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Influence of Plant Age, Soil Moisture, and Temperature Cylcing Date on Containter-Grown Herbaceous Perennials

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INFLUENCE OF PLANT AGE, SOIL MOISTURE, AND TEMPERATURE CYCLING DATE ON CONTAINER-GROWN HERBACEOUS PERENNIALS

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Abstract

Perennial growers overwintering plant stock require information to assist in deciding which containerized plants are most likely to successfully overwinter. Three studies on container-grown herbaceous perennials were conducted to examine the influence of plant age, soil moisture, and temperature cycling date on cold hardiness. In January, plants were exposed to controlled freezing temperatures of -2, -5, -8, -11, and -14C and then returned to a 3-5C greenhouse. In June, plants were assessed using a visual rating scale of 1-5 (1 = dead, 3-5 = increasing salable quality, varying by cultivar) and dry weights of new growth were determined. Controlled freezing in November and March were also included in the third study.

In the first study, two ages of plants were exposed to controlled freezing temperatures in January. For *Geranium* x *cantabrigiense* 'Karmina', age had no effect on either rating or dry weight in one study year. In two *Sedum* 'Matrona' study years, age had no effect on dry weight but ratings were higher for older plants than younger plants in the first year and higher for younger plants than older plants in the second year. In two *Leucanthemum* x *superbum* 'Becky' study years, age had an effect on both rating and dry weight which were both generally higher for younger plants than older plants.

In the second study, plants were maintained in pots at two different soil moisture levels prior to exposure to controlled freezing temperatures in January. *Coreopsis* 'Tequila Sunrise' and *Carex morrowii* 'Ice Dance' showed no effect on either rating or dry weight from soil moisture level. Soil moisture level had no effect on dry weight but ratings were higher for *Geranium* x *cantabrigiense* 'Cambridge' “wet” plants and for *Heuchera* 'Plum Pudding' “dry” plants. *Carex laxiculmus* 'Hobb' (Bunny Blue™) soil moisture level had an effect where dry weight was higher for “dry” plants. Means at were of salable quality for *Geranium* and *Heuchera* at all temperatures and *Carex laxiculmus* at temperatures above -11C. The effects of soil moisture level on *Carex oshimensis* were inconclusive.

In the third study, during November, January, and March, plants were subjected to temperature cycling treatments prior to exposure to controlled freezing temperatures. *Geranium* x *cantabrigiense* 'Cambridge' were more tolerant of both temperature cycling and freezing temperatures in January and an increased number of cycles in November had an advantageous effect. *Sedum* 'Matrona' were more tolerant of temperature cycling and freezing temperatures in January and an increased number of cycles in March had an advantageous effect. *Leucanthemum* x *superbum* 'Becky' were more tolerant of temperature cycling in January in the second year of the study and an increased number of cycles in November had an advantageous effect in the first year and in all months in the second year.

Overwintering younger container-grown plants is likely to result in more growth and higher quality following exposure to freezing temperatures. Effects of soil moisture level on overwintering container-grown plant growth and quality are cultivar-specific and a general effect could not be established in these studies. Overwintering container-grown plants are likely to be hardier in January and slight temperature cycles prior to exposure to freezing temperatures generally increase hardiness.

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Introduction

Container production of herbaceous perennials continues to be popular within the nursery industry and consumers have come to expect plants of certain size, quality and bloom. In northern climates, this may require multiple seasons of plant growth or vernalization events which, in turn, require overwintering periods during which the containerized plants are subjected to freezing temperatures. Additionally, growers may wish to overwinter propagation stock, plants not sold within a season, or newly potted plants prepared for the following season. Factors such as plant age and degree of establishment, plant health, moisture content of the plant and/or growing media, type of growing media, fertility, cultivar variation, and temperature fluctuations a plant is subjected to during the winter period, may affect survival following freezing winter temperatures. Research relating these factors to cold hardiness will assist growers in planning containerized plant production practices and schedules, and in deciding which containerized plants are most likely to successfully overwinter at the end of a season, potentially saving some of the expense required to prepare and protect containerized plants from freezing temperatures. The objective of the following studies was to examine the influence of plant age, soil moisture, and temperature cycling date on cold hardiness of several cultivars of container-grown herbaceous perennials.

Plant Cold Hardiness

In order to survive in cold climates, plants must withstand periodic freezing temperatures. Plants that have the genetic ability to survive chilling or freezing undergo acclimation, a process of physiological changes to plant cells during a drop in temperature that prevents injury to the cells. A reversible suspension of growth, commonly referred to as dormancy, occurs in many plants during conditions unsuitable for growth.

Dormancy and Acclimation

Terminology and definitions of dormancy are myriad and sometimes contradictory. An attempt was made by Lang in 1987 to define the phenomena of dormancy. Dormancy itself is presented as the temporary suspension of visible growth of any plant structure containing a meristem. Ecodormancy is dormancy due to environmental factors, such as temperature extremes or water stress, evoking nonspecific responses. The other forms of dormancy presented are paradormancy, regulated by physiological factors outside the affected structure such as apical dominance, and endodormancy, regulated by physiological factors inside the affected structure such as chilling responses. Photoperiod influences both para- and endodormancy (Lang, 1987).

Woody plants are usually stimulated to acclimate by shortening day length and cease growth once acclimation begins. Woody plants generally undergo two distinct acclimation phases: first the plant to ceases growth despite otherwise favorable growing conditions then low temperatures stimulate the metabolic processes that promote survival of freezing temperatures. A third stage induced by temperatures below -30C has been speculated for woody plants although its occurrence in nature is not thought to be common (Weiser, 1970).

Most herbaceous perennials are stimulated to acclimate by low temperatures, likely independent of day length (Kohn et al., 1965; Li et al., 1978; Iles et al., 1995) and maintain meristematic potential despite the cessation of growth, a condition that is not commonly considered true dormancy. Herbaceous perennial acclimation may occur in two stages: the first when temperatures are above freezing and the second when temperatures drop below freezing (Kacperska-Palacz, 1978). Accumulation of carbohydrates is a key to hardiness in herbaceous plants so sufficient light intensity may actually be required for photosynthesis during the early stages (Levitt, 1980; Sakai et al., 1987).

The Acclimation Process

As temperatures drop, the lipids in the plasma membrane and organelle membranes shift to a solid state (Levitt, 1980) and the cytoskeleton is rearranged (Jian et al., 1993). Some plants are able to unsaturate their membrane lipids and lower the temperature at which they solidify (Sakai et al., 1987; Yoshida et al., 1989). Changes in the plasma lipids affect membrane proteins such as the ATPase pumps that maintain ion concentrations within the cells. Ion leakage then occurs from the cells (Palta et al., 1993). Solidification of the membranes is thought by some to be the impetus for the chain of enzyme reactions and expression of cold-induced genes that allow for plant survival at lower temperatures (Lynch, 1990). Abscisic acid accumulation is also thought to play a role during acclimation (Guy, 1990; Nordin et al., 1993). Photosynthesis continues during acclimation and shifts in Calvin cycle enzymes, sucrose synthesis, and reallocation of inorganic phosphate allow this process to persist (Strand et al., 1999; Hurry et al., 2002).

During acclimation, ice formation outside of the cell is common due to lower solute concentration and more nucleating sites but most hardy plants tolerate it (Sakai et al., 1987; Palta et al., 1993). Extracellular ice can cause water to be drawn out of the cell to the point where the cell will die, but up until that point the exodus of water increases the solution concentration within the cell (Levitt, 1980). The solution within the cell becomes more concentrated, particularly with sugars. Because it is a solution and not pure water, the cell contents will remain liquid below the freezing point of water, a condition known as supercooling (Sakai et al., 1987). As long as the temperature drops slowly (1-2C/hour), this state will normally persist in hardy plants (Levitt, 1980; Palta et al., 1993). A more rapid drop in temperature causes ice crystals to form within the cell. Formation of ice crystals within a cell is almost always fatal to the cell (Levitt, 1980) unless the freeze happens swiftly and very small ice crystals form (Sakai et al., 1987). A broken cell membrane leads to cell death, but it is uncertain if the membrane breaks due to ice formation or if the ice forms after the cell membrane breaks (Steponkus, 1990; Yamada et al., 2002). To combat the effects of ice, cells may synthesize ‘anti-freeze’ proteins that regulate the formation and size of ice crystals outside and inside the cell (Griffith et al., 1993; Yeh et al., 2000).

The Perennial Industry

Nursery and greenhouse is the third largest plant industry, and one of the top five agricultural industries, in the United States in terms of net cash income. Herbaceous perennials and other bedding/garden plants make up over half of the value of sales for floriculture crops and is the highest valued category behind woody nursery stock of all nursery and greenhouse industries (USDA, 2007). In New England, the horticulture industry generates $4.7 billion and growing annually with over half of that income from locally grown plant sales (Perry et al., 2009).

Container Production

Production of herbaceous perennial plants in containers continues to be popular within the nursery industry and accounts for the majority of ornamental plant production (Perry, 1998; Perry, 2006; Pilon, 2006; Diver et al., 2008). Growing plants in containers allows growers to produce more plants in less space with more control over propagation, culture, and pests than traditional field production. Plants in containers are easier to handle within the nursery, require less labor overall, and are more efficient to transport. Consumers generally prefer to purchase smaller, uniform, well-grown plants in containers that are easy to handle and transplant. Container-grown plants experience less root loss than field-harvested plants which allows them to better survive and establish following transplanting (Perry, 1998; Perry, 2006; Diver et al., 2008; Eaton et al., 2009).

Irrigation

One distinct aspect of container production is the increased need for irrigation (Perry, 1998; Diver et al., 2008; Eaton et al., 2009). Irrigation is critical to production of quality plants without the constraints imposed by dependence on irregular natural rainfall (Tilt, 2000). However such methods require an abundant source of quality water, intensive labor (Eaton et al., 2009), and specialized equipment. Water quality can in turn be impacted by the act of irrigation due to runoff (Diver et al., 2008). Quality water sources are often subject to regulation, liable to decrease in availability, and likely to increase in cost to acquire. Increasing efficiency of water delivery to plants will offset these concerns (Beeson et al., 2004) and can shorten production time (Tilt, 2000).

Overwintering

Overwintering is typically the most limiting factor in production of container-grown plants for growers in northern climates (Pellett et al., 1985). Inevitably, all plants will not be sold within a single growing season resulting in the necessity of disposing, field planting or overwintering container-grown stock. Additionally, many cultivars and propagation methods require production periods longer than a single season prior to sale, again necessitating overwintering (Pilon, 2006; Svendsen et al., 2006; Pyle, 2009). A recent trend by consumers to grow herbaceous perennials as ornamental container plants, has led to an interest in overwintering through multiple years of growth (Dimke et al., 2008). Successful methods for overwintering containerized plants are generally labor intensive and expensive (Taylor et al., 1983; Pilon, 2006).

Factors That Affect Hardiness of Herbaceous Perennials

Herbaceous perennials must first have the genetic ability to survive chilling or freezing. Secondly, they must be given sufficient time to acclimate or prepare for freezing, provided they have the ability to do so (Levitt, 1980; Sakai et al., 1987). Plants acclimate when given certain environmental cues, such as light intensity, and therefore optimal timing of the temperature drop is tied to these cues (Kohn et al., 1965; Weiser, 1970; Li et al., 1978; Iles et al., 1995). The rate at which temperatures drop, as well as the rate at which they rise, will provide time for acclimation (Palta et al., 1993; Bruce, 2003). The lowest temperature reached and how long that temperature is maintained will influence how well the plant will survive (Perry et al., 1996; Bruce, 2003). Cycling of temperatures, or the number of times the plant is frozen, will also factor into plant survival (Bruce, 2003; Luchini, 2005). Insulation, such as snow or plastic covering, is a factor in plant survival in pots or in the ground (Perry, 1998; Smith, 2004). Other factors such as plant age and degree of establishment, plant health, moisture content of the plant and/or growing media, type of growing media, fertility, and cultivar variation will affect hardiness

Maintaining adequate moisture in overwintering plants is necessary to prevent freeze-drying (Berghage et al., 1999; Pilon, 2006). Steps to maintain moisture in overwintering plants include irrigating thoroughly prior to storage under cover and regular monitoring and irrigating when plants are stored within an accessible structure (Smith, 2004; Hulme, 2010). Regular watering can alleviate plant injury from buildup of soluble salts in the growing media due to water loss (Hulme, 2010). Maximizing water content of growing media has been shown to regulate duration of temperature extremes of plants stored under cover during freezing periods (van de Werken, 1987). Water content will provide a source of heat and slow freezing of the growing media, although too much water can foster diseases (Smith, 2004). Plant loss due to overly wet conditions is the leading reason for plant loss when overwintering (Berghage et al., 1999; Pilon, 2006).

One special condition when looking at hardiness of perennials in pots is that they do not have the same amount of thermal reservoir that plants in the ground do to buffer against temperature changes and may therefore have less extreme temperature tolerances. Plants in containers are exposed to air temperatures that are colder than they may experience when growing in the ground (Perry, 1998; Pilon, 2006), challenging the plants natural survival mechanisms. Many cold-sensitive roots are found on the outer top and sides of a container where media temperature approaches this colder air temperature (Pellett et al., 1985; Perry, 1998; Pilon, 2006). These are often young roots that are first to be injured by cold temperatures (Mathers, 2003). The smaller the container, the more rapidly media temperature will react to air temperature changes (Svendsen et al., 2006). Because of this, potted plants must be protected from temperature extremes. Pot size and insulation methods are critical factors in potted plant survival.

Research Techniques

Assessment of electrical conductivity of excised plant tissue following freezing is a neat way to evaluate cell damage. The more damage a cell, the more ions will have escaped. The collected data is very unambiguous, inherently quantitative, and free of bias. This method has the advantage of working with discrete amounts of tissue, such as a piece of root, which can be unified, such as by weight. Additionally, assessment usually occurs within 24 hours following the freezing event. However, this method is labor intensive and the strength of correlation between these measurements and whole plant assessments is variable (Levitt, 1980; Sakai et al., 1987; Iles et al., 1995; Meyer, 1999).

Whole plant assessment following freezing allows for more variety of measurements such as dry weight, height, and visual rating of plant quality. However, in order to make these assessments, plants must be allowed to re-grow following freezing treatments then processing and drying time are needed prior to dry weight measurement. The visual rating is a particularly useful tool when assessing salability and ornamental value of perennials. Plants that do not maintain a certain level of whole-plant performance will not be appealing or marketable, regardless of survival (Iles et al., 1995; Herrick, 1996; Bruce, 2003).

Applicable Research

Plant Age

It is generally accepted that an established plant with a well developed root system will better survive overwintering (Smith, 2004; Pilon, 2006) although age of the plant is not specified. The effects of plant age, how long a plant has been established in the same pot, on survival of freezing winter temperatures is relatively unstudied, particularly for herbaceous perennial container production.

Young plants and plant parts have shown certain biological traits that help them to withstand freezing temperatures. Young, uniform tissue will freeze more uniformly and is more flexible than mature, differentiated tissue that may have developed structural rigidity which could lead to mechanical injury from ice formation (Olien, 1964). Younger, smaller plants may have fewer nucleation sites where ice forms during freezing events since the frequency of these sites appears to increase with mass (Ashworth et al., 1985). Studies with cucumber showed that young plants produced antioxidants that prevented damage to protein and DNA during low temperature events (Kuk et al., 2007). In alfalfa, older plants were "consistently associated with markedly lower levels of expression of cold-regulated genes" (Castonguay et al., 2002).

Older plants may have an advantage of prior exposure to freezing events. Faults and anchorage points in cells, regions where tissue is arranged to accommodate formation of extracellular ice, may not develop until initial exposure to freezing temperatures (McCully et al., 2004). It is generally accepted that a well developed root system will better survive freezing temperatures (Smith, 2004; Pilon, 2006). A larger shoot to root ratio has not been shown to affect survival of freezing temperatures in studies of *Plantago lanceolata* (Skinner, 2005). This would suggest that a mature plant with full root system that has been exposed to prior freezing events may overwinter at least as effectively as a younger plant with a less established root system.

Plant age can have positive or negative effects on survival following a freezing event. Seedlings of onion (Warnock et al., 1993) and the woody plant *Phellodendron sachalinense* were less cold-hardy than mature plants (McNamara et al., 2000). On the other hand, seedlings of various legumes were more cold-hardy when they were younger (Meyer et al., 2001) as were younger alfalfa plants (Castonguay et al., 2002). Studies of container-grown herbaceous perennials generally found younger plants to be more marketable than established plants following freezing events although results varied by cultivar. Younger plants of *Tiarella*, *Dianthus* and *Geranium* 'Cambridge' rated better in salable quality following freezing, whereas older plants of *Geranium* 'St. Ola' fared better following freezing (Bruce, 2003; Luchini, 2005).

Soil Moisture

The effects of soil moisture levels in the period prior to storage on survival of freezing winter temperatures has been extensively studied yet not always particularly for container production. However, it is a common conception that withholding water during acclimation can increase cold hardiness, provided thorough watering occurs prior to freeze (Pilon, 2006).

A reduction in available water can occur during both drought and freezing periods (Verslues et al., 2006). Certain physiological effects in plants during water drought closely resemble those that occur during cold acclimation of plants. These effects include an accumulation of abscisic acid, proteins, and carbohydrates (Pagter et al., 2008); decrease in tissue water content (Brule-Babel et al., 1989; Iles et al., 1995; Gusta et al., 2004; Nobel et al., 2008); and reduced shoot growth (Herzog, 1987; Arnott et al., 1993; Pagter et al., 2008). With the assumption that plants experiencing water drought have already acquired the factors necessary for freezing tolerance, attempts to relate drought stress to increases in cold hardiness has been widely researched.

Water deficit stress during the growing season has been shown to increase ability to survive exposure to freezing temperatures in Austrian winter pea (*Pisum sativum* subsp. *arvense*) (Kephart, 1984), *Rhododendron* 'Catawbiense Boursault' (Anisko et al., 1996b), cacti (*Nopalea cochinellifera* and *Opuntia robusta*) (Nobel et al., 2008), chicory (*Cichorium intybus* 'Grasslands Puna') and narrow leaf plantain (*Plantago lanceolata* 'Ceres Tonic') in the field (Skinner et al., 2002) and narrow leaf plantain (*Plantago lanceolata* 'Grasslands Lancelot') in a growth chamber (Skinner, 2005). Water deficit stress did not affect freezing tolerance of European varieties of winter faba beans grown at a constant temperature but did have an effect when combined with a day/night temperature difference (Herzog, 1987). Lower tissue water content has been shown to increase ability to survive exposure to freezing temperatures in strawberry (*Fragaris* x *ananassa* 'Earliglow') (Warmund et al., 1992), saltbush (*Atriplex halimus*) (Walker et al., 2008), and may have been a contributing factor in *Sedum* 'Autumn Joy' cold tolerance (Iles et al., 1995).

Conversely, water deficit stress during the growing season has not been shown to increase ability to survive exposure to freezing temperatures in *Fuschia magellanica* 'Riccartonii' (Pagter et al., 2008), Azalea (*Rhododendron* 'Coral Bell', 'Hinodegiri', and 'Red Ruffle') (Anisko et al., 1996a), cypress rooted cuttings (*Chamaecyparis nootkatensis*) (Arnott et al., 1993), and chicory (*Cichorium intybus* 'Grasslands Puna') in a growth chamber (Skinner, 2005). Water deficit stress during the growing season did not affect freezing tolerance of Japanese beech (*Fagus crenata*) buds (Yonekura et al., 2004). Tissue water content is not a consistent indicator of cold hardiness of the winter cereals wheat (*Triticum aestivum*) and rye (*Secale cereale*) (Brule-Babel et al., 1989).

An increase in available water during the growing season is less commonly studied than drought situations. However, plentiful water supports plant processes during the growing season and encourages development of strong root systems to better survive overwintering (Pilon, 2006). Soils with high water content do not immediately reach the lower temperatures during freezing periods that dry soils do (van de Werken, 1987; Smith, 2004).

In a study of apple trees (*Malus* x *domestica*), proximity to a water source correlated with increased survival of freezing periods (Quamme et al., 1989). Alfalfa (*Medicago sativa*) has been shown to increase survival following exposure to freezing temperatures as soil saturation increased (Van Ryswyk et al., 1993). *Rhododendron* 'Catawbiense Boursault' has been shown to improve in cold hardiness over several seasons of growth in saturated conditions, although not to the extent of cold hardiness exhibited under normal water conditions (Anisko et al., 1996b). Studies of container-grown herbaceous perennials *Coreopsis* 'Tequila Sunrise' and *Geranium* 'Cambridge' comparing moisture level stresses during the growing season followed by a freezing event showed some significant effects favoring higher moisture levels during the growing season, although *Coreopsis* 'Moonbeam' in the same study did not show any significant preference (Luchini et al., 2004). Water saturation stress did not affect freezing tolerance of European varieties of winter faba beans grown at a constant temperature but did have an effect when combined with a day/night temperature difference. This same effect was observed with water deficit stress as noted above (Herzog, 1987).

Temperature Cycling Date

In every overwintering period, temperatures will inevitably fluctuate, most notably during a typical midwinter (January thaw), and keeping plants from thawing during these events is difficult (Smith, 2004). The effects of these temperature changes on survival of freezing winter temperatures are relatively unstudied, particularly for herbaceous perennial container production.

After a temporary thaw, reacclimation of oilseed rape (*Brassica napus*) to freezing temperatures is possible (Rife et al., 2003) provided no elongation growth occurs (Rapacz, 2002). A damaging effect of temperature fluctuations is embolism caused by cavitating gas bubbles in the vascular system that form during ice formation and are released during thaw periods (Mayr et al., 2003). Plants with smaller vessels, such as conifers, have less dissolved gas and will form smaller bubbles that cause less cavitation damage (Sperry et al., 1992).

Temperature fluctuations where a warm spell occurs amidst freezing winter temperatures have not been seen to significantly affect hardiness of woody plant twigs of European birch (*Betula pubescens*), *Populus gelrica*, *Salix dasyclados*, *S. daphnoides*, and *Larix laricina* when they occur during the winter but a 'rapid' loss of hardiness is observed in the spring (Sakai, 1973). Daily temperature fluctuations increased hardiness of winter wheat (*Triticum aesitivum*) (Andrews et al., 1974). Strawberry (*Fragaris* x *ananassa*) plants show a decrease in hardiness during multiple freeze-thaw events, but root regrowth and leaf number the following season are unaffected (Warmund et al., 1992). Studies of grasslands show an increase in above ground growth but a decrease in root length following multiple freeze-thaw cycles (Kreyling et al., 2008). Apple trees (*Malus* x *domestica*) demonstrate lower survival rates as well as reduced leaf, shoot, and root regrowth when following multiple freeze-thaw events, with as few as two cycles (Prive et al., 2001).

Studies of container-grown herbaceous perennials showed freeze-thaw cycles to increase hardiness of *Campanula takesimana* (Herrick, 1996), *Dianthus deltoides* 'Vampire', *Geranium* x *cantabrigiense* 'Cambridge' (Bruce, 2003), and *Geranium* 'Dilys (Luchini, 2005) although more extreme fluctuations may have the opposite effect (Bruce, 2003). No effect on hardiness was observed for *Iris siberica* 'Pirate Prince', *Coreopsis* 'Tequila Sunrise', or *Geranium* x *cantabrigiense* 'Karmina' (Luchini, 2005).

From early winter to mid winter, azalea (*Rhododendron* species) buds appear to increase in hardiness and decrease in rehardening capacity. Extent of dehardening is greater in late winter than in early winter when subjected to warming temperatures (Kalberer et al., 2007). In January, March, and April, artificial freeze-thaw cycles did not affect hardiness of strawberry (*Fragaris* x *ananassa*) plants (Linden et al., 2000). Studies of herbaceous perennial sedum (*Sedum spectabile* x *telephium* 'Autumn Joy' and *Sedum spectabile* 'Brilliant') showed an increase in hardiness from September to maximum acclimation and highest shoot regrowth quality in January, with the sharpest increase in hardiness occurring in November (Iles et al., 1995). Studies of *Aquilegia* 'McKana's Giant' mix and *Dianthus deltoides* 'Vampire' both showed higher survival and salable quality in January than in November (Perry et al., 1996). A better salable quality of the herbaceous perennial *Geranium* 'Dilys was observed in January than in March. *Geranium* x *cantabrigiense* 'Cambridge' and *Coreopsis* 'Tequila Sunrise' showed no difference between January and March controlled freezing events (Luchini, 2005).

