback. No visible growth differences among grasses growing in the three soil mixes were noted during the study (data not shown). The soil mixture containing all-purpose play sand, Barnes soil, and peat moss mixed 5:4:1 (by volume) was selected for both studies because it is similar to a well-draining rain garden mix recommended by the MPCA (2021); 50-65% coarse sand, 25-35% topsoil, and 10-15% compost. Based on the preliminary study, visual plant damage did not occur until the soil VWC was less than 0.14 $m^3 \cdot m^{-3}$ (no visible plant damage) while severe visual plant damage occurred at 0.07 $m^3 \cdot m^{-3}$ (leaf wilt and leaf dieback) (Fig 2-1). Based on preliminary results, the drought set points of 0.14 $m^3 \cdot m^{-3}$ (drought onset) and 0.07 $m^3 \cdot m^{-3}$ (severe drought) were selected.

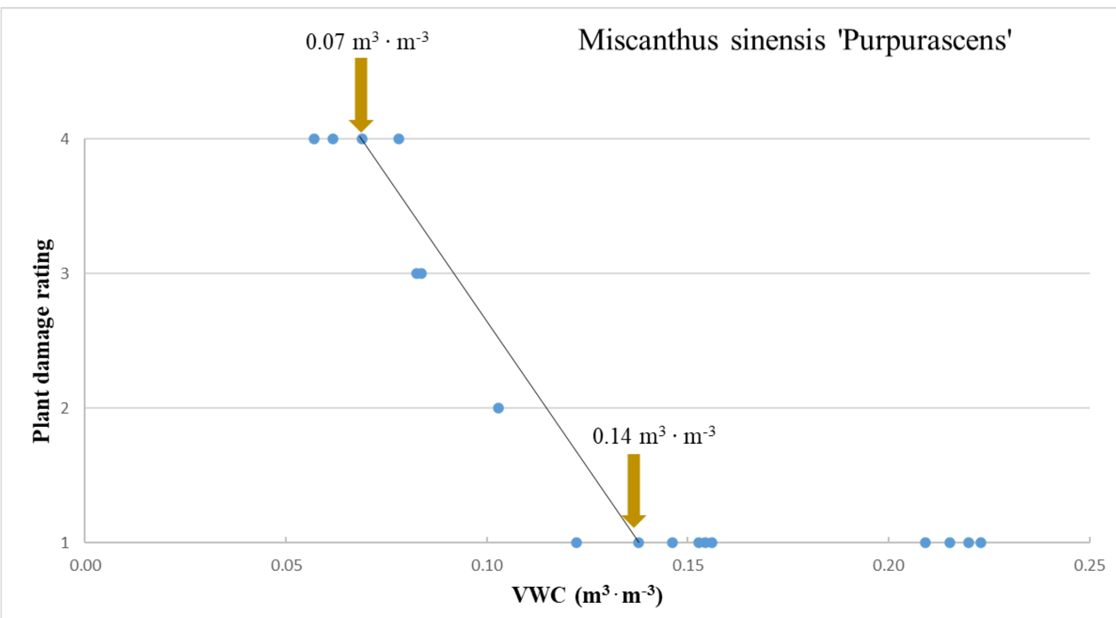

Figure 2-1. Typical plant damage rating (1= no plant damage; 2= beginning leaf roll; 3= leaf roll or leaf roll and leaf wilt; 4= leaf dieback) for a given substrate volumetric water content (VWC). Visual damage ratings and VWC were taken daily from 9 – 29 Sept. 2019 from perennial ornamental grasses growing in a greenhouse on the NDSU campus, Fargo, ND.

Table 2-1. Ornamental grass species and cultivar, common name, photosynthetic pathway, wetland indicator status, and origin of plant material. Wetland indicator status, description, and designation are from Lichvar et al. (2016) and the U.S. Army Corps of Engineers (2022).

Scientific name and cultivar	Common name	Origin of plant material	Photosynthetic pathway	Wetland indicator status (Great Plains)	Wetland indicator description and designation
Deschampsia cespitosa (L.) P. Beauv. ‘Pixie Fountain’	Tufted hairgrass	Emerald Coast Growers, Pensacola, FL	C_3	Facultative wetland (FACW)	Usually occur in wetland, but may occur in non-wetland (hydrophyte)
Panicum virgatum L. ‘Northwind’	Switchgrass	Emerald Coast Growers, Pensacola, FL	C_4	Facultative (FAC)	Occur in wetland and non-wetland (hydrophyte)
Andropogon gerardii Vitman ‘Red October’	Big bluestem	Emerald Coast Growers, Pensacola, FL Hoffman Nursery, Rougemont, NC Paul Bunyan Nurseries, West Fargo, ND	C_4	Facultative Upland (FACU)	Usually occur in non-wetland, but may occur in wetland. (non-hydrophyte)
Miscanthus sinensis Andersson ‘Purpurascens’	Chinese silvergrass	Emerald Coast Growers, Pensacola, FL Hoffman Nursery, Rougemont, NC Walters Gardens, Zeeland, MI	C_4	Facultative Upland (FACU)	Usually occur in non-wetland, but may occur in wetland. (non-hydrophyte)
Schizachyrium scoparium (Michx.) Nash ‘Blue Heaven’	Little bluestem	Hoffman Nursery, Rougemont, NC Walters Gardens, Zeeland, MI	C_4	Facultative Upland (FACU)	Usually occur in non-wetland, but may occur in wetland. (non-hydrophyte)
Bouteloua gracilis (Kunth) Lag. ex Griffiths ‘Blonde Ambition’	Blue grama grass	Emerald Coast Growers, Pensacola, FL Hoffman Nursery, Rougemont, NC	C_4	Upland*	Almost never occur in wetland (non-hydrophyte)
Calamagrostis x *acutiflora* (Schrad.) Rchb. ‘Karl Foerster’	Feather reed grass	Emerald Coast Growers, Pensacola, FL	C_3	Upland*	Almost never occur in wetland (non-hydrophyte)

*Plant is not listed on National Wetland Plant List and therefore considered an upland plant.

Sensor calibration. The GS3 volumetric water content sensor was calibrated as described by Nelson et al. (2018). Briefly, soil was added to containers and a range of water contents was created by adding water in increments of 50 mL. Soil and water were carefully mixed and allowed to sit for 24 h. The GS3 sensor was inserted into the soil and a reading was taken. After taking the reading, gravimetric water content was determined and converted to VWC by multiplying by soil bulk density. Actual VWC (as determined by gravimetric water content) was plotted against VWC measured by the sensor. Because variation existed between actual and predicted VWC using factory settings, a soil specific equation was developed and used for the experiments:

$$\text{VWC} = (0.000134 \times \text{dielectric permittivity}^3) - (0.005598 \times \text{dielectric permittivity}^2) + (0.085629 \times \text{dielectric permittivity}) - 0.207856 \quad (1)$$

A water retention curve was developed for the soil mix containing all-purpose play sand, Barnes soil, and peat moss mixed 5:4:1 (by volume) as described by Nelson et al. (2018) (Fig. 2-2). Briefly, soil was placed into pressure chambers, pressure plates, and a dew point potentiometer to determine soil moisture between matric potentials of -10 to -300, -500 to -1500, and < -1500 kPa, respectively. Once removed from pressure chambers and plates, soil was weighed and oven dried for 48 hours at 105 ^oC. After drying, soil was weighed and gravimetric water content determined by subtracting soil wet weight from soil dry weight and dividing by dry weight. Gravimetric water content was converted to VWC by multiplying weight by the bulk density of the soil mix (i.e.,1.25 $g \cdot cm^{-3}$). To obtain the bulk density, three containers of known volume were filled with soil mix, placed in the greenhouse, and watered for 60 d. After 60 d, soil was weighed and dried at 105 ^oC for 48 h and reweighed. The mean soil bulk density was determined by dividing the dry weight of the soil mix by the volume of the soil mix for the three samples. Dewpoint potentiometer (WP4C, Decagon Devices Inc., Pullman, WA) readings were taken in a 20 °C constant temperature room and gravimetric and VWC of soil samples were determined as previously described. The measured VWC data were fitted to the van Genuchten (1980) model. Particle density for the soil mix (sand + Barnes soil + peat moss), sand, Barnes soil, and peat moss were 2.64, 2.68, 2.62, and 1.58 $g \cdot cm^{-3}$, respectively. Particle density was determined by the pycnometer method as described by Blake and Hartge (1986).

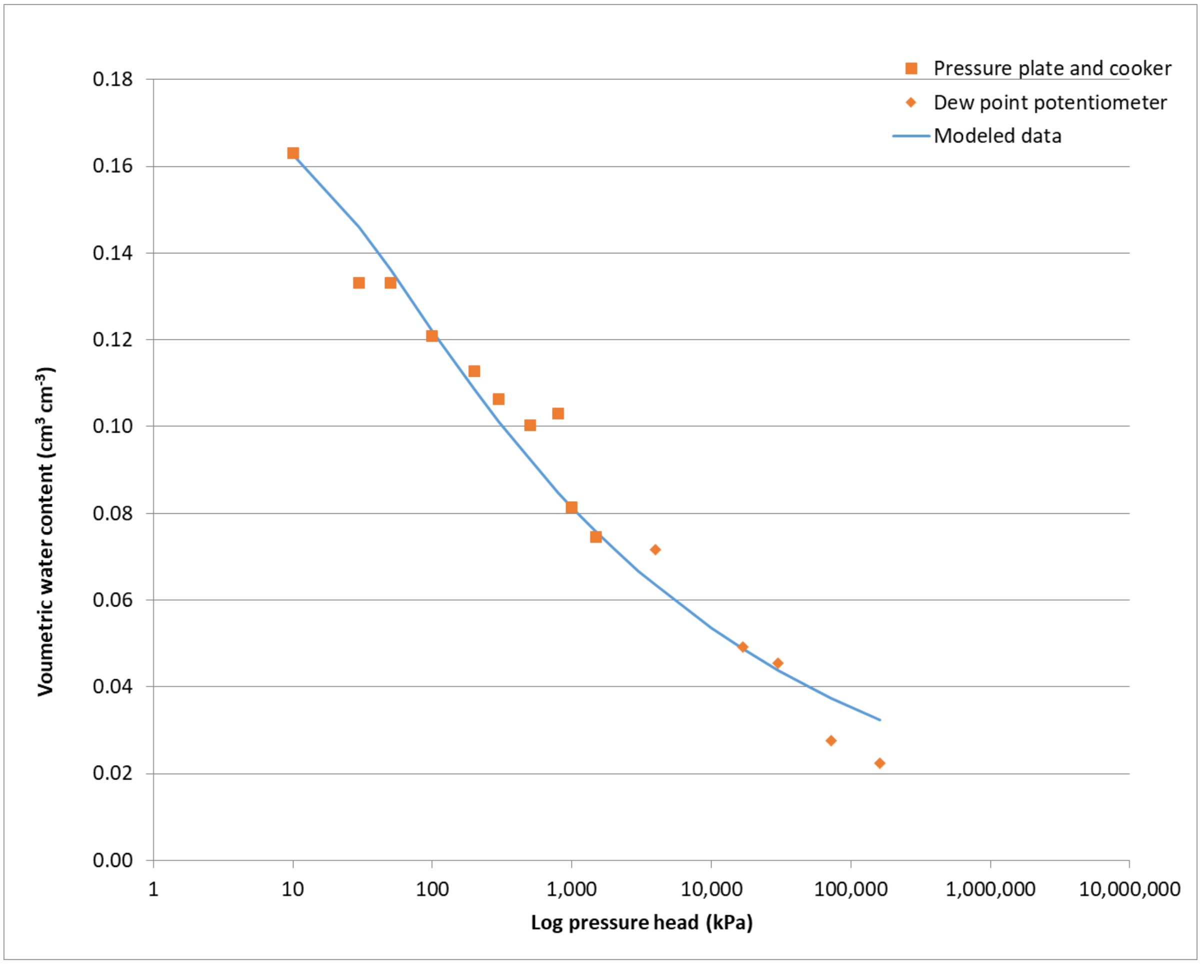

Figure 2-2. Water retention curve of a soil mixture containing all-purpose play sand, Barnes soil, and peat moss mixed 5:4:1 (by volume).

Soil and media mix. The Barnes soil used for both experiments was collected from a commercial farm field located in Fergus Falls, MN on 22 May 2019 that was planted with soybean [*Glycine max* (L.) Merr.] and managed without residual herbicides during the previous year. Soil was collected from the 0-15 cm profile, screened through a 9.5 mm sieve to remove large clods, and placed into 114-L plastic containers. Soil was dried in a greenhouse by spreading soil over a tarp laid over the greenhouse floor. Soil was raked every two days to facilitate drying. Soil was air dried for 18 d and three soil samples were randomly collected and sent to Agvise Laboratories, Northwood, ND, for analysis of pH, organic matter, electrical conductivity, NO_3, Olsen soil test P, K, Ca, Mg, Zn, S, Cl, Cu, Fe, Mn, B, Na, $CaCO_3$, and cation exchange capacity (Table 2-2). Dry soil was screened through 6.4-mm sieve to remove any remaining large clods and placed into 114-L plastic containers until needed for the experiment. Sand, Barnes soil, and peat moss (5:4:1 by volume) were added to a cement mixer (38 L volume) and allowed to mix for 5 m. After mixing, soil was placed into 11- L plastic containers until needed for the experiment. Three soil samples were collected from mixed soil and sent to Agvise Laboratories for the same analysis as previously described (Table 2-2).

Experiment 1. Grasses were provided a 12-h photoperiod with supplemental lighting using 400-w high-pressure sodium lights (P.L. Light Systems, Beamsville, ON, Canada) producing ≈ 139 $\mu mol \cdot m^{-2} \cdot s$ irradiance for the duration of the experiment. Grasses were flooded for 2 d or 7 d and allowed to dry down to one of two soil VWC set points for a total of four treatments plus a well-watered control. Control plants were watered as needed to maintain a soil VWC above 0.14 $m^3 \cdot m^{-3}$. The soil VWC set points of 0.14 $m^3 \cdot m^{-3}$ (drought onset) and 0.07 $m^3 \cdot m^{-3}$ (severe drought) had soil matric potentials of -40 kPa and -2500 kPa, respectively, and were selected based on data from the preliminary study. Flooding for 2 d represents a functioning rain garden while the 7-d flood represents a poorly drained rain garden. Flooding treatments were performed by placing the 2.9-L container with plant into another 2.9-L container lined with a 26.8 × 27.3 cm plastic bag (SC Johnson, Racine, WI).

Table 2-2. Soil chemical properties for Barnes soil and Mix containing 50% sand, 40% Barnes soil, and 10% peat moss (by volume).

Soil property	Barnes	Mix
Organic matter (%)	5.03 ± 0.15	2.33 ± 0.35
pH	7.87 ± 0.06	7.97 ± 0.06
Electrical conductivity ($dS{\cdot}m^{-1}$)	0.98 ± 0.03	0.45 ± 0.08
Calcium carbonate (%)	9.53 ± 0.35	7.53 ± 0.25
Cation exchange capacity ($cmol{\cdot}kg^{-1}$)	39.7 ± 0.78	31.3 ± 1.06
Nitrate ($mg{\cdot}kg^{-1}$)	120 ± 19.5	51.2 ± 6.25
Phosphorous (Olsen) ($mg{\cdot}kg^{-1}$)	78.0 ± 5.00	53.3 ± 8.39
Potassium ($mg{\cdot}kg^{-1}$)	328 ± 24.0	196 ± 15.7
Calcium ($mg{\cdot}kg^{-1}$)	6401 ± 108	5315 ± 136
Magnesium ($mg{\cdot}kg^{-1}$)	812 ± 22.4	499 ± 37.7
Sulfur ($mg{\cdot}kg^{-1}$)	8.67 ± 0.58	7.67 ± 0.58
Zinc ($mg{\cdot}kg^{-1}$)	2.22 ± 0.24	1.72 ± 0.27
Chlorine ($mg{\cdot}kg^{-1}$)	22.7 ± 1.15	27.0 ± 13.9
Copper ($mg{\cdot}kg^{-1}$)	0.93 ± 0.02	0.56 ± 0.05
Iron ($mg{\cdot}kg^{-1}$)	8.60 ± 0.10	8.67 ± 0.21
Manganese ($mg{\cdot}kg^{-1}$)	9.43 ± 0.25	11.2 ± 0.85
Boron ($mg{\cdot}kg^{-1}$)	2.28 ± 0.02	1.30 ± 0.12
Sodium ($mg{\cdot}kg^{-1}$)	22.0 ± 2.00	27.0 ± 2.65

Tap water was added to maintain a 1.25 cm layer of water on the soil surface. Water was added daily as needed to maintain the depth. After the flood duration was met, grasses were removed from flooding and allowed to freely drain for 24 h. After 24 h, soil VWC readings were taken daily, as previously described, until the respective drought set point was reached. Once the drought set point was reached the flood cycle was repeated. A grass species was removed from the trial once the 7-d flood and 0.07 $m^3{\cdot}m^{-3}$ severe drought set point went through four cycles of flood and drought. Individual plants were removed from the trial if no living tissue was visible.

After removal from the study, the following parameters were determined on each plant; plant height, shoot count, visual damage rating, shoot dry weight, and root dry weight. Plant height was determined by measuring from the soil surface to the height of the highest living leaf (grasses were pulled straight and then measured). Shoot counts were taken by counting all living shoots that were at least 1.25 cm above the soil surface. A visual damage rating was assigned to each plant using a 1 – 10 scale (1 = 0% to 10% dieback, 4 = 31% to 40% dieback, 7 = 61% to 70% dieback, and 10 = 91% to 100% dieback). Shoots were cut off at the soil line and roots washed free of soil, placed into separate paper bags, and set in a 65 ˚C dryer for 96 h. After drying, the dry weight of shoots and roots were determined using an electronic balance (LP6200S, Sartorius AG, Gottingen, Germany).

Experiment 2. Grasses were provided a 16 h photoperiod with supplemental lighting using 40-w fluorescent lights (Signify North America Corporation, Somerset, NJ) producing ≈ 13 $\mu mol \cdot m^{-2} \cdot s$ irradiance for the duration of the experiment. Grasses were submerged in tap water at 15 cm or 30 cm above the soil surface for 2, 4, or 7 d. After the submergence duration was met, grasses were removed and allowed to drain for two days and then submergence was repeated. The experiment was ended after the 7-d submergence duration treatments went through four cycles. Individual plants were removed from the trial if no living tissue was visible. Control plants were watered as needed to maintain a soil VWC above 0.14 $m^3 \cdot m^{-3}$. The same datapoints listed in experiment 1 were collected in experiment 2.

The soil VWC of the control plants was periodically monitored using a GS3 sensor as described previously. Submergence treatments were conducted by placing the 2.9-L container with grass into a 26.5-L pail (ULINE, Pleasant Prairie, WI). Tap water was added to bring the water depth 15 cm or 30 cm above the soil surface. Water was added as needed every two days to maintain the respective depth. Starting 24 h after submergence, water temperature, electrical conductivity, and dissolved oxygen were measured daily and water pH, nitrate, ammonium, and chloride levels measured periodically on all submergence treatments. All water measurements were taken approximately 7.6 cm above the soil using a HI9829 multiparameter probe (Hanna Instruments, Smithfield, RI) fit with sensors to determine the parameters previously described.

Reducing soil conditions (i.e., substrate oxygen status) were measured in one replicate of each run by placing a section of IRIS (Indicator of Reducing Conditions in Soil) tube (InMass Technologies, West Lafayette, IN) measuring approximately 15.25 cm × 2.2 cm in each container. Briefly, IRIS tubes were made by lightly sanding polyvinyl chloride pipe and applying iron oxide paint. Under reducing conditions, Fe (III) is converted to Fe (II) and removed from the IRIS tube (Castenson and Rabenhorst; Rabenhorst, 2008). Prior to placement, a soil core measuring approximately 15 cm × 2.54 cm was removed from each pot allowing for placement of the IRIS tube. The IRIS tube was located approximately 3.75 cm from the edge of the container. After placement, containers were watered to insure good soil contact with tubes. At the end of the study, IRIS tubes were gently pulled from containers, washed clean of soil using tap water and a soft bristle brush, and allowed to air dry. After drying, IRIS tubes were photographed (Nikon D5000 digital camera using a 18-55 mm lens; Melville, NY) with a black background, rotated 180 degrees, and photographed again. The amount of iron removal from each tube was calculated using ImageJ Software (Schneider et al., 2012). Each photograph was analyzed to determine the total pixel area of the IRIS tube and the total pixel area of removed iron. For each tube, the total pixel area of iron removed from both photographs were added together and divided by the sum of the total pixel area of the IRIS tube to determine a percentage of iron removal. Each IRIS tube was giving a rating on a 1-10 scale where each integer represented an additional 10% iron removal (i.e., 1 = 0% to 10% removal, 2 = 11% to 20% removal, …, and 10 = 91% to 100% removal).

Experimental design and statistical analysis. The experiments were arranged as a randomized complete block design with a 7×2×2 factorial arrangement consisting of seven species, two flood durations, and two drought set points with three single plant replicates (experiment 1) and a 7×3×2 factorial arrangement consisting of seven species, three submergence durations, and two submergence depths with three single plant replicates (experiment 2). Experiment 1 was conducted three times (i.e., runs) and experiment 2 was conducted two times. Error mean square values were within a factor of 10 among runs. Therefore, the variance of each run was considered similar, and those data were pooled for both experiments. All data was expressed as a percent of the control, except for visual damage rating and iron removal from IRIS tubes, and subjected to a mixed linear model analysis of variance (Proc MIXED, SAS 9.4; SAS Institute, Cary, NC). Root mass data was square root transformed prior to analysis to standardize the variance and back transformed for data presentation (experiment 1). Experimental run and rep were considered random effects. Species, flood, and drought (experiment 1) and species, submergence duration, and submergence depth (experiment 2) were used as fixed effects. Tukey-Kramer's honestly significant difference test was used to separate treatment means. Means were considered significant at the $p < 0.05$ level.

Results

Experiment 1. Relative shoot and root characteristics. A significant species by drought set point interaction occurred for relative shoot height, count and mass and relative root mass (Figs. 2-3, 2-4, 2-5 and Appendix A1). For these plant characteristics, the drought set point treatments caused between >30% in relative gains to >90% in relative losses to the control. Across all grass species, the 7% soil VWC drought set point resulted in a lower relative shoot height compared with the 14% soil VWC drought set point but the difference was only significant for switchgrass, Chinese silvergrass, blue grama grass, and feather reed grass (Appendix fig. A1). No significant difference between the 7% and 14% soil VWC drought set points occurred for tufted hairgrass, big bluestem, and little bluestem. Within a grass species, the 7% soil VWC drought set point resulted in a significantly lower relative shoot count and mass when compared with the 14% soil VWC drought set point, except for big bluestem and little bluestem, respectively (Figs. 2-3 and 2-4). Although the 7% soil VWC drought set point had a lower relative shoot count compared with the 14% soil VWC drought set point for big bluestem, the difference was not significant. The 14% soil VWC drought set point treatment resulted in a positive relative shoot count for switchgrass, Chinese silvergrass, and little bluestem while all other grasses had a negative relative shoot count. Although the 7% soil VWC drought set point had a lower relative shoot mass when compared with the 14% soil VWC set point for little bluestem, the difference was not significant. For tufted hair grass, Chinese silvergrass, blue grama grass, and feather reed grass, the 14% soil VWC drought set point had a positive relative shoot mass while the other grasses had a negative relative shoot mass. Within a grass species, the 7% soil VWC drought set point had significantly less relative root mass when compared with the 14% soil VWC drought set point except for big bluestem, little bluestem, and blue grama grass (Fig. 2-5). For big bluestem, little bluestem, and blue grama grass, the 7% soil VWC drought set point had lower relative root mass compared with the 14% soil VWC drought set point but the difference was not significant.

In addition to the species by drought interactions, a flood main effect occurred for relative shoot count and root mass. The 7-d flood duration resulted in a significantly lower relative shoot count and root mass compared with the 2-d flood duration. Relative shoot count was reduced more than 20% and almost 30% for the 2-d and 7-d flood durations, respectively.

Relative root mass was reduced more than 50% and almost 60% for the 2-d and 7-d flood durations, respectively.