Plant Genera and Cultivars

Carex, *Coreopsis*, *Geranium*, *Heuchera*, *Leucanthemum*, *Sedum* were used in these studies. *Geranium*, *Leucanthemum*, and *Sedum* were used in multiple studies.

Carex

Ornamental sedge, sometimes known by their genus name *Carex*, include roughly 1000 species within the Cyperaceae botanical family. The Cyperaceae is known as the sedge family and includes approximately 3600 species such as papyrus, bulrush and star sedge, although only the *Carex* are referred to as ‘sedge’ in the narrow sense (Darke, 2007). The genus occurs natively in many regions worldwide, usually in moist environments such as marshes. Sedges are grass-like in their appearance and ornamental appeal but are not true grasses. Triangular, solid (not hollow) flower stems bearing separate male and female flowers distinguish sedges from grasses. Foliage colors range from blue-green to red-brown and leaf widths from < ½ - 2 inches depending on species (Armitage, 2008). Most ornamental species prefer sunny and moist conditions (Darke, 2007).

The cultivar *Carex oshimensis* 'Evergold' is a popular ornamental plant with cream-colored, narrow, weeping leaves edged in green (Armitage, 2008). The cultivar is native to Japan and variegation may revert to solid green on parts of a plant (Darke, 2007). This clump-forming cultivar prefers good drainage in moist soils and can reach a height of 15 inches. Hardiness is listed for U.S. Zones 5-8 (northcreeknurseries.com, 2010) and Zones 5-9 (perennialresource.com, 2010).

The cultivar *Carex morrowii* 'Ice Dance' was introduced from Japan in 1996. Long, shiny, green leaves edged in white reach a height up to 15 inches. Adaptable to many soil types, this cultivar spreads by rhizomes and can be drought tolerant once established. Hardiness is listed for U.S. Zones 5-9 (northcreeknurseries.com, 2010; perennialresource.com, 2010).

The cultivar *Carex laxiculmus* 'Hobb' Bunny Blue™ is a North American native with blue-green foliage. This clump-forming cultivar prefers moist soil in partial shade and can reach a height of 8 inches (Darke, 2007). Hardiness is listed for U.S. Zones 6-10 (northcreeknurseries.com, 2010).

Coreopsis

Tickseeds, often known by their genus name *Coreopsis*, include over 100 species within the Asteraceae botanical family. The common name and Latin name of the genus is derived from the color and appearance of the seeds. Many annuals and perennials exist within the genus. All *Coreopsis* perform best in well-drained soil in full sun.

Leaves are opposite and may be lobed. A distinguishing feature of the genus is a characteristic circle of green outer and yellow inner bracts around the flower head (Armitage, 2008). Daisy-like yellow, pink or red flowers bloom continuously throughout the summer in cooler climates. Plants are relatively disease-free and most species are easily propagated by division, cuttings, or seed. The tendency of some species to self-sow can be problematic in some gardens (Hill et al., 2003).

The cultivar 'Tequila Sunrise' is listed as a stand-alone cultivar (RHS, 2009-2010). Yellow flowers with dark orange centers bloom continuously but this cultivar is popular largely for its variegated foliage. Elongated leaves are edged or irregularly variegated with creamy yellow and pink tinges. Plants may reach a height of 16 inches. Hardiness is listed for U.S. Zones 4-8 in some references (northcreeknurseries.com, 2010) and Zones 6-9 in others (perennialresource.com, 2010) although the cultivar is known to lack vigor and be short-lived (Armitage, 2008).

Geranium

Hardy perennial geraniums, also known as cranesbill, of the *Geranium* genus are not to be confused with the generally annual geraniums of the *Pelargonium* genus. *Pelargonium* are native to southern Africa whereas *Geranium* are native to temperate regions worldwide. Both are members of the Geraniaceae botanical family distinguished by a slender fruiting structure resembling a bird's beak, hence the common name for hardy geraniums (Yeo, 2002).

The *Geranium* genus consists of over 250 species and various hybrids that are widely popular for ornamental use. Palmate foliage forms basal rosettes (Armitage, 2008) above thick roots that are sometimes tuberous or creep as rhizomes or stolons. Upright flowering stems arise from the axils of the basal leaves to bear a cymule of two flowers, although one to three flowers sometimes arise. Flowers have five petals, ten stamens (Yeo, 2002), and are 1-2 inch wide cup-shaped in pink, lavender, blue, white, or purple, depending on species (Hill et al., 2003). They grow under a range of conditions but prefer full sun to partial shade and moist soil. Temperature hardiness is generally dependent on the native range of the species (Armitage, 2008). The genus is relatively disease-free and most species are easily propagated by division, root cuttings, or seed (Yeo, 2002).

The cultivar *Geranium* x *cantabrigiense* is a hybrid developed in 1974 at Cambridge University in England from a cross of *G. macrorrhizum* (female) and *G. dalmaticum* (male) (Armitage, 2008). This cultivar is a low growing (up to 30cm (11.8in)) groundcover with aromatic, seemingly hairless, light green foliage and purple-violet flowers. Clones of this cultivar have assumed the cultivar name 'Cambridge' for the city where they were developed (Yeo, 2002). Hardiness is listed for U.S. Zones 5-9 (Hogan, 2003). Very similar to 'Cambridge' in appearance (Yeo, 2002), the cultivar 'Karmina', aka 'Biokovo Karmina', exhibits flowers of a deeper red raspberry color (Armitage, 2008). Hardiness is listed for U.S. Zones 4-8 (perennialresource.com, 2010) and Zones 5-7 (northcreeknurseries.com, 2010). Both cultivars have proven hardy in Zone 4 field conditions in Vermont (Perry, 2010).

Heuchera

Alumroots or coral bells, often known by their genus name *Heuchera*, are entirely native to North America. Thirty-six species, thirty-seven sub-species, two natural hybrids and numerous cultivated hybrids are all members of the Saxifragaceae botanical family (Heims et al., 2005). Alumroot is a common name for *H. americana* and coral bells are a common name for *H. sanguine* (Hill et al., 2003). Most Heucheras perform best in well-drained soil, acidic pH, and moderate moisture retention. They are especially suited to container gardening due to their evergreen foliage and drought resistance.

All Heuchera species form mounding rosettes of heart-shaped, lobed, sometimes hairy leaves (Heims et al., 2005). Flowers borne on tall panicles where the sepals are usually the conspicuous element of the flower are also an attractive component of some species. The wide range of natural and cultivated ornamental foliage form and color has contributed to increased popularity of this genus in recent years (Armitage, 2008). Plants are relatively disease-free and most species are easily propagated by division, cuttings, or seed (Heims et al., 2005).

The cultivar *Heuchera* 'Plum Pudding' (aka 'Plum Puddin') was introduced in 1996 during the recent wave of breeding founded on the *H. americana* species. A favorite within the industry, the cultivar is admired for its shiny purple foliage and unobtrusive flowers (Heims et al., 2005). It has a compact growth habit, up to 16 inches in foliage height (terranovanurseries.com, 2010), and prefers moist, well-drained soil in full to partial shade (northcreeknurseries.com, 2010). Hardiness is listed for U.S. Zones 3-8 (Hill et al., 2003; perennialresource.com, 2010) and Zones 5-9 (northcreeknurseries.com, 2010).

Leucanthemum

The Shasta daisies have historically been members of the *Chrysanthemum* genus although in recent years they have been reassigned to the *Leucanthemum* genus, also within the Asteraceae botanical family. Original members of the *Chrysanthemum* genus number over 100 species and various hybrids with widely varying growth habits that include the autumnal mums, ox-eye and marguerite daisies, and feverfew. All species perform best in full sun with well drained soil (Armitage, 2008).

The species *Leucanthemum* x *superbum* is a hybrid developed in 1890 from a cross of *L. lacustre* and *L. maximum*. Leaves have coarse teeth, are dark green, and may be up to 12 inches long, decreasing in size as they rise on the stem. Flowers are large, single- or double-petalled, and borne one per stem. Plants tend to be short lived, 2-3 years (Armitage, 2008) but are easily propagated by division. The species is relatively disease-free, vigorous and easy to grow (Hill et al., 2003).

The cultivar *Leucanthemum* x *superbum* 'Becky' is a selection named for a plantswoman in Georgia, U.S. (Armitage, 2008). This cultivar has 3-4 inch white flowers (Hill et al., 2003) on 3 foot stems that are desirable as cut flowers. The foliage is particularly tolerant of heat and humidity, making it popular in areas of the southern U.S. (northcreeknurseries.com, 2010). Hardiness is listed for U.S. Zones 4-9 in some references (northcreeknurseries.com, 2010) and Zones 5-9 in others (perennialresource.com, 2010).

Sedum

Stonecrops, often known by their genus name *Sedum*, include roughly 650 species within the Crassulaceae botanical family. The widely diverse genus is informally divided into those species with creeping habits and those with upright habits. Common upright forms, such as *S. telephium* and *S. spectabile*, have recently been reassigned to the genus *Hylotelephium* but the name ‘sedum’ has remained in use for the genus. All *Sedum* perform best in well-drained soil in full sun.

Leaves of *Sedum* are alternate or whorled and distinctly fleshy. The five sepals are often also fleshy below 5-petaled flowers with 10 stamens. Flower colors are usually pink, yellow, or white (Armitage, 2008). Plants are susceptible to rots and fungal diseases but are otherwise relatively easy to grow. Most species are easily propagated by cuttings. Generally hardy, suggestions vary depending on cultivar from U.S. Zones 3-10 (Hill et al., 2003).

The cultivar 'Matrona' was formerly listed under the species *Sedum telephium* (RHS, 2006-2007) and is now listed as a stand-alone cultivar (RHS, 2009-2010). It was bred in 1990 in Germany, as a cross between *S. telephium* subsp. *maximum* 'Atropurpureum' and *S. spectabile* (Galitzki, 2003). This robust and sturdy plant reaches heights of 2-3 feet with purple-red stems bearing pink flowers in autumn. Hardiness is listed for U.S. Zones 3-9 (northcreeknurseries.com, 2010; perennialresource.com, 2010).

Chapter 2:

Influence of Plant Age on Cold Hardiness of Three Container-Grown Herbaceous Perennials

(In the format appropriate for submission to the *Journal of Environmental Horticulture*)

Abstract

Overwintering container-grown plants is often necessary to perennial production. Two ages of plants, plugs potted at the beginning of the growing season and plugs that had been potted at the beginning of the previous growing season, were exposed to controlled freezing temperatures of -2, -5, -8, -11, and -14C (28.4, 23.0, 17.6, 12.2, 6.8F) in January then returned to a 3-5C (37-41F) greenhouse. In June, plants were assessed using a visual rating scale (1 = dead, 3-5 = increasing salable quality) and dry weight of new growth. For *Geranium* x *cantabrigiense* 'Karmina', studied for one year, age had no effect on either rating or dry weight. For *Sedum* 'Matrona', studied for two years, age had no effect on dry weight but ratings were higher for older plants than younger plants in the first year and higher for younger plants than older plants in the second year. For *Leucanthemum* x *superbum* 'Becky', studied for two years, age had an effect on both rating and dry weight, which were generally higher for younger plants. Overwintering younger container-grown plants is likely to result in more growth and higher quality following exposure to freezing temperatures.

Index words: nursery, production, cold stress, overwintering, freezing injury, root-bound, pot-bound, Shasta daisy, *Geranium*, *Sedum*, *Leucanthemum*, *Hylotelephium*.

Species used in this study: *Geranium* x *cantabrigiense* L. 'Karmina' (syn. 'Biokovo Karmina'); *Leucanthemum* x *superbum* L. 'Becky'; *Sedum* L. 'Matrona'.

Significance to the Nursery Industry

Container production of herbaceous perennials continues to be popular within the nursery industry and consumers have come to expect plants of certain size, quality and bloom. In northern climates, this may require multiple seasons of plant growth or vernalization events which, in turn, require overwintering periods during which the containerized plants are subjected to freezing temperatures. Additionally, growers may wish to overwinter propagation stock, plants not sold within a season, or newly potted plants prepared for the following season. How long a plant has been established in a container, plant age, may affect survival following freezing winter temperatures. Research relating plant age to cold hardiness is uncommon and not always specific to herbaceous perennial container production. This study demonstrated that plant age can be a factor in containerized herbaceous perennial survival and salable quality following exposure to freezing temperatures. In general, younger plants produced more growth and rated higher in quality following exposure to freezing temperatures, although for one very hardy cultivar plant age had no effect. This information will assist growers in planning containerized plant production schedules and in deciding which containerized plants are most likely to overwinter successfully, potentially saving some of the expense required to prepare and protect containerized plants from freezing temperatures.

Introduction

Production of herbaceous perennial plants in containers continues to be popular within the nursery industry and accounts for the majority of ornamental plant production (Perry, 1998; Perry, 2006; Pilon, 2006; Diver et al., 2008). Herbaceous perennials and other bedding/garden plants make up over half of the value of sales for floriculture crops and is the highest valued category behind woody nursery stock of all nursery and greenhouse industries (USDA, 2007). Growing plants in containers allows growers to produce more plants in less space with more control over propagation, culture, and pests than traditional field production. Plants in containers are easier to handle within the nursery, require less labor overall, and are more efficient to transport. Consumers generally prefer to purchase smaller, uniform, well-grown plants in containers that are easy to handle and transplant. Container-grown plants experience less root loss than field-harvested plants which allows them to better survive and establish following transplanting (Perry, 1998; Perry, 2006; Diver et al., 2008; Eaton et al., 2009).

Overwintering is typically the most limiting factor in production of container-grown plants for growers in northern climates (Pellett et al., 1985). Inevitably, all plants will not be sold within a single growing season resulting in the necessity of disposing, field planting or overwintering container-grown stock. Additionally, many cultivars and propagation methods require production periods longer than a single season prior to sale, again necessitating overwintering (Pilon, 2006; Svendsen et al., 2006; Pyle, 2009). A recent trend by consumers to grow herbaceous perennials as ornamental container plants, has led to an interest in overwintering through multiple years of growth (Dimke et al., 2008). Successful methods for overwintering containerized plants are generally labor intensive and expensive (Taylor et al., 1983; Pilon, 2006).

Plants in containers are exposed to air temperatures that are colder than they may experience when growing in the ground (Perry, 1998; Pilon, 2006), challenging the plants natural survival mechanisms. Many cold-sensitive roots are found on the outer top and sides of a container where media temperature approaches this colder air temperature (Pellett et al., 1985; Perry, 1998; Pilon, 2006). These are often young roots that are first to be injured by cold temperatures (Mathers, 2003). The smaller the container, the more rapidly media temperature will react to air temperature changes (Svendsen et al., 2006). It is generally accepted that an established plant with a well developed root system will better survive overwintering (Smith, 2004; Pilon, 2006) although age of the plant is not specified. The effects of plant age, how long a plant has been established in the same pot, on survival of freezing winter temperatures is relatively unstudied, particularly for herbaceous perennial container production.

Young plants and plant parts have shown certain biological traits that help them to withstand freezing temperatures. Young, uniform tissue will freeze more uniformly and is more flexible than mature, differentiated tissue that may have developed structural rigidity which could lead to mechanical injury from ice formation (Olien, 1964). Younger, smaller plants may have fewer nucleation sites where ice forms during freezing events since the frequency of these sites appears to increase with mass (Ashworth et al., 1985). Studies with cucumber showed that young plants produced antioxidants that prevented damage to protein and DNA during low temperature events (Kuk et al., 2007). In alfalfa, older plants were “consistently associated with markedly lower levels of expression of cold-regulated genes” (Castonguay et al., 2002).

Older plants may have an advantage of prior exposure to freezing events. Faults and anchorage points in cells, regions where tissue is arranged to accommodate formation of extracellular ice, may not develop until initial exposure to freezing temperatures (McCully et al., 2004). It is generally accepted that a well developed root system will better survive freezing temperatures (Smith, 2004; Pilon, 2006). A larger shoot to root ratio has not been shown to affect survival of freezing temperatures in studies of *Plantago lanceolata* (Skinner, 2005). This would suggest that a mature plant with full root system that has been exposed to prior freezing events may overwinter at least as effectively as a younger plant with a less established root system.

Plant age can have positive or negative effects on survival following a freezing event. Seedlings of onion (Warnock et al., 1993) and the woody plant *Phellodendron sachalinense* were less cold-hardy than mature plants (McNamara et al., 2000). On the other hand, seedlings of various legumes were more cold-hardy when they were younger (Meyer et al., 2001) as were younger alfalfa plants (Castonguay et al., 2002). Studies of container-grown herbaceous perennials generally found younger plants to be more marketable than established plants following freezing events although results varied by cultivar. Younger plants of *Tiarella*, *Dianthus* and *Geranium* 'Cambridge' rated better in salable quality following freezing, whereas older plants of *Geranium* 'St. Ola' fared better following freezing (Bruce, 2003; Luchini, 2005).

The purpose of this study was to examine how the duration that a plant had been established in a container, plant age, affected survival and salable quality following exposure to freezing temperatures for three herbaceous perennial cultivars. The species and cultivars used in this study are different from those examined previously (Bruce, 2003; Luchini, 2005).

Materials and Methods

Plants that had been in pots for two different lengths of time were used in the study. “Young” plants were obtained as liners of 36-72 individual plants per flat (56x28cm (22x11in)) depending on cultivar and transferred into #SP3 (10cm (4in), 400ml (24.4in^3)) plastic pots at the beginning of the study growing season. “Old” plants had been established from liners in #SP3 plastic pots for one prior growing season and were a year old at the beginning of the study. Two complete growing seasons in the same pot represents an extreme condition that may occur for various reasons. All plants were potted with ProMix BX medium (Premier Horticultural Products, Red Hill, PA).

The study was conducted over two years. In the first year, *Leucanthemum* x *superbum* 'Becky', *Sedum* 'Matrona', and *Geranium* x *cantabrigiense* 'Karmina' were used. In the second year, *Leucanthemum* x *superbum* 'Becky' and *Sedum* 'Matrona' were used. These recently introduced cultivars are readily available and information on their culture will be of value to growers.

Shasta daisies are vigorous and easy to grow perennial plants (Hill et al., 2003) that tend to be short lived, 2-3 years (Armitage, 2008) but are easily propagated by division. The cultivar *Leucanthemum* x *superbum* 'Becky' has 3-4 inch white flowers (Hill et al., 2003) on 3 foot stems that are desirable as cut flowers. The foliage is particularly tolerant of heat and humidity. Hardiness is listed for U.S. Zones 4-9 in some references (northcreeknurseries.com, 2010) and Zones 5-9 in others (perennialresource.com, 2010).

Sedum (syn. *Hylotelephium*) have distinctly fleshy leaves, are relatively easy to grow, and perform best in well-drained soil in full sun (Armitage, 2008). *Sedum*

'Matrona' was formerly listed under the species *Sedum telephium* (RHS, 2006-2007) and is now listed as a stand-alone species (RHS, 2009-2010). This robust and sturdy plant reaches heights of 2-3 feet with purple-red stems bearing pink flowers in autumn. Hardiness is listed for U.S. Zones 3-9 (northcreeknurseries.com, 2010; perennialresource.com, 2010).

Hardy perennial geraniums, also known as cranesbill, are native to temperate regions worldwide (Yeo, 2002). They grow under a range of conditions but prefer full sun to partial shade and moist soil (Armitage, 2008). The cultivar *Geranium* x *cantabrigiense* 'Karmina', (syn. 'Biokovo Karmina'), exhibits flowers of a red raspberry color (Armitage, 2008) with aromatic, seemingly hairless, light green foliage, forming a low growing (up to 30cm (11.8in)) groundcover (Yeo, 2002). Hardiness is listed for U.S. Zones 4-8 (perennialresource.com, 2010) and Zones 5-7 (northcreeknurseries.com, 2010). This cultivar has proven hardy in Zone 4 field conditions in Vermont (Perry, 2010).

In each year of the study, 30 plants per cultivar were established for each plant age group. Plants were allowed to establish over a normal growing season in a glass greenhouse at the University of Vermont, Burlington, Vermont, under near-ambient temperature. Greenhouse temperatures were managed by direct venting and radiant heat as needed. Plants were watered by greenhouse staff as needed throughout the studies. Water soluble fertilizer was applied once weekly throughout the growing season: Jack's Professional 17-4-17 (J.R. Peters, Inc, Allentown, PA) delivered at 150ppm nitrogen and Peters Professional S.T.E.M. soluble trace elements (The Scotts Company) delivered at 5ppm boron, 12ppm copper, 28ppm iron, 30ppm manganese, 0.15ppm molybdenum, 52.5ppm sulfur, and 16.9ppm zinc. Temperatures in the greenhouse were reduced beginning in October of each year at a rate of 3C (5F) per week until temperatures of 3-5C (37-41F) were reached at the end of November. This low temperature was maintained in the greenhouse until spring when the temperature was increased by the same increments beginning in April of each year until ambient temperature was reached.

During the month of January, the 30 plants in each age group were randomly divided into five, six-pot groups, pruned back to within one inch above the level of the pot rim, and evenly watered. Controlled freezing of each six-pot group to temperatures of -2, -5, -8, -11, and -14C (28.4, 23.0, 17.6, 12.2, 6.8F) was performed as developed in previous studies (Herrick, 1996; Meyer, 1999; Bruce, 2003; Luchini, 2005). Plants were randomized by target freezing temperature and placed in heavy-weight standard open-mesh flats (‘1020’, 56x28cm (22x11in)). Flats were loaded into the freezer alternately stacked with wooden supports to allow air flow around pots to achieve uniform temperature within the freezer. Plants with the lowest target freezing temperatures were loaded first, followed by the second-lowest, and so on until the highest target temperature plants were loaded on the top level within the freezer. Loading by target freezing temperature minimized the amount of time that the freezer was open while removing plants, in turn minimizing temperature fluctuations, during the course of the entire freezing event.

Temperature in the insulated chest freezer (Model VWC15-ZL/E, W.C. Wood Co., Guelph, Canada) was controlled using a Dyna-Sense Mk III Versa-Lab Microprocessor Temperature Controller (Scientific Instruments, Skokie, IL) and monitored separately using a digital thermometer (Model HH611P4C, Omega

Engineering, Stanford, CT) with a probe suspended within the freezer and a probe placed within a pot with the lowest target temperature. A 7.6cm (3in) cooling fan (Radio Shack, Fort Worth, TX) was placed on the floor of the freezer to circulate air within the freezer. A thermocouple-based temperature recorder with internal temperature sensor (TC4000, Madgetech, Contoocook, NH) was placed alongside the pots with the lowest target temperature to record temperatures during the course of the freezing event.

Freezer temperatures were held at -2C (28.4F) for 24 hours prior to loading plants then maintained at that temperature for 48 hours following loading of plants to thoroughly achieve a uniform soil temperature among the plants. At that point, a six-pot group of each cultivar and treatment was removed from the freezer. The freezer air temperature was then set to -5C (23.0F), which was achieved within 30 minutes, and then held for 2 hours. During this time, the pot soil temperatures achieved target temperature 2 hours after the initial temperature setting and remained at the target temperature for 30 minutes. After this period, a six-pot group of each cultivar and treatment was removed. The freezer was then set to -8C (17.6F) and the process continued, with subsequent removal of pots, at -11C (12.2F) and -14C (6.8F) target temperatures. Following removal from the freezer, plants were returned to the 3-5C (37-41F) greenhouse where they were maintained through the return to ambient temperatures in spring as described above.

In June, plants were assessed for survival, growth and vigor. A visual rating scale of 1-5 was used with specific growth parameters defined for each cultivar (Tables 2.1, 2.2 and 2.4). A rating of 3 or more was considered satisfactory for retail sale. Salable quality, with attractive factors such as flowers and growing points, is more important than quantity of growth to growers and consumers. Following visual rating, plant regrowth from each pot was harvested to within one inch above the level of the pot rim. Harvested growth from each plant was placed in an individual paper bag and stored in a drying oven at 60C (140F) for one week prior to weighing to 0.01g on an electronic balance for determination of dry weight.

Data from each cultivar was analyzed for each year of the study to compare effects of plant age on susceptibility to freezing temperatures. Visual ratings and dry weights were assessed for analysis of variance (ANOVA) using SAS 9.1 and Tukey's procedure was used for mean separation when appropriate.

Results and Discussion

Geranium x *cantabrigiense* 'Karmina' was studied for one year. Neither age nor temperature had any effect on either quality rating or dry weight (Table 2.1). No interaction was observed between plant age and temperature for either rating or dry weight and all plants achieved at least minimal salable quality (rating of 3) following all freezing temperatures, indicating a general hardiness for this cultivar. Cultivars of *Geranium* x *cantabrigiense* are known to be very hardy from previous studies (Meyer, 1999; Bruce, 2003; Luchini, 2005) and were included as a standard only in this first year of study.

Sedum 'Matrona' was studied for two years. An endemic powdery mildew presence across all study plants did inhibit plant vigor but not to the point of impacting salable quality parameters. Quality ratings were significantly higher for older plants than younger plants in the first year and significantly higher for younger plants than older plants in the second year (Table 2.2). In both years, however, age had no effect on dry weight (Table 2.3). No interaction was observed between plant age and temperature for either rating or dry weight. Ratings included both mass and number of flowers which may explain how ratings showed differences between older and younger plants when dry weight did not. The reversal of results between older and younger plants in the two years is certainly related to plant loss following lower temperatures by younger plants in the first year whereas ratings for older plants were consistent from year to year.

For *Sedum* 'Matrona' in the first year, temperature effects on rating (-14C significantly lower than other temperatures) and dry weight were observed (-14C significantly lower than -2C and -11C; -5C and -8C not significantly different from any other temperature). No temperature effects were observed on either rating or dry weight in the second year.

The reason for the higher plant loss for *Sedum* 'Matrona' in the first year among younger plants is uncertain, given that plants were established in the same manner each year and ambient conditions did not differ greatly from one year to the next. This succulent species can be sensitive to overwatering. Possible differences in watering regimen by greenhouse staff may have led to a lack of sufficient root establishment prior to acclimation. Dry weights were drastically higher in the second year for both younger and older plants. This indication of more vigorous growth lends more credence to the rating results from the second year of the study.

While some individual *Sedum* 'Matrona' plants achieved at least minimal salable quality (rating of 3, disregarding disease presence) in the first year, means following each temperature for either plant age were below salable quality. No individual plants were of salable quality following -14C for either plant age in the first year. In the second year, all younger plants following all freezing temperatures and all older plants following -5C achieved at least minimal salable quality. Means were below salable quality for older plants following all other freezing temperatures, although some individual older plants achieved at least minimal salable quality.

Leucanthemum x *superbum* 'Becky' was studied for two years. In the first year, age had an effect on both quality rating (Table 2.4) and dry weight (Table 2.5) with better quality and more growth for younger plants. No interaction was observed between plant age and temperature for either rating or dry weight. In the second year, there was interaction between plant age and temperature for both rating and dry weight. Age had an effect on rating in the second year following exposure to -2C, -8C, and -11C for which means were higher for younger plants (Table 2.4). For -5C and -14C there was no significant difference between ages. Age also had an effect on dry weight in the second year with means higher for younger plants following every temperature (Table 2.5). The difference in rating following -2C is certainly due to an unusual lack of salable quality in all older plants following this temperature. The mean ratings following -11C for both younger and older plants are above salable quality and the difference is of no particular practical value. The overall tendency of age on both rating and dry weight was for means of younger plants to be higher than means of older plants.

For *Leucanthemum* x *superbum* 'Becky' in the first year, temperature effects on rating (-14C significantly lower than -2C, -5C, and -8C; -11C significantly lower than -2C and -5C) and dry weight were observed (-14C significantly lower than -2C, -5C, and -8C; -8C and -11C significantly lower than -2C and -5C). In the second year for younger plants, similar temperature effects on both rating and dry weight were observed (-14C significantly lower than other temperatures; -8C significantly lower than -2C; -8C also significantly lower than -5C for dry weight). In the second year for older plants, temperature effects on rating (-14C and -2C significantly lower than the other temperatures; -8C and -11C significantly lower than -5C) and dry weight were observed (-2C and -14C significantly lower than -5C). The low rating following -2C for older plants is again certainly due to an unusual lack of salable quality in all plants following this temperature. Temperature effects on rating and dry weight for both years were observed to be means generally decreasing with decreasing temperature.

In the first year, nearly all younger *Leucanthemum* x *superbum* 'Becky' plants achieved at least minimal salable quality (rating of 3) following -2C and -5C. While some individual plants achieved at least minimal salable quality, means were below salable quality following -8C for younger plants and following all freezing temperatures for older plants. No individual plants were of salable quality following -8C for older plants or following -11C or -14C for either plant age.

In the second year, all *Leucanthemum* x *superbum* 'Becky' plants achieved at least minimal salable quality following -2C, -5C, -8C, and -11C for younger plants and following -5C and -11C for older plants. Following -8C for older plants the mean achieved salable quality although some individual plants were below minimal salable quality. No individual plants were of salable quality following -2C for older plants or following -14C for either plant age. The poor performance of older plants following -2C is unusual and cannot be explained when younger plants performed very well following the same temperature and other older plants also performed well following similar temperatures under the same experimental conditions.

From the three containerized herbaceous perennial cultivars studied, a definitive effect of plant age on survival and salable quality following exposure to freezing temperatures could not be established. In general however, when an effect was observed, younger plants produced more growth and rated higher in quality following exposure to freezing temperatures. Only for *Sedum* did the older plants statistically rate higher than the younger for one of the years, although in practice this difference was unremarkable as plants were largely below salable quality. The second year for *Sedum*, the first year for *Leucanthemum* and many of the second year temperatures for *Leucanthemum* all rated higher for younger plants. The generally better response of younger plants suggests that overwintering plants beyond a single season in the same pot would not be an acceptable practice for maintaining salable plants, particularly if they are root-bound. If plants are being overwintered with the intent to divide and propagate in the spring, not to sell immediately, age would be less of a factor although the study indicates that some losses would be expected with older plants. Lack of plant vigor due to overcrowding in the pot is perhaps more critical to survival and successful propagation than plant age. Cold hardiness of the cultivar likely also plays a role as the very hardy *Geranium* (Meyer, 1999; Bruce, 2003; Luchini, 2005) showed no effect of age whereas the other two less hardy cultivars did show effects in the current study.

Dividing or repotting into larger containers to establish new growth prior to a second overwintering may be conducive to survival, although this will increase the number and volume of plants that will require protection from freezing temperatures as well as increasing costs. A study relating the container size that plugs were potted into in mid-summer to overwintering success under insulating covers did not reach a consensus across all cultivars tested but did indicate that a larger container at least yielded a larger plant the following spring than plugs potted into and overwintered in smaller containers (Svendsen et al., 2006). Either method should be performed early enough in the season to allow adequate root growth to establish. A subsequent study in Vermont during 2009-2010 clearly showed with *Leucanthemum* x *superbum* 'Becky' and *Achillea millefolium* 'Pink Grapefruit' that dividing late in the season did not allow for sufficient root growth and resulted in poor overwintering survival (Perry, 2011). The cost and timing of labor to divide or repot will have to be considered if choosing this overwintering strategy. The optimal timing of division or plug with the intent of successful overwintering is worthy of further study for individual species and cultivars.

There are many factors that a grower will need to consider for overwintering perennials. This study indicates that plant age may be a significant factor for the survival of some cultivars following exposure to freezing temperatures. Other factors related to the effects of age (root volume, condition of media, available nutrients, moisture content, level of vigor) may be of more concern than simply the chronological plant age and should be explored in conjunction with age in future studies.

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Table 2.1. Effect of plant age and freezing temperatures on quality rating and dry weight of *Geranium* x *cantabrigiense* 'Karmina' regrowth.

	Rating[a] 2005-2006			Dry weight (g) 2005-2006		
Treatment temp °C	Younger plants[b]	Older plants[c]	Mean (SEM[d])	Younger plants	Older plants	Mean (SEM)
-2	3.17	3.17	3.17 (0.11)[e]	0.83	0.65	0.74 (0.06)
-5	3.17	3.17	3.17 (0.11)	0.73	0.89	0.81 (0.05)
-8	3.00	3.00	3.00 (0.00)	0.81	0.65	0.73 (0.08)
-11	3.17	3.00	3.08 (0.08)	0.90	0.73	0.81 (0.07)
-14	3.00	3.00	3.00 (0.00)	0.88	0.72	0.80 (0.06)
Mean (SEM)	3.10[f] (0.06)	3.07 (0.05)		0.83 (0.04)	0.73 (0.04)	

ANOVA significance:

	df[g]	F[h]	p-value[i]	df	F	p-value
Temperature	4	1.00	0.4164	4	0.37	0.8300
Plant age	1	0.20	0.6567	1	3.31	0.0748
Interaction	4	0.20	0.9372	4	1.34	0.2695

[a]Rating scale 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 0-2 flowering stems and regrowth extending over edge of pot, 4 = 3-5 flowering stems and regrowth equal to or greater than above, 5 = 6 or more flowering stems and regrowth as above.
[b]Younger plants were obtained as liners at the beginning of the study growing season.
[c]Older plants had been established for one prior growing season and were a year old at the beginning of the study growing season.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[f]Where no interaction present between factors, plant age means with a capital letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 2.2. Effect of plant age and freezing temperatures on quality rating of *Sedum* 'Matrona' regrowth.

Rating[a]						
	2005-2006			2006-2007		
Treatment temp °C	Younger plants[b]	Older plants[c]	Mean (SEM[d])	Younger plants	Older plants	Mean (SEM)
-2	2.50	2.83	2.67 (0.19) a[e]	3.50	2.67	3.08 (0.29)
-5	2.50	2.33	2.42 (0.15) a	4.00	3.17	3.58 (0.19)
-8	2.17	2.50	2.33 (0.22) a	4.00	2.67	3.33 (0.31)
-11	1.67	2.83	2.25 (0.28) a	4.00	2.00	3.00 (0.37)
-14	1.00	1.67	1.33 (0.14) b	4.17	1.83	3.00 (0.44)
Mean (SEM)	1.97 B[f] (0.17)	2.43 A (0.11)		3.93 A (0.10)	2.47 B (0.20)	

ANOVA significance:

	df[g]	*F*[h]	*p*-value[i]	df	*F*	*p*-value
Temperature	4	7.40	<.0001	4	1.12	0.3587
Plant Age	1	7.78	0.0075	1	46.54	<.0001
Interaction	4	1.73	0.1589	4	2.01	0.1077

[a]Rating scale 1 = Dead, no regrowth, 2 = Foliage regrowth of less than or equal to 6 inches (15 cm), 3 = 1 flowering stem, regrowth over 6 inches (15 cm), 4 = 2 flowering stems, regrowth over 6 inches (15 cm), 5 = 3 or more flowering stems, regrowth over 6 inches (15 cm).
[b]Younger plants were obtained as liners at the beginning of the study growing season.
[c]Older plants had been established for one prior growing season and were a year old at the beginning of the study growing season.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[f]Where no interaction present between factors, plant age means with a capital letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 2.3. Effect of plant age and freezing temperatures on dry weight of *Sedum* 'Matrona' regrowth.

Dry weight (g)						
	2005-2006			2006-2007		
Treatment temp °C	Younger plants [b]	Older plants [c]	Mean (SEM [d])	Younger plants	Older plants	Mean (SEM)
-2	1.33	1.64	1.49 (0.25) a [e]	3.75	3.30	3.53 (1.01)
-5	0.84	0.75	0.80 (0.21) ab	5.85	3.81	4.83 (1.07)
-8	1.07	0.87	0.97 (0.25) ab	3.68	2.03	2.85 (0.58)
-11	0.87	1.51	1.19 (0.33) a	2.14	4.34	3.24 (1.33)
-14	0.00	0.21	0.11 (0.05) b	2.79	2.30	2.54 (1.06)
Mean (SEM)	0.82 [f] (0.20)	0.20 (0.14)		3.64 (0.50)	3.15 (0.78)	

ANOVA significance:

	df [g]	F [h]	p-value [i]	df	F	p-value
Temperature	4	4.56	0.0032	4	0.70	0.5982
Plant Age	1	0.66	0.4196	1	0.26	0.6103
Interaction	4	0.48	0.7505	4	0.61	0.6547

[b]Younger plants were obtained as liners at the beginning of the study growing season.
[c]Older plants had been established for one prior growing season and were a year old at the beginning of the study growing season.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[f]Where no interaction present between factors, plant age means with a capital letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[g]df=degrees of freedom.
[h]F=F distribution.
[i]p-value=level of significance.

Table 2.4. Effect of plant age and freezing temperatures on quality rating of *Leucanthemum* x *superbum* 'Becky' regrowth.

Rating[a]						
	2005-2006			2006-2007		
Treatment temp °C	Younger plants[b]	Older plants[c]	Mean (SEM[d])	Younger plants	Older plants	Mean (SEM)
-2	3.00	2.50	2.75 (0.22) a[e]	4.33 Aa[k]	1.50 Bc	2.92 (0.45)
-5	3.17	2.33	2.75 (0.22) a	3.83 ab	3.67 a	3.75 (0.13)
-8	2.50	1.67	2.08 (0.26) ab	3.67 Ab	3.00 Bb	3.33 (0.22)
-11	1.67	1.50	1.58 (0.15) bc	4.00 Aab	3.00 Bb	3.50 (0.15)
-14	1.00	1.33	1.17 (0.11) c	2.00 c	1.67 c	1.83 (0.11)
Mean (SEM)	2.27 A[f] (0.19)	1.87 B (0.14)		3.57 (0.16)	2.57 (0.18)	

ANOVA significance:

	df[g]	F[h]	p-value[i]	df	F	p-value
Temperature	4	14.35	<.0001	4	29.18	<.0001
Plant age	1	5.81	0.0197	1	64.29	<.0001
Interaction	4	1.77	0.1488	4	14.82	<.0001

[a]Rating scale 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 1 flowering stem and minimal regrowth, 4 = 0-1 flowering stems and vigorous regrowth, 5 = 2 or more flowering stems and vigorous regrowth.
[b]Younger plants were obtained as liners at the beginning of the study growing season.
[c]Older plants had been established for one prior growing season and were a year old at the beginning of the study growing season.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[f]Where no interaction present between factors, plant age means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[k]Where interaction present between factors, means between plant age for a single treatment temperature with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 2.5. Effect of plant age and freezing temperatures on dry weight of *Leucanthemum* x *superbum* 'Becky' regrowth.

Dry weight (g)						
	2005-2006			2006-2007		
Treatment temp °C	Younger plants [b]	Older plants [c]	Mean (SEM [d])	Younger plants	Older plants	Mean (SEM)
-2	1.61	0.75	1.18 (0.22) a [e]	3.67 Aa [k]	0.62 Bb	2.14 (0.50)
-5	1.50	0.78	1.14 (0.14) a	3.32 Aa	1.36 Ba	2.34 (0.32)
-8	0.87	0.24	0.56 (0.19) b	2.53 Ab	1.01 Bab	1.77 (0.26)
-11	0.29	0.09	0.19 (0.07) bc	3.10 Aab	0.94 Bab	2.02 (0.35)
-14	0.00	0.07	0.03 (0.02) c	1.23 Ac	0.35 Bb	0.79 (0.18)
Mean (SEM)	0.86 A [f] (0.15)	0.39 B (0.07)		2.77 (0.18)	0.86 (0.10)	

ANOVA significance:

	df [g]	*F* [h]	*p*-value [i]	df	*F*	*p*-value
Temperature	4	17.95	<.0001	4	16.25	<.0001
Plant age	1	17.84	0.0001	1	201.10	<.0001
Interaction	4	2.46	0.0571	4	7.11	0.0001

[b]Younger plants were obtained as liners at the beginning of the study growing season.
[c]Older plants had been established for one prior growing season and were a year old at the beginning of the study growing season.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[f]Where no interaction present between factors, plant age means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[k]Where interaction present between factors, means between plant age for a single treatment temperature with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Chapter 3:

Influence of Soil Moisture on Cold Hardiness of Six Container-Grown Herbaceous Perennials

(In the format appropriate for submission to the *Journal of Environmental Horticulture*)

Abstract

Overwintering container-grown plants is often necessary to perennial production. Plants maintained in pots at soil moisture levels above and below 10% volumetric water content, were exposed to controlled freezing temperatures of -2, -5, -8, -11, and -14C (28.4, 23.0, 17.6, 12.2, 6.8F) in January then returned to a 3-5C (37-41F) greenhouse. In June, plants were assessed using a visual rating scale (1 = dead, 3-5 = increasing salable quality) and dry weight of new growth. *Coreopsis* 'Tequila Sunrise' and *Carex morrowii* 'Ice Dance' showed no effect on either rating or dry weight from soil moisture level. Soil moisture level had no effect on dry weight but ratings were higher for *Geranium* x *cantabrigiense* 'Cambridge' “wet” plants and for *Heuchera* 'Plum Pudding' “dry” plants. *Carex laxiculmus* 'Hobb' (Bunny Blue™) soil moisture level had an effect where dry weight was higher for “dry” plants. Means were of salable quality for *Geranium* and *Heuchera* following all temperatures and *Carex laxiculmus* following temperatures above -11C (12.2F). The effects of soil moisture level on *Carex oshimensis* were inconclusive. Effects of soil moisture level on overwintering container-grown plant growth and quality are cultivar-specific and a general effect could not be established in these studies.

Index words: nursery, production, cold stress, overwintering, freezing injury, irrigation, moisture, sedge, tickseed, coral bells, *Carex*, *Coreopsis*, *Geranium*, *Heuchera*.

Species used in this study: *Carex oshimensis* L. 'Evergold'; *Carex morrowii* Bott. 'Ice Dance'; *Carex laxiculmus* Schwein. 'Hobb' (Bunny Blue™); *Coreopsis* L. 'Tequila Sunrise'; *Geranium x cantabrigiense* L. 'Cambridge'; *Heuchera* L. 'Plum Pudding'.

Significance to the Nursery Industry

Container production of herbaceous perennials continues to be popular within the nursery industry and consumers have come to expect plants of certain size, quality and bloom. In northern climates, this may require multiple seasons of plant growth or vernalization events which, in turn, require overwintering periods during which the containerized plants are subjected to freezing temperatures. Additionally, growers may wish to overwinter propagation stock, plants not sold within a season, or newly potted plants prepared for the following season. The conditions a plant has been grown under, including water stresses such as drought, may affect survival with freezing winter temperatures. Research relating soil moisture to cold hardiness, and to acclimation to cold temperatures, has been extensive yet not always specific to herbaceous perennial container production. This study demonstrated soil moisture as an occasional factor in containerized herbaceous perennial survival and salable quality following exposure to freezing temperatures. Two cultivars either produced more growth or rated higher in quality following exposure to freezing temperatures when grown under “dry” conditions. One cultivar rated higher in quality following exposure to freezing temperatures when grown under “wet” conditions. Soil moisture level had no effect or results were inconclusive for three other cultivars. This information will assist growers in planning containerized plant irrigation practices and in deciding which containerized plants are most likely to overwinter successfully, potentially saving some of the expense required to prepare and protect containerized plants from freezing temperatures.

Introduction

Production of herbaceous perennial plants in containers continues to be popular within the nursery industry and accounts for the majority of ornamental plant production (Perry, 1998; Perry, 2006; Pilon, 2006; Diver et al., 2008). Herbaceous perennials and other bedding/garden plants make up over half of the value of sales for floriculture crops and is the highest valued category behind woody nursery stock of all nursery and greenhouse industries (USDA, 2007). Growing plants in containers allows growers to produce more plants in less space with more control over propagation, culture, and pests than traditional field production. Plants in containers are easier to handle within the nursery, require less labor overall, and are more efficient to transport. Consumers generally prefer to purchase smaller, uniform, well-grown plants in containers that are easy to handle and transplant. Container-grown plants experience less root loss than field-harvested plants which allows them to better survive and establish following transplanting (Perry, 1998; Perry, 2006; Diver et al., 2008; Eaton et al., 2009).

One distinct aspect of container production is the increased need for irrigation (Perry, 1998; Diver et al., 2008; Eaton et al., 2009). Irrigation is critical to production of quality plants without the constraints imposed by dependence on irregular natural rainfall (Tilt, 2000). However such methods require an abundant source of quality water, intensive labor (Eaton et al., 2009), and specialized equipment. Water quality can in turn be impacted by the act of irrigation due to runoff (Diver et al., 2008). Quality water sources are often subject to regulation, liable to decrease in availability, and likely to increase in cost to acquire. Increasing efficiency of water delivery to plants will offset these concerns (Beeson et al., 2004) and can shorten production time (Tilt, 2000).

Overwintering is typically the most limiting factor in production of container-grown plants for growers in northern climates (Pellett et al., 1985). Inevitably, all plants will not be sold within a single growing season resulting in the necessity of disposing, field planting or overwintering container-grown stock. Additionally, many cultivar and propagation methods require production periods longer than a single season prior to sale, again necessitating overwintering (Pilon, 2006; Svendsen et al., 2006; Pyle, 2009). A recent trend by consumers to grow herbaceous perennials as ornamental container plants, has led to an interest in overwintering through multiple years of growth (Dimke et al., 2008). Successful methods for overwintering containerized plants are generally labor intensive and expensive (Taylor et al., 1983; Pilon, 2006).

Maintaining adequate moisture in overwintering plants is necessary to prevent freeze-drying (Berghage et al., 1999; Pilon, 2006). Steps to maintain moisture in overwintering plants include irrigating thoroughly prior to storage under cover and regular monitoring and irrigating when plants are stored within an accessible structure (Smith, 2004; Hulme, 2010). Regular watering can alleviate plant injury from buildup of soluble salts in the growing media due to water loss (Hulme, 2010). Maximizing water content of growing media has been shown to regulate duration of temperature extremes of plants stored under cover during freezing periods (van de Werken, 1987). Water content will provide a source of heat and slow freezing of the growing media, although too much water can foster diseases (Smith, 2004). Plant loss due to overly wet conditions is the leading reason for plant loss when overwintering (Berghage et al., 1999; Pilon, 2006). The effects of soil moisture levels in the period prior to storage on survival of freezing winter temperatures has been extensively studied yet not always particularly for container production. However, it is a common conception that withholding water during acclimation can increase cold hardiness, provided thorough watering occurs prior to freeze (Pilon, 2006).

A reduction in available water can occur during both drought and freezing periods (Verslues et al., 2006). Certain physiological effects in plants during water drought closely resemble those that occur during cold acclimation of plants. These effects include an accumulation of abscisic acid, proteins, and carbohydrates (Pagter et al., 2008); decrease in tissue water content (Brule-Babel et al., 1989; Iles et al., 1995; Gusta et al., 2004; Nobel et al., 2008); and reduced shoot growth (Herzog, 1987; Arnott et al., 1993; Pagter et al., 2008). With the assumption that plants experiencing water drought have already acquired the factors necessary for freezing tolerance, attempts to relate drought stress to increases in cold hardiness has been widely researched.

Water deficit stress during the growing season has been shown to increase ability to survive exposure to freezing temperatures in Austrian winter pea (*Pisum sativum* subsp. *arvense*) (Kephart, 1984), *Rhododendron* 'Catawbiense Boursault' (Anisko et al., 1996b), cacti (*Nopalea cochinellifera* and *Opuntia robusta*) (Nobel et al., 2008), chicory (*Cichorium intybus* 'Grasslands Puna') and narrow leaf plantain (*Plantago lanceolata* 'Ceres Tonic') in the field (Skinner et al., 2002) and narrow leaf plantain (*Plantago lanceolata* 'Grasslands Lancelot') in a growth chamber (Skinner, 2005). Water deficit stress did not affect freezing tolerance of European varieties of winter faba beans grown at a constant temperature but did have an effect when combined with a day/night temperature difference (Herzog, 1987). Lower tissue water content has been shown to increase ability to survive exposure to freezing temperatures in strawberry (*Fragaris* x *ananassa* 'Earliglow') (Warmund et al., 1992), saltbush (*Atriplex halimus*) (Walker et al., 2008), and may have been a contributing factor in *Sedum* 'Autumn Joy' cold tolerance (Iles et al., 1995).

Conversely, water deficit stress during the growing season has not been shown to increase ability to survive exposure to freezing temperatures in *Fuschia magellanica* 'Riccartonii' (Pagter et al., 2008), Azalea (*Rhododendron* 'Coral Bell', 'Hinodegiri', and 'Red Ruffle') (Anisko et al., 1996a), cypress rooted cuttings (*Chamaecyparis nootkatensis*) (Arnott et al., 1993), and chicory (*Cichorium intybus* 'Grasslands Puna') in a growth chamber (Skinner, 2005). Water deficit stress during the growing season did not affect freezing tolerance of Japanese beech (*Fagus crenata*) buds (Yonekura et al., 2004). Tissue water content is not a consistent indicator of cold hardiness of the winter cereals wheat (*Triticum aestivum*) and rye (*Secale cereale*) (Brule-Babel et al., 1989).