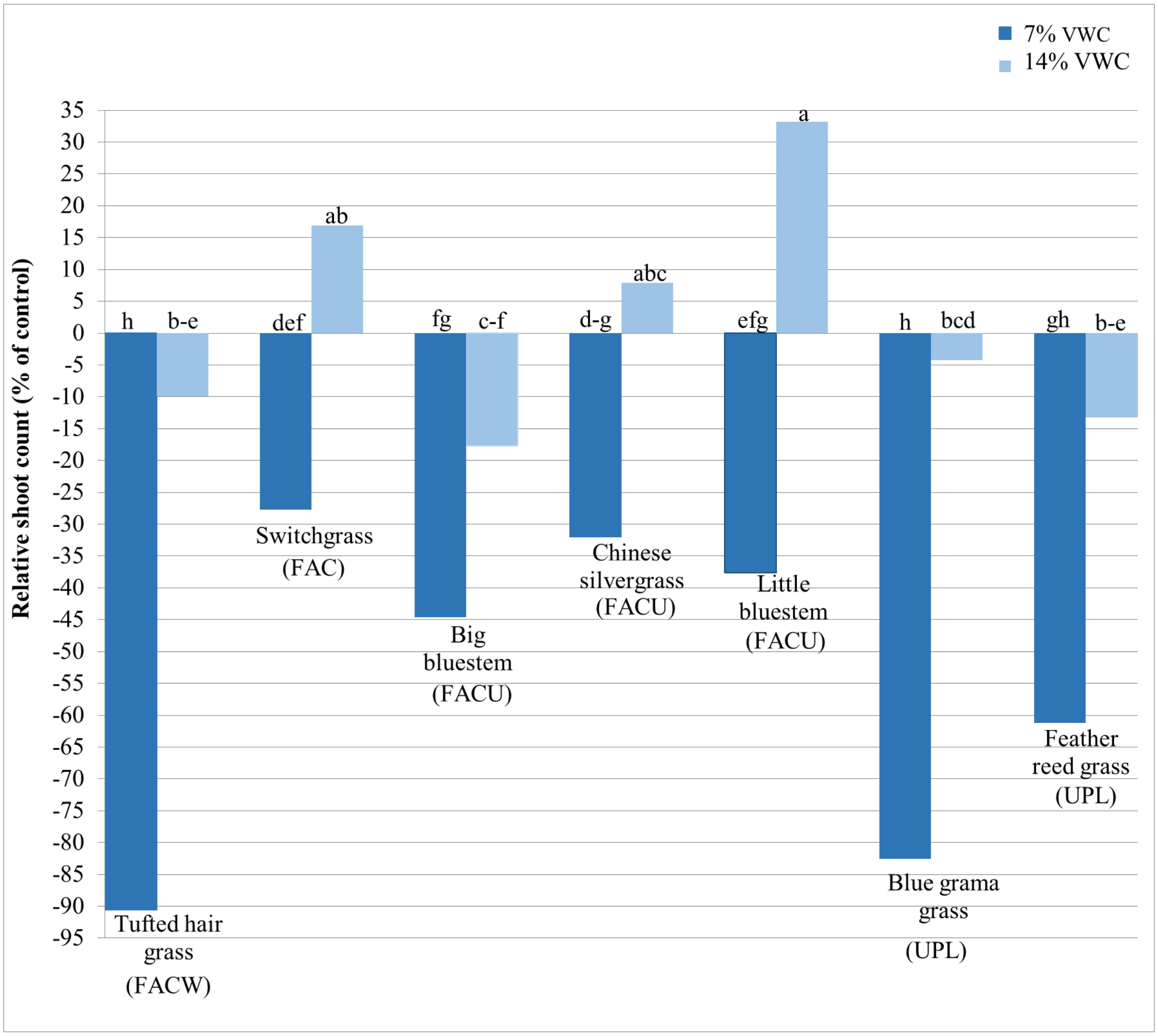

Figure 2-3. Relative shoot count as a percentage of the control for seven perennial ornamental grass species subjected to cyclical flood and drought periods. Mean values are averaged across flood duration treatments. Grasses were flooded for two or seven days and allowed to dry down to 0.07 or 0.14 $m^3 \cdot m^{-3}$ substrate volumetric water content (VWC). Mean (n = 18) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

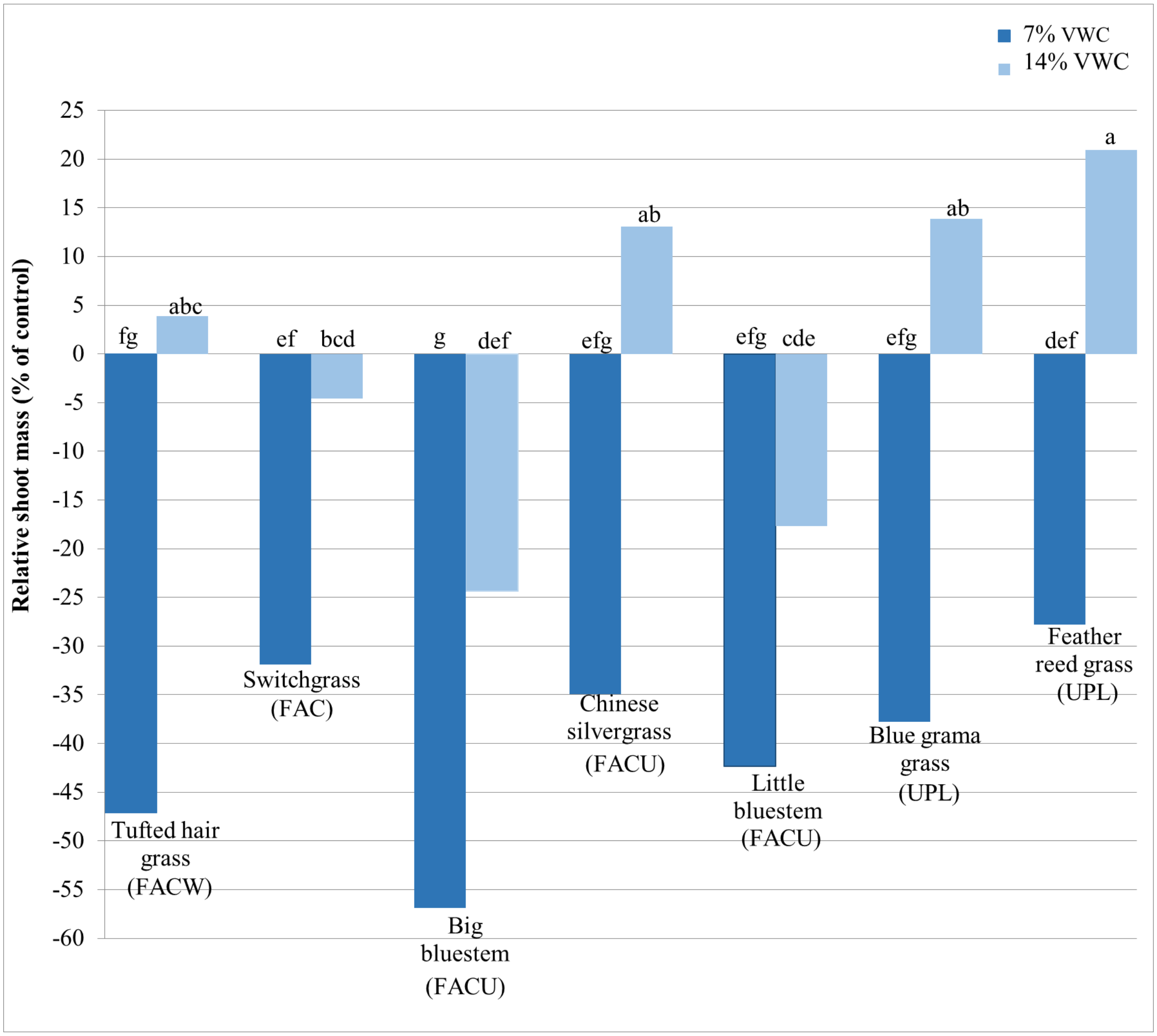

Figure 2-4. Relative shoot mass as a percentage of the control for seven perennial ornamental grass species subjected to cyclical flood and drought periods. Mean values are averaged across flood duration treatments. Grasses were flooded for two or seven days and allowed to dry down to 0.07 or 0.14 $m^3 \cdot m^{-3}$ substrate volumetric water content (VWC). Mean (n = 18) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

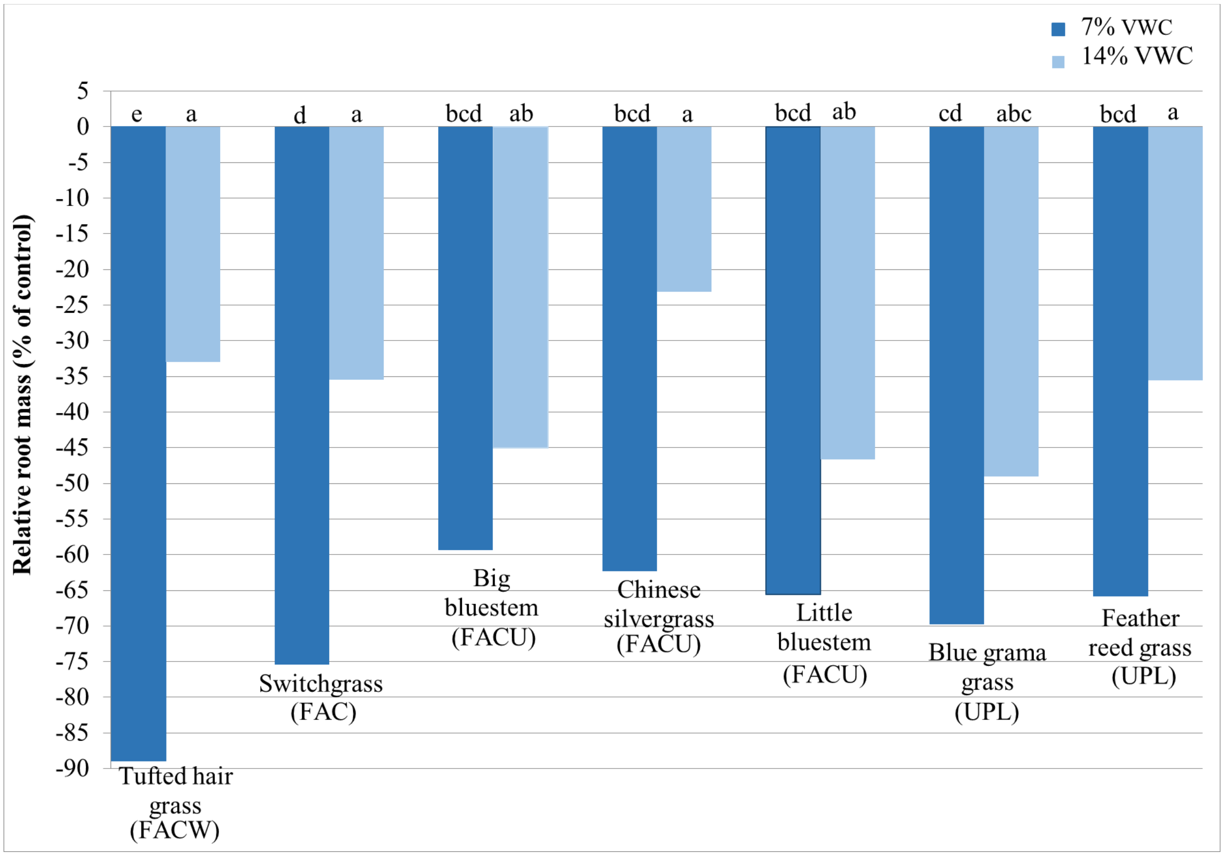

Figure 2-5. Relative root mass as a percentage of the control for seven perennial ornamental grass species subjected to cyclical flood and drought periods. Mean values are averaged across flood duration treatments. Grasses were flooded for two or seven days and allowed to dry down to 0.07 or 0.14 $m^3 \cdot m^{-3}$ substrate volumetric water content (VWC). Mean (n = 18) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

Experiment 1. Relative total biomass, visual damage rating, and survival. A three-way interaction occurred for relative total biomass among species, flood duration, and drought set point. For tufted hair grass, Chinese silvergrass, and blue grama grass, the 7% soil VWC drought set point had significantly lower relative total biomass when compared with the 14% soil VWC drought set point regardless of flood duration (Appendix fig. A2). For switchgrass, there was no significant difference between the 7% and 14% soil VWC drought set points for the 2-d flood duration. However, these did differ for the 7-d flood duration, where the 7% soil VWC drought set point had significantly less relative total biomass compared with the 14% soil VWC drought set point. For big bluestem and feather reed grass, the 7% soil VWC drought set point had significantly less relative total biomass when compared with the 14% soil VWC drought set point for the 2-d flood duration. However, there was no significant difference between the 7% and 14% soil VWC drought set points for big bluestem and feather reed grass for the 7-d flood duration. For little bluestem, there was no significant differences among treatments.

The main effects of species, flood duration, and drought set point were significant for visual damage rating. The visual damage rating was significantly higher for tufted hair grass when compared with all other grass species except for blue grama grass (Fig. 2-6). Switchgrass, big bluestem, Chinese silvergrass, and little bluestem had a significantly lower visual damage when compared with all other grasses except for feather reed grass. The 7-day flood duration resulted in a significantly higher visual damage rating (~4.75) when compared with the 2-day flood duration (4.0). The 7% VWC drought set point had a significantly higher visual damage rating (~ 7.0) when compared with the 14% VWC drought set point (~1.8).

All grasses survived the 14% soil VWC drought set point regardless of flood duration. The 7% soil VWC drought set point resulted in a few plants dying for blue grama grass, tufted hair grass, feather reed grass, and little bluestem (Table 2-3).

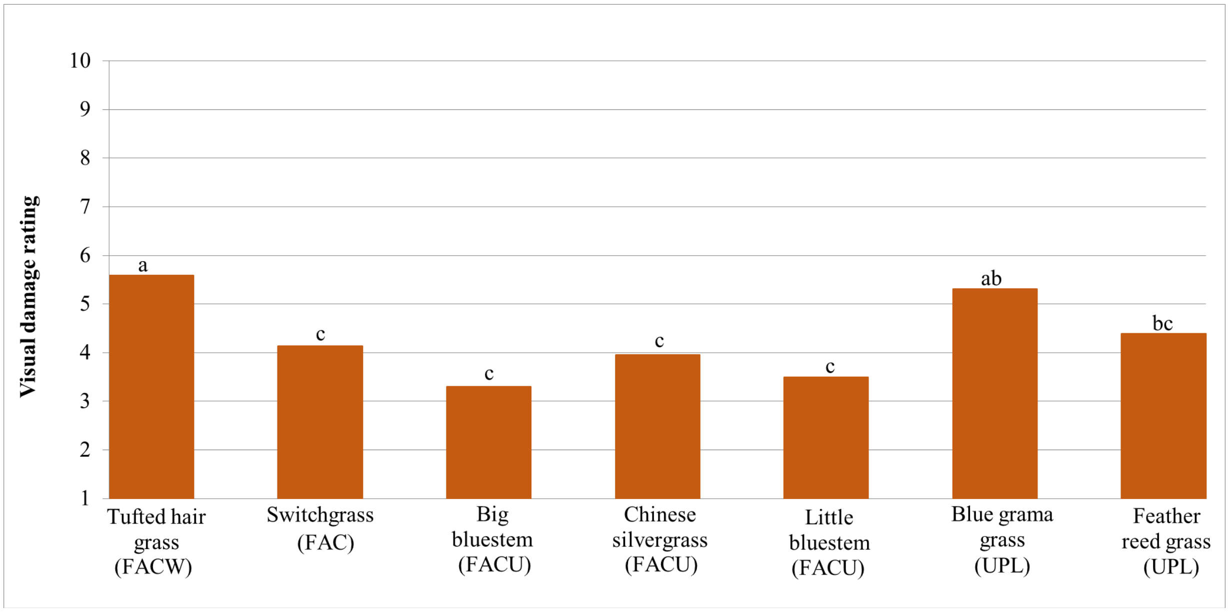

Figure 2-6. Visual damage rating (1-10 scale; 1= 0-10% dieback, 2 = 11-20% dieback, …, 10= 91-100% dieback) of perennial ornamental grasses subjected to cyclical flood and drought periods. Mean values are averaged over flood duration and drought set point treatments. Grasses were flooded for two or seven days and allowed to dry down to 0.07 or 0.14 $m^3 \cdot m^{-3}$ substrate volumetric water content (VWC). Mean (n = 36) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at P< 0.05.

Table 2-3. Cyclical flood and drought experiment treatments with at least one plant dying during the experiment conducted at Fargo, ND from Oct. 2019 to July 2020 (top). The experiment was repeated three times during the stated time period. Grass species listed had nine plants per treatment. A total of 11 out of 252 plants died during the experiment. Submergence experiment treatments with at least one plant dying during the experiment conducted at Fargo, ND from Dec. 2020 to Feb. 2021 (bottom). Grass species listed had six plants per treatment. The experiment was repeated two times during the stated time period. A total of 26 out of 252 plants died during the experiment (bottom).

Grass species	Flood duration (d)	Drought set point (%)	Plants dead
Tufted hair grass	2	7	1
Tufted hair grass	7	7	2
Little bluestem	7	7	2
Blue grama grass	2	7	1
Blue grama grass	7	7	4
Feather reed grass	7	7	1

Grass species	Submergence duration (d)	Submergence depth (cm)	Plants dead
Tufted hair grass	2	15	1
Tufted hair grass	4	15	1
Tufted hair grass	7	15	4
Tufted hair grass	2	30	1
Tufted hair grass	4	30	3
Tufted hair grass	7	30	4
Big bluestem	4	15	2
Big bluestem	7	15	2
Big bluestem	4	30	2
Big bluestem	7	30	1
Little bluestem	4	30	2
Feather reed grass	7	15	1
Feather reed grass	7	30	2

Experiment 2. Floodwater chemistry and substrate oxygen status. The average temperature of floodwater during the experiment was 21.8 °C. As the submergence duration increased from 2-d to 7-d, dissolved oxygen, and pH of floodwater decreased for all species regardless of water depth. The decrease in dissolved oxygen and pH was most pronounced for

grasses submerged for 7-d and ranged from ~11.0 $mg \cdot L^{-1}$ and 9.1 pH at the beginning of the submergence duration and 0.5 $mg \cdot L^{-1}$ and 6.7 pH at the end of the submergence duration. The greatest decrease in dissolved oxygen occurred for blue grama grass submerged for 7-d at a depth of 30 cm submergence (7.0 $mg \cdot L^{-1}$ to 1.8 $mg \cdot L^{-1}$) while tufted hair grass submerged for 7-d at a depth of 15 cm lost the least amount of dissolved oxygen during submergence (5.7 $mg \cdot L^{-1}$ to 2.9 $mg \cdot L^{-1}$). Little bluestem submerged for 7-d at a depth of 30 cm had the greatest reduction in pH from day 1 to day 7 (8.7 to 7.5) while tufted hairgrass submerged for 7-d at a depth of 15 cm had the least amount of change in pH from day 1 to day 7 (7.9 to 7.2). Electrical conductivity increased as the submergence duration increased from 2-d to 7-d for all species. The increase in EC was most pronounced for grasses submerged for 7-d and ranged from 0.3 $dS \cdot m^{-1}$ at the beginning of the submergence duration and 0.7 $dS \cdot m^{-1}$ at the end of the submergence duration. Nitrate, ammonium, and chloride in the floodwater remained low for all grasses and averaged 1.2 ± 1.1, 0.8 ± 0.5, and 25.8 ± 5.6 $mg \cdot L^{-1}$, respectively.

The main effects of species and submergence duration were significant for substrate oxygen status as measured by iron removal from IRIS tubes. Feather reed grass had significantly higher iron removal (~ 60%) from IRIS tubes compared with all other grasses except for little bluestem (~50%). Chinese silvergrass had significantly lower iron removal from IRIS tubes (30%) compared with little bluestem and feather reed grass but not big bluestem (~40%), switchgrass (~40%), tufted hair grass (~35%) and blue grama grass (35%). The 2-d submergence duration had significantly less iron removal from IRIS tubes (~30%) compared with the 4-d (~40%) and 7-d (~50%) submergence durations. No significant difference occurred between the 4-d and 7-d submergence duration treatments.

Experiment 2. Relative shoot and root characteristics. A significant species by submergence duration interaction occurred for relative shoot height and count. Within a grass species, there was no significant difference among the 2, 4, or 7-d submergence durations except for tufted hair grass and feather reed grass (Fig. 2-7). For tufted hair grass and feather reed grass, the 2-d submergence duration had significantly higher relative shoot height when compared with the 7-d submergence duration, but not the 4-d submergence duration. All grasses had reduced shoot height for some or all submergence durations relative to the respective control except for switchgrass. For switchgrass, all submergence durations had increased shoot height relative to the respective control. Increased shoot height relative to the respective control also occurred for the 7-d submergence duration of Chinese silvergrass and the 2-d submergence duration of feather reed grass.

For tufted hair grass and blue grama grass, the 2-d submergence duration had significantly higher relative shoot counts when compared with the 7-d submergence duration but not the 4-d submergence duration (Fig. 2-8). For little bluestem, the 2-d submergence duration had a significantly higher relative shoot count when compared with submergence for 4-d and 7-d while no difference was observed between submergence for 4-d or 7-d. For feather reed grass, the 2-d and 4-d submergence durations had significantly higher relative shoot counts when compared with the 7-d submergence duration. Although the 2-d submergence duration for feather reed grass had a higher relative shoot count compared with the 4-d submergence duration, the difference was not significant. Relative shoot counts for switchgrass, big bluestem, and Chinese silvergrass were not significantly affected by submergence duration. All grasses had a lower shoot count relative to the respective control except for the 2-d and 4-d submergence durations for switchgrass which were higher than the respective control.

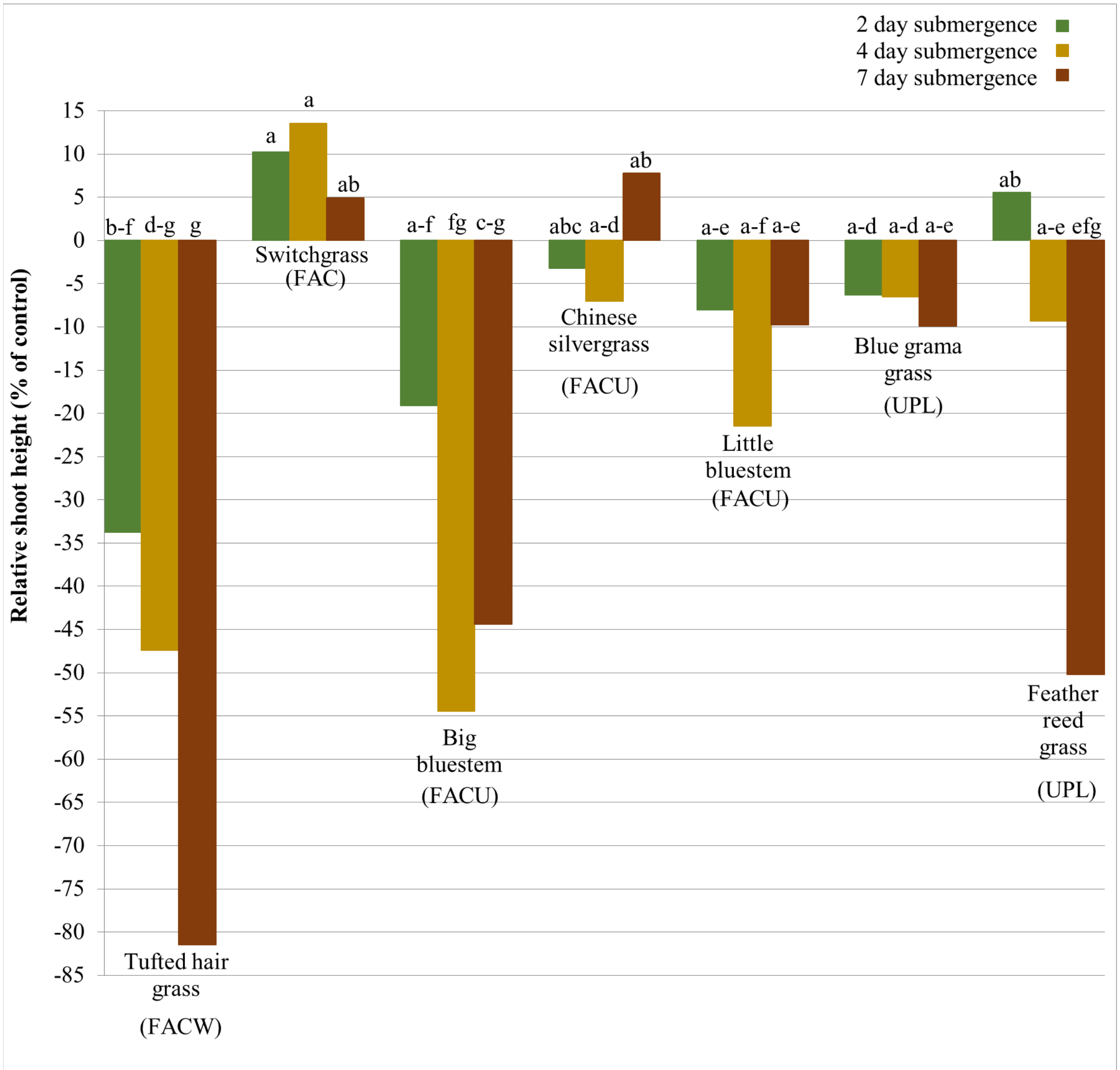

Figure 2-7. Relative shoot height as a percentage of the control for seven perennial ornamental grass species subjected to repeated submergence. Mean values are averaged across submergence depth treatments. Grasses were submerged in tap water at depths of 15 or 30 cm above the soil surface for two, four, or seven days. Mean (n = 12) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P <$ 0.05. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

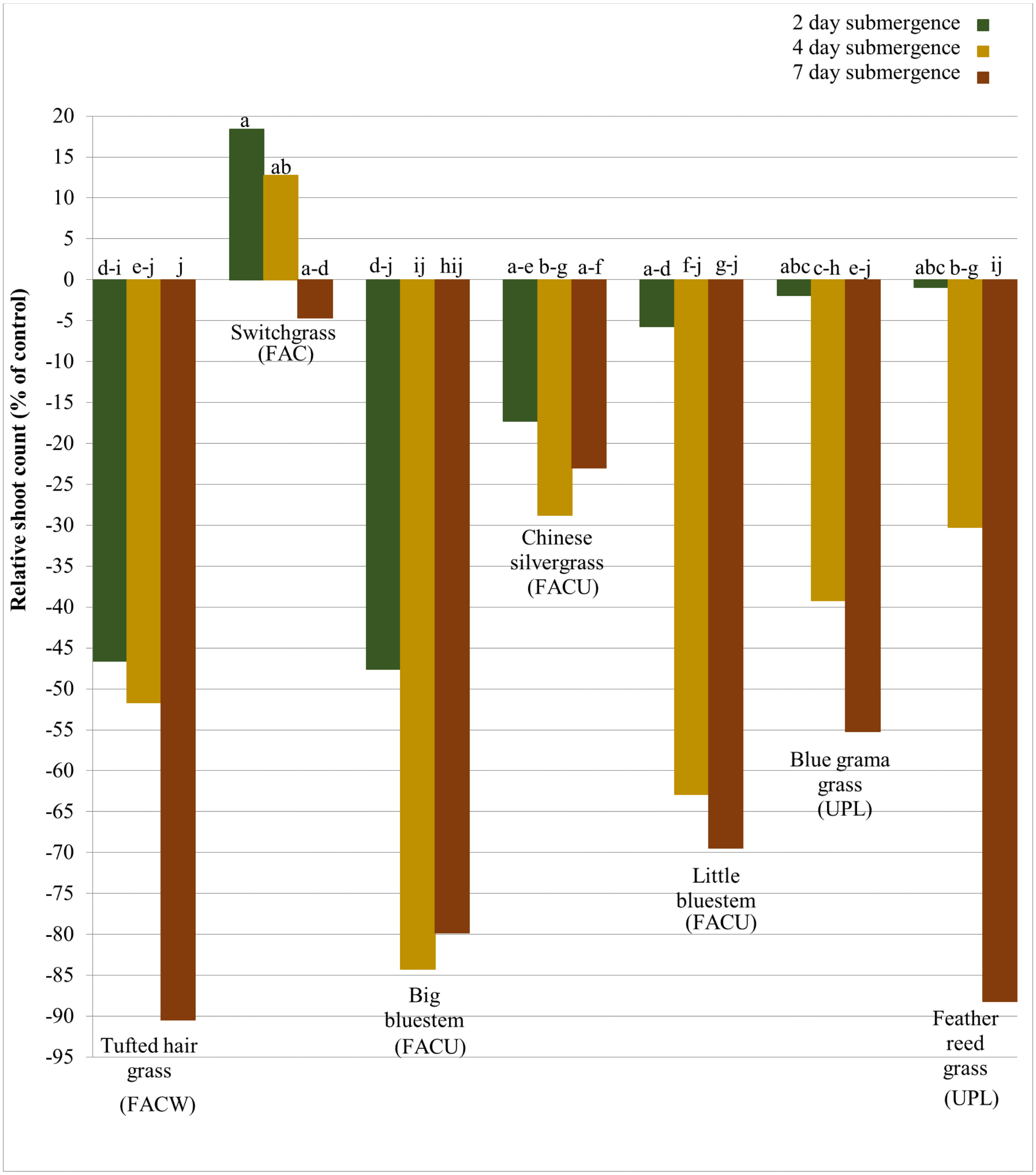

Figure 2-8. Relative shoot count as a percentage of the control for seven perennial ornamental grass species subjected to repeated submergence. Mean values are averaged across submergence depth treatments. Grasses were submerged in tap water at depths of 15 or 30 cm above the soil surface for two, four, or seven days. Mean (n = 12) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

A significant submergence duration by submergence depth interaction and species main effect occurred for relative shoot mass. The interaction occurred in the 4-d submergence duration where the 15 cm submergence depth had approximately 20% more relative shoot mass compared with the 30 cm submergence depth. The 15 cm submergence depth with a 4-d submergence duration was the only treatment to have a positive relative shoot mass (approximately 2%). Submergence durations of 2-d and 7-d had similar reductions in relative shoot mass (approximately 4% and 10% respectively) regardless of submergence depth. Switchgrass had significantly higher relative shoot mass compared with all other grass species except little bluestem and feather reed grass (Fig. 2-9). Switchgrass, little bluestem, and feather reed grass were the only grasses to have a positive shoot mass relative to the control. Chinese silvergrass and tufted hair grass had the lowest relative shoot mass compared with all other grass species except for blue grama grass and big bluestem.

The main effects of species and submergence duration were significant for relative root mass. Little bluestem had significantly higher relative root mass compared with all other grasses except big bluestem (Fig. 2-9). Little bluestem was the only grass species to have a positive relative root mass. Tufted hair grass had significantly lower relative root mass when compared with all other grass species except feather reed grass. No significant differences in relative root mass were observed among switchgrass, big bluestem, Chinese silvergrass, blue grama grass, and feather reed grass. Submergence durations of 2, 4, and 7-d resulted in root mass losses relative to the controls of >10%, >20%, and >25%, respectively. The 7-d submergence duration had significantly less relative root mass compared with the 2-d but not the 4-d submergence duration. No significance difference in relative root mass was observed between the 2-d and 4-d submergence durations.

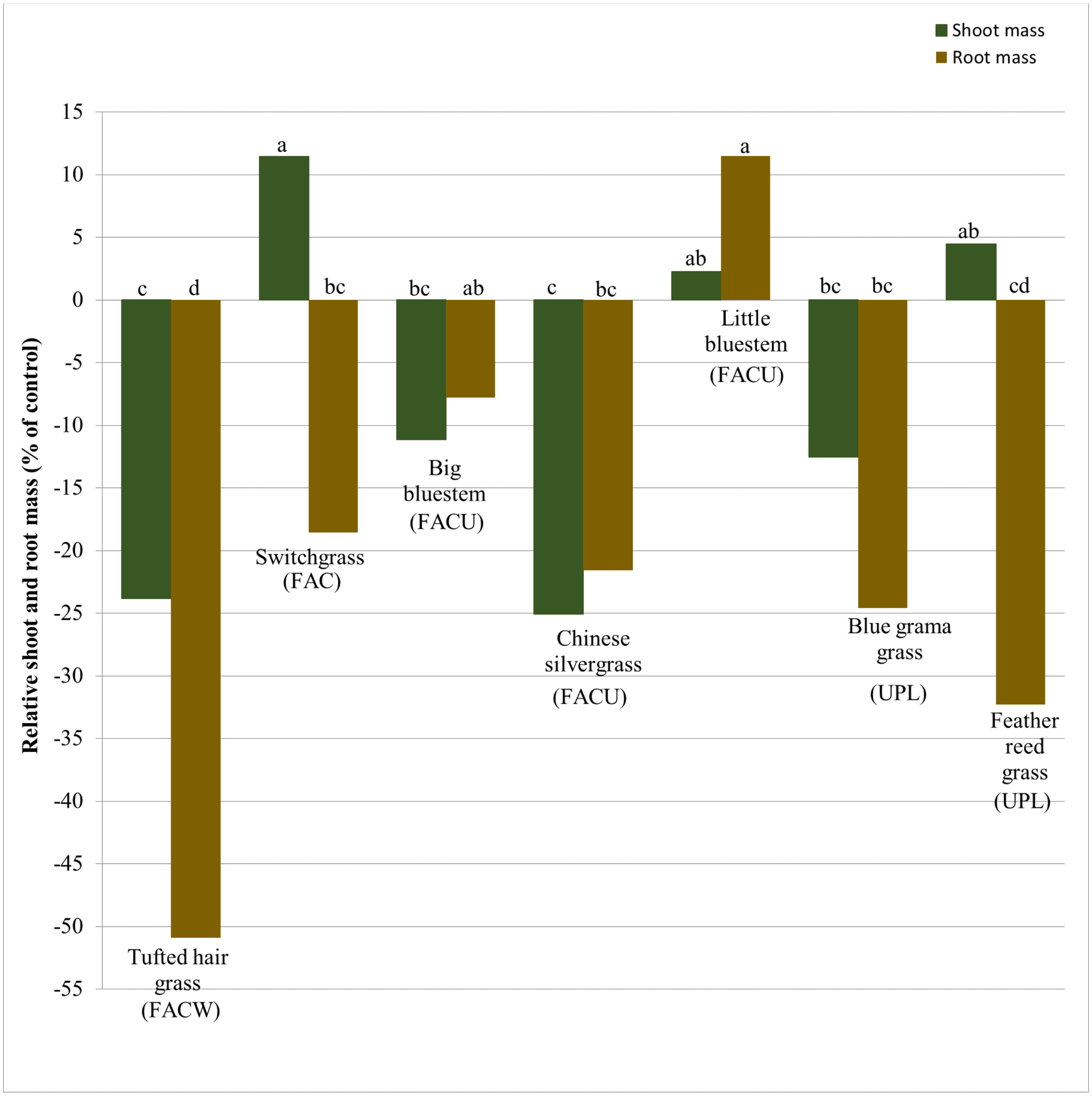

Figure 2-9. Relative shoot mass and root mass as a percentage of the control for seven perennial ornamental grass species subjected to repeated submergence. Mean values are averaged across submergence duration and depth treatments. Grasses were submerged in tap water at depths of 15 or 30 cm above the soil surface for two, four, or seven days. Mean (n = 36) values labeled with different lower case letters within shoot mass or root mass were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

Experiment 2. Relative total biomass, visual damage rating, and survival. The main effects of species and submergence duration were significant for relative total biomass. Little bluestem had an increase in relative total biomass (>5%) while all other grasses were reduced from >5% to almost 40% compared with the respective control. Relative total biomass was significantly higher for little bluestem compared with all other grass species except for switchgrass and big bluestem. Tufted hair grass had the lowest relative total biomass (almost 40%) and was significantly lower compared with all other grass species except for Chinese silvergrass. No significant differences were observed among feather reed grass, blue grama grass, Chinese silvergrass, big bluestem, and switchgrass. Relative total biomass was reduced by 10%, 18%, and >20% for the 2, 4, and 7-d submergence durations compared with the respective controls. The 2-d submergence duration was significantly higher compared with the 7-d but not the 4-d submergence duration for relative total biomass.

Visual damage rating had several significant two-way interactions occur. These included a species by submergence duration interaction, a species by submergence depth interaction, and a submergence duration by submergence depth interaction. For little bluestem, blue grama grass, and feather reed grass, the 2-d submergence duration had a significantly lower visual damage rating when compared with the 7-d submergence duration but not the 4-d submergence duration within each grass species (Fig. 2-10). Within each species, no significant differences were observed among submergence durations for tufted hair grass, switchgrass, big bluestem, and Chinese silvergrass. All submergence duration treatments for switchgrass and Chinese silvergrass had significantly lower visual damage ratings when compared with tufted hair grass and big bluestem submergence durations.

The species by submergence depth interaction occurred for tufted hair grass, where the 15 cm submergence depth had a significantly lower visual damage rating when compared with the 30 cm submergence depth (Fig. 2-11). For all other grass species, there was no significant difference between the submergence depths of 15 cm and 30 cm. Switchgrass submerged at depths of 15 cm and 30 cm had a significantly lower visual damage rating compared with all other grass species submerged at the same depths, except for Chinese silvergrass, blue grama grass, and feather reed grass.

Visual damage ratings were affected by submergence duration and submergence depth. For all submergence durations, visual damage ratings were significantly lower for the 15-cm depth compared with the 30 cm depth except for the 2-d submergence duration where there was no difference between depths. The 2-d submergence duration at a 15 cm depth had a significantly lower visual damage rating (~3.5) compared with the 7-d submergence duration at a depth of 15 cm (almost 7) but not when the submergence duration was 4-d at a depth of 15 cm (almost 4). When submerged at a depth of 30 cm, visual damage ratings were significantly lower for the 2-d submergence duration (~3.5) compared with the 4-d (~5.5) and 7-d submergence durations (almost 7). Also, the 4-d submergence duration at a 30 cm depth was significantly lower than the 7-d submergence duration at the same depth.

Grass survival was dependent on species, with all grasses surviving the 2-d submergence duration regardless of depth with the exception of tufted hair grass (Table 2-3). Tufted hair grass lost one out of six plants when submerged for 2-d at depths of 15 cm and 30 cm. As submergence duration and depth increased the number of tufted hair grass plants dying also increased. A few plants of big bluestem, feather reed grass, and little bluestem also died during the experiment.

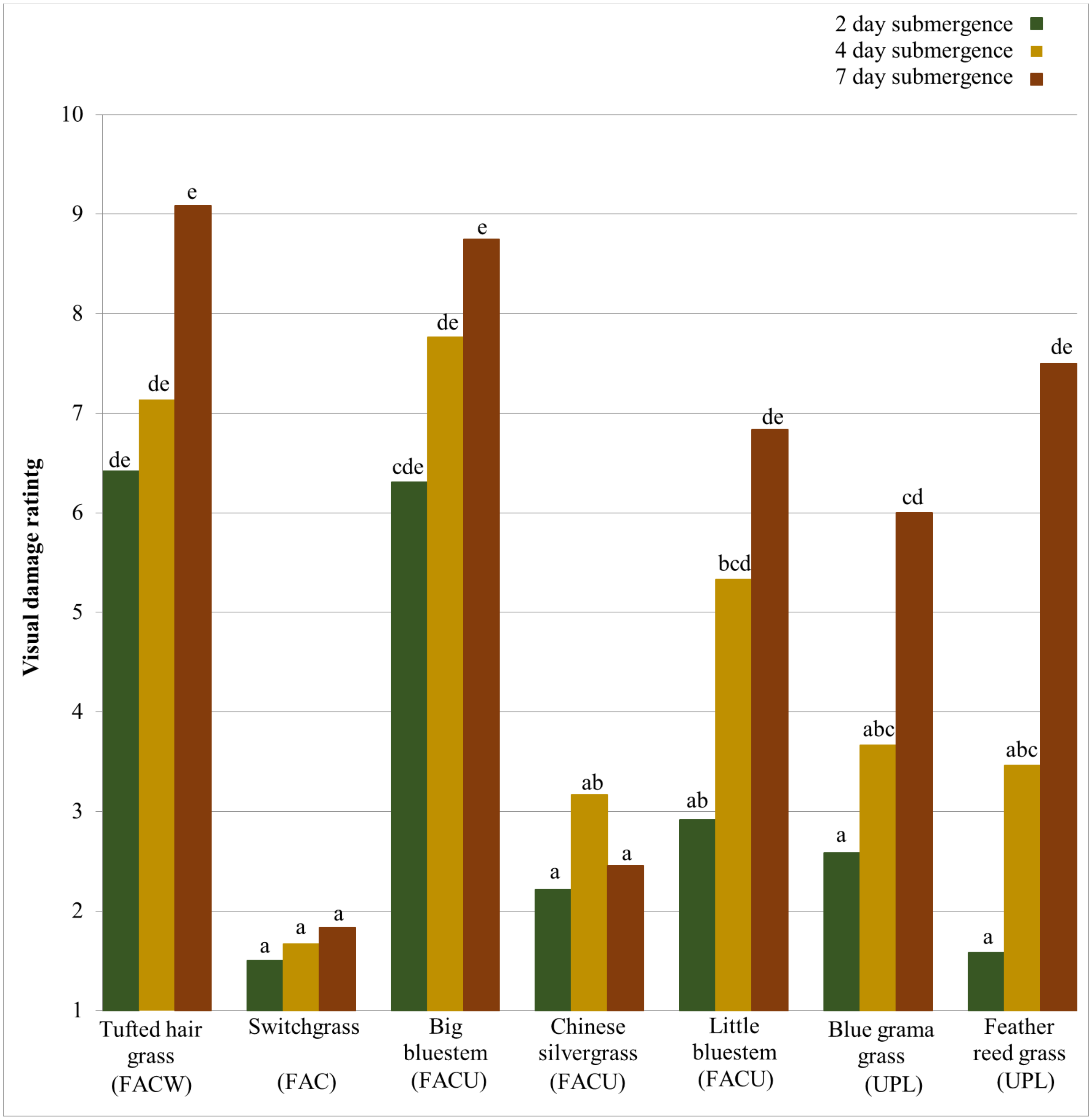

Figure 2-10. Visual damage rating (1-10 scale; 1= 0-10% dieback, 2 = 11-20% dieback, …, 10= 91-100% dieback) of seven perennial ornamental grass species subjected to repeated submergence. Mean values are averaged across submergence depth treatments. Grasses were submerged in tap water at depths of 15 or 30 cm above the soil surface for two, four, or seven days. Mean (n = 12) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

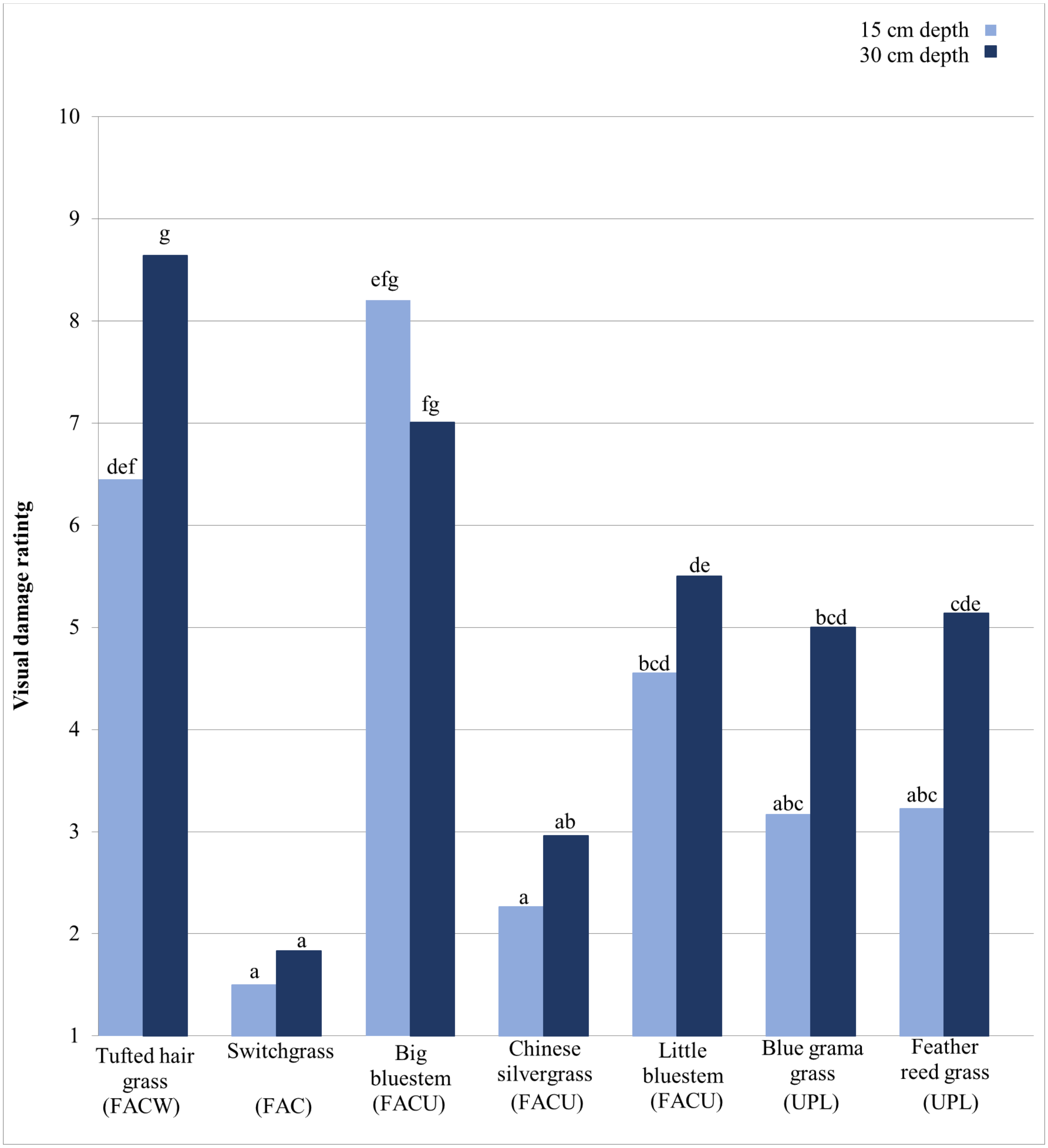

Figure 2-11. Visual damage rating (1-10 scale; 1= 0-10% dieback, 2 = 11-20% dieback, …, 10= 91-100% dieback) of seven perennial ornamental grass species subjected to repeated submergence. Mean values are averaged across submergence duration treatments. Grasses were submerged in tap water at depths of 15 or 30 cm above the soil surface for two, four, or seven days. Mean (n = 18) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at P< 0.05. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

Discussion

Perennial ornamental grasses are often recommended for rain gardens but, little data exists to support their recommendation. These two experiments are the first to evaluate ornamental grass cultivars on their ability to grow while being subjected to cyclical flooding and drought and periodic submergence, conditions typically found in a rain garden. For experiment 1, severe drought (7% soil VWC) reduced relative shoot height, shoot count, and shoot and root mass relative to their respective well-watered controls for all grasses with the exception of the shoot height for tufted hair grass. Drought was expected to reduce plant growth parameters because drought stress reduces cell elongation and division resulting in reduced growth (Farooq et al., 2012).

Plant growth data is only one measure of environmental stress. Visual damage ratings which are a function of plant dieback percentages helps complete the picture. Tufted hair grass had the highest visual damage rating (~5.5) which is consistent with the lower growth parameters observed in the experiment. Severe drought negatively impacted shoot count and shoot mass for tufted hair grass. Tufted hair grass had the lowest shoot count but was not significantly different from blue grama grass and feather reed grass. Similarly, tufted hair grass had the lowest root mass under severe drought compared to all other grasses and three plants died during the experiment. The negative response to severe drought was expected because this species is a facultative wetland plant that usually occurs in wetlands (Lichvar et al., 2016; U.S. Army Corps of Engineers, 2022). Blue grama grass had a visual damage rating (~5.2) similar to tufted hair grass and feather reed grass (~4.3). Relative root mass of blue grama grass was reduced >45% and 70% under mild and severe drought, respectively. It is worth noting that no difference in relative root mass reduction occurred between the mild and severe drought set points. Blue grama grass suffered the highest plant mortality with five plants dying during the experiment. The high visual damage rating, lack of significant difference between drought set points for relative root mass across flood duration, and the high plant mortality can be partially explained based on the wetland indicator status of blue grama grass. Blue grama grass is an upland plant (Lichvar et al., 2016; U.S. Army Corps of Engineers, 2022), able to withstand drought, but is not adapted to flooding (Wynia, 2007).

The lowest visual damage ratings (≤4.3) were observed for switchgrass, big bluestem, Chinese silvergrass, little bluestem, and feather reed grass, although feather reed grass was not significantly lower when compared to blue grama grass. Switchgrass, big bluestem, and little bluestem are native to the north central United States. All switchgrass and big bluestem plants survived the experiment while only two little bluestem plants died. Under mild drought conditions, switchgrass and little bluestem continued to grow because both grasses had a positive relative shoot count regardless of flood duration. The adaptability of switchgrass to flooding and drought conditions is not a surprise because switchgrass is adapted to several soil types and conditions, from sandy to clay loam soils with soil water contents from dry to fully saturated (USDA-NRCS, 2006). Switchgrass is also a facultative wetland plant meaning it is equally likely to be found in a wetland or non-wetland setting (Lichvar et al., 2016; U.S. Army Corps of Engineers, 2022). Although relative root mass was reduced for all grasses under mild and severe drought set points, it is worth noting that within a species the difference was not significant for big bluestem and little bluestem. Relative root mass was reduced between 45% and 65% for both grasses when compared with the respective control. The lack of significant differences between drought set points for these two grasses can be partially explained based on their native habitat. Big bluestem is a tallgrass prairie species widely distributed in the midwestern U.S. and known to tolerate mean annual rainfall ranging from 58 to 116 cm (Gray et al., 2014). Little bluestem is commonly found on dry upland sites such as ridges and is known to tolerate sandy to clay-loam textured soils (Tober and Jensen, 2013). Both big bluestem and little bluestem are facultative upland plants meaning they are usually found in non-wetland environments (Lichvar et al., 2016; U.S. Army Corps of Engineers, 2022). Besides having reduced relative root mass, both big bluestem and little bluestem had reduced relative plant height when the soil VWC drought set point was 14% or 7%. The reduced plant growth for big bluestem and little bluestem under stressful conditions likely led to both plants having a low visual damage rating (~3).

Chinese silvergrass and feather reed grass were able to tolerate cyclical flooding and drought conditions and, in some cases, increase growth. Under mild drought, Chinese silvergrass, was able to increase relative shoot count across all flood durations. During the experiment all Chinese silvergrass plants survived while only one feather reed grass plant died. Similar survival results were observed for Chinese silvergrass by Yuan and Dunnett (2018) where all plants survived cyclic flooding for 1-d and 4-d. The adaptability of Chinese silvergrass and feather reed grass can be partially explained based on their origins and wetland indicator status. The cultivar of Chinese silvergrass used in our study was 'Purpurascens' which is considered a hybrid between Chinese silvergrass and Amur silvergrass [*M. sacchariflorus* (Maxim.) Franch.] (Jiang et. al., 2013). Amur silvergrass is typically found near wetlands and along waterways which helps explain the tolerance of 'Purpurascens' to flooded soils (Bonin et al., 2014). Chinese silvergrass is tolerant of soil water potentials as low as -4.05 MPa which helps explain the tolerance of 'Purpurascens' to drought stress (Dougherty et al., 2015). Clifton-Brown and Lewandowski (2000) found that Chinese silvergrass was able to minimize leaf senescence under drought conditions by reducing stomatal conductance and leaf area, which helps explain the low visual damage rating observed in our study (~4). The feather reed grass cultivar 'Karl Foerster' is reported as a hybrid between chee reedgrass [*C. epigejos* (L.) Roth] and *C. arundinacea*. (L.) Roth. Both grasses are native to central Europe where chee reedgrass grass is found in dry, mesic, and flooded soils, while *C. arundinacea* is known to tolerate submergence (Lei et al., 2014; Rebele and Lehmann, 2001; USDA-NRCS, 2022). This helps explain the ability of 'Karl Foerster' to tolerate both flood and drought stress.

A previous study by Nelson et al. (2018) evaluated seven sedge species to determine their tolerance to cyclical flooding and drought using a similar setup as the present experiment except the lowest drought set point was -14,800 kPa. Interestingly, no sedges died during the experiment. Sedges with wetland indicators of facultative wetland, facultative, and facultative upland tolerated cyclical flooding and drought better than obligate and upland sedges. A similar result was observed in the present study except for tufted hair grass. Tufted hair grass did not tolerate cyclical flooding and drought even though it is a facultative wetland plant. Sedges also had a higher relative shoot mass when flooding increased from 2- to 7-d. This was not observed for the seven species of perennial ornamental grasses used in the current experiment.

For experiment 2, as submergence duration and depth increased, relative shoot height and count and relative root mass decreased while visual damage rating increased for the most susceptible perennial grasses. The results were expected because as submergence duration increased, the amount of oxygen in submergence water and soil decreased due to oxygen diffusion from the air being 10^4 fold slower through water (Armstrong and Drew, 2002). Low soil oxygen levels reduce plant root respiration and ultimately plant growth (Pederson et al., 2021). Substrate oxygen status were monitored using IRIS tubes and as submergence duration increased from 2-d, significantly more iron was removed from the tubes indicating roots and soil microbes used up available soil oxygen.

The increase in submergence duration and depth had little effect on plant growth parameters for switchgrass and Chinese silvergrass. For switchgrass, relative shoot height, shoot count, and shoot mass were mostly positive while relative root mass was reduced ~20% when compared with the respective control. Our results were similar to Barney et al. (2009) where flooded switchgrass plants were similar in plant height, shoot count, and shoot and root mass when compared with the non-flooded plants. It is important to note that Barney et al. (2009) flooded switchgrass continuously for 11 weeks at a depth of 2-5 cm above the soil surface while our experiment submerged plants intermittently at depths of 15 cm or 30 cm above the soil surface. Results for Chinese silvergrass were similar to switchgrass except Chinese silvergrass had a greater reduction in shoot mass.

Relative shoot count was generally reduced as submergence duration increased for tufted hair grass, little bluestem, blue grama grass, and feather reed grass. Big bluestem did not show a significant difference between 2-, 4-, and 7-day submergence treatments. However, big bluestem had a large reduction in relative shoot count for all treatments in comparison to the control. The results for big bluestem are similar to experiment 1 and not surprising considering big bluestem is a facultative upland plant. The results were unanticipated for tufted hair grass given it is a facultative wetland plant and therefore expected to perform better than the other grasses which are facultative upland or upland plants. The poor performance of tufted hair grass can be partially explained by shoot height. Tufted hair grass had the shortest shoot height of all the grasses in the experiment and submergence at 15 cm and 30 cm resulted in a majority of the shoots being underwater likely resulting in greater plant damage. Given the short stature of tufted hair grass, it was not surprising that relative shoot and root mass were reduced >20% and >50%, respectively. Little bluestem had a positive relative shoot and root mass which was surprising given the grass is a facultative upland plant.

Similar to experiment 1, visual damage ratings were lowest for switchgrass (<2) and Chinese silvergrass (<3.5) regardless of submergence duration. All switchgrass and Chinese silvergrass plants survived the experiment suggesting both are able to tolerate intermittent submergence. Tufted hair grass and big bluestem had reduced growth for all plant parameters, but it did not help reduce visual damage ratings or improve survival. The visual damage rating was highest for tufted hair grass and big bluestem, ranging from >6 to about 9. During the experiment, 14 tufted hair grass plants died and seven big bluestem plants died. Big bluestem was able to tolerate cyclical flood and drought but it does not tolerate intermittent submergence. As previously stated, tufted hair grass was the shortest grass in the experiment and having most of the foliage covered by water significantly reduced survival and increased the visual damage rating. Tufted hair grass was the only grass to have a better visual damage rating when submerged at a depth of 15 cm (~6.5) compared to a depth of 30 cm (~8.5).

Visual damage ratings were similar for little bluestem, blue grama grass, and feather reed grass when submerged up to 4-d. Both blue grama grass and feather reed grass had a lower relative root mass compared with little bluestem which may have allowed the plants to withstand submergence better than little bluestem. All three grasses had a visual damage rating of 6 or higher when submerged for 7-d. Surprisingly, all the blue grama grasses survived the experiment while only two little bluestem and three feather reed grass plants died. As stated earlier, blue grama grass is known to be intolerant to soil flooding and submergence so it is interesting that all plants survived the duration of the experiment. It is important to note that grasses only went through four cycles of submergence with a 2-d draining period between each cycle. Had the number of submergence cycles been greater than four, blue grama grass survival may have been reduced.

Practical implications for rain gardens and bioretention systems

Perennial ornamental grasses are a popular garden and landscape plant because of year-long interest and their minimal maintenance requirement. These two experiments show that perennial ornamental grasses have the ability to survive in tough environmental conditions such as water-logged and drought-stressed soils and when plants are partially submerged by water. The perennial ornamental grasses ‘Northwind’ switchgrass and ‘Purpurascens’ Chinese silvergrass were able to survive cyclical flooding and drought as well as repeated submergence of up to 30 cm for periods of 7-d. Given the extreme environmental conditions tolerated by these two grasses make them candidates for bioretention systems or portions of rain gardens where periodic drought and submergence are likely to occur. The grasses, ‘Blue Heaven’ little bluestem, ‘Karl Foerster feather reed grass, and ‘Blonde Ambition’ blue grama grass, were able to tolerate cyclical flooding and drought, especially when soil VWC was at 14%. The grasses suffered significant plant damage when submerged for 7-d. The grasses are well suited for situations of fluctuating drought and soil flooding but should not be planted in locations where prolonged submergence may occur. The grasses, ‘Pixie Fountain’ tufted hairgrass and ‘Red October’ big bluestem suffered significant plant damage when submerged for 2-d or longer. Big bluestem was able to handle drought better than tufted hairgrass. The cultivar Red October big bluestem would be suited for areas that experience cyclical soil flooding and drought as long as plant submergence does not occur. The cultivar Pixie Fountain tufted hairgrass should be used with caution given the poor tolerance to submergence and drought. The cultivar Pixie Fountain would be suitable for areas where whole plant submergence will not occur and the soil VWC will not drop below 14%.

Conclusion

Based on these two experiments, Chinese silvergrass and switchgrass were able to survive cyclical soil flooding and drought as well as submergence for 7-d at a depth of 30 cm while maintaining an acceptable amount of foliar damage. All grasses survived cyclical flood and drought when the soil VWC was maintained at 14% suggesting all seven grasses can withstand periodic soil flooding as long as the water is not too deep. As water depth and duration increased from 4-d to 7-d, little bluestem, blue grama grass and feather reed grass suffered significant foliar damage. Tufted hair grass and big bluestem suffered significant foliar damage when submerged for 2-d.

Our results show that perennial ornamental grasses can tolerate cyclical flood and drought and periodic submergence, but plant condition and survival vary by species and not wetland indicator status. Future research could focus on evaluating other commonly used perennial ornamental grasses to determine their suitability for use in biorientation environments.