An increase in available water during the growing season is less commonly studied than drought situations. However, plentiful water supports plant processes during the growing season and encourages development of strong root systems to better survive overwintering (Pilon, 2006). Soils with high water content do not immediately reach the lower temperatures during freezing periods that dry soils do (van de Werken, 1987; Smith, 2004).

In a study of apple trees (*Malus* x *domestica*), proximity to a water source correlated with increased survival of freezing periods (Quamme et al., 1989). Alfalfa (*Medicago sativa*) has been shown to increase survival following exposure to freezing temperatures as soil saturation increased (Van Ryswyk et al., 1993). *Rhododendron* 'Catawbiense Boursault' has been shown to improve in cold hardiness over several seasons of growth in saturated conditions, although not to the extent of cold hardiness exhibited under normal water conditions (Anisko et al., 1996b). Studies of container-grown herbaceous perennials *Coreopsis* 'Tequila Sunrise' and *Geranium* 'Cambridge' comparing moisture level stresses during the growing season followed by a freezing event showed some significant effects favoring higher moisture levels during the growing season, although *Coreopsis* 'Moonbeam' in the same study did not show any significant preference (Luchini et al., 2004). Water saturation stress did not affect freezing tolerance of European varieties of winter faba beans grown at a constant temperature but did have an effect when combined with a day/night temperature difference. This same effect was observed with water deficit stress as noted above (Herzog, 1987).

The purpose of this study was to examine how continuous drought and saturation soil moisture levels during the entire growing season and acclimation period affected survival and salable quality following exposure to freezing temperatures for six herbaceous perennial cultivars. Two of the cultivars used in this study were also used in a previous study (Luchini et al., 2004).

Materials and Methods

Plants that had been maintained in pots at different moisture levels were used in the study. Plants were obtained as liners of 36-72 individual plants per flat (56x28cm (22x11in)) depending on cultivar or as divisions of previously established plants (existing in #SP4 (‘Classic 100’, 900ml (54.9in^3)) or in #SP3 (10cm (4in), 400ml (24.4in^3)) plastic pots) at the beginning of the study growing season. All plants were potted in #SP4 pots with ProMix BX medium (Premier Horticultural Products, Red Hill, PA).

In the study *Coreopsis* 'Tequila Sunrise', *Geranium x cantabrigiense* 'Cambridge', *Heuchera* 'Plum Pudding', *Carex oshimensis* 'Evergold', *Carex morrowii* 'Ice Dance', and *Carex laxiculmus* 'Hobb' (Bunny Blue™) were used. These recently introduced cultivars, with varying soil moisture requirements, are readily available and information on their culture will be of value to growers.

The genus *Coreopsis*, often known as tickseeds, perform best in well-drained soil in full sun (Armitage, 2008). *Coreopsis* 'Tequila Sunrise' is listed as a stand-alone species (RHS, 2009-2010). Yellow flowers with dark orange centers bloom continuously but this cultivar is popular largely for its variegated foliage. Elongated leaves are edged or irregularly variegated with creamy yellow and pink tinges. Plants may reach a height of 16 inches. Hardiness is listed for U.S. Zones 4-8 in some references (northcreeknurseries.com, 2010) and Zones 6-9 in others (perennialresource.com, 2010) although the cultivar is known to lack vigor and be short-lived (Armitage, 2008).

Hardy perennial geraniums, also known as cranesbill, are native to temperate regions worldwide (Yeo, 2002). They grow under a range of conditions but prefer full sun to partial shade and moist soil (Armitage, 2008). The cultivar *Geranium* x *cantabrigiense* 'Cambridge' is a low growing (up to 30cm (11.8in)) groundcover with aromatic, seemingly hairless, light green foliage and purple-violet flowers (Yeo, 2002). Hardiness is listed for U.S. Zones 5-9 (Hogan, 2003), and proven hardy in Zone 4 field conditions in Vermont (Perry, 2010).

Members of the genus *Heuchera*, are entirely native to North America (Heims et al., 2005). The wide range of natural and cultivated ornamental foliage forms and colors has contributed to increased popularity of this genus in recent years (Armitage, 2008).

The cultivar *Heuchera* 'Plum Pudding' (aka 'Plum Puddin') was introduced in 1996 founded on the *H. americana* species. A favorite within the industry, the cultivar is admired for its shiny purple foliage and unobtrusive flowers (Heims et al., 2005). It has a compact growth habit, up to 16 inches in foliage height (terranovanurseries.com, 2010), and prefers moist, well-drained soil in full to partial shade. Hardiness is listed for U.S. Zones 3-8 (Hill et al., 2003; perennialresource.com, 2010) and Zones 5-9 (northcreeknurseries.com, 2010).

The *Carex* sedge genus occurs natively in many regions worldwide, usually in moist environments such as marshes. Sedges are grass-like in their appearance and ornamental appeal but are not true grasses (Armitage, 2008). The cultivar *Carex oshimensis* 'Evergold' is a popular ornamental plant with cream-colored, narrow, weeping leaves edged in green (Armitage, 2008). The cultivar is native to Japan and variegation may revert to solid green on parts of a plant (Darke, 2007). This clump-forming cultivar prefers good drainage in moist soils and can reach a height of 15 inches. Hardiness is listed for U.S. Zones 5-8 (northcreeknurseries.com, 2010) and Zones 5-9 (perennialresource.com, 2010). The cultivar *Carex morrowii* 'Ice Dance' was introduced from Japan in 1996. Long, shiny, green leaves edged in white reach a height up to 15 inches. Adaptable to many soil types, this cultivar spreads by rhizomes and can be drought tolerant once established. Hardiness is listed for U.S. Zones 5-9 (northcreeknurseries.com, 2010; perennialresource.com, 2010). The cultivar *Carex laxiculmus* 'Hobb' Bunny Blue™ is a North American native with blue-green foliage. This clump-forming cultivar prefers moist soil in partial shade and can reach a height of 8 inches (Darke, 2007). Hardiness is listed for U.S. Zones 6-10 (northcreeknurseries.com, 2010).

In the study, 60 plants were established for each cultivar. These plants were randomly divided into “wet” and “dry” treatments in late summer. Moisture level within potting media was then monitored as volumetric water content (VWC) using a Field Scout TDR 100 soil moisture meter (Spectrum Technologies, Plainfield, IL) throughout the remaining growing season and acclimation period. Plants designated as “wet” were maintained above 10% VWC, and plants designated as “dry” were maintained below 10% VWC. Seasonal average was 16.5% VWC for all “wet” plants and 6.6% for all “dry” plants. The intent was to stress the plants without excessively affecting growth. Plants were allowed to establish over a normal growing season in a glass greenhouse at the University of Vermont, Burlington, Vermont, under ambient temperature. Greenhouse temperatures were managed by direct venting and radiant heat as needed. Water soluble fertilizer was applied once weekly throughout the growing season: Jack’s Professional 17-4-17 (J.R. Peters, Inc, Allentown, PA) delivered at 150ppm nitrogen and Peters Professional S.T.E.M. soluble trace elements (The Scotts Company) delivered at 5ppm boron, 12ppm copper, 28ppm iron, 30ppm manganese, 0.15ppm molybdenum, 52.5ppm sulfur, and 16.9ppm zinc. Temperatures in the greenhouse were reduced beginning in October of each year at a rate of 3C (5F) per week until temperatures of 3-5C (37-41F) were reached at the end of November. This low temperature was maintained in the greenhouse until spring when the temperature was increased by the same increments beginning in April of each year until ambient temperature was reached.

During the month of January, the 30 plants in each treatment were randomly divided into five, six-pot groups, pruned back to within one inch above the level of the pot rim, and evenly watered. Controlled freezing of each six-pot group to temperatures of -2, -5, -8, -11, and -14C (28.4, 23.0, 17.6, 12.2, 6.8F) was performed as developed in previous studies (Herrick, 1996; Meyer, 1999; Bruce, 2003; Luchini, 2005). Plants were randomized by target freezing temperature and placed in heavy-weight standard open-mesh flats (‘1020’, 56x28cm (22x11in)). Flats were loaded into the freezer alternately stacked with wooden supports to allow air flow around pots to achieve uniform temperature within the freezer. Plants with the lowest target freezing temperatures were loaded first, followed by the second-lowest, and so on until the highest target temperature plants were loaded on the top level within the freezer. Loading by target freezing temperature minimized the amount of time that the freezer was open while removing plants, in turn minimizing temperature fluctuations, during the course of the freezing event.

Temperature in the insulated chest freezer (Model VWC15-ZL/E, W.C. Wood Co., Guelph, Canada) was controlled using a Dyna-Sense Mk III Versa-Lab Microprocessor Temperature Controller (Scientific Instruments, Skokie, IL) and monitored separately using a digital thermocouple (Model HH611P4C, Omega Engineering, Stanford, CT) with a probe suspended within the freezer and a probe placed within a pot with the lowest target temperature. A 7.6cm (3in) cooling fan (Radio Shack, Fort Worth, TX) was placed on the floor of the freezer to circulate air within the freezer. A thermocouple-based temperature recorder with internal temperature sensor (TC4000, Madgetech, Contoocook, NH) was placed alongside the pots with the lowest target temperature to record temperatures during the course of the freezing event.

Freezer temperatures were held at -2C (28.4F) for 24 hours prior to loading plants then maintained at that temperature for 48 hours following loading of plants to thoroughly achieve a uniform soil temperature among the plants. At that point, a six-pot group of each cultivar and treatment was removed from the freezer. The freezer air temperature was then set to -5C (23.0F), which was achieved within 30 minutes, and then held for 2 hours. During this time, the pot soil temperatures achieved target temperature 2 hours after the initial temperature setting and remained at the target temperature for 30 minutes. After this period, a six-pot group of each cultivar and treatment was removed. The freezer was then set to -8C (17.6F) and the process continued, with subsequent removal of pots, at -11C (12.2F) and -14C (6.8F) target temperatures. Following removal from the freezer, plants were returned to the 3-5C (37-41F) greenhouse where they were maintained through the return to ambient temperatures in spring as described above.

In June, plants were assessed for survival, growth and vigor. A visual rating scale of 1-5 was used with specific growth parameters defined for each cultivar (Tables 3.1-3.6). A rating of 3 or more was considered satisfactory for retail sale. Salable quality, with attractive factors such as flowers and growing points, is more important than quantity of growth to growers and consumers. Following visual rating, plant regrowth from each pot was harvested to within one inch above the level of the pot rim. Harvested growth from each plant was placed in an individual paper bag and stored in a drying oven at 60C (140F) for one week prior to weighing to 0.01g on an electronic balance for determination of dry weight.

The data from each cultivar was analyzed for each year of the study to compare effects of soil moisture level on susceptibility to freezing temperatures. Visual ratings and dry weights were assessed for analysis of variance (ANOVA) using SAS 9.1 and Tukey's procedure was used for mean separation when appropriate.

Results and Discussion

Coreopsis 'Tequila Sunrise' soil moisture level had no effect on either quality rating or dry weight and no interaction was observed (Table 3.1). Temperature effects on rating were observed (-14C significantly lower than -2C and -5C; -8C and -11C not significantly different from any other temperature) although no temperature effects on dry weight were observed. While some individual plants achieved at least minimal salable quality (rating of 3), means were below salable quality following all freezing temperatures. No individual plants were of salable quality following -11C for "wet" plants and following -14C freezing temperature for both moisture levels. Temperatures in a previous study showed hardiness to -11C, however, salable quality in the study was much higher following freezing temperatures (Luchini, 2005). A general decrease in ratings with decreasing temperature is consistent between the studies. Another previous study showed a significant effect of moisture level on both rating and dry weight favoring "wet" growing conditions, again with higher salable quality following all temperatures (Luchini et al., 2004). The extreme lack of overall vigor of the plants used in this study undoubtedly contributed to the lack of moisture effects and decreased hardiness. This is not entirely unexpected given the known low vigor and short lifespan of this cultivar, particularly when compared to other cultivars of the species. Additionally, the genus is known to perform best in well-drained soil (Armitage, 2008). Because “wet” and “dry” are two extremes of soil moisture levels, neither may be the optimal conditions for the cultivar. The “wet” soil moisture level may have been suffocating and the plants may not have been established enough to tolerate or thrive in the “dry” soil moisture level. A better balanced irrigation of this cultivar, particularly during the establishment year, may improve hardiness. Further study of this cultivar is necessary to reach a definitive conclusion on the effects of soil moisture level.

Geranium x cantabrigiense 'Cambridge' soil moisture level had no effect on dry weight but quality ratings were higher for “wet” plants (Table 3.2). No temperature effects were observed on either rating or dry weight. No interaction was observed between soil moisture level and temperature for either rating or dry weight. Combined means of both moisture levels achieved at least minimal salable quality (rating of 3) for all temperatures although means for “wet” plants following -2C freezing temperatures and for “dry” plants following -8C and -11C freezing temperatures were below minimal salable quality. Additionally, some individual plants were below minimal salable quality following -11C freezing temperature for “wet” plants and following -5C and -14C freezing temperatures for “dry” plants. Cultivars of *Geranium* x *cantabrigiense* are known to be very hardy from previous studies (Meyer, 1999; Bruce, 2003; Luchini et al., 2004; Luchini, 2005) and adaptable to many soil moisture levels (Armitage, 2008). While a significant difference was seen between moisture levels for ratings, combined means for all plants at either moisture level were of salable quality, making the difference of no particular practical value. This is consistent with another previous study, which showed some significant effect of moisture level on dry weight favoring “wet” growing conditions, for which salable quality of each moisture level made the difference of no practical value (Luchini et al., 2004). Ratings included both mass and number of flowers which may explain how ratings in this study showed differences when dry weight did not. From both this and the previous study, the “wet” soil moisture level appears more beneficial to *Geranium* prior to exposure to freezing temperatures than the “dry” soil moisture level, although the modest impact on salable quality may not justify the additional irrigation input. Because the “dry” soil moisture ratings were all of salable quality, it might even be possible to reduce irrigation to a “dry” moisture level and still obtain satisfactory overwintering survival, saving some of the expense required to prepare and protect containerized plants from freezing temperatures. Because “wet” and “dry” are two extremes of soil moisture levels, neither may be the optimal conditions for the cultivar. The higher soil moisture levels might simply be closer to the preferable conditions for plant performance. Both soil moisture levels should be directly compared to a baseline soil moisture level (10% VWC) to verify the suggestion to increase or decrease irrigation with the intent of improving overwintering survival.

Heuchera 'Plum Pudding' soil moisture level had no effect on dry weight but quality ratings were higher for “dry” plants (Table 3.3). No interaction was observed between soil moisture level and temperature for either rating or dry weight. Temperature effects on rating (-14C significantly lower than -5C; -2C, -8C, and -11C not significantly different from any other temperature) and dry weight were observed (-14C significantly lower than -2C, -5C, and -8C; -11C not significantly different from any other temperature). The rating scale used for this cultivar did not include a rating for dead plants (all plants survived freezing temperatures), instead using health of the remaining foliage and the number of flowering stems as an indicator of salable quality. Because of this, a rating of 2 or more was considered of salable quality. Means achieved salable quality (rating of 3 or higher) following all freezing temperatures. While a significant difference was seen between moisture levels for ratings, combined means for all plants at either moisture level were of salable quality, making the difference of no particular practical value. Ratings included both mass, health of foliage, and number of flowers which may explain how ratings showed differences when dry weight did not. The modest improvement of salable quality for “dry” plants suggests that it may be possible to reduce irrigation and still obtain satisfactory overwintering survival, saving some of the expense required to prepare and protect containerized plants from freezing temperatures. Because “wet” and “dry” are two extremes of soil moisture levels, neither may be the optimal conditions for the cultivar. The lower soil moisture levels might simply be closer to the preferable conditions for plant performance. The “dry” soil moisture levels should be directly compared to a baseline soil moisture level (10% VWC) to verify the suggestion to decrease irrigation with the intent of improving overwintering survival.

Carex oshimensis 'Evergold' soil moisture level had no effect on dry weight (Table 3.4). No interaction was observed between soil moisture level and temperature within dry weight but was observed within quality rating (Table 3.4). Moisture level had an effect on rating only following -8C freezing temperature for which mean was higher for “dry” plants than “wet” plants. Temperature effects were observed for “wet” plant ratings (-14C significantly lower than all other temperatures; -11C significantly lower than -2C, -5C, and -8C), for “dry” plant ratings (-14C and -11C significantly lower than all other temperatures; -8C significantly higher than all other temperatures), and combined dry weights (-11C and-14C significantly lower than -2C, -5C, and -8C). Temperature effects on rating were observed to decrease with decreasing temperature, with the exception of an increase between -5C and -8C for the “dry” soil moisture level. While some individual plants achieved at least minimal salable quality (rating of 3), means were below salable quality following -11C freezing temperatures and no individual plants were of salable quality following -14C freezing temperature for both moisture levels. All plants achieved at least minimal salable quality (rating of 3) following the other freezing temperatures for both moisture levels. While a significant difference was seen between moisture levels for ratings following -8C freezing temperature, means for all plants were of salable quality above -11C at either moisture level, making the difference of no particular practical value. The abnormally high salable quality rating following -8C freezing temperature for “dry” plants is the reason ratings showed differences when dry weight did not. This is unexplainable given that dry weights for that temperature and salable quality and dry weights for the “wet” plants were not abnormal. Because of this, the effect of soil moisture level on salable quality cannot be determined and the dry weight results are more conclusive despite showing no effects from either soil moisture level. Further study of this cultivar is necessary to reach a definitive conclusion on the effects of soil moisture level. Additionally, because “wet” and “dry” are two extremes of soil moisture levels, neither may be the optimal conditions for the cultivar. Both soil moisture levels should be directly compared to a baseline soil moisture level (10% VWC) to verify the suggestion to increase or decrease irrigation with the intent of improving overwintering survival.

Carex morrowii 'Ice Dance' soil moisture level had no effect on either quality rating or dry weight and no interaction was observed (Table 3.5). The same temperature effects on rating and on dry weight were observed (-11C and-14C significantly lower than -2C, -5C, and -8C; -5C and -8C significantly lower than -2C). Means of both moisture levels achieved at least minimal salable quality (rating of 3) for -2C, -5C, and -8C temperatures although some individual plants following -5C freezing temperatures for both moisture levels and following -8C freezing temperatures for “dry” plants were below minimal salable quality. No individual plants were of salable quality following -11C and -14C freezing temperature for either moisture level. The lack of impact on salable quality suggests that it may be possible to reduce irrigation and still obtain satisfactory overwintering survival, saving some of the expense required to prepare and protect containerized plants from freezing temperatures. Because “wet” and “dry” are two extremes of soil moisture levels, neither may be the optimal conditions for the cultivar. The “dry” soil moisture levels should be directly compared to a baseline soil moisture level (10% VWC) to verify the suggestion to decrease irrigation with the intent of improving overwintering survival.

Carex laxiculmus 'Hobb' (Bunny Blue™) soil moisture level had an on effect dry weight for which means were higher for “dry” plants (Table 3.6). No interaction was observed between soil moisture level and temperature within dry weight but was observed within quality rating (Table 3.6). Moisture level had an effect on rating only following -8C freezing temperature for which mean was higher for “wet” plants than “dry” plants. Temperature effects were observed for “wet” plant ratings (-11C and -14C significantly lower than all other temperatures), for “dry” plant ratings (-11C and -14C significantly lower than all other temperatures; -8C significantly lower than -2C), and combined dry weights (-11C and-14C significantly lower than all other temperatures; -2C and -5C significantly higher than all other temperatures). Temperature effects on rating were observed to generally decrease with decreasing temperature, with the exception of an increase between -5C and -8C for the “wet” soil moisture level. Means were below salable quality (rating of 3) following -11C and -14C freezing temperatures with no individual plants of salable quality for “wet” plants and very few individual plants of salable quality for “dry” plants. All plants achieved at least minimal salable quality (rating of 3) following all other freezing temperatures for both moisture levels. While a significant difference was seen between moisture levels for ratings following -8C freezing temperature, means for all plants were of salable quality above -11C at either moisture level, making the difference of no particular practical value. The increase of salable quality for “wet” plants following a single temperature is outweighed by the “dry” plants’ slightly better salable quality following other temperatures, higher dry weights, and slightly better survival following lower temperatures. The slight improvements seen for “dry” plants suggests that it may be possible to reduce irrigation and still obtain satisfactory overwintering survival, saving some of the expense required to prepare and protect containerized plants from freezing temperatures. Because “wet” and “dry” are two extremes of soil moisture levels, neither may be the optimal conditions for the cultivar. The lower soil moisture levels might simply be closer to the preferable conditions for plant performance. Due to the lack of a clear effect of soil moisture level, both soil moisture levels should be directly compared to a baseline soil moisture level

(10% VWC) to verify the suggestion to increase or decrease irrigation with the intent of improving overwintering survival.

From the six containerized herbaceous perennial cultivars studied, a general effect of soil moisture level on survival and salable quality following exposure to freezing temperatures could not be established. *Geranium* grown at a "wet" soil moisture level rated higher, as seen in a previous study (Luchini et al., 2004), whereas *Heuchera* grown at a "dry" soil moisture level rated higher. *Carex laxiculmus* was the only cultivar where soil moisture level had an effect on dry weight, for which growth was greater for plants grown at a "dry" soil moisture level. Salable quality, with attractive factors such as flowers and growing points, is more practically significant than quantity of growth to growers and consumers. However, while a significant difference was seen between moisture levels for ratings of *Geranium* and *Heuchera*, combined means for all plants at either moisture level were of salable quality, making the difference of no particular practical value. The same can be said for *Carex laxiculmus* following freezing temperatures above the -11C (12.2F) freezing temperature.

Coreopsis and *Carex morrowii* showed no effect of soil moisture level, in contrast to a previous study showing a preference for "wet" soil moisture level for *Coreopsis* (Luchini et al., 2004). The effects of soil moisture level on *Carex oshimensis* were inconclusive. Further study of *Coreopsis*, *Carex oshimensis* and *Carex morrowii* is necessary to reach any definitive conclusions on the effects of soil moisture level on these cultivars. The extreme lack of overall vigor of the *Coreopsis* plants used in this study undoubtedly contributed to the lack of moisture effects. Additionally, because "wet" and "dry" are two extremes of soil moisture levels, neither may be the optimal conditions for any of the cultivar in this study. Both soil moisture levels should be directly compared to a baseline soil moisture level (10% VWC) to verify the suggestion to increase or decrease irrigation with the intent of improving overwintering survival.

Unfortunately, a universal recommendation of plant irrigation practices for purposes of improving survival and salable quality following overwintering cannot be recommended based on this study. This is not unexpected given the native soil moisture requirements for different cultivars. However, the modest improvement for "dry" plants or lack of impact of soil moisture level on practical salable quality suggests that it may be possible to reduce irrigation and still obtain satisfactory overwintering survival of *Geranium*, *Heuchera, Carex laxiculmus,* and *Carex morrowii,* saving some of the expense required to prepare and protect containerized plants from freezing temperatures. Future studies of the impacts of soil moisture level on these and other cultivars of containerized herbaceous perennials would be of tremendous use to growers. Results suggesting that minimal irrigation better prepares particular cultivars for overwintering could be used by growers to save on expense of irrigation. Results suggesting that excessive irrigation better prepares other cultivars for overwintering could be used by growers to plan for irrigation. Concurrent to this, irrigation practices that actually weaken particular cultivars prior to overwintering could be concluded.

Irrigation is a necessity in containerized perennial plant production and a major expense during production. Native soil moisture requirements largely determine irrigation regimes for different cultivars. Overwintering these plants is an additional expense in northern climates. The possibility that alteration of irrigation regimes could affect plant survival following exposure to freezing temperatures would be a valuable tool in planning containerized plant irrigation practices and protection methods in preparation for successfully overwintering, potentially saving some of the expense required to protect containerized plants from freezing temperatures.

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Table 3.1. Effect of soil moisture and freezing temperatures on quality rating and dry weight of *Coreopsis* 'Tequila Sunrise' regrowth.