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CHAPTER III. THE RESPONSE OF SEVEN ORNAMENTAL GRASS CULTIVARS TO SODIUM CHLORIDE AND PETROLEUM HYDROCARBON POLLUTION

Introduction

Grasses with eye-appealing attributes such as attractive leaf color, unique inflorescences, or upright form are commonly referred to as ornamental grasses. Perennial ornamental grasses are a popular landscape plant because they can provide year-long interest and require minimal maintenance if the appropriate species is selected and planted in the proper location (Meyer, 2013; Zuk et al., 2016). In the U.S., sales of ornamental grasses increased from approximately $158 million to $179 million from 2014 to 2019 (USDA, 2015 and 2020). Given their minimal maintenance requirement, perennial ornamental grasses are often recommended for use in rain gardens, but little research exists to support the recommendation (Hausken and Thompson, 2018; Meyer, 2004; Meyer 2012; Steiner and Domm, 2012). Often, only the species is recommended even though many perennial ornamental grasses have improved cultivars that are commercially available. The improved cultivars, when compared with the species, often have better foliage coloration, reduced lodging, or unique inflorescenes such as, 'Pixie Fountain' tufted hairgrass [*Deschampsia cespitosa* (L.) P. Beauv.], 'Northwind' switchgrass (*Panicum virgatum* L.), 'Red October' big bluestem (*Andropogon gerardii* Vitman), 'Purpurascens' Chinese silvergrass (*Miscanthus sinensis* Andersson), 'Blue Heaven' little bluestem [*Schizachyrium scoparium* (Michx.) Nash], 'Blonde Ambition' blue grama grass [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths], and 'Karl Foerster' feather reed grass [*Calamagrostis* x *acutiflora* (Schrad.) DC] (Thetford et al., 2011 and Springer, 2012). Chinese silvergrass has the synonym *Miscanthus sinensis* var. *purpurascens* and is frequently sold in the horticultural trade under this name (Integrated Taxonomic Information System, 2022).

Tufted hairgrass, switchgrass, big bluestem, little bluestem, and blue grama are native to the north central United States (USDA-NRCS, 2020). Chinese silvergrass is native to eastern Asia and was introduced into the U.S. as early as 1893 (Dougherty et al., 2014). Feather reed grass is thought to be a hybrid between two species native to Europe and Asia, *C. arundinacea* [(L.) Roth] and *C. epigejos* [(L.) Roth], first discovered by Karl Foerster in Germany during the 1930's (Missouri Botanical Garden, 2020).

A rain garden is a shallow basin in the landscape that is planted with herbaceous and sometimes woody perennial plants. Rain gardens are used to intercept stormwater runoff from impervious surfaces such as driveways, streets, and parking lots. Stormwater runoff from such areas may contain salt and petroleum hydrocarbons. In the U.S., NaCl is commonly used to control ice and snow on roadways, parking lots, and sidewalks. The U.S. in 2005 applied an estimated 21 million Mg of NaCl to roadways to combat snow and ice (Sander et al., 2007). Sodium chloride is readily available and inexpensive compared with other products such as CaCl and MgCl (Kelting and Laxson, 2010). When applied to an impervious surface, snowmelt and rainfall may transport the salt to stormwater catchment basins such as retention ponds and rain gardens (Sander et al., 2007). Rain gardens that collect runoff from parking lots or streets are likely to receive significant quantities of NaCl during spring melt that could increase to harmful levels in some plants.

Petroleum hydrocarbons are a common pollutant detected in stormwater runoff (Davis et al., 2009) and may come from impervious surfaces such as parking lots and streets, as a result of motor vehicle use, or from the erosion of tar-based seal coats used on driveways and parking lots (LeFevre et al., 2012). Some petroleum hydrocarbons such as, coal tar-based seal coats, are of special concern because they contain high concentrations of polycyclic aromatic hydrocarbons

(PAHs) which are known human carcinogens and are known to cause harm to aquatic environments (Mahler et al., 2016).

Rain gardens that collect stormwater from driveways, parking lots, and streets are likely to have higher amounts of petroleum hydrocarbons in the soil compared with sites not collecting stormwater runoff. For example, Lefevre et al. (2012) sampled 58 rain gardens in Minneapolis, MN and quantified the total petroleum hydrocarbon (TPH) concentrations and compared the value with four upland sites that did not collect stormwater runoff. Rain gardens collecting stormwater from commercial parking lots had higher median TPH concentrations of approximately 1.1 $\mu g \cdot kg^{-1}$ of dry soil compared with rain gardens collecting stormwater from residential streets and roofs (approximately 0.3 $\mu g \cdot kg^{-1}$ of dry soil). These values were not significantly different from one another and all TPH concentrations were well below limits requiring corrective action (in excess of 10,000 $\mu g \cdot kg^{-1}$). The TPH levels in the rain garden soils were significantly greater than the TPH levels found in the upland sites. Levels of TPH were far less than expected in rain garden soils given TPH concentrations in stormwater suggesting that rain gardens are able to biodegrade petroleum hydrocarbons.

As salt levels increase in the soil, plants will become stressed once a certain threshold is reached. The first to occur is osmotic stress followed by ion toxicity. Osmotic stress occurs once the salt concentration around the roots reaches a threshold resulting in reduced shoot growth and growth rate. If plants survive osmotic stress, then over time, ions could accumulate in plant tissues to toxic levels resulting in senescence (Munns and Tester, 2008). The threshold needed to induce osmotic stress and ion toxicity will vary based on plant species and their ability to tolerate soil salinity.

Plant mechanisms to tolerate soil salinity may include reduced salt uptake into the plant (i.e., by exclusion from the root system and reduced leaf and shoot growth) and reducing salt concentration in the cytoplasm (i.e., compartmentalizing salt into the vacuole and excretion by salt glands) (Munns and Tester, 2008). Plants with a low soil salinity threshold will have reduced shoot growth and increased leaf senescence and over time will result in plant death while plants with a higher threshold will be able to tolerate the saline soil conditions.

Scientific studies evaluating sodium chloride tolerance of the perennial ornamental grasses listed previously is limited and almost nonexistent for the listed cultivars. A study by Sun and Palmer (2018) evaluated the salt tolerance of blue grama grass as well as seven other species. Grasses were greenhouse grown in 3.8-L containers and watered weekly with saline solutions with an electrical conductivity (EC) of 1.2 $dS \cdot m^{-1}$ (control), 5.0 $dS \cdot m^{-1}$, and 10 $dS \cdot m^{-1}$. The 5.0 and 10 $dS \cdot m^{-1}$ saline solutions were prepared using NaCl and CaCl. After nine weeks, blue grama grass irrigated with saline solutions with an EC of 5.0 $dS \cdot m^{-1}$ and 10 $dS \cdot m^{-1}$ had a significantly lower visual score rating (3.8) when compared with the control (5.0) when using a 0-5 rating scale [0 = dead, 3 = slight foliar damage (<50%), 5= no foliar salt damage] although the foliar damage was only slight. Plant height was also reduced, approximately 13%, for blue grama plants irrigated with the saline solution with an EC of 10 $dS \cdot m^{-1}$ compared with the other two treatments. After 19 weeks, blue grama plant height was significantly reduced by 18% and 22% when compared with the control for plants irrigated with saline solutions with an EC of 5.0 and 10 $dS \cdot m^{-1}$. Although height was reduced, no significant differences appeared among treatments for the number of inflorescences, number of tillers, leaf area, or dry weight of shoots and roots indicating that the grasses were still growing. A study by Miyamoto (2008) found two cultivars of blue grama grass, 'Alamo' and 'Bad River' continued to produce top growth when irrigated with a saline solution at an EC of 9.4 $dS \cdot m^{-1}$ but top growth stopped when the saline solution increased to an EC of 13.7 $dS \cdot m^{-1}$.

A similar study by Wang et al. (2019) evaluated the salt tolerance of 'Gracillimus' Chinese silvergrass, 'Northwind' switchgrass, little bluestem, and purple love grass by watering greenhouse grown plants (7.6-L containers) every four days using saline solutions with an EC of 1.2 (control), 5.0, or 10 $dS \cdot m^{-1}$ over the course of 65 days. Saline solutions with an EC of 5.0 and 10 $dS \cdot m^{-1}$ were prepared using NaCl and CaCl. Saline solutions with an EC of 5.0 and 10 $dS \cdot m^{-1}$ did not reduce the visual score (0 – 5 scale; Sun and Palmer, 2018) for little bluestem or switchgrass when compared to their respective control. The visual score for Chinese silvergrass was significantly reduced for the 5.0 and 10 $dS \cdot m^{-1}$ saline solutions when compared to the control but the scores were 3.3 and 3.7, respectively, indicating only slight foliar salt damage. Plant height was significantly reduced by 15% for all grass species irrigated with the saline solution with an EC of 10 $dS \cdot m^{-1}$ when compared with the control while plants irrigated with the saline solution at an EC of 5.0 $dS \cdot m^{-1}$ were similar to the control. The leaf area of all grasses were reduced when irrigated with solutions with an EC of 5.0 or 10 $dS \cdot m^{-1}$ by 22% and 47%, respectively, and shoot dry weight was reduced by 25% and 46%, respectively, when compared with the control.

The salt tolerance of tufted hair grass was evaluated by Henschke (2016) using different concentrations of NaCl to give the following EC values of the soil saturation extract (EC_e); 2.0 (control), 2.5, 3.5, 4.0, and 5.7 $dS \cdot m^{-1}$. Salt solutions were applied only once to plants growing in 750 cc pots. After 56 days of growth, all saline solutions significantly reduced the number of mature shoots from 21% - 47% when compared with the control. The length of shoots and leaves were similar to the control for solutions with an EC_e of 2.5 and 3.5 $dS \cdot m^{-1}$ while plants irrigated with solutions with an EC_e of 4.0, and 5.7 $dS \cdot m^{-1}$ were significantly reduced when compared with the control. Although previous research has been conducted with blue grama grass, Chinese silvergrass, little bluestem, tufted hairgrass, and switchgrass, the cultivars that were used are different than the cultivars being used in this research with the exception of 'Northwind' switchgrass.

LeFevre et al. (2012) also found that rain gardens planted with deep-rooted vegetation (deeper than 15 cm) had more soil bacteria compared with rain gardens covered with turfgrass or just mulch suggesting that rain gardens with deep-rooted plants are better able to assimilate petroleum hydrocarbons. Plant roots increase microbial populations due to the release of root exudates and oxygen used by soil microbes (Chaudhry et al., 2005). Grasses have a fibrous root system, as opposed to a taproot, allowing for ample surface area for soil microorganisms. As the soil microbial population increases, so does the breakdown of petroleum hydrocarbons. A study evaluating nine Australian native grass species found that all the grass species increased the soil microbial population when seeded into a soil contaminated with a diesel and oil mixture at concentrations of 1% (w/w), 0.5% (w/w), and 0% (control). Three of the species had increased root biomass in contaminated soil compared with the control (Gaskin et al., 2008).

No research has been conducted with the seven perennial ornamental grass cultivars previously listed to determine their ability to survive in soil contaminated with hydrocarbons. Robson et al. (2003) screened 39 species of perennial plants, commonly found in western Canada to determine survival when grown in soil contaminated with crude oil at concentrations of 0.5%, 1%, and 5% (crude oil weight/fresh soil weight). After 35 d of growth, only 12 of the 39 species had a high enough survival rate to be useful for phytoremediation.

It is likely that rain gardens in northern climates receiving runoff from parking lots will have higher concentrations of sodium chloride as well as petroleum hydrocarbons. Therefore, determining the ability of the seven grass cultivars to breakdown petroleum hydrocarbons while enduring salt stress is essential for making recommendations for rain gardens to provide multiple ecosystem services. Currently, there is no research available evaluating the seven grass cultivars previously listed to determine their ability to tolerate both sodium chloride and petroleum hydrocarbon pollution.

Two experiments were conducted to answer our research objectives: Experiment 1) determine the salt tolerance, using NaCl, of the listed grass cultivars. Experiment 2) determine the ability of the listed grasses to degrade petroleum hydrocarbons while enduring NaCl salt stress (rates determined from experiment 1).

Materials and methods

Plant material. Grass plugs were purchased from commercial greenhouses (Table 3-1) and transplanted into 1.07-L (10.7 cm wide x 8.7 cm tall) square pots (T.O. Plastic, Clearwater, MN). Pots were filled with Pro Mix BRK (Premier Tech Horticulture, Quakertown, PA) containing 45-55% sphagnum peat moss, processed pine bark, perlite, and limestone (to adjust pH). Five grams of Multicote 14-14-16 (Haifa North America, Savannah, GA) was added into the potting medium used to fill each 1.07-L pot. Grasses were maintained in a greenhouse on the campus of North Dakota State University, Fargo, ND, U.S.A. (latitude 46° 52’ 38” N and longitude 96° 48’ 18” W). The greenhouse was maintained at a minimum of 21 °C with a 14-h photoperiod.

For both experiments, grass roots were washed free of potting media, shoots cut to a height of 25 cm, and grasses planted into 2.9-L (16.5 cm wide x 17.8 cm tall) nursery containers

(Meyers Industries, Akron, Ohio) filled with a 5:4:1 by volume mixture of all-purpose play sand (TCC Materials, Mendota Heights, MN), Barnes soil (fine-loamy, mixed, superactive, frigid Calcic Hapludolls) (Soil Survey Staff, 2011), and peat moss (Premier Tech Horticulture, Quakertown, PA). Shoot counts at planting for tufted hair grass, switchgrass, big bluestem, Chinese silvergrass, little bluestem, blue grama grass, and feather reed grass were 30, 7, 10, 25, 22, 25, and 20, respectively (experiment 1) and 40, 10, 12, 12, 15, 25, and 20, respectively (experiment 2). Grasses were placed in a greenhouse and allowed to establish for at least 4 months before starting experiments. During establishment, grasses were fertilized every two weeks with a water-soluble fertilizer (20N-8.7P-16.6K; JR Peters Inc., Allentown, PA) with each pot receiving 200 $mg \cdot L^{-1}$ (N), 87 $mg \cdot L^{-1}$ (P), and 166 $mg \cdot L^{-1}$ (K) at each application. Grasses were given a 16 h photoperiod with supplemental lighting using 400-w high-pressure sodium lights (P.L. Light Systems, Beamsville, ON, Canada) producing ≈ 91 $\mu mol \cdot m^{-2} \cdot s$ irradiance. The greenhouse temperature was maintained between 18 ˚C and 25 ˚C. While grasses were establishing, iron deficiency chlorosis was observed. A onetime application of 1.0 g FeDTPA (Sprint 330, BASF Corporation, Triangle Park, NC) was applied to each container to correct the nutrient deficiency. For experiment 2, a onetime application of 5.3 g of imidacloprid (Marathon 1% G, OHP, Inc., Bluffton, SC) was applied to each pot for mealybug control. Experiment 1 was started in 2020 on 3 Oct. and completed on 17 Nov. (45 d). The average temperature during the study was 26.2 ˚C. Experiment 2 was started in 2021 on 22 Feb. and completed on 16 April (53 d). The average temperature during the study was 29.5 ˚C.

Soil and media mix. The 5:4:1 by volume mixture of sand, Barnes soil, and peat moss was used for both experiments because the mixture is similar to a rain garden mix recommended by the MPCA (2021); 50-65% coarse sand, 25-35% topsoil, and 10-15% compost. A commercial farm field located near Fergus Falls, MN, planted with corn (*Zea mays* L.) the previous year, was the soil source. No residual herbicides were used for >5 previous years at the farm. Soil was taken from the 0-15 cm profile on 4 May 2020 and screened through a 6.4 mm sieve to remove plant debris and soil clods. Screened soil was spread on top of a tarp and raked three times a week to hasten air drying. After air drying soil for 27 d, three random soil samples were collected for analysis. Soil samples were sent to Agvise Laboratories, Northwood, ND, for analysis of pH, organic matter, $CaCO_3$, cation exchange capacity (CEC), electrical conductivity (EC), NO_3-N, Olsen soil test P, K, Ca, Mg, Zn, S, Cl, Cu, Fe, Mn, B, and Na (Table 3-2).

A 38-L capacity cement mixer was used to blend sand, Barnes soil, and peat moss by allowing the components to mix for 5 min. Three random samples of the soil mixture were collected and sent to Agvise Laboratories for the same analysis as previously described (Table 3-2).

Table 3-1. Ornamental grass species and cultivar, common name, and origin of plant material.

Scientific name and cultivar	Common name	Origin of plant material
Deschampsia cespitosa (L.) P. Beauv. 'Pixie Fountain'	Tufted hairgrass	Emerald Coast Growers, Pensacola, FL
Panicum virgatum L. 'Northwind'	Switchgrass	Emerald Coast Growers, Pensacola, FL
		Twixwood Nursery, Berrien Springs, MI
Andropogon gerardii Vitman 'Red October'	Big bluestem	Hoffman Nursery, Rougemont, NC
Miscanthus sinensis Andersson 'Purpurascens'	Chinese silvergrass	Hoffman Nursery, Rougemont, NC
		Walters Gardens, Zeeland, MI
Schizachyrium scoparium (Michx.) Nash 'Blue Heaven'	Little bluestem	Hoffman Nursery, Rougemont, NC
Bouteloua gracilis (Kunth) Lag. ex Griffiths 'Blonde Ambition'	Blue grama grass	Hoffman Nursery, Rougemont, NC
Calamagrostis x *acutiflora* (Schrad.) Rchb. 'Karl Foerster'	Feather reed grass	Emerald Coast Growers, Pensacola, FL

Table 3-2. Soil chemical properties for Barnes soil and Mix containing 50% sand, 40% Barnes soil, and 10% peat moss (by volume). Means and standard deviations are presented.

Soil property	Barnes			Mix		
Organic matter (%)	5.13	±	0.12	1.97	±	0.06
pH	7.90	±	0.00	8.00	±	0.00
Electrical conductivity (dS·m^{-1})	0.61	±	0.02	0.48	±	0.02
Calcium carbonate (%)	10.23	±	1.53	9.40	±	0.69
Cation exchange capacity (cmol·kg^{-1})	35.7	±	1.42	27.3	±	0.47
Nitrate (mg·kg^{-1})	22	±	3.6	19.5	±	5.29
Phosphorous (Olsen) (mg·kg^{-1})	29.3	±	8.50	15.3	±	2.89
Potassium (mg·kg^{-1})	321	±	14.7	147	±	12.6
Calcium (mg·kg^{-1})	5709	±	217	4611	±	61
Magnesium (mg·kg^{-1})	758	±	42.0	462	±	18.0
Sulfur (mg·kg^{-1})	8.00	±	2.65	13.00	±	0.00
Zinc (mg·kg^{-1})	1.83	±	0.03	0.95	±	0.04
Chlorine (mg·kg^{-1})	49.5	±	6.76	24.0	±	4.1
Copper (mg·kg^{-1})	1.09	±	0.01	0.60	±	0.04
Iron (mg·kg^{-1})	11.83	±	0.68	10.90	±	0.98
Manganese (mg·kg^{-1})	17.50	±	1.18	13.4	±	2.76
Boron (mg·kg^{-1})	2.37	±	0.06	1.25	±	0.05
Sodium (mg·kg^{-1})	14.3	±	0.06	15.0	±	1.00

Sensor calibration and soil moisture characteristic curve. A GS3 volumetric water content sensor connected to a ProCheck sensor readout storage system (Decagon Devices, Pullman, WA) was calibrated as described by Nelson et al. (2018). Briefly, water was added to containers filled with soil and carefully mixed and allowed to sit for 24 h. The GS3 sensor was inserted into each container, a measurement was taken, and gravimetric water content was determined. The soil bulk density was multiplied by gravimetric water content to determine soil VWC. The soil VWC determined by the sensor was plotted against soil VWC determined by gravimetric water content. A soil specific equation was developed and used for both experiments because variation existed between the predicted soil VWC (using factory settings) and the actual soil VWC:

$$\text{VWC} = (0.000134 \times \text{dielectric permittivity}^3) - (0.005598 \times \text{dielectric permittivity}^2) + (0.085629 \times \text{dielectric permittivity}) - 0.207856. \quad (2)$$

Bulk density of the soil mixture was determined by filling three containers of known volume, placing them on a greenhouse bench, and watering the containers for 60 d. Soil was removed from containers, weighed, dried at 105 °C for 48 h, and reweighed. The mean soil bulk density was determined by dividing the dry weight of the soil mix by the volume of the soil mix. Particle densities of the soil mix (sand + Barnes soil + peat moss), sand, Barnes soil, and peat moss were 2.64, 2.68, 2.62, and 1.58 $g \cdot cm^{-3}$, respectively. Particle densities were determined using the pycnometer method as described by Blake and Hartge (1986). A soil moisture characteristic curve was developed for the soil mix described above as described by Nelson et al. (2018) (Fig. 3-1).

Experiment 1. Sodium chloride concentrations were determined based on the assumption that a model rain garden measuring 33 m^2 would receive runoff from a 93 m^2 parking lot treated with NaCl ranging from 0 to 9 $Mg \cdot ha^{-1}$. The total amount of NaCl for each treatment was evenly applied over three weekly irrigations to avoid salt shock and simulate freeze and thaw cycles common to the North Central region of the US. Soil VWC was taken daily on control plants using a GS3 sensor. When the soil VWC of a control plant for a given species fell below 0.20 $m^3 \cdot m^{-3}$ (i.e., < -2.0 kPa matric potential), 300 mL of tap water was applied to all treatments within the species for that replicate. Salt solutions were prepared using NaCl (Avantor-Macron Fine Chemicals, Paris, KY) and tap water in 7.8 L batches with each grass container receiving 300 mL of salt solution (Table 3-3).

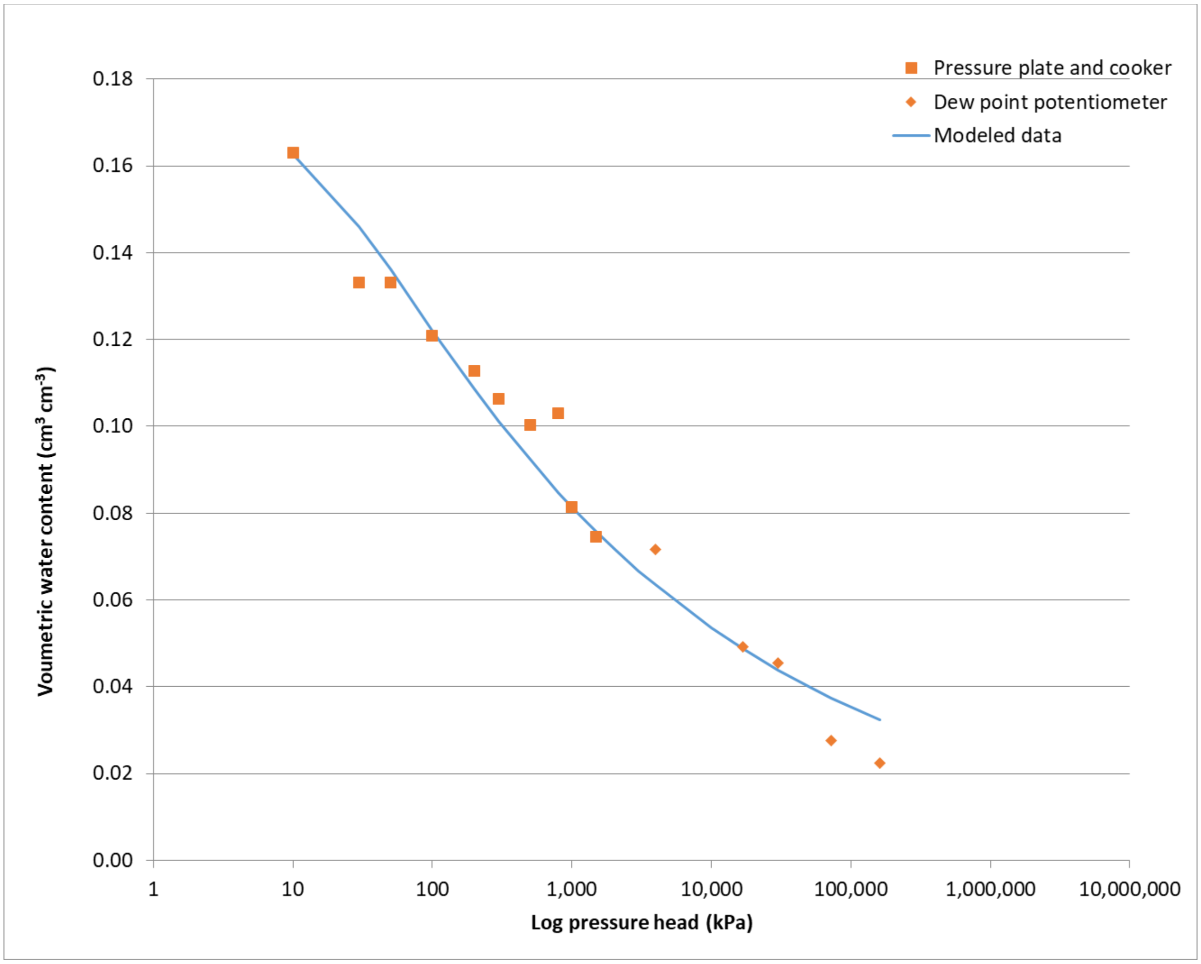

Figure 3-1. Water retention curve of a soil mixture containing all-purpose play sand, Barnes soil, and peat moss mixed 5:4:1 (by volume).

Table 3-3. Unit conversions of sodium chloride treatment solutions and mean electrical conductivity (EC) and pH of NaCl batches used in experiment 1.

Simulated parking lot NaCl application rate	Salt load per 300 mL application	Total salt load per container	Salt concentration of solution	Mean EC and pH of the three 7.8-L batch salt solutions					
($Mg \cdot ha^{-1}$)	-------------(mg)-------------		($mg \cdot L^{-1}$)	($dS \cdot m^{-1}$)			------pH----		
0	0	0	0	0.36	±	0.0	9.1	±	0.1
1.1	2,274	6,821	7,579	14.1	±	0.3	8.9	±	0.1
2.2	4,548	13,643	15,159	26.0	±	0.2	8.9	±	0.0
3.4	6,821	20,464	22,738	36.5	±	0.3	8.8	±	0.0
4.5	9,095	27,286	30,317	48.8	±	0.5	8.6	±	0.2
5.6	11,369	34,107	37,897	58.6	±	0.4	8.7	±	0.0
6.7	13,643	40,929	45,476	68.6	±	0.2	8.6	±	0.1
7.8	15,917	47,750	53,056	75.6	±	0.9	8.6	±	0.0
9.0	18,190	54,571	60,635	86.3	±	0.5	8.6	±	0.0

Salt solutions were applied on 3, 10, and 17 Oct. 2020. After applying NaCl solution or tap water, the leachate from one replicate was collected to determine leachate volume, pH, and EC. Solution pH and EC were measured using a HI9829 multiparameter probe (Hanna Instruments, Smithfield, RI). A plastic plant saucer (10.2 cm diameter x 2.8 cm tall) (Curtis Wagner Plastics Corp., Houston, TX) was placed under the grass plant, salt solution or tap water was applied, and allowed to sit for 30 min. After 30 min., leachate collected in the saucer was emptied into a graduated cylinder to determine volume and then transferred to a 100-mL glass beaker to determine pH and EC.

At the conclusion of the experiment, plant height, shoot count, and visual damage rating were determined. Plant height was measured from the soil surface to the highest living leaf when the leaf was held upright. Living shoot counts were taken on all shoots with a height of at least 1.25 cm. Visual damage was assessed using a 1-10 scale (1 = 0% to 10% dieback, 4 = 31% to 40% dieback, 7 = 61% to 70% dieback, and 10 = 91% to 100% dieback). Shoots were cut at the soil line and placed into paper bags. Root balls were removed from plastic containers and four soil slices, approximately 2.5 cm wide, were cut from just before the crown of the grass plant and lengthwise to the base of the root ball and placed onto aluminum trays to dry. The remaining root ball was washed free of soil and placed into a paper bag for drying. Soil placed onto aluminum trays was allowed to dry for 21 d in a greenhouse and screened through a 2.0 mm sieve to remove roots and small pebbles. Roots were placed into paper bags for drying and screened soil was placed into plastic bags and used to determine soil EC using the saturated paste method. Paper bags containing shoots and roots were placed into a dryer set at 65 °C and allowed to dry for 96 h. After drying, shoot and root dry weights were determined using an electronic balance (LP6200S, Sartorius AG, Gottingen, Germany).

Saturated paste extract was collected using the method outlined by Whitney (2015). Approximately 250 g of screened and air-dried soil was added to a 270 mL disposable plastic cup. Distilled water was added to the soil while mixing until a slightly flowable paste was formed. Containers were covered with a plastic lid and allowed to sit for 24 h. After 24 h, soil was stirred again and immediately placed into a filter funnel. Vacuum was applied to the filter funnel, extract was collected into plastic vials, and sent to Agvise Laboratories to determine EC, and concentration of Ca, Mg, and Na to calculate the SAR.

Experiment 2. Grasses received one of three NaCl concentrations (0, 3.4 or 6.7 $Mg \cdot ha^{-1}$) and one of three rates of petroleum hydrocarbon (0%, 2.5%, and 5.0% weight of oil/weight of air-dried soil). Sodium chloride concentrations were selected based on results of Experiment 1. The petroleum hydrocarbon source was new 5W-20 motor oil (FormulaShell Motor Oil SAE 5W-20, Houston, TX). The amount of motor oil applied to grasses was 0%, 2.5%, or 5% of the air-dried soil weight used to plant grasses in 2.9-L nursery containers. Soil weight was determined by adding air-dried soil to three nursery containers, weighing container and soil, and subtracting the container weight. The average soil weight was 2,352 g ± 8.5 g. The amount of motor oil applied to each grass receiving the 2.5% and 5.0% treatment was 59 g and 118 g, respectively. The application rates of motor oil used in the study are similar to application rates of crude oil used by Robson et al. (2003). The total amount of NaCl and motor oil for each treatment was evenly applied over three weekly applications to avoid salt and hydrocarbon shock similar to Experiment 1. Soil VWC was also taken daily on control plants and tap water was applied as needed as described in Experiment 1. Salt solutions were prepared using NaCl (Avantor-Macron Fine Chemicals, Paris, KY) and tap water in 13.8 L batches with each grass receiving 300 mL of salt solution (Table 3-4). Motor oil was carefully measured into a 100 mL glass beaker and applied near the crown of the plant being careful not to contaminate foliage with motor oil. Motor oil was applied immediately after applying NaCl solution or tap water.

Sodium chloride solutions and motor oil were applied on 22 and 27 Feb. and 5 Mar. 2021. After applying NaCl solution or tap water, the leachate from one replicate was collected to determine leachate volume, pH, and EC as described in Experiment 1. At the conclusion of the experiment, plant parameters listed in Experiment 1 were determined. Soil was collected from each plant as described in Experiment 1, placed on aluminum trays, dried in a greenhouse for 14 d, and screened through a 2.0 mm sieve to remove roots and small pebbles. Roots were placed into paper bags for drying and screened soil was placed into plastic bags. Paper bags containing shoots and roots were placed into a dryer set at 65 ˚C and allowed to dry for 96 h. After drying, shoot and root dry weights were determined using an electronic balance (LP6200S, Sartorius AG, Gottingen, Germany).

A subsample of the screened soil was sent to Agvise Laboratories to determine total carbon, total organic carbon, and calcium carbonate equivalent and EC and concentrations of Ca, Mg, and Na using saturated paste extracts to calculate SAR. Another subsample of screened soil was sent to Pace Analytical Services, LLC, Minneapolis, MN, to determine total petroleum hydrocarbons (TPTH).

Experimental design and statistical analysis. Experiment 1 consisted of seven grass species and nine different NaCl concentrations. Each species by NaCl treatment consisted of three single plant replicates. Regression analysis was used to describe each grass cultivars behavior as a function of salinity level and used to identify NaCl load and soil EC thresholds for plant performance using SigmaPlot 14.5 (Systat Software, Inc., San Jose, CA). Experiment 2 was arranged as a randomized complete block designs with a 7×3×3 factorial arrangement consisting of seven species, three petroleum hydrocarbon levels, and three NaCl concentrations with two single plant replicates. Data was subjected to a mixed linear model analysis of variance (Proc MIXED, SAS 9.4; SAS Institute, Cary, NC). Species, petroleum hydrocarbon, and NaCl concentration were fixed effects and the experimental replicate was a random effect. Tukey-Kramer's honestly significant difference test was used to separate treatment means. Means were considered significant at the p <0.05 level.

Table 3-4. Unit conversions of sodium chloride treatment solutions and mean electrical conductivity (EC) and pH of NaCl batches used in experiment 2.

Simulated parking lot NaCl application rate	Salt load per 300 mL application	Total salt load per container	Salt concentration of solution	Mean EC and pH of the three 13.8-L batch salt solutions	
($Mg \cdot ha^{-1}$)	-------------(mg)-------------		($mg \cdot L^{-1}$)	---($dS \cdot m^{-1}$)---	---pH---
0	0	0	0	0.33 ± 0.04	8.8 ± 0.17
3.4	6,821	20,464	22,738	37.0 ± 0.02	8.7 ± 0.21
6.7	13,643	40,929	45,476	68.0 ± 0.40	8.7 ± 0.04

Results

Experiment 1. Leachate and soil parameters. Average leachate volume and EC generally increased with NaCl concentrations with leachate volume varying by species (Appendix Table 1). Feather reed grass had the lowest average leachate volume (~620 mL) while big bluestem had the highest leachate volume (~1534 mL) when summed across NaCl application rates. The average EC range was similar for all grass species across NaCl concentrations with the lowest EC value for each grass species ranging from 0.6-1.2 $dS \cdot m^{-1}$ and highest ranging from 43.4-59.1 $dS \cdot m^{-1}$. For all grass species, the average leachate pH generally decreased as the NaCl concentration increased. The range of pH were similar across grass species and NaCl concentrations with the lowest pH for each grass species ranging from 7.1-7.6 and the highest pH ranging from 8.0-8.6.

The soil mix's Ca, Mg, and Na concentrations, SAR and EC as determined from saturated paste extract, are presented in Appendix Table 2. For all grass species, the Ca and Mg concentrations generally decreased and Na concentrations and SAR generally increased as NaCl concentrations increased, which all varied by species. The lowest Ca and Mg concentrations for each grass species across all NaCl concentrations ranged from 41.3 $mg \cdot L^{-1}$ (tufted hairgrass) to 341.7 $mg \cdot L^{-1}$ (switchgrass) and 8.3 $mg \cdot L^{-1}$ (tufted hairgrass) to 27.9 $mg \cdot L^{-1}$ (switchgrass), respectively. Whereas, the highest Ca and Mg concentrations ranged from 236 $mg \cdot L^{-1}$ (big bluestem) to 819 $mg \cdot L^{-1}$ (switchgrass) and 66.9 $mg \cdot L^{-1}$ (big bluestem) to 222 $mg \cdot L^{-1}$ (switchgrass), respectively. The lowest Na concentrations for each grass species across all NaCl concentrations ranged from 147 $mg \cdot L^{-1}$ (big bluestem) to 439 $mg \cdot L^{-1}$ (tufted hairgrass), while the highest ranged from 886 $mg \cdot L^{-1}$ (little bluestem) to 2864 $mg \cdot L^{-1}$ (switchgrass), respectively. The lowest SAR observed for each grass species across all NaCl concentrations ranged from 2.5 (big bluestem) to 5.2 (blue grama grass and feather reed grass) while the highest SAR ranged from 24.5 (little bluestem) to 46.7 (big bluestem). The EC for all grass species varied regardless of NaCl concentration and ranged from 1.66-13.02 $dS \cdot m^{-1}$. Some NaCl leached from the soil when tap water was applied to grasses (i.e., when the soil VWC of the control plant fell below 0.2 $m^3 \cdot m^{-3}$). The number of tap water applications made during the experiment varied by species and ranged from about 14 (big bluestem) to about 36 (feather reed grass) with all grass species, except big bluestem, receiving at least ~29 applications (Appendix Table 2).

Experiment 1. Visual damage rating. The visual damage rating for all grass species increased as the NaCl application rate increased from 0 to 9 $Mg \cdot ha^{-1}$, but the magnitude of increase varied by species (Fig. 3-2). A linear relationship was observed between visual damage rating and NaCl application rate for tufted hairgrass, little bluestem, and feather reed grass while a sigmoidal logistic relationship was observed for switchgrass, big bluestem, Chinese silvergrass, and blue grama grass. The NaCl application rate causing 50% foliage dieback was highest for blue grama grass and feather reed grass (~6 $Mg \cdot ha^{-1}$) and lowest for big bluestem (~1 $Mg \cdot ha^{-1}$) followed by little bluestem (~3 $Mg \cdot ha^{-1}$). Tufted hairgrass, switchgrass, and Chinese silvergrass had 50% foliage dieback with NaCl application rates of approximately 4-5 $Mg \cdot ha^{-1}$. The relationship between visual damage rating and saturated paste EC was poor (Appendix fig. A3). Shoot height and count and shoot and root mass generally decreased as the NaCl application rate increased but the relationship was not as strong as the visual damage rating (data not shown).

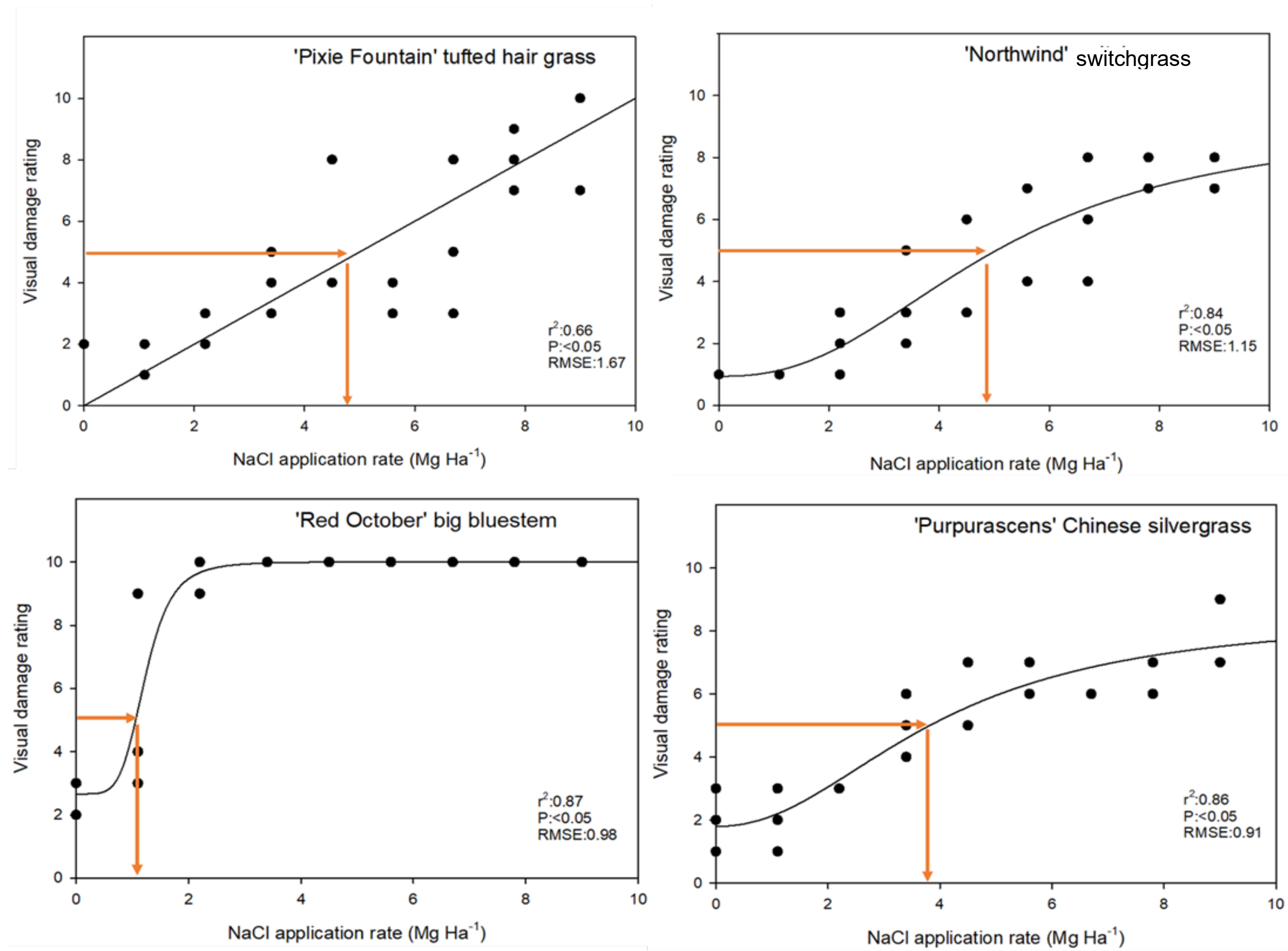

Figure 3-2. Relationship between visual damage rating (1-10 scale; 1= 0-10% dieback, 4= 31-40% dieback, 7= 61-70% dieback, 10= 91-100% dieback) and NaCl application rate (0-9 $Mg \cdot Ha^{-1}$) of seven perennial ornamental grasses. Orange arrows represent NaCl application rate causing 50% foliage dieback. Experiment was conducted in a greenhouse from 3 Oct. to 17 Nov. 2020.

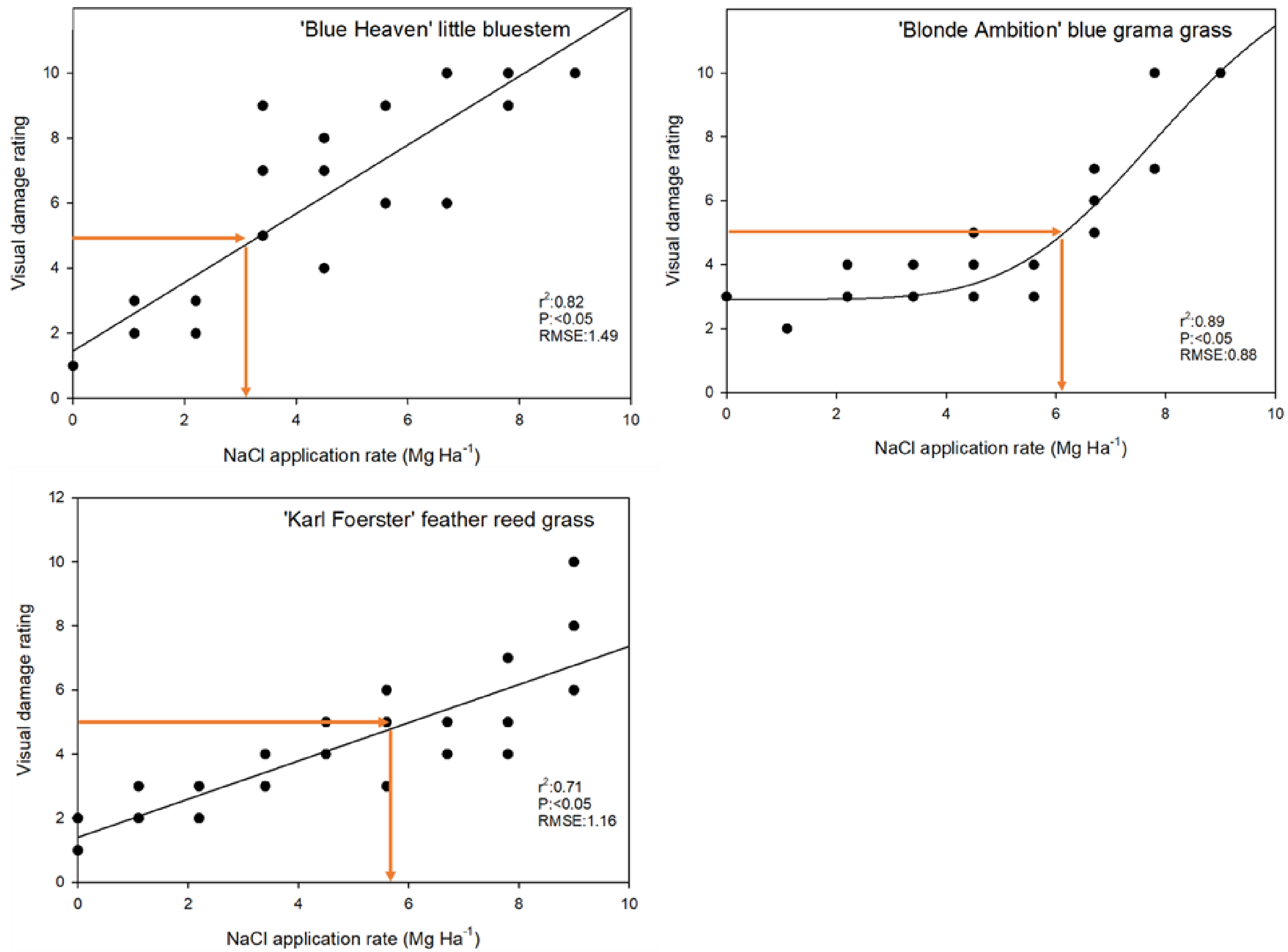

Figure 3-2. Relationship between visual damage rating (1-10 scale; 1= 0-10% dieback, 4= 31-40% dieback, 7= 61-70% dieback, 10= 91-100% dieback) and NaCl application rate (0-9 Mg·Ha^{-1}) of seven perennial ornamental grasses. Orange arrows represent NaCl application rate causing 50% foliage dieback. Experiment was conducted in a greenhouse from 3 Oct. to 17 Nov. 2020 (continued).

Experiment 2. Leachate and saturated paste parameters. Average leachate volume generally increased with NaCl and motor oil application rates (Appendix Table 3). The average leachate EC increased and pH generally decreased as the NaCl application rate increased regardless of motor oil application rate. The average leachate volume for the control of each grass species ranged from 33 mL (tufted hairgrass) to 193 mL (big bluestem) while the highest average leachate volume for each species ranged from 145 mL (feather reed grass) to 210 mL (Chinese silvergrass). The lowest average leachate EC for each grass species ranged from 0.6 $dS \cdot m^{-1}$ (switchgrass) to 1.2 $dS \cdot m^{-1}$ (tufted hair grass and Chinese silvergrass) and the highest average leachate EC ranged from 35.1 $dS \cdot m^{-1}$ (tufted hair grass) to 60.3 $dS \cdot m^{-1}$ (big bluestem). The lowest average leachate pH for each grass species ranged from 7.4 (Chinese silvergrass) to 7.9 (little bluestem) and the highest average pH for each grass species ranged from 7.9 (Chinese silvergrass) to 8.3 (feather reed grass).

The soil mix's Ca, Mg, and Na concentrations, SAR and EC as determined from saturated paste extract, are presented in Appendix Table 4. For all grass species, the Ca and Mg concentrations generally decreased as the NaCl application rate increased, while the Na concentration and the SAR generally increased regardless of motor oil application rate. The lowest Ca and Mg concentrations for each grass species across all NaCl and motor oil application rates ranged from 36 $mg \cdot L^{-1}$ (tufted hairgrass and blue grama grass) to 90 $mg \cdot L^{-1}$ (switchgrass) and 9 $mg \cdot L^{-1}$ (tufted hairgrass) to 29 $mg \cdot L^{-1}$ (Chinese silvergrass), respectively, while the highest Ca and Mg concentrations ranged from 159 $mg \cdot L^{-1}$ (tufted hairgrass) to 436 $mg \cdot L^{-1}$ (big bluestem) and 48 $mg \cdot L^{-1}$ (feather reed grass) to 130 $mg \cdot L^{-1}$ (big bluestem), respectively. The lowest Na concentration for each grass species across all NaCl and motor oil application rates ranged from 71 $mg{\cdot}L^{-1}$ (Chinese silvergrass) to 179 $mg{\cdot}L^{-1}$ (blue grama grass) while the highest ranged from 842 $mg{\cdot}L^{-1}$ (blue grama grass) to 3174 $mg{\cdot}L^{-1}$ (big bluestem).

The lowest SAR for each grass species across all NaCl and motor oil application rates ranged from 1.4 (Chinese silvergrass) to 2.9 (blue grama grass) while the highest SAR ranged from 13.7 (tufted hairgrass) to 34.3 (big bluestem). The EC for all grass species generally increased with NaCl application rate regardless of the motor oil application rate. The lowest EC for each grass species across all NaCl and motor oil application rates ranged from 0.9 $dS{\cdot}m^{-1}$ (tufted hairgrass) to 1.5 $dS{\cdot}m^{-1}$ (blue grama grass) while the highest EC ranged from 2.2 $dS{\cdot}m^{-1}$ (tufted hairgrass) to 10.0 $dS{\cdot}m^{-1}$ (big bluestem).

Tap water was applied to all the grasses within a species and replicate when the soil VWC of the control plant fell below 0.2 $m^3{\cdot}m^{-3}$. The number of tap water applications made during the experiment varied by species and ranged from 21 (big bluestem) to 44 (feather reed grass) (Appendix Table 4).

Experiment 2. Relative shoot and root characteristics. A three-way interaction occurred for shoot height (Fig. 3-3). Tufted hairgrass, switchgrass and Chinese silvergrass' shoot height were not affected by any NaCl or motor oil treatments and their combinations. However, all other species' shoot heights decreased from the control (zero NaCl or motor oil applied) or plants died when NaCl was applied or when NaCl and motor oil occurred in combination. For instance, big bluestem shoot height was significantly less than the control when NaCl was applied regardless of motor oil applications. Little bluestem shoot height behaved similar to big bluestem, but only for the highest NaCl application rate. In contrast, blue gramma grass shoot height was significantly less than the control only when the highest NaCl application rates were in combination with any amount of motor oil. Feather reed grass shoot height was significantly less than the control only when NaCl and motor oil occurred at their highest rates.

A three-way interaction also occurred for shoot counts, but the trends differed among species somewhat from shoot heights (Fig. 3-4). Shoot counts for switchgrass, big bluestem, Chinese silvergrass, and little bluestem were not affected by any NaCl or motor oil treatments and their combinations. However, all other species' shoot counts decreased from the control (zero NaCl or motor oil applied) or plants died when NaCl was applied or when NaCl and motor oil occurred in combination. Tufted hair grass shoot counts were substantially less than the control when any amount of NaCl or motor oil was applied. Blue grama grass shoot counts behaved similar to tufted hair grass, but with shoot counts reduced more when NaCl and motor oil occurred in combination. Feather reed grass shout counts were only significantly lower than the control when any amount of NaCl and motor oil occurred in combination.

Shoot mass was only affected by a species main effect. Blue grama grass had the highest shoot mass (>50 g) compared with all other grass species. Tufted hair grass and feather reed grass had higher shoot masses (>40 g) compared with switchgrass, little bluestem, big bluestem, and Chinese silvergrass. Switchgrass and little bluestem had a higher shoot mass (~15 g) compared with big bluestem (~5 g) and Chinese silvergrass (~7 g).

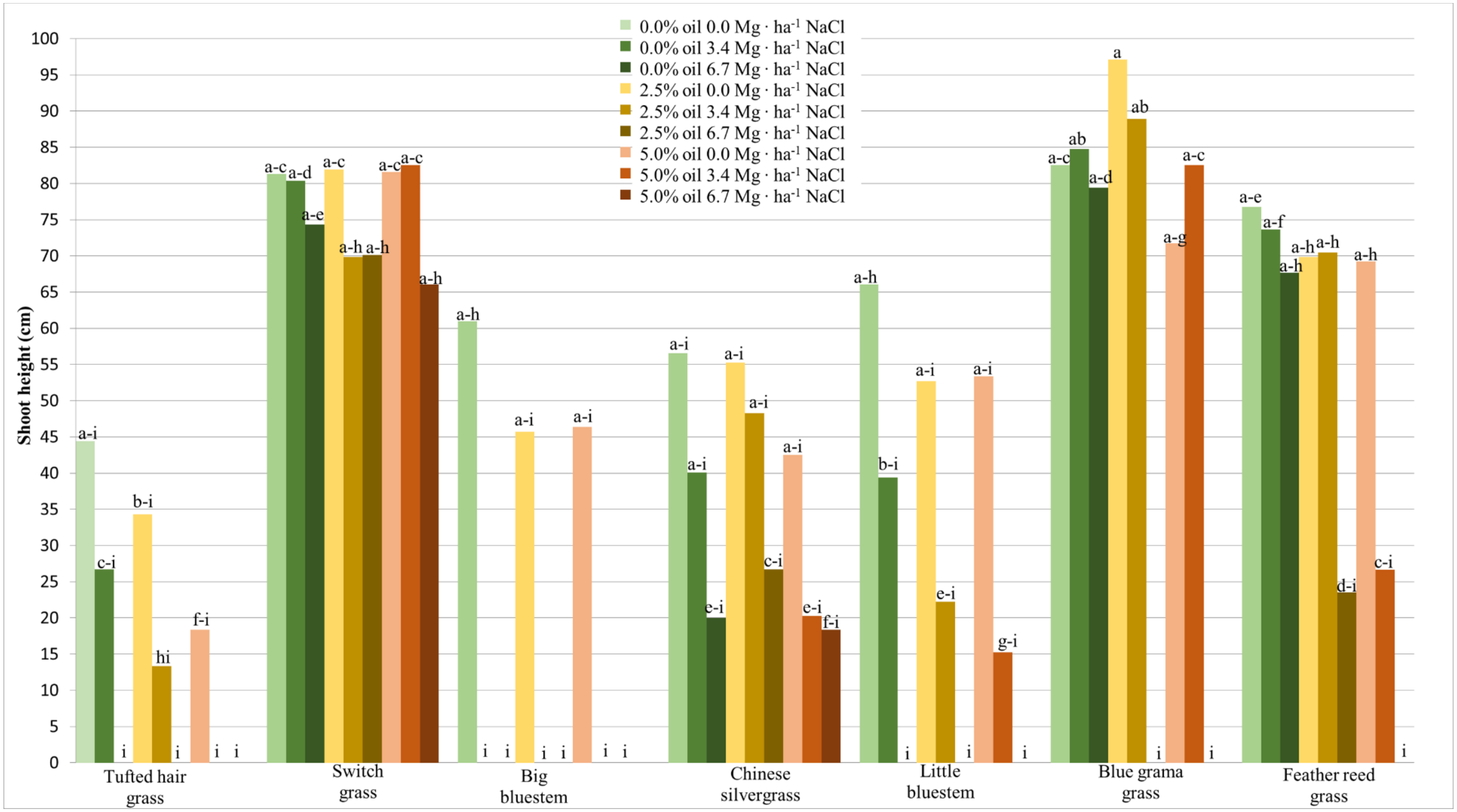

Figure 3-3. Shoot height of seven perennial ornamental grass species treated with motor oil and NaCl. Grasses were treated with 0, 2.5, or 5.0% motor oil (w/w) and 0, 3.4, or 6.7 Mg · ha-1 NaCl. Mean (n = 2) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at P< 0.05. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

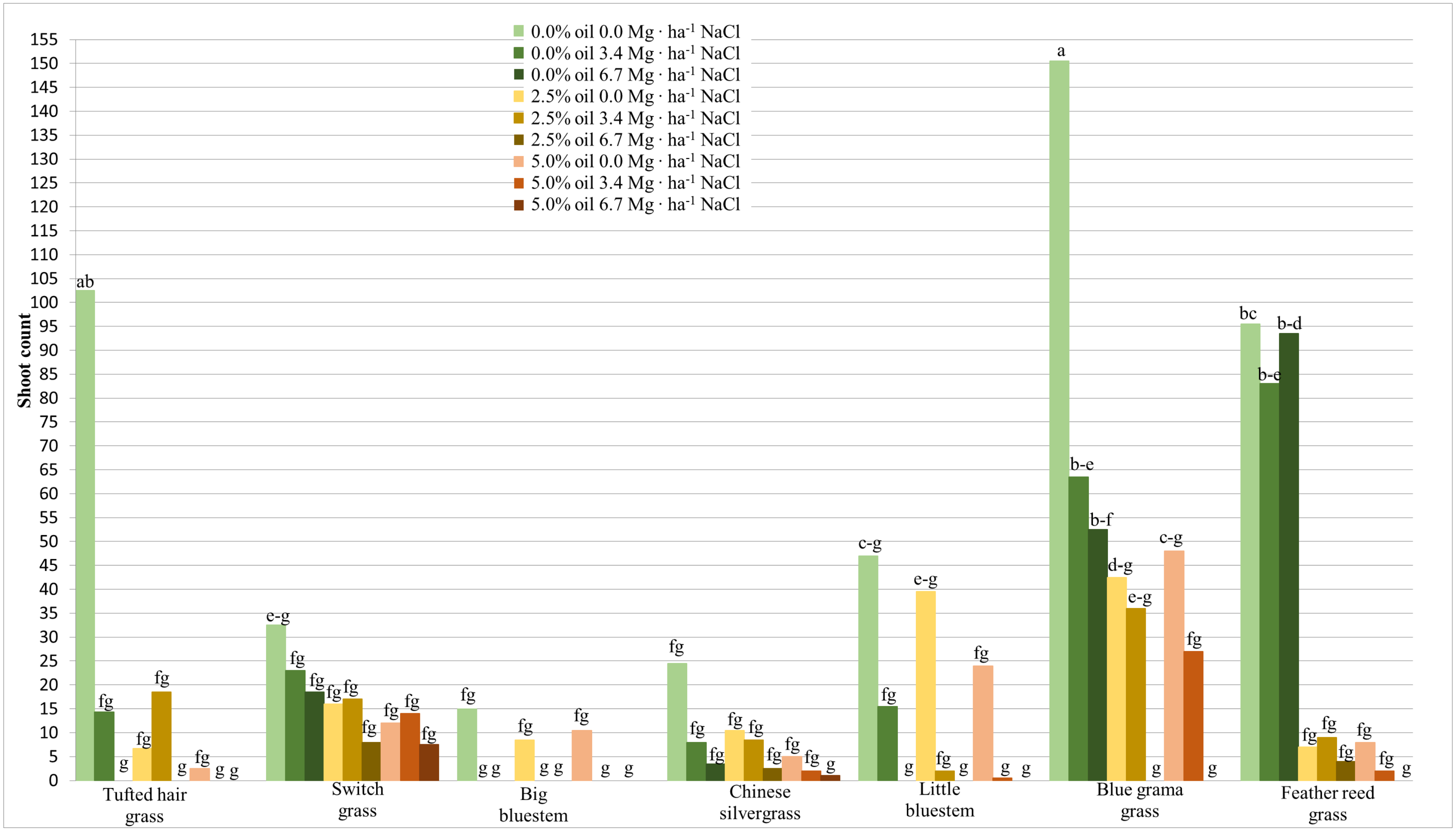

Figure 3-4. Shoot count of seven perennial ornamental grass species treated with motor oil and NaCl. Grasses were treated with 0, 2.5, or 5.0% motor oil (w/w) and 0, 3.4, or 6.7 Mg · ha^{-1} NaCl. Mean (n = 2) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at *P*< 0.05. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

Root mass was affected by an interaction of species by motor oil application rate and main effects of NaCl application rate. The interaction occurred because blue grama grass was the only species affected by motor oil additions. However, root mass for blue grama grass was only lower than the control for the intermediate motor oil rate of 2.5% (w/w) (i.e., root mass 17 g vs. 34 g). Root mass at the highest motor oil rate of 5% (25 g) was not different then the control. Root masses were similar among the two NaCl application rates of 3.4 $Mg \cdot ha^{-1}$ (16 g) and 6.7 $Mg \cdot ha^{-1}$ (~15 g), but significantly lower than the control (~21 g).