	Rating[a]			Dry weight (g)		
Treatment temp °C	Wet plants[b]	Dry plants[c]	Mean (SEM[d])	Wet plants	Dry plants	Mean (SEM)
-2	2.83	2.00	2.42 (0.40) a[e]	0.02	0.00	0.01 (0.01)
-5	2.33	2.83	2.58 (0.23) a	0.13	0.01	0.07 (0.07)
-8	1.83	1.50	1.67 (0.22) ab	0.07	0.00	0.04 (0.04)
-11	1.33	2.17	1.75 (0.28) ab	0.00	0.01	0.00 (0.00)
-14	1.33	1.00	1.17 (0.12) b	0.00	0.00	0.00 (0.00)
Mean (SEM)	1.93[f] (0.18)	1.90 (0.20)		0.04 (0.03)	0.00 (0.00)	

ANOVA significance:

	df[g]	*F*[h]	*p*-value[i]	df	*F*	*p*-value
Temperature	4	4.95	0.0019	4	0.77	0.5469
Moisture	1	0.02	0.8870	1	1.83	0.1821
Interaction	4	1.70	0.1638	4	0.65	0.6303

[a]Rating scale 1 = Dead, no regrowth, 2 = No flowering stems and foliage regrowth of less than 3 inches (8cm), 3 = Less than 3 flowering stems and regrowth of 3-5 inches (8-12cm), 4 = Less than 3 flowering stems and regrowth over 5 inches (12cm), 5 = 3 or more flowering stems and regrowth as above.
[b]Plants designated as 'Wet' were maintained above 10% volumetric water content during the growing season prior to freezing.
[c]Plants designated as 'Dry' were maintained below 10% volumetric water content during the growing season prior to freezing.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[f]Where no interaction present between factors, plant soil moisture means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 3.2. Effect of soil moisture and freezing temperatures on quality rating and dry weight of *Geranium* x *cantabrigiense* 'Cambridge' regrowth.

	Rating[a]			Dry weight (g)		
Treatment temp °C	Wet plants[b]	Dry plants[c]	Mean (SEM[d])	Wet plants	Dry plants	Mean (SEM)
-2	2.83	3.50	3.17 (0.21)[e]	0.66	0.48	0.57 (0.08)
-5	3.83	3.17	3.50 (0.23)	0.47	0.54	0.50 (0.03)
-8	3.50	2.83	3.17 (0.21)	0.56	0.47	0.51 (0.04)
-11	3.50	2.83	3.17 (0.21)	0.54	0.57	0.55 (0.04)
-14	3.50	3.00	3.25 (0.18)	0.51	0.63	0.57 (0.05)
Mean (SEM)	3.43 A[f] (0.13)	3.07 B (0.12)		0.55 (0.04)	0.54 (0.03)	

ANOVA significance:

	df[g]	*F*[h]	*p*-value[i]	df	*F*	*p*-value
Temperature	4	0.56	0.6899	4	0.35	0.8396
Moisture	1	4.55	0.0379	1	0.03	0.8542
Interaction	4	2.29	0.0723	4	1.35	0.2634

[a]Rating scale 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 0-2 flowering stems and regrowth extending over edge of pot, 4 = 3-5 flowering stems and regrowth equal to or greater than above, 5 = 6 or more flowering stems and regrowth as above.
[b]Plants designated as ‘Wet’ were maintained above 10% volumetric water content during the growing season prior to freezing.
[c]Plants designated as ‘Dry’ were maintained below 10% volumetric water content during the growing season prior to freezing.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[f]Where no interaction present between factors, plant soil moisture means with a capital letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 3.3. Effect of soil moisture and freezing temperatures on quality rating and dry weight of *Heuchera* 'Plum Pudding' regrowth.

	Rating[a]			Dry weight (g)		
Treatment temp °C	Wet plants[b]	Dry plants[c]	Mean (SEM[d])	Wet plants	Dry plants	Mean (SEM)
-2	2.67	3.00	2.83 (0.21) ab[e]	5.53	5.75	5.64 (0.24) a
-5	2.67	4.67	3.67 (0.43) a	4.83	5.95	5.39 (0.30) a
-8	3.17	3.17	3.17 (0.24) ab	5.49	5.69	5.59 (0.25) a
-11	2.17	3.17	2.67 (0.31) ab	4.80	5.40	5.10 (0.31) ab
-14	2.33	2.67	2.50 (0.34) b	4.38	4.06	4.22 (0.28) b
Mean (SEM)	2.60 B[f] (0.21)	3.33 A (0.18)		5.01 (0.19)	5.37 (0.20)	

ANOVA significance:

	df[g]	*F*[h]	*p*-value[i]	df	*F*	*p*-value
Temperature	4	2.57	0.0493	4	4.46	0.0037
Moisture	1	8.07	0.0065	1	2.19	0.1454
Interaction	4	1.90	0.1250	4	0.94	0.4460

[a]Rating scale 1 = Foliage dieback evident and 0-1 flowering stems, 2 = Foliage dieback minimal and 2 flowering stems, 3 = Foliage healthy and 3 flowering stems, 4 = Foliage healthy and 4 flowering stems, 5 = Foliage healthy and 5 or more flowering stems.
[b]Plants designated as ‘Wet’ were maintained above 10% volumetric water content during the growing season prior to freezing.
[c]Plants designated as ‘Dry’ were maintained below 10% volumetric water content during the growing season prior to freezing.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[f]Where no interaction present between factors, plant soil moisture means with a capital letter in common are not significantly different according to Tukey’s procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 3.4. Effect of soil moisture and freezing temperatures on quality rating and dry weight of *Carex oshimensis* 'Evergold' regrowth.

	Rating[a]			Dry weight (g)		
Treatment temp °C	Wet plants[b]	Dry plants[c]	Mean (SEM[d])	Wet plants	Dry plants	Mean (SEM)
-2	4.00 a[ef]	4.00 b	4.00 (0.00)	3.24	2.85	3.04 (0.17) a
-5	4.00 a	3.83 b	3.92 (0.08)	2.32	2.95	2.63 (0.24) a
-8	4.00 Ba	5.00 Aa	4.50 (0.15)	2.14	2.69	2.42 (0.13) a
-11	2.00 b	1.67 c	1.83 (0.24)	0.89	0.52	0.71 (0.24) b
-14	1.17 c	1.33 c	1.25 (0.13)	0.06	0.27	0.16 (0.09) b
Mean (SEM)	3.03 (0.24)	3.17 (0.28)		1.73[k] (0.24)	1.86 (0.24)	

ANOVA significance:

	df[g]	F[h]	p-value[i]	df	F	p-value
Temperature	4	122.86	<0.0001	4	49.59	<0.0001
Moisture	1	1.29	0.2614	1	0.61	0.4373
Interaction	4	3.91	0.0077	4	1.83	0.1371

[a]Rating scale 1 = Dead, no regrowth, 2 = Dieback evident and regrowth less than 6 inches (15cm), 3 = Minimal regrowth less than 6 inches (15cm), 4 = Vigorous regrowth 6 inches (15cm) or more, 5 = Vigorous regrowth 6 inches (15cm) or more and filling or extending over edge of pot.
[b]Plants designated as 'Wet' were maintained above 10% volumetric water content during the growing season prior to freezing.
[c]Plants designated as 'Dry' were maintained below 10% volumetric water content during the growing season prior to freezing.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[f]Where interaction present between factors, means between plant soil moisture for a single treatment freezing temperatures on regrowth of with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[k]Where no interaction present between factors, plant soil moisture means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 3.5. Effect of soil moisture and freezing temperatures on quality rating and dry weight of *Carex morrowii* 'Ice Dance' regrowth.

	Rating[a]			Dry weight (g)		
Treatment temp °C	Wet plants[b]	Dry plants[c]	Mean (SEM[d])	Wet plants	Dry plants	Mean (SEM)
-2	4.83	4.83	4.83 (0.11) a[e]	1.50	2.74	2.12 (0.29) a
-5	4.00	3.33	3.67 (0.41) b	1.39	1.26	1.32 (0.22) b
-8	3.50	3.50	3.50 (0.29) b	0.76	1.22	0.99 (0.24) b
-11	1.17	1.17	1.17 (0.11) c	0.12	0.03	0.07 (0.06) c
-14	1.00	1.17	1.08 (0.08) c	0.00	0.10	0.05 (0.05) c
Mean (SEM)	2.90[f] (0.31)	2.80 (0.32)		0.75 (0.13)	1.07 (0.23)	

ANOVA significance:

	df[g]	F[h]	p-value[i]	df	F	p-value
Temperature	4	45.11	<0.0001	4	22.83	<0.0001
Moisture	1	0.21	0.6523	1	3.79	0.0571

[a]Rating scale 1 = Dead, no regrowth, 2 = Dieback evident and regrowth less than 6 inches (15cm), 3 = Minimal regrowth less than 6 inches (15cm), 4 = Vigorous regrowth less than 6 inches (15cm), 5 = Vigorous regrowth 6 inches (15cm) or more.
[b]Plants designated as 'Wet' were maintained above 10% volumetric water content during the growing season prior to freezing.
[c]Plants designated as 'Dry' were maintained below 10% volumetric water content during the growing season prior to freezing.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[f]Where no interaction present between factors, plant soil moisture means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Table 3.6. Effect of soil moisture and freezing temperatures on quality rating and dry weight of *Carex laxiculmus* 'Hobb' (Bunny Blue™) regrowth.

	Rating[a]			Dry weight (g)		
Treatment temp °C	Wet plants [b]	Dry plants [c]	Mean (SEM [d])	Wet plants	Dry plants	Mean (SEM)
-2	4.17 b [ef]	4.50 a	4.33 (0.19)	3.14	3.73	3.43 (0.15) a
-5	4.00 b	4.00 ab	4.00 (0.21)	2.51	3.20	2.86 (0.19) a
-8	5.00 Aab	3.50 Bb	4.25 (0.25)	2.19	2.32	2.25 (0.13) b
-11	1.50 c	2.00 c	1.75 (0.22)	0.10	0.34	0.22 (0.12) c
-14	1.17 c	2.17 c	1.67 (0.33)	0.10	0.57	0.33 (0.19) c
Mean (SEM)	3.17 (0.29)	3.23 (0.25)		1.61 B [k] (0.24)	2.03 A (0.28)	

ANOVA significance:

	df [g]	*F* [h]	*p*-value [i]	df	*F*	*p*-value
Temperature	4	38.69	<0.0001	4	99.69	<0.0001
Moisture	1	0.11	0.7360	1	10.32	0.0023
Interaction	4	4.64	0.0029	4	0.64	0.6397

[a]Rating scale 1 = Dead, no regrowth, 2 = Dieback evident and regrowth less than 6 inches (15cm), 3 = Minimal regrowth less than 6 inches (15cm), 4 = Vigorous regrowth less than 6 inches (15cm), 5 = Vigorous regrowth 6 inches (15cm) or more.
[b]Plants designated as 'Wet' were maintained above 10% volumetric water content during the growing season prior to freezing.
[c]Plants designated as 'Dry' were maintained below 10% volumetric water content during the growing season prior to freezing.
[d]SEM=Standard Error of the Mean.
[e]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[f]Where interaction present between factors, means between plant soil moisture for a single treatment freezing temperatures on regrowth of with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[k]Where no interaction present between factors, plant soil moisture means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]df=degrees of freedom.
[h]*F*=*F* distribution.
[i]p-value=level of significance.

Chapter 4:

Influence of Temperature Cycling Date on Cold Hardiness of Three Container-Grown Herbaceous Perennials

(In the format appropriate for submission to the *Journal of Environmental Horticulture*)

Abstract

Overwintering container-grown plants is often necessary to perennial production. During November, January, and March, plants were subjected to 24 hour temperature cycling treatments at -3C/+3C (26.6/36.8F) prior to exposure to controlled freezing temperatures of -2, -5, -8, -11, and -14C (28.4, 23.0, 17.6, 12.2, 6.8F) then returned to a 3-5C (37-41F) greenhouse. In June, plants were assessed using a visual rating scale (1 = dead, 3-5 = increasing salable quality) and dry weight of new growth. *Geranium* x *cantabrigiense* 'Cambridge' were more tolerant of both temperature cycling and freezing temperatures in January and an increased number of cycles in November had an advantageous effect. *Sedum* 'Matrona' were more tolerant of temperature cycling and freezing temperatures in January and an increased number of cycles in March had an advantageous effect. *Leucanthemum* x *superbum* 'Becky', studied for two years, were more tolerant of temperature cycling in January in the second year of the study and an increased number of cycles in November had an advantageous effect in the first year and in all months in the second year. Overwintering container-grown plants are likely to be hardier in January and minor temperature cycles prior to exposure to freezing temperatures generally increase hardiness.

Index words: nursery, production, cold stress, overwintering, freezing injury, thawing injury, Shasta daisy, *Geranium*, *Sedum*, *Leucanthemum*, *Hylotelephium*.

Species used in this study: *Geranium* x *cantabrigiense* L. 'Cambridge'; *Leucanthemum* x *superbum* L. 'Becky'; *Sedum* L. 'Matrona'.

Significance to the Nursery Industry

Container production of herbaceous perennials continues to be popular within the nursery industry and consumers have come to expect plants of certain size, quality and bloom. In northern climates, this may require multiple seasons of plant growth or vernalization events which, in turn, require overwintering periods during which the containerized plants are subjected to freezing temperatures. Additionally, growers may wish to overwinter propagation stock, plants not sold within a season, or newly potted plants prepared for the following season. Temperature fluctuations a plant is subjected to during the winter period, such as a midwinter thaw, may affect survival following subsequent freezing temperatures. This may be further influenced by the time of year these temperature fluctuations occur due to state of acclimation/deacclimation of the plant and intensity of the subsequent temperatures. Research relating winter temperature fluctuations to cold hardiness is limited and not always specific to herbaceous perennial container production. This study demonstrated that minor freeze-thaw temperature fluctuations prior to exposure to freezing temperatures generally increased containerized herbaceous perennial survival and salable quality. This effect was generally greater in January than in November or March. However, these tendencies were not consistent when one cultivar was followed through two study periods. This information will assist growers in determining containerized plant sensitivity to temperature fluctuations and in deciding which containerized plants are most likely to overwinter successfully, potentially saving some of the expense required to protect containerized plants from freezing temperatures.

Introduction

Production of herbaceous perennial plants in containers continues to be popular within the nursery industry and accounts for the majority of ornamental plant production (Perry, 1998; Perry, 2006; Pilon, 2006; Diver et al., 2008). Herbaceous perennials and other bedding/garden plants make up over half of the value of sales for floriculture crops and is the highest valued category behind woody nursery stock of all nursery and greenhouse industries (USDA, 2007). Growing plants in containers allows growers to produce more plants in less space with more control over propagation, culture, and pests than traditional field production. Plants in containers are easier to handle within the nursery, require less labor overall, and are more efficient to transport. Consumers generally prefer to purchase smaller, uniform, well-grown plants in containers that are easy to handle and transplant. Container-grown plants experience less root loss than field-harvested plants which allows them to better survive and establish following transplanting (Perry, 1998; Perry, 2006; Diver et al., 2008; Eaton et al., 2009).

Overwintering is typically the most limiting factor in production of container-grown plants for growers in northern climates (Pellett et al., 1985). Inevitably, all plants will not be sold within a single growing season resulting in the necessity of disposing, field planting or overwintering container-grown stock. Additionally, many cultivar and propagation methods require production periods longer than a single season prior to sale, again necessitating overwintering (Pilon, 2006; Svendsen et al., 2006; Pyle, 2009). A recent trend by consumers to grow herbaceous perennials as ornamental container plants, has led to an interest in overwintering through multiple years of growth (Dimke et al., 2008). Successful methods for overwintering containerized plants are generally y labor intensive and expensive (Taylor et al., 1983; Pilon, 2006).

Plants in containers are exposed to air temperatures that are colder than they may experience when growing in the ground (Perry, 1998; Pilon, 2006), challenging the plants natural survival mechanisms. Many cold-sensitive roots are found on the outer top and sides of a container where media temperature approaches this colder air temperature (Pellett et al., 1985; Perry, 1998; Pilon, 2006) and are first to be injured by cold temperatures (Mathers, 2003). The smaller the container, the more rapidly media temperature will react to air temperature changes (Svendsen et al., 2006). In every overwintering period, temperatures will inevitably fluctuate, most notably during a typical midwinter (January thaw), and keeping plants from thawing during these events is difficult (Smith, 2004). The effects of these temperature changes on survival of freezing winter temperatures are relatively unstudied, particularly for herbaceous perennial container production.

After a temporary thaw, reacclimation of oilseed rape (*Brassica napus*) to freezing temperatures is possible (Rife et al., 2003) provided no elongation growth occurs (Rapacz, 2002). A damaging effect of temperature fluctuations is embolism caused by cavitating gas bubbles in the vascular system that form during ice formation and are released during thaw periods (Mayr et al., 2003). Plants with smaller vessels, such as conifers, have less dissolved gas and will form smaller bubbles that cause less cavitation damage (Sperry et al., 1992).

Temperature fluctuations where a warm spell occurs amidst freezing winter temperatures have not been seen to significantly affect hardiness of woody plant twigs of

European birch (*Betula pubescens*), *Populus gelrica*, *Salix dasyclados, S. daphnoides*, and *Larix laricina* when they occur during the winter but a ‘rapid’ loss of hardiness is observed in the spring (Sakai, 1973). Daily temperature fluctuations increased hardiness of winter wheat (*Triticum aesitivum*) (Andrews et al., 1974). Strawberry (*Fragaris* x *ananassa*) plants show a decrease in hardiness during multiple freeze-thaw events, but root regrowth and leaf number the following season are unaffected (Warmund et al., 1992). Studies of grasslands show an increase in above ground growth but a decrease in root length following multiple freeze-thaw cycles (Kreyling et al., 2008). Apple trees (*Malus* x *domestica*) demonstrate lower survival rates as well as reduced leaf, shoot, and root regrowth when following multiple freeze-thaw events, with as few as two cycles (Prive et al., 2001).

Studies of container-grown herbaceous perennials showed freeze-thaw cycles to increase hardiness of *Campanula takesimana* (Herrick, 1996), *Dianthus deltoides* 'Vampire', *Geranium* x *cantabrigiense* 'Cambridge' (Bruce, 2003), and *Geranium* 'Dilys (Luchini, 2005) although more extreme fluctuations may have the opposite effect (Bruce, 2003). No effect on hardiness was observed for *Iris siberica* 'Pirate Prince', *Coreopsis* 'Tequila Sunrise', or *Geranium* x *cantabrigiense* 'Karmina' (Luchini, 2005).

From early winter to mid winter, azalea (*Rhododendron* species) buds appear to increase in hardiness and decrease in rehardening capacity. Extent of dehardening is greater in late winter than in early winter when subjected to warming temperatures (Kalberer et al., 2007). In January, March, and April, artificial freeze-thaw cycles did not affect hardiness of strawberry (*Fragaris* x *ananassa*) plants (Linden et al., 2000). Studies of herbaceous perennial sedum (*Sedum spectabile* x *telephium* 'Autumn Joy' and *Sedum* *spectabile* 'Brilliant') showed an increase in hardiness from September to maximum acclimation and highest shoot regrowth quality in January, with the sharpest increase in hardiness occurring in November (Iles et al., 1995). Studies of *Aquilegia* 'McKana's Giant' mix and *Dianthus deltoides* 'Vampire' both showed higher survival and salable quality in January than in November (Perry et al., 1996). A better salable quality of herbaceous perennial *Geranium* 'Dilys' was observed in January than in March. *Geranium* x *cantabrigiense* 'Cambridge' and *Coreopsis* 'Tequila Sunrise' showed no difference between January and March controlled freezing events (Luchini, 2005).

The purpose of this study was to examine how varying numbers of freezing and thawing cycles at different times during the winter season affected survival and salable quality following subsequent exposure to freezing temperatures for of three herbaceous perennial cultivars. One of the cultivars used in this study was also used in previous studies (Iles et al., 1995; Luchini, 2005).

Materials and Methods

Plants were obtained as liner plugs of 36-72 individual plants per flat (56x28cm (22x11in)) depending on cultivar or as divisions of previously established plants (existing in #SP3 (10cm (4in), 400ml (24.4in^3)) plastic pots) at the beginning of the study growing season. All plants were potted in #SP3 plastic pots with ProMix BX medium(Premier Horticultural Products, Red Hill, PA).

The study was conducted over two years. In the first year, *Leucanthemum* x *superbum* 'Becky' and *Geranium x cantabrigiense* 'Cambridge' were used. In the second year, *Leucanthemum* x *superbum* 'Becky' and *Sedum* 'Matrona' were used. These recently introduced cultivars are readily available and information on their culture will be of value to growers.

Shasta daisies are vigorous and easy to grow perennial plants (Hill et al., 2003) that tend to be short lived, 2-3 years (Armitage, 2008) but are easily propagated by division. The cultivar *Leucanthemum* x *superbum* 'Becky' has 3-4 inch white flowers (Hill et al., 2003) on 3 foot stems that are desirable as cut flowers. The foliage is particularly tolerant of heat and humidity. Hardiness is listed for U.S. Zones 4-9 in some references (northcreeknurseries.com, 2010) and Zones 5-9 in others (perennialresource.com, 2010).

Hardy perennial geraniums, also known as cranesbill, are native to temperate regions worldwide (Yeo, 2002). They grow under a range of conditions but prefer full sun to partial shade and moist soil (Armitage, 2008). The cultivar *Geranium* x *cantabrigiense* 'Cambridge' is a low growing (up to 30cm (11.8in)) groundcover with aromatic, seemingly hairless, light green foliage and purple-violet flowers (Yeo, 2002). Hardiness is listed for U.S. Zones 5-9 (Hogan, 2003), and proven hardy in Zone 4 field conditions in Vermont (Perry, 2010).

Sedum have distinctly fleshy leaves, are relatively easy to grow, and perform best in well-drained soil in full sun (Armitage, 2008). *Sedum* 'Matrona' was formerly listed under the species *Sedum telephium* (RHS, 2006-2007) and is now listed as a stand-alone species (RHS, 2009-2010). This robust and sturdy plant reaches heights of 2-3 feet with purple-red stems bearing pink flowers in autumn. Hardiness is listed for U.S. Zones 3-9 (northcreeknurseries.com, 2010; perennialresource.com, 2010).

In each year of the study, 270 plants were established for each plant cultivar. Plants were allowed to establish over a normal growing season in a glass greenhouse at the University of Vermont, Burlington, Vermont, under ambient temperature. Greenhouse temperatures were managed by direct venting and radiant heat as needed. Plants were watered by greenhouse staff as needed throughout the studies. Water soluble fertilizer was applied once weekly throughout the growing season: Jack's Professional 17-4-17 (J.R. Peters, Inc, Allentown, PA) delivered at 150ppm nitrogen and Peters Professional S.T.E.M. soluble trace elements (The Scotts Company) delivered at 5ppm boron, 12ppm copper, 28ppm iron, 30ppm manganese, 0.15ppm molybdenum, 52.5ppm sulfur, and 16.9ppm zinc. Temperatures in the greenhouse were reduced beginning in October of each year at a rate of 3C (5F) per week until temperatures of 3-5C (37-41F) were reached at the end of November. This low temperature was maintained in the greenhouse until spring when the temperature was increased by the same increments beginning in April of each year until ambient temperature was reached.

During the months of November, January, and March, 90 plants from each cultivar were randomly selected and divided into three treatments: '0-cycles', '1-cycle', and '2-cycles'. The 30 plants in each treatment were then randomly divided into five, six-pot groups, pruned back to within one inch above the level of the pot rim, and evenly watered. Plants were randomized by cycle treatment and placed in heavy-weight standard flats ('1020', 56x28cm (22x11in)). Flats were loaded into a freezer alternately stacked with wooden supports to allow air flow around pots to achieve uniform temperature within the freezer.

Temperature in the insulated chest freezer (Model VWC15-ZL/E, W.C. Wood Co., Guelph, Canada) was controlled using a Dyna-Sense Mk III Versa-Lab Microprocessor Temperature Controller (Scientific Instruments, Skokie, IL) and monitored separately using a K-type thermocouple (Model HH611P4C, Omega Engineering, Stanford, CT) with a probe suspended within the freezer and a probe placed within a pot with the lowest target temperature. A 7.6cm (3in) cooling fan (Radio Shack, Fort Worth, TX) was placed on the floor of the freezer to circulate air within the freezer. A thermocouple-based temperature recorder with internal temperature sensor (TC4000, Madgetech, Contoocook, NH) was placed alongside the pots with the lowest target temperature to record temperatures during the course of the freezing event.