Experiment 2. Relative total biomass, visual damage rating, and survival. A significant species by motor oil application rate interaction and a NaCl application rate main effect occurred for total biomass. The species by motor oil interaction occurred because feather reed grass was the only species to be affected by motor oil. The motor oil applied at 2.5% and 5% was similar (66g), but significantly lower than the control (>90g) for feather reed grass' total biomass. Total biomass was significantly lower when NaCl was applied at 6.7 $Mg \cdot ha^{-1}$ (~37 g) compared to the 3.4 $Mg \cdot ha^{-1}$ rate (~42 g) and the control (~48 g), which were similar.

A three-way interaction occurred for the visual damage rating (Fig. 3-5). All species were either affected by the application of NaCl, motor oil, or their combination. For instance, blue grama grass visual damage was significantly higher than the control when NaCl was applied at the highest rate with more damage occurring when in combination with motor oil applications. Chinese silvergrass and little bluestem behaved similarly, but with significantly higher damage also occurring for the intermediate NaCl applications. This occurred in Chinese silvergrass when in combination with the highest motor oil application. However, the damage in little bluestem increased with or without motor oil but with the highest damage occurring when in combination with any level of motor oil. Big bluestem's visual damage was severe and significantly higher than the control for any level of NaCl applications with some damage occurring as motor oil application rate increased. Tufted hair grass' visual damage was also severe and significantly higher than the control for any level of NaCl and motor oil applications. In contrast, switchgrass and feather reed grass were not affected by NaCl applications unless when in combination with motor oil. Significant damage occurred for feather reed grass when NaCl was in combination with any level of motor oil applications, whereas this only occurred for switchgrass when the highest levels of both NaCl and motor oil occurred in combination. Overall, switchgrass sustained the least amount of visual damage from NaCl and motor oil applications. Switchgrass was also the only perennial ornamental grass species with all plants surviving applications of NaCl, motor oil, or their combination. The application of NaCl alone or in combination with motor oil resulted in most of the plant deaths (Table 3-9). Big bluestem lost the most grasses during the experiment while Chinese silvergrass had the fewest plants die after switchgrass.

Experiment 2. TPH and TOC remaining in soil. Total petroleum hydrocarbons and TOC remaining in the soil at the end of the experiment increased as the motor oil application rate increased from 0% to 5% (Appendix Table 5). However, the remaining concentrations varied by species. When motor oil was applied at 2.5%, the lowest remaining TPH concentrations occurred for tufted hair grass (11,085 $mg \cdot kg^{-1} \pm 1577$ to 13,000 $mg \cdot kg^{-1} \pm 3677$), whereas the highest remaining concentrations occurred for little bluestem (16,850 $mg \cdot kg^{-1} \pm 1343$ to 20,450 $mg \cdot kg^{-1} \pm 1626$) across NaCl treatments. When motor oil was applied at 5%, the lowest remaining TPH concentrations occurred also for tufted hair grass (18,300 $mg \cdot kg^{-1} \pm 1414$ to 26,500 $mg \cdot kg^{-1} \pm 5515$), whereas the highest remaining concentrations occurred for blue grama grass (31,200 $mg \cdot kg^{-1} \pm 0$ to 34,500 $mg \cdot kg^{-1} \pm 849$) across NaCl treatments.

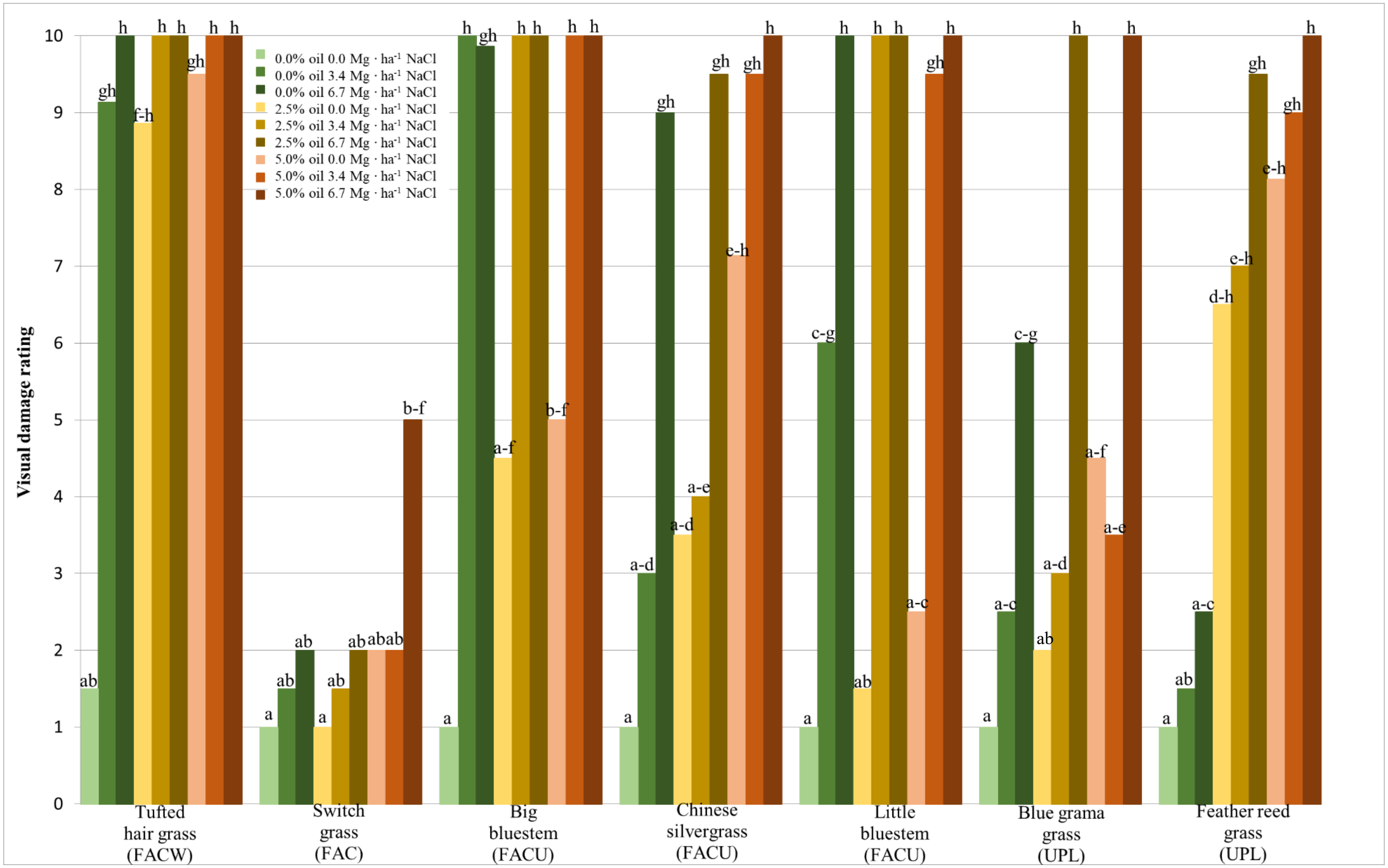

Figure 3-5. Visual damage rating (1-10 scale; 1= 0-10% dieback, 2 = 11-20% dieback, …, 10= 91-100% dieback) of seven perennial grass species treated with motor oil and NaCl. Grasses were treated with 0, 2.5, or 5.0% motor oil (w/w) and 0, 3.4, or 6.7 Mg · ha^{-1} NaCl. Mean (n = 2) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

When motor oil was applied at 2.5%, the lowest and highest TOC occurred for tufted hair grass (3.25% ± 0.63 to 4.15% ± 0.35) across NaCl treatments. When motor oil was applied at 5%, the lowest TOC occurred for blue grama grass (4.65% ± 0.35 to 5.80% ± 0.28) while the highest TOC occurred for switchgrass (5.65% ± 0.07 to 6.7% ± 0.99) across NaCl treatments.

Table 3-5. Experiment 2 treatments with at least one plant dying during the experiment conducted at Fargo, ND from 22 Feb. to 16 Apr. 2021. Grass species listed had two plants per treatment. A total of 36 out of 126 plants died during the experiment.

Grass species	Petroleum hydrocarbon (%w/w)	Sodium chloride ($Mg \cdot ha^{-1}$)	Plants dead
Tufted hair grass	0	6.7	2
Tufted hair grass	2.5	3.4	1
Tufted hair grass	5.0	0	1
Tufted hair grass	5.0	3.4	2
Tufted hair grass	5.0	6.7	2
Big bluestem	0	3.4	2
Big bluestem	0	6.7	2
Big bluestem	2.5	3.4	2
Big bluestem	2.5	6.7	2
Big bluestem	5.0	3.4	2
Big bluestem	5.0	6.7	2
Chinese silvergrass	0	6.7	1
Little bluestem	0	6.7	2
Little bluestem	2.5	6.7	2
Little bluestem	5.0	3.4	1
Little bluestem	5.0	6.7	2
Blue grama grass	2.5	6.7	2
Blue grama grass	5.0	6.7	2
Feather reed grass	2.5	6.7	1
Feather reed grass	5.0	3.4	1
Feather reed grass	5.0	6.7	2

Discussion

Perennial ornamental grasses are versatile plants making them candidates for rain gardens. These two experiments are the first to evaluate these seven cultivars for tolerance to intermittent applications of NaCl alone or in combination with petroleum hydrocarbons (motor oil). The experiments show that perennial ornamental grasses are significantly damaged but capable of surviving in soil contaminated with NaCl, motor oil, or both depending on contaminant concentration and grass cultivar. Experiment 1 assessed the NaCl tolerance of the grasses and was used to determine NaCl rates for experiment 2. As expected, increasing NaCl rates from 0 to 9 $Mg{\cdot}ha^{-1}$ increased the visual damage rating for all grasses, but the magnitude of increase varied by species. The response of switchgrass, big bluestem, Chinese silvergrass, and blue grama grass to increasing NaCl rates was somewhat different than tufted hair grass, little bluestem, and feather reed grass (i.e., sigmoidal vs. linear curves). These different response curves may indicate different plant defense mechanisms against saline conditions or ion toxicities (Wang et al., 2019; Henschke, 2016; and Munns and Gilliham, 2015). The NaCl induced 50% foliage dieback when applied at 1.0, 3.1, 3.9, 4.8, 4.8, 5.8, and 6.1 $Mg{\cdot}ha^{-1}$ for big bluestem, little bluestem, Chinese silvergrass, tufted hair grass, switchgrass, feather reed grass, and blue grama grass, respectively. Given the known range of NaCl applications to parking lots in the North Central region of the US (i.e., up to 14.5 $Mg{\cdot}ha^{-1}$), the performance and long-term function of perennial ornamental grasses for raingardens will depend on species selection (MPCA, 2016). The different response curves and increased tolerance to NaCl for some species may be due to greater ionic tolerances, production of osmoprotectants for osmotic adjustment, or physical cell wall hardening giving the plants a higher salt tolerance (Munns and Tester, 2008; Singh et al., 2015). Based on the results of experiment 1, a low (3.4 $Mg{\cdot}ha^{-1}$) and a high (6.7

$Mg \cdot ha^{-1}$) rate of NaCl was selected for experiment 2. Most grasses had less than 50% foliage dieback at the low rate while most grasses had less than 80% foliage dieback for the high rate.

For experiment 2, NaCl and motor oil reduced shoot and root growth parameters and increased tissue damage for most grasses. This was expected since NaCl causes osmotic stress around plant roots resulting in immediate and potentially long-term reduction in growth (Munns and Tester, 2008). Additionally, previous experiments have shown a decrease of root and shoot growth in plants grown in soil treated with 5%-8% crude oil (w/w) (Brandt et al, 2006; Basumatary et al., 2012). However, the grasses response to NaCl, motor oil, and their combination was strongly influenced by the species. Therefore, species selection in raingardens and other bioretention basins are expected to have a direct impact on the system's ability to process storm water (i.e., remove via evapotranspiration), provide phytoremediation of pollutants, have limited maintenance needs, and serve as an aesthetic feature in urban environments. Moreover, some species had mild or no impact from one type of contamination (NaCl or motor oil alone), but severe damage when multiple contaminants occurred together at sufficient levels. This may be related to water stress since motor oil does not readily mix with water and can limit water transfer towards and into plant roots, magnifying other osmotic stresses (i.e., salinity) (Da Silva et al., 2022). Alternatively, trace amounts of water-soluble constituents from the motor oil may be taken up by the plants and induce additional ion stresses to cellular functions and metabolism (Cui et al, 2016 and Da Silva et al., 2022).

Limitations of this research to inform management of rain gardens in practice

The current research took place in a greenhouse using grasses planted in 2.9 L containers. Sodium chloride and motor oil were applied evenly over three applications and tap water was applied as needed to all plants within a species based on the VWC of the control plant. Tap water was allowed to leach from the container along with NaCl and motor oil so grass roots never experienced the full loading rate of NaCl or motor oil. In a rain garden, leaching of NaCl and motor oil out of the grass root zone is expected to be slower and grasses will likely experience more damage if loading rates of NaCl and motor oil were similar to those used in the current experiments.

Sodium chloride was the only deicing salt used in the experiments. Other deicing salts such as, MgCl and CaCl, are also used and it is possible that the grasses used in our study would respond differently to those salts assuming similar loading rates.

Our source of petroleum hydrocarbon was unused motor oil. Unused motor oil had little aroma making it suitable for greenhouse use. In practice, used motor oil and fuel (i.e., gasoline and diesel) would be the most likely petroleum hydrocarbon contaminants entering a rain garden. It is possible the grasses tested in our experiment would encounter more plant damage when exposed to petroleum hydrocarbons other than unused motor oil.

Future research needs

Future research could evaluate the effect of using MgCl, CaCl, and other deicing salts on the seven species of perennial ornamental grasses used in our experiments. Switchgrass, big bluestem, little bluestem, blue grama grass, and Chinese silvergrass were able to tolerate motor oil contaminated soil. Future research could look at the ability of these grasses to survive soil contaminated with other petroleum hydrocarbons such as used motor oil, gasoline, and diesel. Future research could also look at the soil microbial community surrounding the roots of these grasses to determine the species of microbes present and determine if specific grasses have more microbes associated with their root system.

Conclusion

The perennial ornamental grasses switchgrass and feather reed grass were able to survive NaCl loads of up to 6.7 $Mg \cdot ha^{-1}$ and maintain a visual damage rating less than 3 making them suitable for planting in rain gardens or bioretention systems receiving NaCl runoff. Switchgrass was also able to tolerate motor oil at rates up to 5% in combination with NaCl at rates up to 6.7 $Mg \cdot ha^{-1}$. Given the tolerance of motor oil and NaCl, switchgrass would be an ideal grass for planting in raingardens or bioretention systems that may receive both contaminates in runoff water. Tufted hair grass has limited tolerance to NaCl or motor oil and should not be planted in areas that may receive runoff water with those contaminates. Big bluestem and little bluestem have limited tolerance to NaCl but have some tolerance to motor oil and may be candidates for planting in areas receiving only motor oil in stormwater runoff. Chinese silvergrass and blue grama grass have the ability to tolerate moderate levels of NaCl and motor oil and would be candidates for planting in areas that receive moderate amounts of both pollutants in stormwater runoff.

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APPENDIX

Table A1. Mean leachate parameters (and standard deviations) collected from three applications of 300 mL of NaCl applied on 3, 10, and 17 Oct. 2020 from one replicate of perennial ornamental grasses in experiment 1.

NaCl application rate		Mean of three, 300 mL applications of NaCl solution		
		Leachate volume	Leachate EC	
(Mg·ha^{-1})	Grasses	------ (mL)------	----(dS·m^{-1})----	Leachate pH
0	Tufted hairgrass	4.3 ± 4.0	.[z] ± .	. ± .
1.1	Tufted hairgrass	41.3 ± 18.2	12.9 ± 2.0	8.6 ± 0.11
2.2	Tufted hairgrass	83.3 ± 37.5	18.7 ± 6.3	7.9 ± 0.58
3.4	Tufted hairgrass	74.3 ± 50.9	31.2 ± 7.3	8.6 ± 0.07
4.5	Tufted hairgrass	104.0 ± 21.0	38.6 ± 4.4	7.7 ± 0.20
5.6	Tufted hairgrass	35.7 ± 35.1	53.9 ± 11.7	7.8 ± 0.24
6.7	Tufted hairgrass	29.3 ± 27.0	61.5 ± 0.5	7.8 ± 0.08
7.8	Tufted hairgrass	130.3 ± 54.6	62.7 ± 5.8	7.7 ± 0.17
9	Tufted hairgrass	148.7 ± 74.3	57.0 ± 5.2	7.6 ± 0.03
0	Switchgrass	166.0 ± 19.5	0.7 ± 0.1	8.1 ± 0.31
1.1	Switchgrass	141.7 ± 75.6	10.4 ± 2.5	7.7 ± 0.17
2.2	Switchgrass	89.0 ± 29.5	19.5 ± 9.4	7.9 ± 0.28
3.4	Switchgrass	158.7 ± 8.1	27.7 ± 5.7	7.5 ± 0.19
4.5	Switchgrass	146.7 ± 4.9	44.1 ± 1.2	7.6 ± 0.06
5.6	Switchgrass	166.0 ± 40.6	48.9 ± 3.8	7.4 ± 0.08
6.7	Switchgrass	141.0 ± 12.3	32.6 ± 9.3	7.3 ± 0.09
7.8	Switchgrass	107.0 ± 4.6	39.6 ± 11.9	7.2 ± 0.07
9	Switchgrass	173.0 ± 68.5	59.1 ± 5.7	7.1 ± 0.06
0	Big bluestem	64.0 ± 90.6	1.2 ± 0.3	8.4 ± 0.00
1.1	Big bluestem	142.0 ± 10.1	11.2 ± 2.1	7.9 ± 0.16
2.2	Big bluestem	176.7 ± 57.7	16.7 ± 12.0	7.9 ± 0.40
3.4	Big bluestem	188.7 ± 44.0	24.6 ± 6.1	7.8 ± 0.16
4.5	Big bluestem	184.0 ± 43.3	38.5 ± 8.3	7.9 ± 0.32
5.6	Big bluestem	204.0 ± 27.1	31.1 ± 11.8	7.4 ± 0.09
6.7	Big bluestem	187.0 ± 18.0	43.4 ± 7.0	7.5 ± 0.16
7.8	Big bluestem	180.3 ± 66.1	32.1 ± 10.6	7.7 ± 0.06
9	Big bluestem	207.7 ± 18.2	39.7 ± 10.0	7.4 ± 0.08

[z]Leachate volume was too low for measurement.

Table A1. Mean leachate parameters (and standard deviations) collected from three applications of 300 mL of NaCl applied on 3, 10, and 17 Oct. 2020 from one replicate of perennial ornamental grasses in experiment 1 (continued).

NaCl application rate		Mean of three, 300 mL applications of NaCl solution								
		Leachate volume			Leachate EC					
(Mg·ha^{-1})	Grasses	----- (mL)-----			---(dS·m^{-1})---			Leachate pH		
0	Chinese silvergrass	117.3	±	86.4	0.6	±	0.2	7.8	±	0.00
1.1	Chinese silvergrass	118.0	±	85.1	10.5	±	3.4	7.7	±	0.11
2.2	Chinese silvergrass	126.0	±	78.8	19.4	±	2.0	7.6	±	0.31
3.4	Chinese silvergrass	152.3	±	38.4	23.3	±	6.2	7.5	±	0.07
4.5	Chinese silvergrass	164.0	±	18.2	26.6	±	6.3	7.3	±	0.02
5.6	Chinese silvergrass	168.3	±	30.6	40.7	±	1.0	7.4	±	0.08
6.7	Chinese silvergrass	149.0	±	63.3	52.8	±	2.2	7.6	±	0.26
7.8	Chinese silvergrass	162.0	±	83.7	47.3	±	1.5	7.4	±	0.11
9	Chinese silvergrass	181.0	±	87.1	44.4	±	6.2	7.4	±	0.09
0	Little bluestem	56.3	±	53.6	1.4	±	0.0	8.0	±	0.00
1.1	Little bluestem	127.0	±	63.2	11.9	±	2.1	7.7	±	0.12
2.2	Little bluestem	98.0	±	22.0	21.2	±	1.4	7.8	±	0.11
3.4	Little bluestem	190.0	±	21.7	28.1	±	6.7	8.0	±	0.23
4.5	Little bluestem	173.0	±	45.2	39.5	±	1.2	7.8	±	0.17
5.6	Little bluestem	168.0	±	48.6	44.7	±	1.9	7.7	±	0.03
6.7	Little bluestem	155.7	±	22.8	48.9	±	3.8	7.6	±	0.07
7.8	Little bluestem	160.3	±	111.8	44.4	±	4.9	7.5	±	0.21
9	Little bluestem	177.0	±	48.4	49.6	±	3.2	7.2	±	0.02
0	Blue grama grass	69.0	±	42.2	0.6	±	0.1	8.6	±	0.05
1.1	Blue grama grass	108.3	±	77.2	11.5	±	2.8	8.1	±	0.39
2.2	Blue grama grass	140.3	±	69.8	21.1	±	4.1	8.2	±	0.32
3.4	Blue grama grass	91.0	±	71.0	30.1	±	3.1	8.0	±	0.06
4.5	Blue grama grass	133.0	±	22.6	34.2	±	13.2	7.7	±	0.15
5.6	Blue grama grass	107.3	±	65.2	47.2	±	5.5	7.9	±	0.03
6.7	Blue grama grass	152.7	±	29.3	45.5	±	7.1	7.8	±	0.10
7.8	Blue grama grass	151.7	±	85.0	55.8	±	12.8	7.9	±	0.45
9	Blue grama grass	184.0	±	57.2	42.1	±	4.8	7.4	±	0.01
0	Feather reed grass	48.7	±	58.9	0.6	±	0.1	8.5	±	0.00
1.1	Feather reed grass	24.7	±	18.8	12.1	±	0.5	7.9	±	0.11
2.2	Feather reed grass	20.0	±	19.5	24.1	±	4.0	8.3	±	0.06
3.4	Feather reed grass	52.3	±	63.0	29.4	±	6.7	7.8	±	0.41
4.5	Feather reed grass	80.0	±	44.5	43.3	±	3.1	7.9	±	0.07
5.6	Feather reed grass	86.0	±	75.3	47.5	±	1.2	7.8	±	0.11
6.7	Feather reed grass	107.7	±	82.1	49.4	±	2.9	7.5	±	0.12
7.8	Feather reed grass	77.3	±	66.3	52.3	±	15.3	7.6	±	0.22
9	Feather reed grass	123.3	±	96.8	42.2	±	2.9	7.2	±	0.18

[z]Leachate volume was too low for measurement.

Table A2. Number of tap water applications and mean saturated paste extract parameters (and standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl rates ranging from 0 – 9 $Mg \cdot ha^{-1}$. Experiment was conducted in Fargo, ND during Oct. and Nov. 2020.

NaCl application rate		Mean of three replicates using extract of saturated paste					
		Ca	Mg	Na	Sodium absorption ratio	EC	Number of 300 mL tap water applications
($Mg \cdot ha^{-1}$)	Grasses	----------------------------(mg·L)----------------------------				($dS \cdot m^{-1}$)	
0	Tufted hairgrass	174.7 ± 70.6	47.0 ± 15.6	438.5 ± 150.8	5.0 ± 1.8	2.37 ± 1.10	35.0 ± 1.0
1.1	Tufted hairgrass	435.1 ± 87.5	119.9 ± 26.8	1382.1 ± 340.9	13.3 ± 3.4	6.72 ± 0.53	35.0 ± 1.0
2.2	Tufted hairgrass	435.2 ± 121.3	110.4 ± 24.7	1942.9 ± 315.3	21.5 ± 0.5	7.07 ± 1.44	35.0 ± 1.0
3.4	Tufted hairgrass	205.6 ± 41.0	50.0 ± 8.5	1413.6 ± 174.7	22.1 ± 1.5	5.96 ± 0.95	35.0 ± 1.0
4.5	Tufted hairgrass	109.8 ± 5.7	27.5 ± 0.7	950.0 ± 75.0	20.8 ± 0.9	3.68 ± 1.36	35.0 ± 1.0
5.6	Tufted hairgrass	55.4 ± 9.1	10.5 ± 2.1	924.0 ± 156.9	30.7 ± 2.4	4.65 ± 1.64	35.0 ± 1.0
6.7	Tufted hairgrass	64.9 ± 13.1	13.7 ± 4.1	1052.7 ± 171.4	31.4 ± 6.4	4.23 ± 0.66	35.0 ± 1.0
7.8	Tufted hairgrass	49.2 ± 12.5	10.0 ± 4.0	599.0 ± 141.7	20.6 ± 4.5	2.55 ± 0.63	35.0 ± 1.0
9	Tufted hairgrass	41.3 ± 9.1	8.3 ± 2.1	538.0 ± 33.1	20.2 ± 2.4	2.18 ± 0.17	35.0 ± 1.0
0	Switchgrass	373.9 ± 71.6	90.9 ± 11.3	191.5 ± 6.3	3.4 ± 1.7	3.00 ± 0.80	25.7 ± 4.2
1.1	Switchgrass	490.3 ± 126.3	126.9 ± 34.0	1125.7 ± 322.3	11.6 ± 1.9	6.65 ± 1.61	25.7 ± 4.2
2.2	Switchgrass	341.7 ± 112.2	73.9 ± 14.2	1019.0 ± 22.6	16.4 ± 4.1	6.71 ± 2.51	25.7 ± 4.2
3.4	Switchgrass	758.9 ± 133.4	194.8 ± 26.9	2462.0 ± 584.0	22.4 ± 3.9	7.46 ± 2.72	25.7 ± 4.2
4.5	Switchgrass	819.3 ± 235.7	221.9 ± 69.2	2863.5 ± 796.9	22.0 ± 2.5	13.02 ± 2.66	25.7 ± 4.2
5.6	Switchgrass	112.3 ± 23.3	30.4 ± 9.2	1288.5 ± 0.7	26.2 ± 4.0	5.36 ± 0.08	25.7 ± 4.2
6.7	Switchgrass	175.6 ± 26.1	47.6 ± 8.6	1469.7 ± 397.7	25.2 ± 5.0	6.03 ± 0.86	25.7 ± 4.2
7.8	Switchgrass	157.7 ± 59.8	42.0 ± 16.5	1594.3 ± 154.9	29.9 ± 4.0	6.16 ± 0.17	25.7 ± 4.2
9	Switchgrass	107.3 ± 23.3	27.9 ± 7.0	1918.7 ± 484.0	36.8 ± 8.2	6.93 ± 1.40	25.7 ± 4.2

Table A2. Number of tap water applications and mean saturated paste extract parameters (and standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl rates ranging from 0 – 9 Mg·ha^{-1}. Experiment was conducted in Fargo, ND during Oct. and Nov. 2020 (continued).

NaCl application rate (Mg·ha^{-1})	Grasses	Ca (mg·L^{-1})	Mg (mg·L^{-1})	Na (mg·L^{-1})	Sodium absorption ratio	EC (dS·m^{-1})	Number of 300 mL water applications
0	Big bluestem	176.7 ± 34.0	48.6 ± 10.0	146.7 ± 51.2	2.5 ± 0.7	1.66 ± 0.38	14.3 ± 1.5
1.1	Big bluestem	205.3 ± 55.4	55.0 ± 14.1	908.3 ± 231.6	14.5 ± 2.0	4.91 ± 0.89	14.3 ± 1.5
2.2	Big bluestem	235.9 ± 131.3	66.9 ± 38.2	1302.6 ± 408.5	20.0 ± 0.3	5.90 ± 1.68	14.3 ± 1.5
3.4	Big bluestem	138.4 ± 17.7	37.3 ± 4.9	1185.7 ± 273.5	23.0 ± 3.9	5.36 ± 0.80	14.3 ± 1.5
4.5	Big bluestem	130.1 ± 89.7	34.6 ± 24.5	1361.0 ± 561.6	28.6 ± 1.8	5.83 ± 2.22	14.3 ± 1.5
5.6	Big bluestem	186.6 ± 97.5	50.9 ± 28.0	2059.3 ± 738.9	34.8 ± 3.0	8.06 ± 2.21	14.3 ± 1.5
6.7	Big bluestem	167.3 ± 65.5	42.0 ± 17.5	2193.3 ± 541.7	40.0 ± 5.7	7.94 ± 1.94	14.3 ± 1.5
7.8	Big bluestem	74.8 ± 11.3	16.9 ± 2.8	1542.0 ± 350.8	41.3 ± 4.5	5.88 ± 0.57	14.3 ± 1.5
9	Big bluestem	175.3 ± 73.9	44.6 ± 21.1	2639.6 ± 575.7	46.7 ± 1.7	9.66 ± 2.38	14.3 ± 1.5
0	Chinese silvergrass	293.7 ± 41.1	79.9 ± 10.1	341.9 ± 54.7	4.6 ± 0.8	2.74 ± 0.29	32.7 ± 1.2
1.1	Chinese silvergrass	383.7 ± 38.9	106.9 ± 11.3	1106.0 ± 155.6	11.4 ± 2.6	5.07 ± 1.55	32.7 ± 1.2
2.2	Chinese silvergrass	233.2 ± 37.0	60.9 ± 10.5	1047.7 ± 148.6	15.8 ± 1.5	5.20 ± 0.90	32.7 ± 1.2
3.4	Chinese silvergrass	130.8 ± 4.4	33.0 ± 1.0	866.0 ± 125.1	17.5 ± 2.5	3.91 ± 0.74	32.7 ± 1.2
4.5	Chinese silvergrass	130.1 ± 18.5	33.0 ± 5.3	823.0 ± 24.4	16.8 ± 1.7	3.61 ± 0.14	32.7 ± 1.2
5.6	Chinese silvergrass	142.1 ± 44.0	35.0 ± 12.0	863.3 ± 43.9	17.4 ± 3.7	3.84 ± 0.08	32.7 ± 1.2
6.7	Chinese silvergrass	89.8 ± 16.1	21.0 ± 3.6	884.4 ± 30.9	22.0 ± 2.4	3.79 ± 0.09	32.7 ± 1.2
7.8	Chinese silvergrass	84.1 ± 9.1	19.6 ± 2.5	966.4 ± 108.1	24.6 ± 2.4	3.90 ± 0.26	32.7 ± 1.2
9	Chinese silvergrass	79.1 ± 7.6	18.0 ± 1.9	884.4 ± 159.9	23.5 ± 5.1	3.65 ± 0.47	32.7 ± 1.2

Table A2. Number of tap water applications and mean saturated paste extract parameters (and standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl rates ranging from 0 – 9 $Mg \cdot ha^{-1}$. Experiment was conducted in Fargo, ND during Oct. and Nov. 2020 (continued).

NaCl application rate		Mean of three replicates using extract of saturated paste					
		Ca	Mg	Na	Sodium absorption ratio	EC	Number of 300 mL water applications
($Mg \cdot ha^{-1}$)	Grasses	------------------------------($mg \cdot L$)------------------------------				($dS \cdot m^{-1}$)	
0	Little bluestem	307.7 ± 35.4	89.6 ± 8.1	391.3 ± 50.7	5.0 ± 0.4	3.17 ± 0.42	28.7 ± 4.0
1.1	Little bluestem	301.1 ± 204.5	85.3 ± 57.8	788.3 ± 406.4	10.3 ± 1.8	4.39 ± 1.83	28.7 ± 4.0
2.2	Little bluestem	291.9 ± 17.7	81.5 ± 3.5	885.6 ± 155.0	13.4 ± 0.9	4.59 ± 0.71	28.7 ± 4.0
3.4	Little bluestem	155.7 ± 25.8	43.9 ± 8.9	797.7 ± 101.7	14.5 ± 0.6	3.99 ± 0.56	28.7 ± 4.0
4.5	Little bluestem	84.1 ± 15.5	22.0 ± 4.3	650.4 ± 56.0	16.4 ± 0.5	2.92 ± 0.20	28.7 ± 4.0
5.6	Little bluestem	110.5 ± 30.6	28.3 ± 8.6	771.3 ± 72.9	17.2 ± 2.0	3.33 ± 0.48	28.7 ± 4.0
6.7	Little bluestem	74.5 ± 24.9	18.0 ± 7.0	732.6 ± 183.9	19.9 ± 2.4	3.05 ± 0.99	28.7 ± 4.0
7.8	Little bluestem	56.5 ± 30.2	19.3 ± 4.0	829.6 ± 167.6	24.5 ± 3.4	3.41 ± 0.79	28.7 ± 4.0
9	Little bluestem	80.8 ± 6.6	19.3 ± 2.1	775.0 ± 69.1	20.2 ± 2.7	3.30 ± 0.39	28.7 ± 4.0
0	Blue grama grass	209.9 ± 33.6	56.9 ± 8.2	331.0 ± 88.7	5.2 ± 1.1	2.25 ± 0.45	32.3 ± 2.5
1.1	Blue grama grass	279.1 ± 107.4	75.9 ± 31.5	1035.7 ± 339.3	14.1 ± 1.8	5.18 ± 1.40	32.3 ± 2.5
2.2	Blue grama grass	211.6 ± 99.7	56.9 ± 27.2	1088.0 ± 366.8	17.2 ± 1.7	4.95 ± 1.37	32.3 ± 2.5
3.4	Blue grama grass	285.8 ± 173.0	74.6 ± 46.4	1589.7 ± 674.2	22.1 ± 1.9	6.67 ± 2.46	32.3 ± 2.5
4.5	Blue grama grass	99.8 ± 11.3	25.5 ± 2.1	953.0 ± 66.5	23.9 ± 3.2	4.33 ± 0.21	32.3 ± 2.5
5.6	Blue grama grass	126.3 ± 19.1	31.5 ± 2.1	1077.3 ± 360.6	25.0 ± 1.6	4.70 ± 1.58	32.3 ± 2.5
6.7	Blue grama grass	57.2 ± 13.3	14.0 ± 4.6	804.7 ± 134.6	24.8 ± 1.3	3.36 ± 0.50	32.3 ± 2.5
7.8	Blue grama grass	47.3 ± 12.0	11.0 ± 3.6	608.7 ± 51.2	21.1 ± 3.8	2.40 ± 0.21	32.3 ± 2.5
9	Blue grama grass	44.0 ± 5.3	10.3 ± 1.6	518.3 ± 12.5	18.4 ± 1.5	2.14 ± 0.12	32.3 ± 2.5

Table A2. Number of tap water applications and mean saturated paste extract parameters (and standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl rates ranging from 0 – 9 Mg·ha^{-1}. Experiment was conducted in Fargo, ND during Oct. and Nov. 2020 (continued).

NaCl application rate		Mean of three replicates using extract of saturated paste																	
		Ca			Mg			Na			Sodium absorption ratio			EC			Number of 300 mL water applications		
(Mg·ha^{-1})	Grasses	------------------------------(mg·L)------------------------------												(dS·m^{-1})					
0	Feather reed grass	268.5	±	80.2	72.3	±	22.4	369.0	±	61.0	5.2	±	0.3	2.51	±	0.40	35.7	±	0.6
1.1	Feather reed grass	733.0	±	30.3	202.8	±	4.2	1869.0	±	224.8	14.5	±	2.7	8.26	±	0.76	35.7	±	0.6
2.2	Feather reed grass	562.2	±	74.3	144.2	±	18.6	1998.0	±	444.1	19.3	±	3.5	7.41	±	0.52	35.7	±	0.6
3.4	Feather reed grass	499.7	±	157.1	131.2	±	39.0	2242.3	±	156.4	23.6	±	4.0	9.14	±	1.04	35.7	±	0.6
4.5	Feather reed grass	279.1	±	82.4	71.2	±	23.7	1919.4	±	585.7	26.3	±	4.2	7.53	±	1.47	35.7	±	0.6
5.6	Feather reed grass	349.3	±	112.6	86.9	±	25.0	2419.0	±	443.1	30.5	±	5.3	7.94	±	1.44	35.7	±	0.6
6.7	Feather reed grass	263.1	±	81.8	65.3	±	17.9	2165.0	±	175.7	31.4	±	2.7	7.66	±	0.97	35.7	±	0.6
7.8	Feather reed grass	137.2	±	41.6	32.5	±	10.6	2400.1	±	444.0	34.0	±	3.6	6.98	±	1.42	35.7	±	0.6
9	Feather reed grass	72.1	±	7.1	14.6	±	0.6	876.4	±	314.1	24.8	±	9.6	3.63	±	1.11	35.7	±	0.6

Table A3. Mean leachate parameters (with standard deviations) collected from three applications of 300 mL of NaCl applied on 22 and 27 Feb. and 5 Mar. 2021 from one replicate of perennial ornamental grasses in experiment 2.

Petroleum hydrocarbon rate	NaCl application rate		Mean of three, 300 mL applications of NaCl solution								
			Leachate volume			Leachate EC					
(%w/w)	(Mg·ha^{-1})	Grasses	(mL)			(dS·m^{-1})			Leachate pH		
0	0	Tufted hairgrass	33.3	±	57.7	2.5	±	0.0	.[z]	±	.
0	3.4	Tufted hairgrass	0.0	±	0.0	.[y]	±	.	.	±	.
0	6.7	Tufted hairgrass	115.0	±	162.6	17.3	±	0.0	7.57	±	.
2.5	0	Tufted hairgrass	186.7	±	60.3	1.2	±	0.1	.	±	.
2.5	3.4	Tufted hairgrass	55.3	±	57.6	28.0	±	6.8	7.93	±	0.13
2.5	6.7	Tufted hairgrass	150.3	±	130.3	23.8	±	9.6	7.57	±	0.11
5	0	Tufted hairgrass	67.7	±	63.9	1.6	±	0.4	.	±	.
5	3.4	Tufted hairgrass	67.7	±	70.1	35.1	±	3.9	8.28	±	0.55
5	6.7	Tufted hairgrass	135.3	±	117.5	30.4	±	1.5	7.52	±	0.07
0	0	Switchgrass	177.0	±	20.0	5.2	±	4.6	.	±	.
0	3.4	Switchgrass	120.0	±	60.7	25.6	±	8.9	8.04	±	0.16
0	6.7	Switchgrass	154.3	±	56.0	50.8	±	11.3	7.92	±	0.17
2.5	0	Switchgrass	189.3	±	63.8	0.9	±	0.3	.	±	.
2.5	3.4	Switchgrass	146.7	±	48.3	26.5	±	8.4	7.98	±	0.36
2.5	6.7	Switchgrass	157.3	±	56.6	52.2	±	8.7	7.80	±	0.20
5	0	Switchgrass	165.3	±	39.2	0.6	±	0.0	.	±	.
5	3.4	Switchgrass	174.7	±	52.1	26.2	±	11.0	8.08	±	0.25
5	6.7	Switchgrass	136.7	±	46.5	53.5	±	10.8	7.85	±	0.13
0	0	Big bluestem	193.0	±	11.8	1.7	±	0.1	.	±	.
0	3.4	Big bluestem	166.0	±	58.6	27.0	±	8.3	7.84	±	0.31
0	6.7	Big bluestem	169.3	±	63.6	60.3	±	4.6	8.20	±	0.08
2.5	0	Big bluestem	187.0	±	26.9	1.1	±	0.3	.	±	.
2.5	3.4	Big bluestem	162.7	±	11.9	25.6	±	6.8	7.85	±	0.22
2.5	6.7	Big bluestem	194.0	±	26.7	47.0	±	6.0	7.78	±	0.13
5	0	Big bluestem	149.3	±	54.8	1.5	±	0.4	.	±	.
5	3.4	Big bluestem	172.3	±	24.8	27.0	±	10.1	8.00	±	0.24
5	6.7	Big bluestem	187.3	±	30.9	44.3	±	7.6	7.55	±	0.23

[z]Data omitted due to sampling error.
[y]Leachate volume was too low for measurement.

Table A3. Mean leachate parameters (with standard deviations) collected from three applications of 300 mL of NaCl applied on 22 and 27 Feb. and 5 Mar. 2021 from one replicate of perennial ornamental grasses in experiment 2 (continued).

Petroleum hydrocarbon rate	NaCl application rate		Mean of three, 300 mL applications of NaCl solution								
			Leachate volume			Leachate EC					
(%w/w)	(Mg·ha^{-1})	Grasses	(mL)			(dS·m^{-1})			Leachate pH		
0	0	Chinese silvergrass	73.7	±	87.8	5.0	±	3.2	·	±	·
0	3.4	Chinese silvergrass	179.0	±	57.3	24.9	±	5.8	7.83	±	0.14
0	6.7	Chinese silvergrass	131.0	±	76.4	37.2	±	6.4	7.44	±	0.06
2.5	0	Chinese silvergrass	194.7	±	43.8	1.2	±	0.3	·	±	·
2.5	3.4	Chinese silvergrass	164.3	±	43.9	23.6	±	8.5	7.92	±	0.08
2.5	6.7	Chinese silvergrass	178.0	±	23.5	49.8	±	8.3	7.64	±	0.17
5	0	Chinese silvergrass	186.7	±	31.6	1.3	±	0.3	·	±	·
5	3.4	Chinese silvergrass	193.0	±	30.1	25.9	±	7.1	7.93	±	0.14
5	6.7	Chinese silvergrass	209.7	±	31.4	45.7	±	11.8	7.60	±	0.18
0	0	Little bluestem	149.7	±	69.9	1.0	±	0.1	·	±	·
0	3.4	Little bluestem	188.0	±	13.2	29.6	±	8.0	8.12	±	0.07
0	6.7	Little bluestem	170.0	±	36.7	56.6	±	2.8	7.88	±	0.11
2.5	0	Little bluestem	138.0	±	79.9	0.8	±	0.1	·	±	·
2.5	3.4	Little bluestem	147.0	±	56.5	26.2	±	7.3	7.96	±	0.16
2.5	6.7	Little bluestem	161.3	±	71.5	58.9	±	6.8	8.03	±	0.16
5	0	Little bluestem	141.7	±	50.6	1.0	±	0.1	·	±	·
5	3.4	Little bluestem	174.0	±	62.4	28.5	±	7.9	8.17	±	0.14
5	6.7	Little bluestem	176.0	±	45.0	54.9	±	7.1	7.90	±	0.19
0	0	Blue grama grass	58.3	±	55.3	1.0	±	0.4	·	±	·
0	3.4	Blue grama grass	77.3	±	74.2	22.1	±	6.7	7.84	±	0.11
0	6.7	Blue grama grass	127.7	±	62.2	47.1	±	7.7	7.80	±	0.06
2.5	0	Blue grama grass	91.3	±	80.2	0.7	±	0.0	·	±	·
2.5	3.4	Blue grama grass	70.3	±	82.4	26.9	±	6.8	7.96	±	0.00
2.5	6.7	Blue grama grass	155.0	±	78.8	47.0	±	3.5	7.83	±	0.08
5	0	Blue grama grass	75.7	±	69.1	1.0	±	0.7	·	±	·
5	3.4	Blue grama grass	130.3	±	77.1	29.0	±	8.1	8.02	±	0.11
5	6.7	Blue grama grass	143.7	±	67.7	52.1	±	7.3	8.04	±	0.07
0	0	Feather reed grass	53.0	±	45.9	1.0	±	0.5	·	±	·
0	3.4	Feather reed grass	74.3	±	72.6	21.5	±	8.3	7.60	±	0.25
0	6.7	Feather reed grass	91.7	±	76.5	38.5	±	6.5	7.58	±	0.00
2.5	0	Feather reed grass	89.0	±	79.8	0.7	±	0.2	·	±	·
2.5	3.4	Feather reed grass	78.3	±	52.4	28.2	±	5.9	8.30	±	0.35
2.5	6.7	Feather reed grass	104.3	±	75.9	51.2	±	4.0	7.71	±	0.12
5	0	Feather reed grass	105.7	±	79.2	0.8	±	0.5	·	±	·
5	3.4	Feather reed grass	54.3	±	22.8	25.6	±	14.2	8.00	±	0.46
5	6.7	Feather reed grass	144.7	±	99.0	40.2	±	11.9	7.67	±	0.33

[z]Data omitted due to sampling error.
[y]Leachate volume was too low for measurement.

Table A4. Number of tap water applications and mean saturated paste extract parameters (with standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl (0 – 9 Mg·ha^{-1}) and motor oil (0-5% w/w). Experiment was conducted in Fargo, ND from 22 Feb. to 16 Apr. 2021.

Petroleum hydrocarbon rate	NaCl application rate		Mean of two replicates using extract of saturated paste					
			Ca	Mg	Na	Sodium absorption ratio	EC	Number of 300 mL tap water applications
(%w/w)	(Mg·ha^{-1})	Grasses	---(mg·L)---				(dS·m^{-1})	
0	0	Tufted hairgrass	159.2 ± 41.6	53.0 ± 11.3	270.0 ± 92.1	4.7 ± 1.0	1.8 ± 0.5	40.0 ± 1.4
0	3.4	Tufted hairgrass	45.0 ± 1.4	12.5 ± 0.7	247.0 ± 36.8	8.4 ± 1.4	1.1 ± 0.1	40.0 ± 1.4
0	6.7	Tufted hairgrass	36.0 ± 5.7	8.5 ± 0.7	351.6 ± 6.3	13.7 ± 1.2	1.4 ± 0.1	40.0 ± 1.4
2.5	0	Tufted hairgrass	104.3 ± 10.6	33.0 ± 1.5	97.4 ± 38.9	2.2 ± 0.9	0.9 ± 0.1	40.0 ± 1.4
2.5	3.4	Tufted hairgrass	78.3 ± 26.2	22.5 ± 7.7	439.5 ± 273.6	10.9 ± 5.2	2.2 ± 1.3	40.0 ± 1.4
2.5	6.7	Tufted hairgrass	47.4 ± 4.8	12.9 ± 2.8	303.0 ± 15.5	10.1 ± 0.2	1.4 ± 0.1	40.0 ± 1.4
5	0	Tufted hairgrass	153.7 ± 14.0	56.0 ± 16.9	95.6 ± 46.0	1.7 ± 0.7	1.2 ± 0.4	40.0 ± 1.4
5	3.4	Tufted hairgrass	91.3 ± 13.4	29.0 ± 4.2	224.9 ± 12.7	5.3 ± 0.1	1.4 ± 0.1	40.0 ± 1.4
5	6.7	Tufted hairgrass	49.4 ± 10.5	13.5 ± 3.6	300.0 ± 31.1	9.8 ± 0.1	1.3 ± 0.2	40.0 ± 1.4
0	0	Switchgrass	140.3 ± 0.7	43.0 ± 0.0	209.0 ± 58.1	4.0 ± 1.1	1.6 ± 0.2	28.5 ± 6.4
0	3.4	Switchgrass	124.2 ± 48.6	35.5 ± 14.8	814.0 ± 138.6	16.8 ± 0.6	4.1 ± 0.9	28.5 ± 6.4
0	6.7	Switchgrass	89.8 ± 94.5	24.0 ± 28.3	1033.5 ± 846.5	25.8 ± 5.4	4.3 ± 3.5	28.5 ± 6.4
2.5	0	Switchgrass	107.8 ± 4.2	33.5 ± 2.1	88.0 ± 5.7	1.9 ± 0.2	1.0 ± 0.0	28.5 ± 6.4
2.5	3.4	Switchgrass	210.6 ± 104.4	64.4 ± 31.8	1172.1 ± 581.3	17.8 ± 4.6	5.7 ± 2.5	28.5 ± 6.4
2.5	6.7	Switchgrass	97.3 ± 4.9	27.9 ± 1.4	979.5 ± 108.2	22.5 ± 3.1	4.5 ± 0.5	28.5 ± 6.4
5	0	Switchgrass	113.8 ± 2.8	38.0 ± 1.5	79.0 ± 8.6	1.6 ± 0.2	1.0 ± 0.0	28.5 ± 6.4
5	3.4	Switchgrass	151.7 ± 122.9	48.4 ± 40.3	899.5 ± 311.9	17.5 ± 2.0	4.6 ± 2.0	28.5 ± 6.4
5	6.7	Switchgrass	120.8 ± 2.8	38.0 ± 2.8	1162.0 ± 73.5	23.6 ± 2.0	5.5 ± 0.2	28.5 ± 6.4

Table A4. Number of tap water applications and mean saturated paste extract parameters (with standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl (0 – 9 Mg·ha^{-1}) and motor oil (0-5% w/w). Experiment was conducted in Fargo, ND from 22 Feb. to 16 Apr. 2021 (continued).

Petroleum hydrocarbon rate	NaCl application rate		Mean of two replicates using extract of saturated paste					
			Ca	Mg	Na	Sodium absorption ratio	EC	Number of 300 mL tap water applications
(%w/w)	(Mg·ha^{-1})	Grasses	-----(mg·L)-----				(dS·m^{-1})	
0	0	Big bluestem	150.7 ± 1.3	49.0 ± 4.3	158.5 ± 17.6	2.9 ± 0.4	1.5 ± 0.2	20.5 ± 0.7
0	3.4	Big bluestem	130.8 ± 129.8	37.0 ± 39.6	756.0 ± 430.0	16.5 ± 0.6	3.5 ± 2.4	20.5 ± 0.7
0	6.7	Big bluestem	436.2 ± 0.0	129.9 ± 0.0	3174.0 ± 0.0	34.3 ± 0.0	10.0 ± 0.0	20.5 ± 0.7
2.5	0	Big bluestem	142.7 ± 29.6	44.0 ± 8.4	103.0 ± 52.4	1.9 ± 0.8	1.2 ± 0.3	20.5 ± 0.7
2.5	3.4	Big bluestem	81.8 ± 15.6	23.0 ± 4.3	522.6 ± 53.0	13.3 ± 2.6	2.5 ± 0.2	20.5 ± 0.7
2.5	6.7	Big bluestem	54.9 ± 31.0	15.5 ± 9.2	763.9 ± 319.6	23.5 ± 3.0	3.2 ± 1.5	20.5 ± 0.7
5	0	Big bluestem	142.2 ± 21.8	47.0 ± 7.1	79.9 ± 1.5	1.5 ± 0.1	1.1 ± 0.1	20.5 ± 0.7
5	3.4	Big bluestem	79.9 ± 46.5	24.0 ± 15.6	510.9 ± 107.5	13.4 ± 1.5	2.5 ± 0.7	20.5 ± 0.7
5	6.7	Big bluestem	97.3 ± 48.8	31.5 ± 13.4	890.0 ± 374.9	19.9 ± 3.7	4.2 ± 2.0	20.5 ± 0.7
0	0	Chinese silvergrass	192.1 ± 38.9	59.5 ± 16.2	238.1 ± 121.7	3.8 ± 1.5	2.1 ± 0.9	20.5 ± 2.1
0	3.4	Chinese silvergrass	172.1 ± 157.4	51.0 ± 48.0	1058.0 ± 642.1	18.9 ± 1.8	4.7 ± 3.3	20.5 ± 2.1
0	6.7	Chinese silvergrass	94.8 ± 93.1	31.0 ± 35.4	1237.1 ± 1043.6	28.1 ± 8.6	4.9 ± 4.3	20.5 ± 2.1
2.5	0	Chinese silvergrass	130.8 ± 5.7	41.0 ± 2.8	73.5 ± 2.1	1.4 ± 0.0	1.1 ± 0.1	20.5 ± 2.1
2.5	3.4	Chinese silvergrass	103.8 ± 43.8	32.0 ± 17.0	660.0 ± 149.8	14.7 ± 0.1	3.1 ± 1.0	20.5 ± 2.1
2.5	6.7	Chinese silvergrass	106.3 ± 79.6	31.0 ± 25.4	1109.5 ± 472.9	25.4 ± 0.2	4.8 ± 2.1	20.5 ± 2.1
5	0	Chinese silvergrass	121.3 ± 23.3	41.4 ± 6.4	70.6 ± 16.3	1.4 ± 0.2	1.0 ± 0.1	20.5 ± 2.1
5	3.4	Chinese silvergrass	117.2 ± 92.5	37.4 ± 31.8	606.5 ± 304.8	12.9 ± 0.8	3.3 ± 2.2	20.5 ± 2.1
5	6.7	Chinese silvergrass	81.4 ± 57.1	28.5 ± 23.3	1048.0 ± 478.0	26.2 ± 1.5	4.5 ± 2.2	20.5 ± 2.1

Table A4. Number of tap water applications and mean saturated paste extract parameters (with standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl (0 – 9 $Mg \cdot ha^{-1}$) and motor oil (0-5% w/w). Experiment was conducted in Fargo, ND from 22 Feb. to 16 Apr. 2021 (continued).