Freezer temperatures were held at -3C (26.6F) for 24 hours prior to loading plants in the '2-cycles' treatment then maintained at that temperature for 24 hours following loading of plants. At that point, freezer temperature was raised to +3C (36.8F) for a 24 hour period. After the warmer temperature period, plants in the '1-cycle' treatment were loaded and the freezer temperature was set back to -3C (26.6F) for 24 hours. Again, at that point, freezer temperature was raised to +3C (36.8F) for a 24 hour period. After this second warmer period, plants in the '0-cycles' treatment were also loaded into the freezer.

Controlled freezing of each six-pot group to temperatures of -2, -5, -8, -11, and -14C (28.4, 23.0, 17.6, 12.2, 6.8F) was then performed as developed in previous studies (Herrick, 1996; Meyer, 1999; Bruce, 2003; Luchini, 2005). Plants were randomized by target freezing temperature with the lowest target freezing temperatures loaded first, followed by the second-lowest, and so on until the highest target temperature plants were loaded on the top level within the freezer. Loading by target freezing temperature minimized the amount of time that the freezer was open while removing plants, in turn minimizing temperature fluctuations, during the course of the freezing event.

Freezer temperatures were held at -2C (28.4F) for 48 hours following final loading of plants to thoroughly achieve a uniform soil temperature among the plants. At that point, a six-pot group of each cultivar and treatment was removed from the freezer. The freezer air temperature was then set to -5C (23.0F), which was achieved within 30 minutes, and then held for 2 hours. During this time, the pot soil temperatures achieved target temperature 2 hours after the initial temperature setting and remained at the target temperature for 30 minutes. After this period, a six-pot group of each cultivar and treatment was removed. The freezer was then set to -8C (17.6F) and the process continued, with subsequent removal of pots, at -11C (12.2F) and -14C (6.8F) target temperatures. Following removal from the freezer, plants were returned to the 3-5C (37-41F) greenhouse where they were maintained through the return to ambient temperatures in spring as described above.

In June, plants were assessed for survival, growth and vigor. A visual rating scale of 1-5 was used with specific growth parameters defined for each cultivar (Tables 4.1, 4.3, 4.5, and 4.6). A rating of 3 or more was considered satisfactory for retail sale. Salable quality, with attractive factors such as flowers and growing points, is more important than quantity of growth to growers and consumers. Following visual rating, plant regrowth from each pot was harvested to within one inch above the level of the pot rim. Harvested growth from each plant was placed in an individual paper bag and stored in a drying oven at 60C (140F) for one week prior to weighing to 0.01g on an electronic balance for determination of dry weight.

Data from each cultivar was analyzed for each year of the study to compare effects of number of cycles at each temperature cycle date on susceptibility to freezing temperatures. Visual ratings and dry weights were assessed for analysis of variance (ANOVA) using SAS 9.1 and Tukey's procedure was used for mean separation when appropriate.

Results and Discussion

Geranium x *cantabrigiense* 'Cambridge' was studied for one year. The number of temperature cycles had effects at each of the (Tables 4.1 and 4.2). In November, cycle had an effect for which 1-cycle was significantly higher than 0-cycles for quality rating and 1-cycle and 2-cycles were significantly higher than 0-cycles for dry weight. Cycle had no effect on either rating or dry weight in January. Cycle had an effect on both rating and dry weight in March for which 1-cycle was significantly higher than 2-cycles. No interaction was observed between cycle and temperature within either rating or dry weight on any of the dates. An increased number of cycles in November had an advantageous effect on plant survival although the opposite effect occurred in March. The difference between November and March in this study is possibly due to the differences in acclimation and deacclimation processes and energy reserve of the plant at the beginning and end of the overwintering season. In previous studies with other cultivars, an increased number of cycles improving hardiness was seen in January and once in March (Perry et al., 1996; Bruce, 2003; Luchini, 2005). The difference of date that cycles had an effect between these studies and the current study may be due to cultivar or cultural differences, although the effect of cycles improving hardiness is consistent.

For *Geranium* x *cantabrigiense* 'Cambridge' temperature effects were observed in November on rating (-14C significantly lower than -2C, -5C, and -8C) and dry weight (-14C significantly lower than -2C, -8C, and -11C). No temperature effects on either rating or dry weight were observed in January. Temperature effects were observed in March on rating (-14C significantly lower than -2C) and dry weight (-8C and -14C significantly lower than -2C).

All *Geranium* x *cantabrigiense* 'Cambridge' plants achieved at least minimal salable quality (rating of 3) in November following -8C freezing temperature with 2-cycles. Mean achieved salable quality, although some individual plants were below minimal salable quality, in November following -2C with 0-cycles and -8C and -11C with 1-cycle; in January following -11C and -14C with 0-cycles and -2C with 2-cycles; and in March following -2C with 0-cycles. While some individual plants achieved at least minimal salable quality, means were below salable quality in November following -5C, -8C, and -11C with 0-cycles, -2C, -5C, -11C, and -14C with 2-cycles, and -2C, -5C, and -14C with 1-cycle; in January following -2C, -5C, and -8C with 0-cycles, -2C, -5C, -11C, and -14C with 1-cycle, and -5C, -8C, -11C, and -14C with 2-cycles; and in March following -5C, -8C, and -11C with 0-cycles, all freezing temperatures with 1-cycle, and -2C, -5C, -8C, and -11C with 2-cycles. No individual plants were of salable quality in November following -14C with 0-cycles; in January following -8C with 1-cycle; and in March following -14C with 0-cycles and 2-cycles.

For *Geranium* x *cantabrigiense* 'Cambridge' no effects of the number of temperature cycles or between temperatures occurred in January whereas both effects were observed in November and in March. This can be interpreted as plants being more tolerant of both temperature cycling and freezing temperatures in January than in November or March. This conclusion is consistent with previous studies of *Geranium* where cycling in January was less detrimental or similar than in March (Luchini, 2005). Cycling in January was also less detrimental than in November, consistent with other cultivars in previous studies (Iles et al., 1995; Perry et al., 1996).

Cultivars of *Geranium* x *cantabrigiense* are known to be very hardy from previous studies (Meyer, 1999; Bruce, 2003; Luchini, 2005). Plant survival was lower than expected in this study, perhaps due to cultural variation from year to year, although this helped to illustrate differences in cycle, date, and temperature. This cultivar was only studied for one year due to consistencies between results from this study and previous studies and in order to study another cultivar not previously studied.

Sedum 'Matrona' was studied in the second year although no data were available for the January 0-cycles treatment due to a lack of available plants (Tables 4.3 and 4.4). Cycle had no effect on either quality rating or dry weight in November and January. In March, cycle had no effect on rating, but did have an effect on dry weight for which 2-cycles were significantly higher than 0-cycles. No interaction was observed between cycle and temperature within either rating or dry weight on any of the dates. An increased number of cycles in March had an advantageous effect on plant survival. In previous studies with other cultivars, an increased number of cycles improving hardiness was seen in January and once in March (Perry et al., 1996; Bruce, 2003; Luchini, 2005).

The difference of date that cycles had an effect between these studies and the current study may be due to cultivar or cultural differences, although the effect of cycles improving hardiness is consistent.

For *Sedum* 'Matrona' temperature effects were observed in November on rating (-8C, -11C, and -14C significantly lower than -2C and -5C) and dry weight (-11C and -14C significantly lower than -2C). No temperature effects on either rating or dry weight were observed in January. In March, temperature effects were observed on rating (-14C significantly lower than -2C, -5C; -11C significantly lower than -5C) although no temperature effects on dry weight were observed.

Mean achieved salable quality (rating of 3), although some individual *Sedum* 'Matrona' plants were below minimal salable quality, in January following -2C, -5C, and -8C freezing temperatures with 1-cycle. While some individual plants achieved at least minimal salable quality, means were below salable quality in November following -2C and -5C with 0-cycles, -2C and -11C with 1-cycle, and -2C, -5C, -8C, and -14C with 2-cycles; in January following -2C, -5C, -11C, and -14C with 1-cycle and all freezing temperatures with 2-cycles; and in March following -5C with 0-cycles, -5C and -8C with 1-cycle, and -2C, -5C, and -8C with 2-cycles. No individual plants were of salable quality in November following -8C, -11C, and -14C with 0-cycles, -5C, -8C, and -14C with 1-cycle, and -11C with 2-cycles; and in March following -2, -8, -11, and -14C with 0-cycles, -2C, -11C, and -14C with 1-cycle, and -11C and -14C with 2-cycles.

For *Sedum* 'Matrona' no effects of the number of temperature cycles or between temperatures occurred in January whereas effects were observed in November on temperature and in March on temperature and number of cycles. This can be interpreted as plants being more tolerant of freezing temperatures in January than in November and more tolerant of both temperature cycling and freezing temperatures in January than in March. This conclusion is consistent with previous studies of *Sedum* where cycling in January was less detrimental than in November (Iles et al., 1995). Cycling in January was also less detrimental than in March, consistent with other cultivars in previous studies (Luchini, 2005).

Leucanthemum x *superbum* 'Becky' was studied for two years. The number of temperature cycles had an effect on each of the dates (Tables 4.5 – 4.8). Interaction was observed between cycle and temperature within quality rating in November, January, and March in the first year and in November and January in the second year. Interaction was also observed within dry weight in January and in March in the first year and in November in the second year. No interaction was observed within rating in March in the second year. No interaction was observed within dry weight in November in the first year and in January and March in the second year.

For *Leucanthemum* x *superbum* 'Becky' cycle had an effect in November in the first year on rating for which 2-cycles were significantly higher than 0-cycles following -5C and 1-cycle was significantly higher than 0- and 2-cycles following -11C (Table 4.7), however cycle had no effect on dry weight (Table 4.8). In November in the second year, cycle had an effect on rating and dry weight for which 2-cycles were significantly higher than 0- and 1-cycles following -8C and -11C. 1-cycles were also significantly higher than 0-cycles following -8C for both rating and dry weight. Also in the second year, cycle also had an effect following -5C on rating for which 0-cycles were significantly higher than 1-cycle and on dry weight for which 0-cycles were significantly higher than

1- and 2-cycles. Cycle had an effect in January in the first year on rating for which 0-cycles were significantly higher than 1- and 2-cycles following -2C, -5C, -8C, and -11C (Table 4.9) and on dry weight following -2C, -5C, and -8C (Table 4.10). The same effect was seen in the second year on rating following -5C. Also in the second year, cycle had an effect on rating for which 2-cycles were significantly higher than 0- and 1-cycles following -11C. Cycle had no effect in the second year on dry weight. Cycle had an effect in March in the first year on rating for which 0- and 1-cycles were significantly higher than 2-cycles following -2C (Table 4.11). The same effect was seen on dry weight following -5C (Table 4.12). Also in the first year on dry weight, 0-cycles were significantly higher than 1- and 2-cycles and 1-cycles were significantly higher than 2-cycles following -2C. In the second year, 2-cycles were significantly higher than 0-cycles for rating with no interactions. Cycle had no effect in the second year on dry weight.

For *Leucanthemum* x *superbum* 'Becky' in the first year, an increased number of cycles in November had an advantageous effect on plant survival although the opposite effect occurred in January and March. The difference between November and January in this study year is a reflection of near compete plant loss in January for 1-cycle and 2-cycles, the reason for which is uncertain. Other cultivars in the same freezer did not show the same losses, although *Leucanthemum* may be less hardy than the others, and *Leucanthemum* did not show the same degree of loss with other cycles, other months, or in the second year. The difference between November and March in this study year is possibly due to the differences in acclimation and deacclimation processes and energy reserve of the plant at the beginning and end of the overwintering season. In the second year, an increased number of cycles in all months had an advantageous effect on plant survival. In previous studies with other cultivars, an increased number of cycles improving hardiness was seen in January and once in March (Perry et al., 1996; Bruce, 2003; Luchini, 2005). The difference of date that cycles had an effect between these studies and the current study may be due to cultivar or cultural differences, although the effect of cycles improving hardiness is consistent.

Where no interaction occurred, temperature effects were observed for *Leucanthemum* x *superbum* 'Becky' in the first year in November on dry weight (-8C, -11C, and -14C significantly lower than -2C and -5C; -5C significantly lower than -2C). Temperature effects observed with no interaction in the second year were in January on dry weight (-11C and -14C significantly lower than -2C, -5C, and -8C; -8C significantly lower than -2C), in March on rating (-14C significantly lower than all other temperatures; -11C significantly lower than -2C, -5C, and -8C; -8C significantly lower than -2C and -5C) and in March on dry weight for (-11C and -14C significantly lower than -2C, -5C, and -8C; -8C significantly lower than -2C and -5C).

Where interaction occurred, the same temperature effects were observed for *Leucanthemum* x *superbum* 'Becky' in the first year on rating in November and on dry weight in March with 0-cycles, also in the second year on both rating and dry weight in November with 0-cycles (-8C, -11C, and -14C significantly lower than -2C and -5C). The same temperature effects were also observed in the first year on rating in November with 2-cycles and on rating in March with 0-cycles, also in the second year on both rating and dry weight in November with 1-cycle and on rating in January with 1-cycle (-11C and -14C significantly lower than -2C, -5C, and -8C; -8C significantly lower than -2C and -5C). Also, the same temperature effects were observed in the first year in March with 1-cycle and in the second year in November with 2-cycles (-11C and -14C significantly lower than -2C, -5C, and -8C).

Additional temperature effects were observed for *Leucanthemum* x *superbum* 'Becky' in the first year on rating in November with 1-cycles (-8C and -14C significantly lower than -2C, -5C, and -11C; -11C significantly lower than -2C), in January with 0-cycles (-14C significantly lower than all other temperatures; -11C significantly lower than -2C, -5C, and -8C; -5C and -8C significantly lower than -2C) and in March with 2-cycles (-14C significantly lower than -2C, -5C, and -8C). In the second year, temperature effects on rating were observed in January with 0-cycles (-14C significantly lower than all other temperatures; -11C significantly lower than -2C, -5C, and -8C), and in January with 2-cycles (-14C significantly lower than -2C, -5C, and -8C; -11C significantly lower than -2C and -5C). Temperature effects were observed in the first year on dry weight in January with 0-cycles (-11C and -14C significantly lower than -2C, -5C, and -8C; -8C significantly lower than -2C and -5C; -5C significantly lower than -2C) and in March with 1-cycle (-8C, -11C, and -14C significantly lower than -2C and -5C; -2C significantly lower than -5C). Temperature effects were observed in the second year on dry weight in November with 2-cycles (-11C and -14C significantly lower than -2C, -5C and -8C; -5C significantly lower than -2C).

In the first year of the study, all individual *Leucanthemum* x *superbum* 'Becky' plants achieved at least minimal salable quality in November following -2C with 0-cycles, -2C with 1-cycle, and -2C and -5C with 2-cycles; in January following -2C and -5C with 0-cycles; and in March following -2C with 0-cycles, and -2C and -5C with

1-cycle. Mean achieved salable quality, although some individual plants were below minimal salable quality, in November following -5C with 1-cycle; in January following -8C with 0-cycles; and in March following -5C with 0-cycles, and -8C with 1-cycle. While some individual plants achieved at least minimal salable quality, means were below salable quality in November following -5C and -8C with 0-cycles, -11C with 1-cycle, and -8C with 2-cycles; in January following -11C with 0-cycles; and in March following -8C with 0-cycles, and -2C, -5C, and -8C with 2-cycles. No individual plants were of salable quality in November following -11C and -14C with 0-cycles, -8C and -14C with 1-cycle, and -11C and -14C with 2-cycles; in January following -14C with 0-cycles, all freezing temperatures with 1-cycle and 2-cycles; and in March following -11C and -14C with all cycles.

In the second year of the study, all *Leucanthemum* x *superbum* 'Becky' plants achieved at least minimal salable quality in November following -5C with 0-cycles, and -2C and -8C with 2-cycles; in January following -2C and -5C with all cycles; and in March following -2C and -5C with 0-cycles and 1 cycle, and -5C with 2-cycles. Mean achieved salable quality, although some individual plants were below minimal salable quality, in November following -2C with 1-cycles; in January following -8C with 0-cycles; and in March following -2C with 2-cycles. While some individual plants achieved at least minimal salable quality, means were below salable quality in November following -2C with 0-cycles, -5C with 1-cycle, and -5C with 2-cycles; in January following -8C with 1-cycle, and -8C, -11C, and -14C with 2-cycles; and in March following -8C with 2-cycles. No individual plants were of salable quality in November following -8C, -11C, and -14C with 0-cycles and 1-cycle, and -11C and -14C with

2-cycles; in January following -11C and -14C with 0-cycles and 1 cycle; and in March following -8C, -11C, and -14C with 0-cycles and 1-cycle, and -11C and -14C with 2-cycles.

For *Leucanthemum* x *superbum* 'Becky' in the first year, the effects of the number of temperature cycles in January in the first year of the study were much more pronounced than in any other month or year of the study. This could be interpreted as plants being more tolerant of temperature cycling in November and March than in January although this conclusion is questionable due to near compete plant loss in January. Indeed, these conclusions are very different from other cultivars in this and previous studies (Iles et al., 1995; Perry et al., 1996; Luchini, 2005). A more plausible conclusion might be made from the second year of the study when there was no drastic plant loss. In the second year of the study, the effects of the number of temperature cycles were more pronounced in November and in March than in January. Dry weights were also higher in January. This can be interpreted as plants being more tolerant of temperature cycling in January than in November or in March. This conclusion is consistent with this and previous studies of other cultivars where cycling in January was less detrimental in November and/or March (Iles et al., 1995; Perry et al., 1996; Luchini, 2005). Temperature effects on rating and dry weight for all months in both years were observed as means generally decreasing with decreasing temperature. This can be interpreted to suggest that tolerance of freezing temperatures is not affected by time of year.

From the three containerized herbaceous perennial cultivars studied, a definitive effect of the number of cycles on containerized herbaceous perennial survival and salable quality following exposure to freezing temperatures could not be established. However, the general tendency was for one or two cycles to increase hardiness over no cycles, as seen with *Geranium* x *cantabrigiense* 'Cambridge', *Sedum* 'Matrona', and *Leucanthemum* x *superbum* 'Becky' in the second study year. This is in agreement with previous studies of container-grown herbaceous perennials that showed an increased number of cycles improving hardiness in January and once in March with other cultivars (Perry et al., 1996; Bruce, 2003; Luchini, 2005). The difference of date that cycles had an effect between these studies and the current study may be due to cultivar or cultural differences, although the effect of cycles improving hardiness is consistent. The effect of cycling appeared more advantageous in November or January than in March for all but *Leucanthemum* in the first study year of. The near complete plant loss in January of *Leucanthemum* undoubtedly contributed to this incongruity.

From the three containerized herbaceous perennial cultivars studied, a definitive effect of temperature cycling date on containerized herbaceous perennial survival and salable quality following exposure to freezing temperatures could not be established in these studies. However, the general tendency was for hardiness to be higher in January than in November or March, as seen with *Geranium* x *cantabrigiense* 'Cambridge', *Sedum* 'Matrona', and *Leucanthemum* x *superbum* 'Becky' in the second study year. This is in agreement with previous studies of container-grown herbaceous perennials that showed increased hardiness of several cultivars in January than in November and in March (Iles et al., 1995; Perry et al., 1996; Luchini, 2005). In contrast, in the first study year of *Leucanthemum*, cycling in November and March were less detrimental than in

January. The near complete plant loss in January of *Leucanthemum* undoubtedly contributed to this incongruity.

Growing season and overwintering conditions may affect response to temperature fluctuations and timing of cycling, possibly explaining why *Leucanthemum* x *superbum* 'Becky' showed opposite results from the first study year to the next study year. These results signify a need for future studies to assess temperature cycling in multiple growing and overwintering periods in order to develop more conclusive results for any cultivar.

The temperature fluctuations a plant is subjected to during the winter period, such as a midwinter thaw, may affect survival of subsequent freezing temperatures. However, this study adds to the evidence suggesting that herbaceous perennial plants can be resistant to these fluctuations, particularly in midwinter. This is valuable information for growers facing these overwintering conditions.

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Table 4.1. Effect of temperature cycling date and freezing temperatures on quality rating[a] of *Geranium* x *cantabrigiense* 'Cambridge' regrowth.

	November 2004-2005				January 2004-2005				March 2004-2005			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	3.00	2.83	2.83	2.89 (0.18) a [f]	2.83	2.50	3.17	2.83 (0.20)	3.17	2.67	2.17	2.67 (0.16) a
-5	2.50	2.67	2.83	2.67 (0.14) a	2.67	2.50	2.83	2.67 (0.14)	2.67	2.50	2.17	2.44 (0.15) ab
-8	2.67	3.00	3.00	2.89 (0.16) a	2.83	2.00	2.33	2.39 (0.14)	2.33	2.67	2.33	2.44 (0.12) ab
-11	2.17	3.00	2.67	2.61 (0.14) ab	3.00	2.83	2.67	2.83 (0.15)	2.17	2.17	2.17	2.17 (0.12) ab
-14	1.33	2.50	2.17	2.00 (0.18) b	3.00	2.50	2.83	2.78 (0.17)	1.83	2.33	1.67	1.94 (0.13) b
Mean (SEM)	2.33 B [g] (0.16)	2.80 A (0.13)	2.70 AB (0.10)		2.87 (0.15)	2.47 (0.10)	2.77 (0.11)		2.43 AB (0.12)	2.47 A (0.09)	2.10 B (0.11)	

ANOVA significance:

	df [h]	*F* [i]	*p*-value [k]	df	*F*	*p*-value	df	*F*	*p*-value
Temperature	4	5.51	0.0006	4	1.33	0.2680	4	4.69	0.0020
Month	2	4.18	0.0190	2	2.75	0.0706	2	4.08	0.0208
Interaction	8	1.07	0.3929	8	0.60	0.7713	8	1.32	0.2451

[a]Rating scale 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 0-2 flowering stems and regrowth extending over edge of pot, 4 = 3-5 flowering stems and regrowth equal to or greater than above, 5 = 6 or more flowering stems and regrowth as above.
[b]0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c]1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d]2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e]SEM=Standard Error of the Mean.
[f]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]Where no interaction present between factors, month means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h]df=degrees of freedom.
[i]*F*=*F* distribution.
[k]p-value=level of significance.

Table 4.2. Effect of temperature cycling date and freezing temperatures on dry weight of *Geranium* x *cantabrigiense* 'Cambridge' regrowth.

	November 2004-2005				January 2004-2005				March 2004-2005			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	0.27	0.38	0.40	0.35 (0.03) a [f]	0.42	0.35	0.22	0.33 (0.03)	0.40	0.46	0.25	0.37 (0.03) a
-5	0.19	0.28	0.28	0.25 (0.03) ab	0.27	0.34	0.30	0.30 (0.03)	0.32	0.32	0.26	0.30 (0.02) ab
-8	0.22	0.26	0.34	0.27 (0.03) a	0.27	0.18	0.30	0.25 (0.04)	0.20	0.29	0.31	0.26 (0.03) b
-11	0.12	0.33	0.34	0.26 (0.03) a	0.30	0.26	0.27	0.28 (0.03)	0.28	0.32	0.26	0.29 (0.03) ab
-14	0.6	0.16	0.22	0.15 (0.02) b	0.34	0.33	0.30	0.32 (0.03)	0.17	0.32	0.17	0.22 (0.03) b
Mean (SEM)	0.17 B [g] (0.02)	0.28 A (0.02)	0.31 A (0.02)		0.32 (0.03)	0.29 (0.02)	0.28 (0.02)		0.27 AB (0.02)	0.34 A (0.02)	0.25 B (0.02)	

ANOVA significance:

	df [h]	F [i]	p-value [k]	df	F	p-value	df	F	p-value
Temperature	4	6.81	<.0001	4	1.05	0.3862	4	4.56	0.0024
Month	2	12.27	<.0001	2	0.65	0.5226	2	5.59	0.0054
Interaction	8	0.54	0.8200	8	1.14	0.3496	8	1.67	0.1195

[b] 0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c] 1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d] 2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e] SEM=Standard Error of the Mean.
[f] Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g] Where no interaction present between factors, month means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h] df=degrees of freedom.
[i] F=F distribution.
[k] p-value=level of significance.