Petroleum hydrocarbon rate	NaCl application rate		Mean of two replicates using extract of saturated paste					
			Ca	Mg	Na	Sodium absorption ratio	EC	Number of 300 mL tap water applications
(%w/w)	($Mg \cdot ha^{-1}$)	Grasses	---(mg·L)---				($dS \cdot m^{-1}$)	
0	0	Little bluestem	204.6 ± 35.4	64.5 ± 13.5	217.0 ± 50.9	3.4 ± 0.5	1.9 ± 0.4	26.0 ± 5.7
0	3.4	Little bluestem	90.8 ± 25.5	27.0 ± 8.4	511.1 ± 110.3	12.1 ± 0.8	2.5 ± 0.6	26.0 ± 5.7
0	6.7	Little bluestem	88.4 ± 69.9	25.0 ± 21.2	753.5 ± 362.7	18.9 ± 0.8	3.4 ± 2.0	26.0 ± 5.7
2.5	0	Little bluestem	214.6 ± 22.6	69.4 ± 7.8	162.0 ± 26.8	2.5 ± 0.3	1.7 ± 0.2	26.0 ± 5.7
2.5	3.4	Little bluestem	129.3 ± 21.9	40.5 ± 7.7	617.0 ± 124.4	12.1 ± 1.4	3.1 ± 0.6	26.0 ± 5.7
2.5	6.7	Little bluestem	133.3 ± 21.9	40.0 ± 5.7	1001.5 ± 181.7	19.5 ± 2.0	4.7 ± 0.8	26.0 ± 5.7
5	0	Little bluestem	147.2 ± 11.9	49.0 ± 4.3	111.6 ± 33.2	2.0 ± 0.5	1.3 ± 0.1	26.0 ± 5.7
5	3.4	Little bluestem	110.2 ± 64.2	36.0 ± 22.7	568.0 ± 193.7	12.2 ± 0.3	2.8 ± 1.1	26.0 ± 5.7
5	6.7	Little bluestem	99.3 ± 72.5	31.0 ± 24.1	808.5 ± 454.7	18.2 ± 3.3	3.7 ± 2.1	26.0 ± 5.7
0	0	Blue grama grass	209.1 ± 36.1	63.4 ± 13.4	263.5 ± 84.1	4.1 ± 0.9	2.0 ± 0.5	39.0 ± 7.1
0	3.4	Blue grama grass	58.4 ± 14.7	16.0 ± 5.6	544.1 ± 62.3	16.4 ± 0.5	2.3 ± 0.3	39.0 ± 7.1
0	6.7	Blue grama grass	36.0 ± 2.8	8.5 ± 0.7	431.0 ± 27.0	16.8 ± 0.4	1.7 ± 0.1	39.0 ± 7.1
2.5	0	Blue grama grass	239.6 ± 5.7	73.4 ± 0.8	272.0 ± 18.4	3.9 ± 0.3	2.2 ± 0.0	39.0 ± 7.1
2.5	3.4	Blue grama grass	142.2 ± 55.7	42.0 ± 16.9	842.0 ± 308.4	15.8 ± 2.7	4.0 ± 1.4	39.0 ± 7.1
2.5	6.7	Blue grama grass	46.9 ± 16.8	12.5 ± 5.0	472.4 ± 174.7	15.7 ± 2.9	2.0 ± 0.9	39.0 ± 7.1
5	0	Blue grama grass	190.1 ± 33.2	60.4 ± 9.2	178.5 ± 68.6	2.9 ± 0.9	1.5 ± 0.2	39.0 ± 7.1
5	3.4	Blue grama grass	101.8 ± 15.6	30.4 ± 3.5	586.0 ± 43.9	13.2 ± 1.9	2.8 ± 0.0	39.0 ± 7.1
5	6.7	Blue grama grass	54.9 ± 21.1	16.0 ± 7.1	543.5 ± 287.9	16.2 ± 5.5	2.4 ± 1.4	39.0 ± 7.1

Table A4. Number of tap water applications and mean saturated paste extract parameters (with standard deviations) collected at the end of a greenhouse experiment from grasses treated with NaCl (0 – 9 Mg·ha^{-1}) and motor oil (0-5% w/w). Experiment was conducted in Fargo, ND from 22 Feb. to 16 Apr. 2021 (continued).

Petroleum hydrocarbon rate	NaCl application rate		Mean of two replicates using extract of saturated paste					
			Ca	Mg	Na	Sodium absorption ratio	EC	Number of 300 mL tap water applications
(%w/w)	(Mg·ha^{-1})	Grasses	(mg·L)				(dS·m^{-1})	
0	0	Feather reed grass	261.5 ± 55.0	86.0 ± 16.9	304.5 ± 53.0	4.2 ± 0.3	2.3 ± 0.3	44.0 ± 5.7
0	3.4	Feather reed grass	131.2 ± 52.9	39.0 ± 18.4	888.0 ± 215.0	17.6 ± 0.4	3.9 ± 1.1	44.0 ± 5.7
0	6.7	Feather reed grass	42.0 ± 8.5	12.0 ± 2.8	449.0 ± 41.0	15.8 ± 0.2	1.8 ± 0.2	44.0 ± 5.7
2.5	0	Feather reed grass	131.8 ± 5.7	44.5 ± 0.7	127.5 ± 10.6	2.4 ± 0.2	1.3 ± 0.1	44.0 ± 5.7
2.5	3.4	Feather reed grass	97.3 ± 2.1	30.4 ± 2.1	345.6 ± 99.7	7.8 ± 2.1	1.8 ± 0.5	44.0 ± 5.7
2.5	6.7	Feather reed grass	44.0 ± 1.4	12.5 ± 0.7	414.5 ± 44.6	14.2 ± 1.8	1.7 ± 0.2	44.0 ± 5.7
5	0	Feather reed grass	143.3 ± 0.7	48.0 ± 1.4	110.5 ± 5.0	2.0 ± 0.1	1.2 ± 0.0	44.0 ± 5.7
5	3.4	Feather reed grass	81.8 ± 14.1	26.4 ± 3.5	352.6 ± 77.1	8.6 ± 1.2	1.8 ± 0.4	44.0 ± 5.7
5	6.7	Feather reed grass	47.4 ± 7.6	13.5 ± 2.1	353.1 ± 15.6	11.7 ± 0.4	1.6 ± 0.1	44.0 ± 5.7

Table A5. Mean total organic carbon of soil from two replicates (with standard deviations) determined at the end of a greenhouse experiment from grasses treated with NaCl (0 – 9 Mg·ha-1) and motor oil (0-5% w/w). Experiment was conducted in Fargo, ND from 22 Feb. to 16 Apr. 2021.

Petroleum hydrocarbon rate	NaCl application rate		Total organic carbon		
(%w/w)	(Mg·ha^{-1})	Grasses	(%)		
0	0	Tufted hairgrass	2.6	±	0.6
0	3.4	Tufted hairgrass	2.6	±	0.1
0	6.7	Tufted hairgrass	2.4	±	0.1
2.5	0	Tufted hairgrass	3.3	±	0.6
2.5	3.4	Tufted hairgrass	3.4	±	0.4
2.5	6.7	Tufted hairgrass	4.2	±	0.4
5	0	Tufted hairgrass	5.6	±	0.3
5	3.4	Tufted hairgrass	5.3	±	0.1
5	6.7	Tufted hairgrass	5.2	±	0.8
0	0	Switch grass	1.8	±	0.1
0	3.4	Switch grass	2.0	±	0.1
0	6.7	Switch grass	2.0	±	0.1
2.5	0	Switch grass	4.0	±	0.1
2.5	3.4	Switch grass	3.8	±	0.3
2.5	6.7	Switch grass	4.0	±	0.3
5	0	Switch grass	6.7	±	1.0
5	3.4	Switch grass	6.2	±	0.8
5	6.7	Switch grass	5.7	±	0.1
0	0	Big bluestem	1.7	±	0.1
0	3.4	Big bluestem	1.7	±	0.3
0	6.7	Big bluestem	1.6	±	0.0
2.5	0	Big bluestem	3.9	±	0.0
2.5	3.4	Big bluestem	3.9	±	0.6
2.5	6.7	Big bluestem	3.5	±	0.3
5	0	Big bluestem	5.6	±	0.1
5	3.4	Big bluestem	5.7	±	0.0
5	6.7	Big bluestem	5.4	±	0.7

Table A5. Mean total organic carbon of soil from two replicates (with standard deviations) determined at the end of a greenhouse experiment from grasses treated with NaCl (0 – 9 Mg·ha^{-1}) and motor oil (0-5% w/w). Experiment was conducted in Fargo, ND from 22 Feb. to 16 Apr. 2021 (continued).

Petroleum hydrocarbon rate (%w/w)	NaCl application rate (Mg·ha^{-1})	Grasses	Total organic carbon ------------(%)------------		
0	0	Chinese silvergrass	1.9	±	0.1
0	3.4	Chinese silvergrass	2.0	±	0.4
0	6.7	Chinese silvergrass	2.4	±	0.4
2.5	0	Chinese silvergrass	3.6	±	0.3
2.5	3.4	Chinese silvergrass	4.0	±	0.3
2.5	6.7	Chinese silvergrass	3.4	±	0.4
5	0	Chinese silvergrass	5.4	±	0.1
5	3.4	Chinese silvergrass	5.0	±	0.1
5	6.7	Chinese silvergrass	5.3	±	0.3
0	0	Little bluestem	1.8	±	0.1
0	3.4	Little bluestem	2.1	±	0.2
0	6.7	Little bluestem	2.1	±	0.1
2.5	0	Little bluestem	3.9	±	0.6
2.5	3.4	Little bluestem	3.8	±	0.4
2.5	6.7	Little bluestem	4.1	±	0.1
5	0	Little bluestem	5.5	±	0.5
5	3.4	Little bluestem	5.9	±	0.1
5	6.7	Little bluestem	5.2	±	0.5
0	0	Blue grama grass	1.9	±	0.1
0	3.4	Blue grama grass	2.3	±	0.6
0	6.7	Blue grama grass	2.0	±	0.0
2.5	0	Blue grama grass	3.5	±	0.1
2.5	3.4	Blue grama grass	3.4	±	0.1
2.5	6.7	Blue grama grass	3.5	±	0.4
5	0	Blue grama grass	5.8	±	0.7
5	3.4	Blue grama grass	5.8	±	0.3
5	6.7	Blue grama grass	4.7	±	0.4
0	0	Feather reed grass	2.1	±	0.2
0	3.4	Feather reed grass	1.6	±	0.4
0	6.7	Feather reed grass	1.9	±	0.0
2.5	0	Feather reed grass	3.5	±	0.2
2.5	3.4	Feather reed grass	3.9	±	0.8
2.5	6.7	Feather reed grass	3.6	±	0.5
5	0	Feather reed grass	5.3	±	0.3
5	3.4	Feather reed grass	5.2	±	0.3
5	6.7	Feather reed grass	5.2	±	0.4

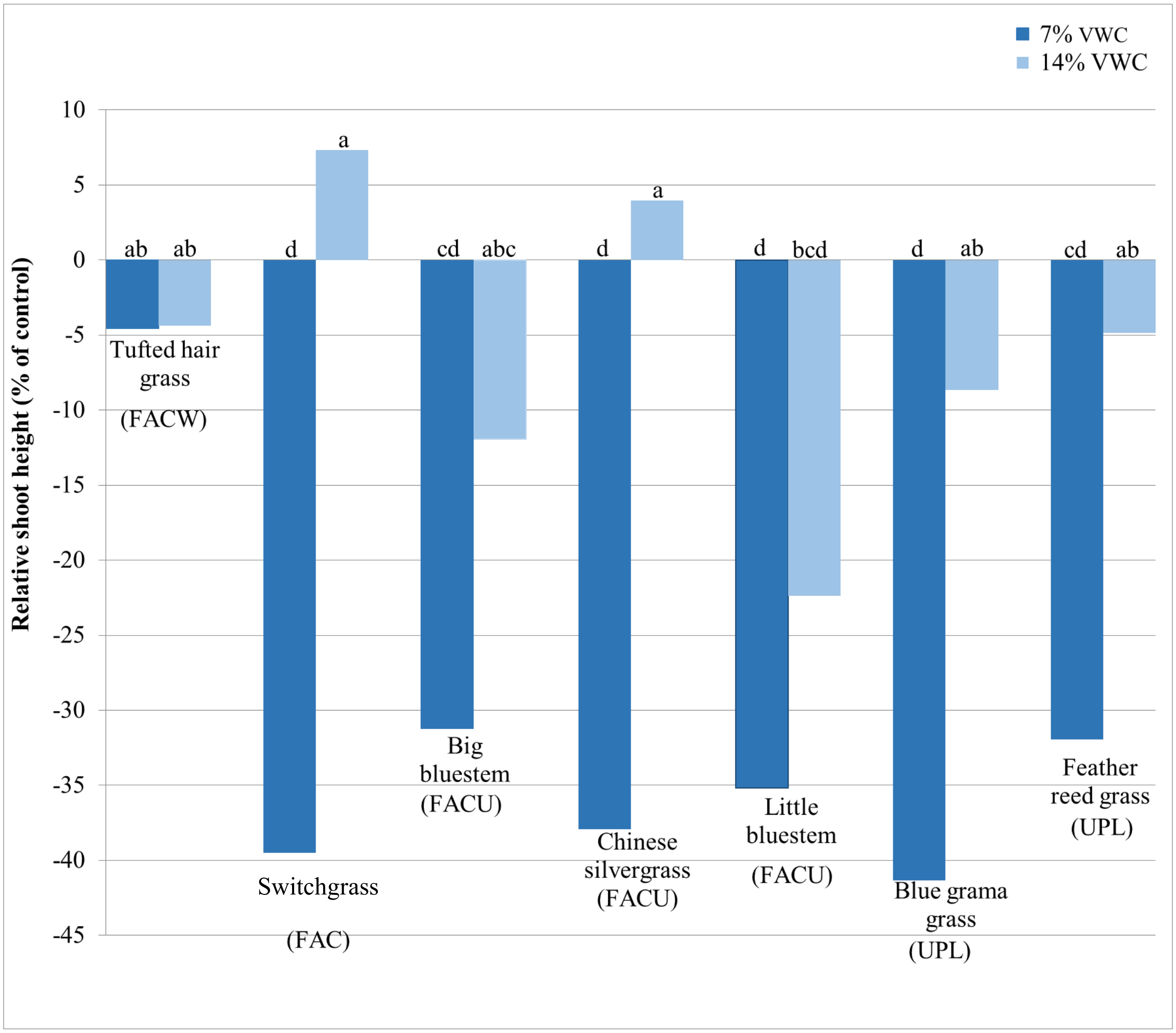

Figure A1. Relative shoot height as a percentage of the control for seven perennial ornamental grass species subjected to cyclical flood and drought periods. Mean values are averaged across flood duration treatments. Grasses were flooded for two or seven days and allowed to dry down to 0.07 or 0.14 $m^3 \cdot m^{-3}$ substrate volumetric water content (VWC). Mean (n = 18) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at $P < 0.05$. The wetland indicator categories are as follows: FACW (facultative wetland), FAC (facultative), FACU (facultative upland), UPL (upland).

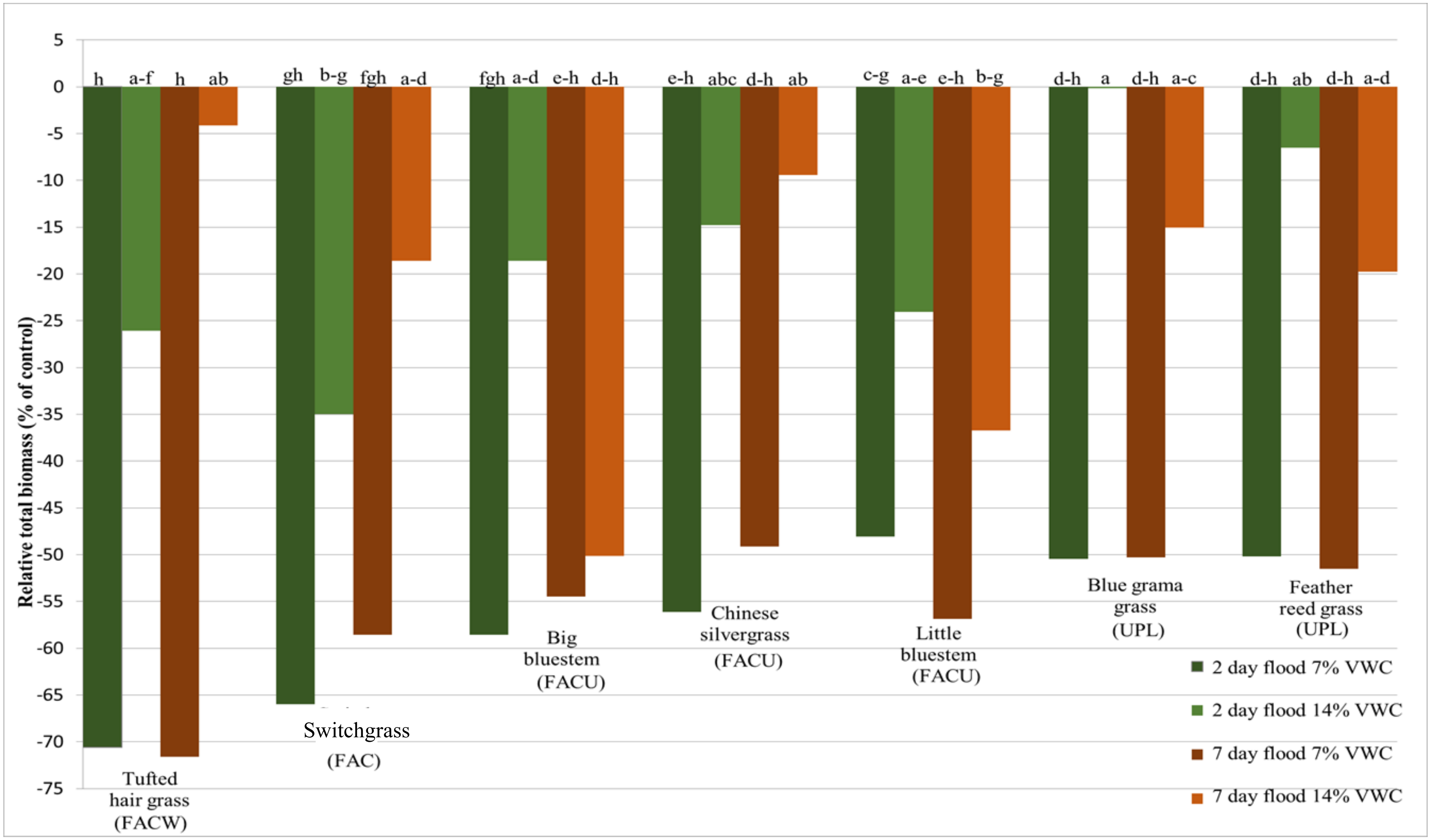

Figure A2. Relative total biomass for perennial ornamental grasses subjected to cyclical flood and drought periods. Grasses were flooded for two or seven days and allowed to dry down to 0.07 or 0.14 $m^3 \cdot m^{-3}$ substrate volumetric water content (VWC). Mean (n = 9) values labeled with different lower case letters were significantly different by Tukey-Kramer honestly significant difference test at *P*< 0.05.

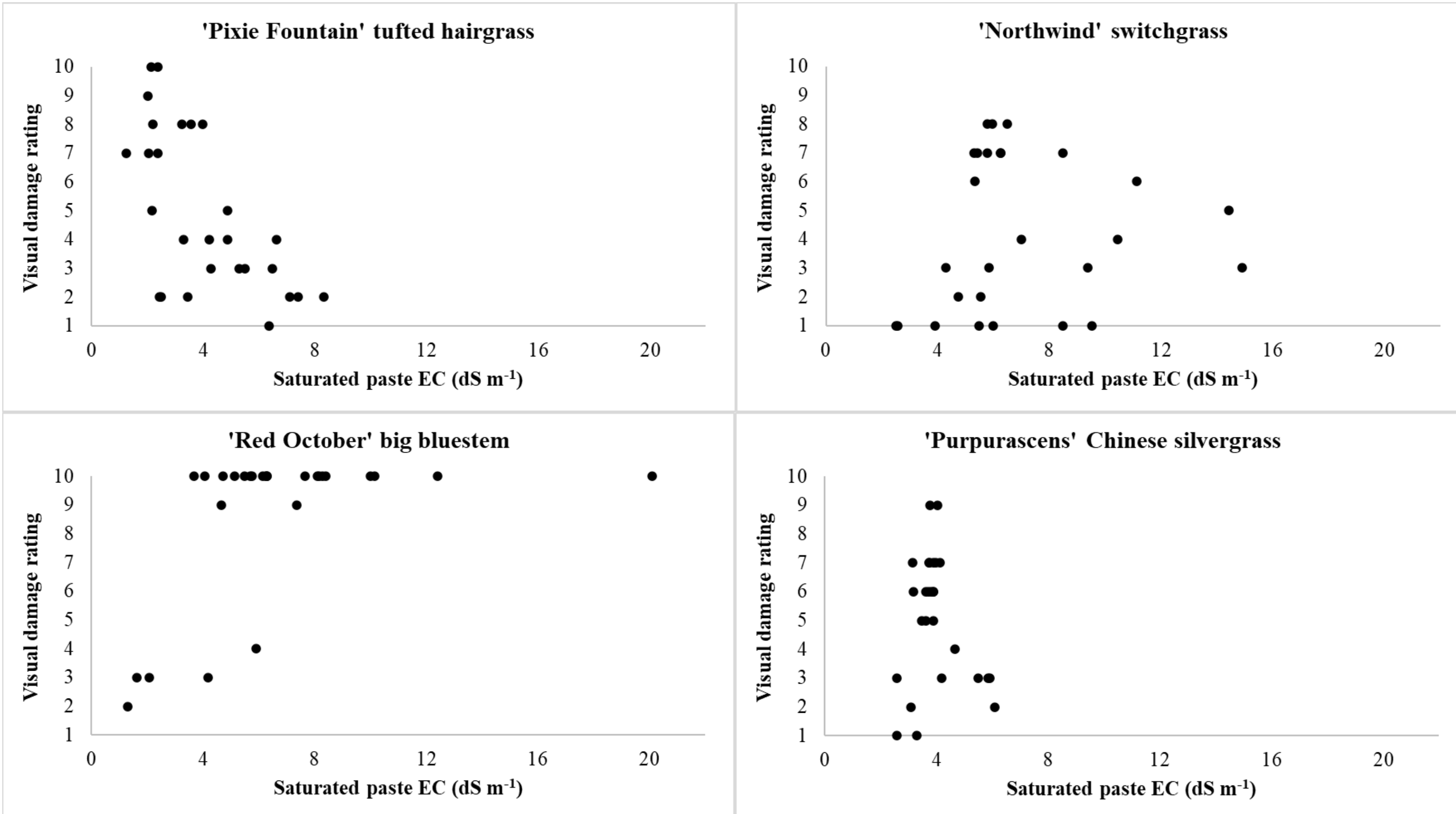

Figure A3. Relationship between visual damage rating (1-10 scale; 1= 0-10% dieback, 4= 31-40% dieback, 7= 61-70% dieback, 10= 91-100% dieback) and saturated paste EC (dS·m^{-1}) of seven perennial ornamental grasses. Experiment was conducted in a greenhouse from 3 Oct. to 17 Nov. 2020.

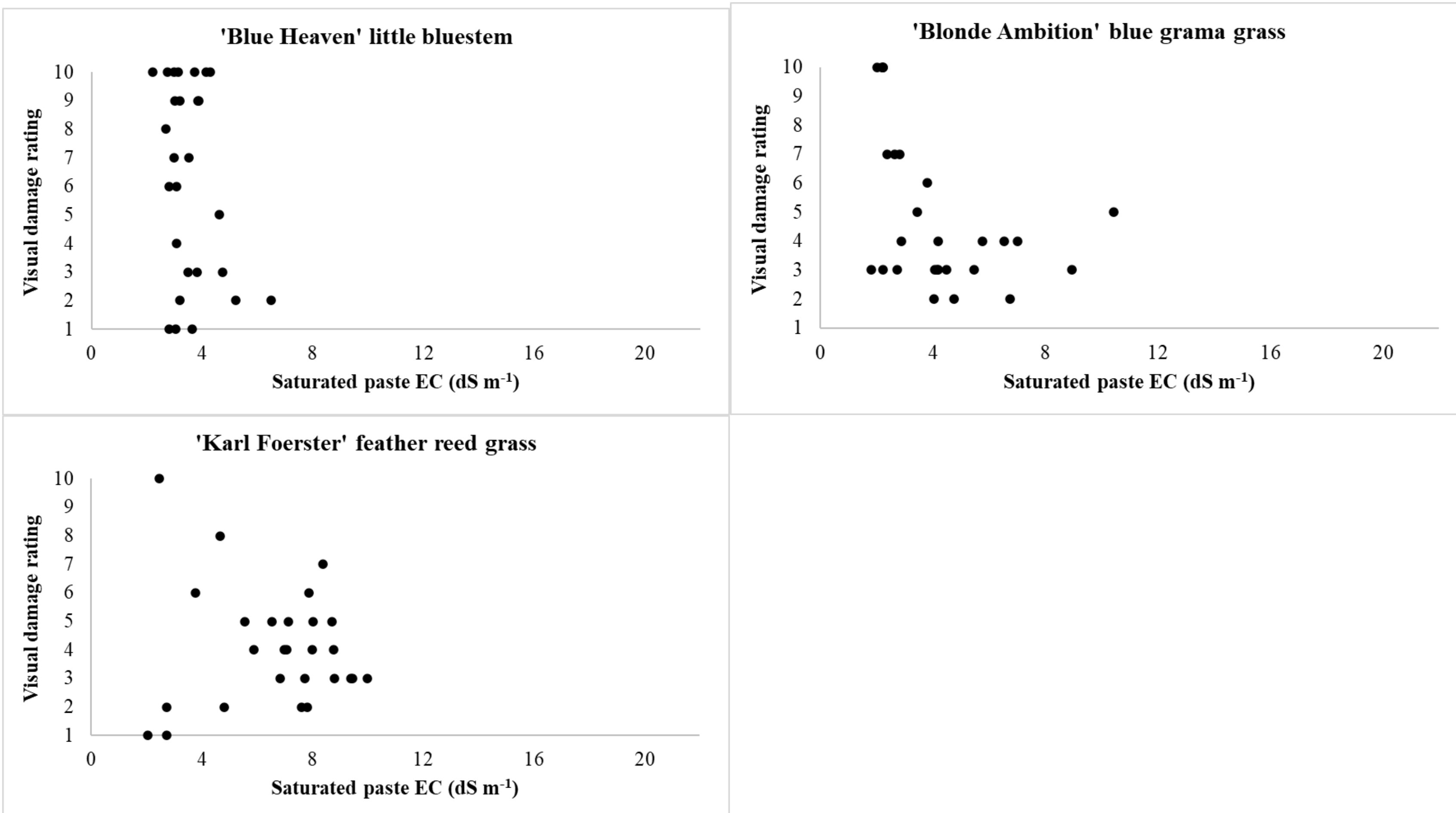

Figure A3. Relationship between visual damage rating (1-10 scale; 1= 0-10% dieback, 4= 31-40% dieback, 7= 61-70% dieback, 10= 91-100% dieback) and saturated paste EC ($dS{\cdot}m^{-1}$) of seven perennial ornamental grasses. Experiment was conducted in a greenhouse from 3 Oct. to 17 Nov. 2020 (continued).