Table 4.3. Effect of temperature cycling date and freezing temperatures on quality rating[a] of *Sedum* 'Matrona' regrowth.

	November 2005-2006				January 2005-2006				March 2005-2006			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	2.50	2.00	2.67	2.39 (0.27) a [f]	na	3.17	2.67	2.92 (0.36)	1.67	1.83	1.67	1.72 (0.14) ab
-5	2.83	1.17	2.17	2.06 (0.31) a	na	3.00	2.67	2.83 (0.24)	2.17	1.83	2.00	2.00 (0.18) a
-8	1.00	1.00	1.33	1.11 (0.11) b	na	3.17	2.83	3.00 (0.28)	1.00	1.67	1.83	1.50 (0.20) abc
-11	1.00	1.50	1.00	1.17 (0.17) b	na	2.67	2.50	2.58 (0.34)	1.17	1.50	1.50	1.39 (0.12) bc
-14	1.00	1.00	1.33	1.11 (0.11) b	na	2.17	2.00	2.08 (0.36)	1.00	1.00	1.17	1.06 (0.06) c
Mean (SEM)	1.67 [g] (0.22)	1.33 (0.15)	1.70 (0.19)		na	2.83 (0.20)	2.53 (0.21)		1.40 (0.10)	1.57 (0.11)	1.63 (0.16)	

ANOVA significance:

	df [h]	F [i]	p-value [k]	df	F	p-value	df	F	p-value
Temperature	4	9.06	<.0001	4	1.27	0.2957	4	5.67	0.0005
Month	2	1.67	0.1958	1	1.04	0.3125	2	1.08	0.3437
Interaction	8	1.57	0.1474	4	0.04	0.9961	8	0.77	0.6294

[a]Rating scale 1 = Dead, no regrowth, 2 = Foliage regrowth of less than or equal to 6 inches (15 cm), 3 = 1 flowering stem, regrowth over 6 inches (15 cm), 4 = 2 flowering stems, regrowth over 6 inches (15 cm), 5 = 3 or more flowering stems, regrowth over 6 inches (15 cm).
[b]0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c]1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d]2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e]SEM=Standard Error of the Mean.
[f]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]Where no interaction present between factors, cycle means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h]df=degrees of freedom.
[i]F=F distribution.
[k]p-value=level of significance.

Table 4.4. Effect of temperature cycling date and freezing temperatures on dry weight of *Sedum* 'Matrona' regrowth.

	November 2005-2006				January 2005-2006				March 2005-2006			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	1.06	0.45	1.49	1.00 (0.24) a [f]	na	1.13	1.63	1.38 (0.43)	0.16	0.51	0.36	0.35 (0.11)
-5	1.12	0.09	1.02	0.74 (0.23) ab	na	1.17	1.20	1.19 (0.24)	0.68	0.40	0.81	0.63 (0.17)
-8	0.00	0.00	0.20	0.07 (0.07) b	na	1.43	1.94	1.68 (0.43)	0.00	0.69	0.85	0.51 (0.19)
-11	0.00	0.78	0.00	0.26 (0.26) ab	na	1.31	1.24	1.28 (0.39)	0.07	0.70	0.73	0.50 (0.19)
-14	0.00	0.00	0.48	0.16 (0.16) b	na	0.82	0.95	0.89 (0.36)	0.00	0.00	0.32	0.11 (0.11)
Mean (SEM)	0.44 [g] (0.15)	0.26 (0.16)	0.64 (0.19)		na	1.17 (0.19)	1.39 (0.27)		0.18 B (0.07)	0.46 AB (0.13)	0.61 A (0.15)	
ANOVA significance:												
	df [h]	F [i]	p-value [k]		df	F	p-value		df	F	p-value	
Temperature	4	4.11	0.0046		4	0.55	0.7033		4	1.63	0.1757	
Month	2	1.47	0.2361		1	0.39	0.5368		2	3.23	0.0450	
Interaction	8	1.49	0.1744		4	0.12	0.9743		8	0.70	0.6883	

[b] 0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c] 1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d] 2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e] SEM=Standard Error of the Mean.
[f] Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g] Where no interaction present between factors, cycle means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h] df=degrees of freedom.
[i] F=F distribution.
[k] p-value=level of significance.

Table 4.5. Effect of temperature cycling date and freezing temperatures on quality rating[a] of *Leucanthemum* x *superbum* 'Becky' regrowth, Year 1.

	November 2004-2005				January 2004-2005				March 2004-2005			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	3.50 a [fg]	3.67 a	3.83 a	3.67 (0.16)	4.17 Aa	1.00 B	1.00 B	2.06 (0.37)	4.67 Aa	4.17 Aa	2.17 Ba	3.67 (0.31)
-5	2.67 Ba	3.50 ABab	4.00 Aa	3.39 (0.23)	3.50 Ab	1.00 B	1.00 B	1.83 (0.29)	3.83 Aa	4.33 Aa	2.83 ABa	3.67 (0.28)
-8	1.50 b	1.33 c	2.00 b	1.61 (0.24)	3.17 Ab	1.00 B	1.00 B	1.72 (0.29)	2.33 b	3.17 ab	2.17 a	2.56 (0.33)
-11	1.00 Bb	2.67 Ab	1.00 Bc	1.56 (0.26)	1.83 Ac	1.00 B	1.00 B	1.28 (0.18)	1.00 c	1.17 c	1.17 ab	1.11 (0.08)
-14	1.00 b	1.00 c	1.00 c	1.00 (0.00)	1.17 d	1.00	1.17	1.11 (0.08)	1.00 c	1.17 c	1.00 b	1.06 (0.06)
Mean (SEM)	1.93 (0.23)	2.43 (0.24)	2.37 (0.27)		2.77 (0.25)	1.00 (0.00)	1.03 (0.03)		2.57 (0.31)	2.80 (0.29)	1.87 (0.21)	

ANOVA significance:

	df [h]	*F* [i]	*p*-value [k]	df	*F*	*p*-value	df	*F*	*p*-value
Temperature	4	43.50	<.0001	4	11.84	<.0001	4	39.33	<.0001
Month	2	3.71	0.0290	2	130.05	<.0001	2	9.23	0.0003
Interaction	8	2.92	0.0068	8	13.54	<.0001	8	2.86	0.0080

[a]Rating scale 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 1 flowering stem and minimal regrowth, 4 = 0-1 flowering stems and vigorous regrowth, 5 = 2 or more flowering stems and vigorous regrowth.
[b]0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c]1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d]2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e]SEM=Standard Error of the Mean.
[f]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]Where interaction present between factors, means between cycle for a single treatment temperature with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h]df=degrees of freedom.
[i]*F*=*F* distribution.
[k]p-value=level of significance.

Table 4.6. Effect of temperature cycling date and freezing temperatures on quality rating[a] of *Leucanthemum* x *superbum* 'Becky' regrowth, Year 2.

	November 2005-2006				January 2005-2006				March 2005-2006			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	2.83 a [fg]	3.00 a	3.00 a	2.94 (0.10)	3.00 a	3.17 a	3.00 a	3.06 (0.06)	3.17	3.33	3.00	3.17 (0.12) a
-5	3.33 Aa	2.67 Ba	2.83 ABa	2.94 (0.19)	3.17 a	3.33 a	3.33 a	3.28 (0.11)	3.33	3.33	3.50	3.39 (0.12) a
-8	1.00 Cb	2.00 Bb	3.17 Aa	2.06 (0.22)	3.50 Aa	2.50 Bb	2.83 Bab	2.94 (0.17)	1.67	2.00	2.33	2.00 (0.14) b
-11	1.00 Bb	1.00 Bc	1.83 Ab	1.28 (0.11)	1.83 Bb	1.67 Bc	2.33 ABbc	1.94 (0.13)	1.00	1.67	2.00	1.56 (0.12) c
-14	1.00 b	1.00 c	1.33 b	1.11 (0.08)	1.00 Bc	1.17 Bc	1.83 Ac	1.33 (0.14)	1.00	1.00	1.17	1.06 (0.06) d
Mean (SEM)	1.83 (0.20)	1.93 (0.17)	2.43 (0.17)		2.50 (0.19)	2.37 (0.18)	2.67 (0.13)		2.03 B [m] (0.20)	2.27 AB (0.19)	2.40 A (0.18)	

ANOVA significance:

	df [h]	F [i]	p-value [k]	df	F	p-value	df	F	p-value
Temperature	4	67.72	<.0001	4	54.13	<.0001	4	91.40	<.0001
Month	2	15.16	<.0001	2	2.93	0.0594	2	5.11	0.0083
Interaction	8	7.76	<.0001	8	3.11	0.0043	8	1.81	0.0877

[a]Rating scale 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 1 flowering stem and minimal regrowth, 4 = 0-1 flowering stems and vigorous regrowth, 5 = 2 or more flowering stems and vigorous regrowth.
[b]0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c]1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d]2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e]SEM=Standard Error of the Mean.
[f]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]Where interaction present between factors, means between cycle for a single treatment temperature with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[m]Where no interaction present between factors, cycle means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h]df=degrees of freedom.
[i]F=F distribution.
[k]p-value=level of significance.

Table 4.7. Effect of temperature cycling date and freezing temperatures on dry weight of *Leucanthemum* x *superbum* 'Becky' regrowth, Year 1.

	November 2004-2005				January 2004-2005				March 2004-2005			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	2.81	3.04	2.70	2.85 (0.20) a [f]	2.23 Aa [g]	0.00 B	0.00 B	0.74 (0.28)	2.94 Aa	2.10 Bb	0.17 C	1.74 (0.35)
-5	1.61	1.76	2.31	1.89 (0.27) b	1.59 Ab	0.00 B	0.00 B	0.53 (0.18)	2.23 Aa	2.91 Aa	0.50 B	1.88 (0.33)
-8	0.00	0.05	0.69	0.25 (0.15) c	1.02 Ac	0.00 B	0.00 B	0.34 (0.17)	0.61 b	0.52 c	0.22	0.45 (0.15)
-11	0.00	0.96	0.00	0.32 (0.19) c	0.22 d	0.00	0.00	0.07 (0.05)	0.00 b	0.00 c	0.05	0.02 (0.02)
-14	0.00	0.00	0.00	0.00 (0.00) c	0.00 d	0.00	0.09	0.03 (0.03)	0.00 b	0.00 c	0.00	0.00 (0.00)
Mean (SEM)	0.88 [m] (0.25)	1.16 (0.25)	1.14 (0.25)		1.01 (0.19)	0.00 (0.00)	0.02 (0.02)		1.15 (0.26)	1.11 (0.26)	0.19 (0.07)	

ANOVA significance:

	df [h]	F [i]	p-value [k]	df	F	p-value	df	F	p-value
Temperature	4	47.22	<.0001	4	12.03	<.0001	4	34.13	<.0001
Month	2	1.20	0.3075	2	73.35	<.0001	2	19.78	<.0001
Interaction	8	1.27	0.2717	8	13.06	<.0001	8	7.07	<.0001

[b] 0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c] 1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d] 2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e] SEM=Standard Error of the Mean.
[f] Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g] Where interaction present between factors, means between cycle for a single treatment temperature with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[m] Where no interaction present between factors, cycle means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h] df=degrees of freedom.
[i] F=F distribution.
[k] p-value=level of significance.

Table 4.8. Effect of temperature cycling date and freezing temperatures on dry weight of *Leucanthemum* x *superbum* 'Becky' regrowth, Year 2.

	November 2005-2006				January 2005-2006				March 2005-2006			
Treatment temp °C	0-cycles [b]	1-cycle [c]	2-cycle [d]	Mean (SEM [e])	0-cycles	1-cycle	2-cycle	Mean (SEM)	0-cycles	1-cycle	2-cycle	Mean (SEM)
-2	1.26 a [fg]	1.32 a	1.40 a	1.32 (0.07)	2.30	2.07	1.93	2.10 (0.10) a	1.51	1.89	1.35	1.58 (0.11) a
-5	1.51 Aa	1.18 Ba	1.06 Bb	1.25 (0.12)	1.77	1.83	1.56	1.72 (0.16) ab	1.92	1.80	1.72	1.81 (0.11) a
-8	0.00 Cb	0.35 Bb	1.29 Aab	0.55 (0.14)	1.50	1.38	1.29	1.39 (0.14) b	0.26	0.66	0.63	0.52 (0.08) b
-11	0.00 Bb	0.00 Bc	0.35 Ac	0.12 (0.05)	0.37	0.40	0.69	0.49 (0.10) c	0.00	0.04	0.27	0.10 (0.03) c
-14	0.00 b	0.00 c	0.06 c	0.02 (0.01)	0.00	0.10	0.24	0.11 (0.06) c	0.00	0.00	0.04	0.01 (0.01) c
Mean (SEM)	0.55 (0.13)	0.57 (0.11)	0.83 (0.12)		1.19 [m] (0.18)	1.16 (0.17)	1.14 (0.14)		0.74 (0.16)	0.88 (0.16)	0.80 (0.14)	

ANOVA significance:

	df [h]	*F* [i]	*p*-value [k]	df	*F*	*p*-value	df	*F*	*p*-value
Temperature	4	86.38	<.0001	4	49.42	<.0001	4	114.24	<.0001
Month	2	9.35	0.0002	2	0.06	0.9426	2	1.33	0.2702
Interaction	8	8.10	<.0001	8	0.63	0.7491	8	1.85	0.0804

[b]0 cycle plants were not subjected to temperature fluctuations prior to controlled freezing at lower temperatures.
[c]1 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing t lower temperatures.
[d]2 cycle plants were held at -2C for 24 hours, then held at 3C for 24 hours, then held at -2C for 24 hours, then held at 3C for 24 hours prior to controlled freezing at lower temperatures.
[e]SEM=Standard Error of the Mean.
[f]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[g]Where interaction present between factors, means between cycle for a single treatment temperature with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[m]Where no interaction present between factors, cycle means with a capital letter in common are not significantly different according to Tukey's procedure (p=0.05).
[h]df=degrees of freedom.
[i]*F*=*F* distribution.
[k]p-value=level of significance.

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<u>Appendix A: Assessment of Cold Hardiness for Newer Varieties of Container-Grown Herbaceous Perennials</u>

Introduction

The plants used in this study can be divided into three functional groups: conventional perennials, ornamental grasses, and perennial groundcovers. The recently introduced cultivars in each of these groups are readily available and information on their cold hardiness will be of value to growers.

Materials and Methods

The conventional perennials studied were *Aster dumosus* 'Wood's Blue', *Campanula carpatica* 'Blue Clips', *Coreopsis* 'Tequila Sunrise', *Dianthus deltoides* 'Microchip', *Echinacea purpurea* 'White Swan', *Geranium* x *cantabrigiense* 'Cambridge', *Heuchera villosa* 'Autumn Bride', *Heuchera* 'Plum Pudding', *Leucanthemum* x *superbum* 'Becky', *Phlox paniculata* 'Robert Poore', *Sedum* 'Matrona', and *Veronica spicata* 'Goodness Grows'. The ornamental grasses studied were *Miscanthus sinensis* 'Adagio', *Miscanthus sinensis* 'Gold und Silber', *Miscanthus sinensis* 'Puenktchen', *Miscanthus sinensis* 'Rigoletto', and *Miscanthus sinensis* 'Sarabande'. The perennial groundcovers studied were *Anacyclus depressus compactum* 'Silver Kisses', *Armeria* 'Victor Reiter', *Armeria maritima* 'Rubifolia', *Artemesia viridis* 'Tiny Green', *Dianthus gratianopolitanus* 'Tiny Rubies', *Erysimum kotschyanum* 'Orange Flame', *Mazus reptans* 'Purple', *Potentilla crantzii* 'Pygmaea', *Veronica allionii (*Alpine Speedwell), and *Veronica surculosa* 'Waterperry Blue'.

In each year of the study, 30 plants per species were established for each cultivar. Plants were obtained as liners with 36-72 individual plants per flat (56x28cm (22x11in), depending on species and transferred into in #SP4 (‘Classic 100’, 900ml (54.9in^3)) (*Miscanthus* cultivars only) or #SP3 (10cm (4in), 400ml (24.4in^3)) (all other cultivars) plastic pots at the beginning of the study growing season. All plants were potted with ProMix BX medium (Premier Horticultural Products, Red Hill, PA).

Plants were allowed to establish over a normal growing season in a glass greenhouse at the University of Vermont, Burlington, Vermont, under near-ambient temperature. Greenhouse temperatures were managed by direct venting and radiant heat as needed. Plants were watered by greenhouse staff as needed throughout the studies. Water soluble fertilizer was applied once weekly throughout the growing season: Jack’s Professional 17-4-17 (J.R. Peters, Inc, Allentown, PA) delivered at 150ppm nitrogen and Peters Professional S.T.E.M. soluble trace elements (The Scotts Company) delivered at 5ppm boron, 12ppm copper, 28ppm iron, 30ppm manganese, 0.15ppm molybdenum, 52.5ppm sulfur, and 16.9ppm zinc. Temperatures in the greenhouse were reduced beginning in October of each year at a rate of 3C (5F) per week until temperatures of 3-5C (37-41F) were reached at the end of November. This low temperature was maintained in the greenhouse until spring when the temperature was increased by the same increments beginning in April of each year until ambient temperature was reached.

During the month of January, the 30 plants of each cultivar were randomly divided into five, six-pot groups and pruned back to within one inch above the level of the pot rim. Controlled freezing of each six-pot group to temperatures of -2, -5, -8, -11, and -14C (28.4, 23.0, 17.6, 12.2, 6.8F) was performed as developed in previous studies

(Herrick, 1996; Meyer, 1999; Bruce, 2003; Luchini, 2005). Plants were randomized by target freezing temperature and placed in heavy-weight standard open-mesh flats (‘1020’, 56x28cm (22x11in)). Flats were loaded into the freezer alternately stacked with wooden supports to allow air flow around pots to achieve uniform temperature within the freezer. Plants with the lowest target freezing temperatures were loaded first, followed by the second-lowest, and so on until the highest target temperature plants were loaded on the top level within the freezer. Loading by target freezing temperature minimized the amount of time that the freezer was open while removing plants, in turn minimizing temperature fluctuations, during the course of the entire freezing event.

Temperature in the insulated chest freezer (Model VWC15-ZL/E, W.C. Wood Co., Guelph, Canada) was controlled using a Dyna-Sense Mk III Versa-Lab Microprocessor Temperature Controller (Scientific Instruments, Skokie, IL) and monitored separately using a digital thermometer (Model HH611P4C, Omega Engineering, Stanford, CT) with a probe suspended within the freezer and a probe placed within a pot with the lowest target temperature. A 7.6cm (3in) cooling fan (Radio Shack, Fort Worth, TX) was placed on the floor of the freezer to circulate air within the freezer. A thermocouple-based temperature recorder with internal temperature sensor (TC4000, Madgetech, Contoocook, NH) was placed alongside the pots with the lowest target temperature to record temperatures during the course of the freezing event.

Freezer temperatures were held at -2C (28.4F) for 24 hours prior to loading plants then maintained at that temperature for 48 hours following loading of plants to thoroughly achieve a uniform soil temperature among the plants. At that point, a six-pot group of each cultivar was removed from the freezer. The freezer air temperature was then set to -5C (23.0F), which was achieved within 30 minutes, then held for 2 hours. During this time, the pot soil temperatures achieved target temperature 2 hours after the initial temperature setting and remained at the target temperature for 30 minutes. After this period, a six-pot group of each cultivar was removed. The freezer was then set to -8C (17.6F) and the process continued, with subsequent removal of pots, at -11C (12.2F) and -14C (6.8F) target temperatures. Following removal from the freezer, plants were returned to the 3-5C (37-41F) greenhouse where they were maintained through the return to ambient temperatures in spring as described above.

In June, plants were assessed for survival, growth and vigor. A visual rating scale of 1-5 was used with specific growth parameters defined for each cultivar (Tables A.1-A.6). A rating of 3 or more was considered satisfactory for retail sale. Salable quality, with attractive factors such as flowers and growing points, is important than quantity of growth to growers and consumers. Following visual rating, plant regrowth from each pot was harvested to within one inch above the level of the pot rim. Harvested growth from each plant was placed in an individual paper bag and stored in a drying oven at 60C (140F) for one week prior to weighing to 0.01g on an electronic balance for determination of dry weight. Dry weights were not assessed for perennial groundcovers due to the compact and dense growth habits of the plants.

Data from each cultivar was analyzed to compare effects of freezing temperatures. Visual ratings and dry weights were assessed for analysis of variance (ANOVA) using SAS 9.1 and Tukey’s procedure was used for mean separation when appropriate.

Results and Discussion

Conventional perennials

(Tables A.2-A.3)

No temperature effects were observed on rating for *Aster dumosus* 'Wood's Blue', although temperature effects on dry weight were observed (-14C significantly lower than -5C and -8C). All plants achieved at least minimal salable quality (rating of 3) following all freezing temperatures.

No temperature effects were observed on either rating or dry weight for *Campanula carpatica* 'Blue Clips'. All plants achieved at least minimal salable quality following all freezing temperatures.

Temperature effects on rating were observed for *Coreopsis* 'Tequila Sunrise' (-14C significantly lower than -2C and -5C), although no temperature effects on dry weight were observed. No individual plants were of salable quality following -2C, -11C, and -14C freezing temperatures. While some individual plants achieved at least minimal salable quality, means were below salable quality following -5C and -8C freezing temperatures.

No temperature effects were observed on rating for *Dianthus deltoides* 'Microchip', although temperature effects on dry weight were observed (-14C significantly lower than -2C). While some individual plants achieved at least minimal salable quality, means were below salable quality following -5C, -8C, -11C, and -14C freezing temperatures. Means achieved at least minimal salable quality following -2C temperatures although some individual plants were below minimal salable quality.

No temperature effects were observed on either rating or dry weight for *Echinacea purpurea* 'White Swan'. Means achieved at least minimal salable quality following -2C, -5C, and -8C temperatures although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on either rating or dry weight for *Geranium* x *cantabrigiense* 'Cambridge'. All plants achieved at least minimal salable quality following all freezing temperatures.

No temperature effects were observed on rating for *Heuchera villosa* 'Autumn Bride', although temperature effects on dry weight were observed (-14C significantly lower than -2C, -5C, and -8C). While some individual plants achieved at least minimal salable quality, means were below salable quality following -14C freezing temperatures. Means achieved at least minimal salable quality following -2C and -11C temperatures although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on rating for *Heuchera* 'Plum Pudding', although temperature effects on dry weight were observed (-11C and -14C significantly lower than all other temperatures). All plants achieved at least minimal salable quality following all freezing temperatures.

Temperature effects were observed for *Leucanthemum* x *superbum* 'Becky' on rating (-(-14C significantly lower than all other temperatures) and on dry weight (-11C and -14C significantly lower than -2C and -5C). While some individual plants achieved at least minimal salable quality, means were below salable quality following -14C freezing temperatures. Means achieved at least minimal salable quality following -11C temperatures although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on either rating or dry weight for *Sedum* 'Matrona'. While some individual plants achieved at least minimal salable quality, means were below salable quality following -11C and -14C freezing temperatures. Means achieved at least minimal salable quality following -5C temperatures although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on rating for *Phlox paniculata* 'Robert Poore', although temperature effects on dry weight were observed (-14C significantly lower than -11C and -5C). While some individual plants achieved at least minimal salable quality, means were below salable quality following -2C, -8C, and -11C freezing temperatures. Means achieved at least minimal salable quality following -5C and -14C temperatures although some individual plants were below minimal salable quality.

Temperature effects were observed for *Veronica spicata* 'Goodness Grows' on rating (-11C and -14C significantly lower than -5C) and on dry weight (-11C and -14C significantly lower than -5C and -8C). While some individual plants achieved at least minimal salable quality, means were below salable quality following -11C and-14C freezing temperatures. All plants achieved at least minimal salable quality following the other freezing temperatures.

Coreopsis 'Tequila Sunrise', *Dianthus deltoides* 'Microchip', and *Phlox paniculata* 'Robert Poore' rated the lowest in salable quality following freezing temperatures with combined means for each below salable quality. *Aster dumosus* 'Wood's Blue', *Campanula carpatica* 'Blue Clips', and *Echinacea purpurea* 'White Swan' rated the highest in salable quality following freezing temperatures. The top three and all other conventional perennial cultivars had combined means above salable quality. In terms of plant loss, *Coreopsis* 'Tequila Sunrise', *Leucanthemum* x *superbum* 'Becky', *Sedum* 'Matrona', and *Veronica spicata* 'Goodness Grows' suffered individual plant deaths. *Aster dumosus* 'Wood's Blue', *Campanula carpatica* 'Blue Clips', *Geranium x cantabrigiense* 'Cambridge', and *Heuchera* 'Plum Pudding' suffered no individual plant death following any freezing temperature.

Ornamental grasses

(Table A.5)

The same temperature effects were observed on both rating and dry weight for all *Miscanthus sinensis* cultivars (-11C and -14C significantly lower than all other temperatures) with the exception of 'Gold und Silber' dry weight (-11C and -14C significantly lower than -2C). Additional temperature effects were observed for 'Adagio' on dry weight (-8C significantly lower than -2C), and for 'Gold und Silber' on rating and for 'Puenktchen' and for 'Sarabande' on both rating and dry weight (-8C significantly lower than -2C and -5C). No individual plants were of salable quality following -11C and -14C freezing temperatures for all cultivars. While some individual plants achieved at least minimal salable quality, means were below salable quality following -8C freezing temperatures for 'Gold und Silber' and 'Sarabande'. Means achieved at least minimal salable quality following -8C temperatures, although some individual plants were below minimal salable quality, for 'Puenktchen'. Following all other freezing temperatures for all cultivars, plants achieved at least minimal salable quality.

All *Miscanthus sinensis* cultivars rated similarly in salable quality following freezing temperatures, although combined means for each were below salable quality. 'Gold und Silber' and 'Sarabande' rated the lowest in salable quality. In terms of plant loss, all cultivars suffered individual plant deaths following -14C. Only 'Rigoletto' had any individual plant survival following -11C, although none of them were of salable quality.

<u>Perennial groundcovers</u>

(Table A.7)

Temperature effects were observed for *Anacyclus depressus compactum* 'Silver Kisses' on rating (-14C significantly lower than all other temperatures). No individual plants were of salable quality following -14C freezing temperatures. Means achieved at least minimal salable quality following -11C temperatures, although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on rating for *Armeria maritima* 'Rubifolia'. While some individual plants achieved at least minimal salable quality, means were below salable quality following -14C freezing temperatures. Means achieved at least minimal salable quality following -11C temperatures, although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on rating for *Armeria* 'Victor Reiter'. Means achieved at least minimal salable quality following -5C, -8C, -11C, and -14C temperatures, although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on rating for *Artemesia viridis* 'Tiny Green'. While some individual plants achieved at least minimal salable quality, means were below salable quality following -14C freezing temperatures. Means achieved at least minimal salable quality following -11C temperatures, although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

No temperature effects were observed on rating for *Dianthus gratianopolitanus* 'Tiny Rubies'. Means achieved at least minimal salable quality following -2C, -5C, and -11C temperatures, although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

Temperature effects were observed for *Erysimum kotschyanum* 'Orange Flame' on rating (-2C significantly lower than -5C). While some individual plants achieved at least minimal salable quality, means were below salable quality following -2C, -8C, and-11C freezing temperatures. Means achieved at least minimal salable quality following -5C and -14C temperatures, although some individual plants were below minimal salable quality.

Temperature effects were observed for *Mazus reptans* 'Purple' on rating (-14C significantly lower than -8C). No individual plants were of salable quality following

-14C freezing temperatures. While some individual plants achieved at least minimal salable quality, means were below salable quality following -2C and -5C freezing temperatures. Means achieved at least minimal salable quality following -8C and -11C temperatures, although some individual plants were below minimal salable quality.

No temperature effects were observed on rating for *Potentilla crantzii* 'Pygmaea'. Means achieved at least minimal salable quality following -2C, -5C, and -14C temperatures, although some individual plants were below minimal salable quality. All plants achieved at least minimal salable quality following the other freezing temperatures.

Temperature effects were observed for *Veronica allionii (*Alpine Speedwell) on rating (-5C significantly lower than -2C, -11C, and -14C). All plants achieved at least minimal salable quality following all freezing temperatures.

Temperature effects were observed for *Veronica surculosa* 'Waterperry Blue' on rating (-14C significantly lower than all other temperatures). All plants achieved at least minimal salable quality following all freezing temperatures.

Erysimum kotschyanum 'Orange Flame' and *Mazus reptans* 'Purple' rated the lowest in salable quality following freezing temperatures with combined means for each below salable quality. *Potentilla crantzii* 'Pygmaea', *Veronica allionii (*Alpine Speedwell), and *Veronica surculosa* 'Waterperry Blue' rated the highest in salable quality following freezing temperatures. The top three and all other perennial groundcover cultivars had combined means above salable quality. In terms of plant loss, *Anacyclus depressus compactum* 'Silver Kisses', *Armeria* 'Victor Reiter', *Erysimum kotschyanum* 'Orange Flame', *Mazus reptans* 'Purple', and *Potentilla crantzii* 'Pygmaea' had individual plant deaths. Only *Veronica allionii (*Alpine Speedwell) and *Veronica surculosa* 'Waterperry Blue' suffered no individual plant death following any freezing temperature.

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Meyer, G.A. 1999. Electrolyte leakage as a predictor of freezing tolerance and seasonal cold acclimation patterns in Aster 'Wood's Pink' and Geranium x cantabrigiense cultivars. M.S. Thesis, Department of Plant and Soil Science, University of Vermont, Burlington, VT.

Table A.1. Rating Scales for Conventional Perennials.

***Aster* 'Woods Blue':** 1 = Dead, no regrowth, 2 = Minimal regrowth, 3 = 0-2 growing points, 4 = 3 growing points, 5 = 4 or more growing points .

***Campanula* 'Blue Clips':** 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 1 flowering stem and minimal regrowth, 4 = 1 or more flowering stems and vigorous regrowth, 5 = 1 or more flowering stems and vigorous regrowth extending to edge of pot.

***Coreopsis* 'Tequila Sunrise':** 1 = Dead, no regrowth, 2 = No flowering stems and foliage regrowth of less than 3 inches (8cm), 3 = Less than 3 flowering stems and regrowth of 3-5 inches (8-12cm), 4 = Less than 3 flowering stems and regrowth over 5 inches (12cm), 5 = 3 or more flowering stems and regrowth as above.

***Dianthus* 'Microchip':** 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = Flowering stems, dieback on 50% or more of foliage, 4 = Flowering stems, dieback on less than 50% of foliage, 5 = Flowering stems and no damaged foliage.

***Echinacea* 'White Swan':** 1 = Dead, no regrowth, 2 = 0-1 flowering stems and minimal regrowth, 3 = 0-1 flowering stems and vigorous regrowth, 4 = 1 flowering stems and vigorous regrowth with 0-2 basal shoots, 5 = 1 or more flowering stems and vigorous regrowth with 3 or more basal shoots.

***Geranium* x *cantabrigiense* 'Cambridge':** 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 0-2 flowering stems and regrowth extending over edge of pot, 4 = 3-5 flowering stems and regrowth equal to or greater than above, 5 = 6 or more flowering stems and regrowth as above.

***Heuchera* 'Autumn Bride':** 1 = Dead, no regrowth, 2 = single growing point, dwarfed foliage, 3 = single growing point, foliage healthy, 4 = two growing points, foliage healthy, 5 = three or more growing points, foliage healthy.

***Heuchera* 'Plum Pudding':** 1 = Foliage dieback evident and 0-1 flowering stems, 2 = Foliage dieback minimal and 2 flowering stems, 3 = Foliage healthy and 3 flowering stems, 4 = Foliage healthy and 4 flowering stems, 5 = Foliage healthy and 5 or more flowering stems.

***Leucanthemum* 'Becky':** 1 = Dead, no regrowth, 2 = No flowering stems and minimal regrowth, 3 = 1 flowering stem and minimal regrowth, 4 = 0-1 flowering stems and vigorous regrowth, 5 = 2 or more flowering stems and vigorous regrowth.

***Phlox pan.* 'Robert Poore':** 1 = Dead, no regrowth, 2 = 1 growing point, 3 = 2 growing points, 4 = 3 growing points, 5 = 4 or more growing points.

***Sedum* 'Matrona':** 1 = Dead, no regrowth, 2 = Foliage regrowth of less than or equal to 6 inches (15 cm), 3 = 1 flowering stem, regrowth over 6 inches (15 cm), 4 = 2 flowering stems, regrowth over 6 inches (15 cm), 5 = 3 or more flowering stems, regrowth over 6 inches (15 cm).

***Veronica* 'Goodness Grows':** 1 = Dead, no regrowth, 2 = Minimal regrowth, 3 = Vigorous regrowth over pot edge, 4 = Vigorous regrowth over pot edge with 1-2 flower stalks, 5 = Vigorous regrowth over pot edge 3 or more flower stalks.

Table A.2. Effect of freezing temperatures on quality rating[a] of conventional perennial regrowth.

Treatment temp °C	AWB [b]	C BC	CTS	DMC	EWS	GCC
-2	4.00 (0.37) [c]	4.17 (0.17)	2.00 (0.00) a	3.50 (0.56)	3.33 (0.49)	3.00 (0.00)
-5	4.00 (0.45)	4.00 (0.37)	2.17 (0.31) a	2.50 (0.34)	3.17 (0.54)	3.17 (0.17)
-8	4.00 (0.26)	4.50 (0.22)	1.83 (0.31) ab	2.33 (0.33)	3.33 (0.42)	3.17 (0.17)
-11	4.33 (0.42)	4.50 (0.22)	1.33 (0.21) ab	2.67 (0.42)	4.50 (0.34)	3.17 (0.17)
-14	4.50 (0.22)	3.83 (0.40)	1.00 (0.00) b	2.67 (0.33)	4.17 (0.31)	3.00 (0.00)
Mean (SEM[d])	4.17 (0.16)	4.20 (0.13)	1.67 (0.10)	2.73 (0.18)	3.70 (0.19)	3.10 (0.06)
df [e]	4	4	4	4	4	4
F [f]	0.44	1.05	5.06	1.22	1.90	0.50
p-value [g]	0.7767	0.4004	0.0040	0.3287	0.1416	0.7359

Treatment temp °C	HAB	HPP	LSB	PRP	SMA	VGG
-2	3.83 (0.54)	3.67 (0.21)	3.83 (0.31) a	2.33 (0.21)	3.17 (0.17)	3.00 (0.45) ab
-5	3.67 (0.33)	3.50 (0.22)	4.33 (0.33) a	3.17 (0.40)	4.00 (0.45)	4.00 (0.37) a
-8	3.33 (0.33)	3.33 (0.21)	4.33 (0.21) a	2.67 (0.33)	3.50 (0.22)	3.67 (0.33) ab
-11	3.17 (0.48)	3.33 (0.21)	3.67 (0.42) a	2.67 (0.21)	2.33 (0.61)	2.33 (0.33) b
-14	2.83 (0.54)	3.00 (0.00)	2.00 (0.45) b	3.17 (0.60)	2.83 (0.75)	2.33 (0.42) b
Mean (SEM[d])	3.37 (0.20)	3.37 (0.09)	3.63 (0.16)	2.80 (0.17)	3.17 (0.22)	3.07 (0.17)
df [e]	4	4	4	4	4	4
F [f]	0.76	1.67	7.35	0.90	1.66	3.94
p-value [g]	0.5599	0.1892	0.0005	0.4767	0.1918	0.0130

[a]Rating scales for individual cultivars are listed in Table A.1.
[b] AWB = *Aster dumosus* 'Wood's Blue', CBC = *Campanula carpatica* 'Blue Clips', CTS = *Coreopsis* 'Tequila Sunrise', DMC = *Dianthus deltoides* 'Microchip',
EWS = *Echinacea purpurea* 'White Swan', GCC = *Geranium* x *cantabrigiense* 'Cambridge', HAB = *Heuchera villosa* 'Autumn Bride', HPP = *Heuchera* 'Plum Pudding',
LSB = *Leucanthemum* x *superbum* 'Becky', PPR = *Phlox paniculata* 'Robert Poore', SMA = *Sedum* 'Matrona', VGG = *Veronica spicata* 'Goodness Grows'.
[c]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[d]SEM=Standard Error of the Mean.
[e]df=degrees of freedom.
[f]*F*=*F* distribution.
[g]p-value=level of significance.

Table A.3. Effect of freezing temperatures on dry weight (g) of conventional perennial regrowth.

Treatment temp °C	AWB	C BC	CTS	DMC	EWS	GCC
-2	2.96 (0.26) ab [c]	0.86 (0.13)	0.01 (0.01)	0.93 (0.10) a	2.92 (0.45)	0.62 (0.11)
-5	3.07 (0.23) a	0.74 (0.08)	0.11 (0.08)	0.82 (0.05) ab	3.10 (0.30)	0.56 (0.07)
-8	3.21 (0.25) a	0.80 (0.05)	0.03 (0.02)	0.82 (0.14) ab	2.61 (0.68)	0.45 (0.10)
-11	2.29 (0.23) ab	0.84 (0.05)	0.00 (0.00)	0.71 (0.10) ab	2.58 (0.39)	0.62 (0.06)
-14	2.02 (0.26) b	0.62 (0.08)	0.00 (0.00)	0.49 (0.09) b	3.03 (0.56)	0.42 (0.13)
Mean (SEM[b])	2.71 (0.11)	0.77 (0.04)	0.03 (0.02)	0.75 (0.05)	2.85 (0.22)	0.53 (0.04)
df [d]	4	4	4	4	4	4
F [e]	4.49	1.35	1.57	2.68	0.23	0.93
p-value [f]	0.0072	0.2778	0.2138	0.0548	0.9178	0.4643

Treatment temp °C	HAB	HPP	LSB	PRP	SMA	VGG
-2	3.17 (0.38) a	2.00 (0.08) a	3.25 (0.38) a	6.39 (0.11) ab	4.07 (1.21)	0.47 (0.16) abc
-5	3.27 (0.43) a	2.25 (0.20) a	3.48 (0.56) a	6.85 (0.23) a	4.29 (1.04)	0.94 (0.18) a
-8	3.21 (0.18) a	2.11 (0.13) a	2.05 (0.22) ab	6.43 (0.16) ab	4.26 (1.19)	0.64 (0.12) a
-11	2.56 (0.31) ab	1.47 (0.11) b	1.04 (0.61) b	6.74 (0.11) a	2.92 (1.75)	0.23 (0.12) bc
-14	1.23 (0.45) b	1.20 (0.04) b	0.35 (0.15) b	5.87 (0.14) b	2.80 (1.19)	0.08 (0.04) bc
Mean (SEM[b])	2.69 (0.16)	1.80 (0.06)	2.03 (0.19)	6.46 (0.07)	3.67 (0.58)	0.47 (0.06)
df [d]	4	4	4	4	4	4
F [e]	5.67	12.67	10.29	5.88	0.33	6.46
p-value [f]	0.0022	<0.0001	<0.0001	0.0018	0.8574	0.0010

[b] AWB = *Aster dumosus* 'Wood's Blue', CBC = *Campanula carpatica* 'Blue Clips', CTS = *Coreopsis* 'Tequila Sunrise', DMC = *Dianthus deltoides* 'Microchip', EWS = *Echinacea purpurea* 'White Swan', GCC = *Geranium* x *cantabrigiense* 'Cambridge', HAB = *Heuchera villosa* 'Autumn Bride', HPP = *Heuchera* 'Plum Pudding', LSB = *Leucanthemum* x *superbum* 'Becky', PPR = *Phlox paniculata* 'Robert Poore', SMA = *Sedum* 'Matrona', VGG = *Veronica spicata* 'Goodness Grows'.

[c]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).

[d]SEM=Standard Error of the Mean.

[e]df=degrees of freedom.

[f]*F*=*F* distribution.

[g]p-value=level of significance.

Table A.4. Rating Scales for Ornamental Grasses.

***Miscanthus* 'Adagio':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = less than 6 inches (15 cm) regrowth with 3 or more growing points, 4 = vigorous 6 inches (15 cm) or more regrowth, 5 = vigorous 6 inches (15 cm) or more regrowth filling over 1/2 of pot.

***Miscanthus* 'Gold und Silber':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = less than 8 inches (20 cm), 4 = vigorous 8 inches (20 cm) or more regrowth, 5 = vigorous 8 inches (20 cm) or more regrowth filling over 1/2 of pot.

***Miscanthus* 'Puenktchen':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = less than 8 inches (20 cm), 4 = vigorous 8 inches (20 cm) or more regrowth, 5 = vigorous 8 inches (20 cm) or more regrowth filling over 1/2 of pot.

***Miscanthus* 'Rigoletto':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = less than 8 inches (20 cm), 4 = vigorous 8 inches (20 cm) or more regrowth, 5 = vigorous 8 inches (20 cm) or more regrowth filling over 1/2 of pot.

***Miscanthus* 'Sarabande':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = less than 8 inches (20 cm), 4 = vigorous 8 inches (20 cm) or more regrowth, 5 = vigorous 8 inches (20 cm) or more regrowth filling over 1/2 of pot.

Table A.5. Effect of freezing temperatures on quality rating[a] and dry weight (g) of ornamental grass regrowth.

	MA [b]		MG		MP		MR		MS	
Treatment temp °C	Rating	Dry Weight	Rating	Dry Weight	Rating	Dry Weight	Rating	Dry Weight	Rating	Dry Weight
-2	4.00 (0.00) a [c]	1.60 (0.08) a	3.67 (0.21) a	1.95 (0.49) a	4.17 (0.17) a	2.82 (0.16) a	4.17 (0.31) a	1.53 (0.16) a	4.00 (0.00) a	2.43 (0.16) a
-5	4.00 (0.00) a	1.34 (0.16) ab	3.67 (0.21) a	1.27 (0.09) ab	4.17 (0.31) a	2.90 (0.30) a	4.00 (0.26) a	1.66 (0.23) a	4.00 (0.00) a	2.45 (0.30) a
-8	3.67 (0.21) a	1.13 (0.11) b	2.33 (0.21) b	0.45 (0.11) bc	3.17 (0.40) b	1.78 (0.29) b	3.67 (0.21) a	1.55 (0.25) a	2.50 (0.22) b	0.96 (0.29) b
-11	1.00 (0.00) b	0.00 (0.00) c	1.00 (0.00) c	0.00 (0.00) c	1.00 (0.00) c	0.00 (0.00) c	1.67 (0.21) b	0.27 (0.11) b	1.00 (0.00) c	0.00 (0.00) c
-14	1.00 (0.00) b	0.00 (0.00) c	1.00 (0.00) c	0.00 (0.00) c	1.00 (0.00) c	0.00 (0.00) c	1.00 (0.00) b	0.00 (0.00) b	1.00 (0.00) c	0.00 (0.00) c
Mean (SEM[d])	2.73 (0.04)	0.81 (0.04)	2.33 (0.07)	0.73 (0.10)	2.70 (0.11)	1.50 (0.09)	2.90 (0.10)	1.00 (0.08)	2.50 (0.04)	1.17 (0.09)
df [e]	4	4	4	4	4	4	4	4	4	4
F [f]	283.75	66.44	66.67	14.12	45.44	52.86	42.67	20.38	225.00	52.86
p-value [g]	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[a]Rating scales for individual cultivars are listed in Table A.4.
[b] MA = *Miscanthus sinensis* 'Adagio', MG = *Miscanthus sinensis* 'Gold und Silber', MP = *Miscanthus sinensis* 'Puenktchen', MR = *Miscanthus sinensis* 'Rigoletto', MS = *Miscanthus sinensis* 'Sarabande'.
[c]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[d]SEM=Standard Error of the Mean.
[e]df=degrees of freedom.
[f]*F*=*F* distribution.
[g]p-value=level of significance.

Table A.6 Rating Scales Perennial Groundcovers.

***Anacyclus depressus compactum* 'Silver Kisses':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = regrowth not dense, 4 = dense regrowth, 5 = dense regrowth over edge of pot.

***Armeria maritima* 'Rubifolia':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = poor spotty regrowth, 4 = vigorous regrowth, 5 = lush regrowth with minimal dieback.

***Armeria* 'Victor Reiter':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = poor spotty regrowth, 4 = vigorous regrowth, 5 = lush regrowth with minimal dieback.

***Artemesia viridis* 'Tiny Green':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = dead center with perimeter regrowth, 4 = acceptable regrowth with minimal dieback, 5 = vigorous regrowth with minimal dieback.

***Dianthus gratianopolitanus* 'Tiny Rubies':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = dead center with perimeter regrowth, 4 = vigorous regrowth with dieback, 5 = lush regrowth with no dieback.

***Erysimum kotschyanum* 'Orange Flame':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = dead center with perimeter regrowth, 4 = vigorous regrowth with dieback, 5 = vigorous regrowth with no dieback.

***Mazus reptans* 'Purple':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = regrowth of less than half of pot, 4 = vigorous regrowth equal to or more than half of pot, 5 = vigorous regrowth over edge of pot.

***Potentilla crantzii* 'Pygmaea':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = regrowth with deformed leaves, 4 = vigorous regrowth, 5 = vigorous regrowth with flowers.

***Veronica allionii* (Alpine Speedwell):** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = "dead" center with vigorous regrowth over pot edge , 4 = vigorous regrowth over pot edge with 1-2 flowers, 5 = vigorous regrowth over pot edge with 3 or more flowers.

***Veronica surculosa* 'Waterperry Blue':** 1 = Dead, no regrowth, 2 = minimal regrowth, 3 = regrowth with dieback, 4 = sparse regrowth no dieback, 5 = vigorous regrowth no dieback.

Table A.7. Effect of freezing temperatures on quality rating[a] of perennial groundcovers regrowth.

Treatment temp °C	ASK [b]	AMR	AVR	ATG	DTR	EOF	MRP	PCP	VAS	VWB
-2	3.83 (0.40) a [c]	3.50 (0.22)	3.33 (0.42)	3.50 (0.22)	3.33 (0.42)	1.67 (0.33) b	2.00 (0.26) ab	4.50 (0.50)	4.50 (0.34) a	4.67 (0.21) a
-5	3.83 (0.40) a	3.50 (0.22)	3.00 (0.68)	3.83 (0.17)	3.83 (0.40)	3.50 (0.43) a	2.83 (0.65) ab	4.17 (0.54)	3.00 (0.26) b	4.67 (0.21) a
-8	4.67 (0.21) a	3.33 (0.21)	3.00 (0.52)	3.50 (0.22)	3.67 (0.21)	2.50 (0.22) ab	4.00 (0.52) a	5.00 (0.00)	3.83 (0.54) ab	4.67 (0.21) a
-11	3.17 (0.70) a	3.00 (0.37)	3.17 (0.48)	3.83 (0.48)	3.00 (0.26)	2.50 (0.50) ab	3.00 (0.63) ab	4.67 (0.33)	4.50 (0.34) a	4.33 (0.33) a
-14	1.00 (0.00) b	2.50 (0.34)	3.17 (0.48)	2.83 (0.17)	3.67 (0.21)	3.00 (0.45) ab	1.00 (0.00) b	3.50 (0.72)	4.83 (0.17) a	3.33 (0.21) b
Mean (SEM[d])	3.30 (0.19)	3.17 (0.13)	3.13 (0.23)	3.50 (0.12)	3.50 (0.14)	2.63 (0.18)	2.57 (0.22)	4.37 (0.22)	4.13 (0.16)	4.33 (0.11)
df [e]	4	4	4	4	4	4	4	4	4	4
F [f]	11.24	2.29	0.07	2.17	1.12	2.92	5.48	1.39	4.29	5.77
p-value [g]	<0.0001	0.0880	0.9902	0.1013	0.3678	0.0413	0.0026	0.2673	0.0089	0.0020

[a]Rating scales for individual cultivars are listed in Table A.6.
[b] ASK = *Anacyclus depressus compactum* 'Silver Kisses', AMR = *Armeria maritima* 'Rubifolia', AVR = *Armeria* 'Victor Reiter', ATG = *Artemesia viridis* 'Tiny Green', DTR = *Dianthus gratianopolitanus* 'Tiny Rubies', EOF = *Erysimum kotschyanum* 'Orange Flame', MRP = *Mazus reptans* 'Purple', PCP = *Potentilla crantzii* 'Pygmaea', VAS = *Veronica allionii* (Alpine Speedwell), VWB = *Veronica surculosa* 'Waterperry Blue'.
[c]Treatment temperature means with a lowercase letter in common are not significantly different according to Tukey's procedure (p=0.05).
[d]SEM=Standard Error of the Mean.
[e]df=degrees of freedom.
[f]*F*=*F* distribution.
[g]p-value=level of significance.