THE EFFECT OF POST-STORAGE TEMPERATURES AND FREEZE/THAW CYCLES ON REGROWTH PERFORMANCE OF BARE-ROOT HERBACEOUS PERENNIALS

By

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ABSTRACT

THE EFFECT OF POST-STORAGE TEMPERATURES
AND
FREEZE/THAW CYCLES
ON REGROWTH PERFORMANCE OF
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Exposure of bare-root herbaceous perennials to post-storage temperatures of 10°C for up to 3 weeks and 20°C for one week after 5 months' storage at 0 or -2°C, did not significantly affect the regrowth quality of the 12 species tested compared to controls. Only four of the species showed a significant decline in regrowth quality following 2 or 3 weeks at 20°C. On the basis of these results, it appears that bare-root perennials may withstand limited exposure to elevated post-storage temperatures provided that they are packaged properly to prevent desiccation.

No significant loss in regrowth quality was observed in 4 of 6 species of bare-root perennials subjected to 6 freeze/thaw cycles with each cycle consisting of one week at 1°C followed by one week at -3°C. For the other two species, both considered "difficult-to-store", exposure to more than one cycle caused a significant decline in regrowth quality and survival rate.

DEDICATION

To my wife, Margo, for her patience and support as I take this detour in life.

ACKNOWLEDGMENTS

I would like to thank my major professor, Dr. Arthur Cameron for his patience, guidance, support and friendship throughout my graduate career.

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CHAPTER II

Introduction

Herbaceous perennials include a large number of species and varieties of plants in which the foliage generally dies back to the ground following a killing frost in the fall. These plants are grown in the garden as ornamentals for their flowers or foliage. Commercially, herbaceous perennials are often field-grown and harvested in the fall or spring. Spring harvested plants may be sold and replanted immediately while those lifted in the fall are placed in refrigerated storage bare-root plants. From winter to spring, the plants are removed from storage and distributed to wholesale and retail outlets or directly to the consumer. The bare-roots are then either potted for sale or may be planted for establishment in garden beds.

Each year, millions of bare-roots representing thousands of species and varieties are successfully handled by growers using traditional storage techniques. However, growers still receive complaints from customers who find that a significant percentage of the stored material is in poor condition or does not perform as expected in the garden (Walters Gardens, Wayside Gardens, personal communications).

Several major problems manifest themselves following long-term storage of herbaceous perennials.

The most visibly apparent of these is the poor physical appearance of the bare-roots caused by severe desiccation or the presence of molds and rots (personal observations). Maqbool (28) identified desiccation as a major factor in poor regrowth performance of stored bare-roots. Depending on the degree of moisture loss, plants may survive and regrow, but the negative initial impression on the customer may be long lasting.

In some cases, the plants do not attain an acceptable regrowth quality following potting or planting in the garden. One difficult situation occurs when bare-roots appear healthy upon visual inspection but fail to regrow when planted. Undefined physiological factors or internal pathological agents may prevent the plants from becoming re-established.

Determining the cause(s) of these problems is complicated by the fact that thousands of species and varieties of herbaceous perennials are commonly produced for the trade. As noted by Mahlstede and Fletcher (26), ideal storage requirements vary from species to species and may even be different for varieties within a single species.

Very little systematic research has been done on the storage and handling of herbaceous perennials. Therefore, the exact cause and effect relationships between storage conditions and regrowth potential and ultimate plant quality remain largely undefined. In

1960, Mahlstede and Fletcher (26) outlined some basic prerequisites for successful storage for many herbaceous perennials. Key among these were the employment of refrigerated storage to control temperature fluctuations and the use of polyethylene films for moisture retention. Among individual growers, however, the degree to which these early recommendations are followed varies greatly. Although some growers have made specific refinements on these techniques based on trial and error studies, the results of their work are not generally available.

Maqbool (28) conducted experiments on long-term storage of herbaceous perennials i.e. from the time the bare-root plants are harvested in the fall until they are removed for shipment to retail outlets. He found that desiccation of the bare-roots was a key factor in subsequent regrowth quality of the plants. Generally, after plants lost 10-20% of their weight through desiccation, regrowth ratings declined drastically. Use of polyethylene films during storage greatly reduced the occurrence of moisture loss. He also determined that many perennials will store well under a variety of temperatures ranging from -2 to 5^{o}C (26)(28).

Although it has been shown that maintenance of low storage temperatures and the prevention of desiccation by the use of polyethylene wraps will help maintain quality of plants during the long-term storage period, problems still occur when the plant reaches the consumer. Low survival rates and poor regrowth quality continue to occur in a certain percentage of the plants marketed annually.

Additional research is needed to adequately identify those factors or steps in the storage process which may be contributing to a reduction in regrowth quality of bare-root herbaceous perennials. One area of concern is that period between removal from the initial, generally long-term, storage and receipt by the ultimate consumer. This "post-storage" phase often includes long-distance shipping and a holding period when the plants must await potting or retail sale. During post-storage handling, the plants may be subjected to a variety of temperatures and relative humidities for up to 3 weeks or more. The bare-roots may encounter stresses which could be detrimental to subsequent survival and regrowth potential.

Another area for investigation is the impact of temperature fluctuations during the storage process. Of specific concern are temperature fluctuations during storage involving below to above freezing temperature exposures. During the months between harvest and retail sale, plants may be shifted between storage areas with differing temperature levels or may be shipped in non-refrigerated conveyances and then re-stored. It is not uncommon for bare-roots to be exposed to one or more shifts between temperatures below and above freezing as part of the storage process.

In order to determine if temperature shifts might account for the poor performance of certain perennials as reported by growers, two sets of experiments were conducted. Regrowth quality of several species and varieties of herbaceous perennials was analyzed following exposure to: 1) a number of post-storage temperatures over varying periods of time; and 2) several cycles of storage in temperatures above and below $0^{o}C$. In each case, with the exception of temperature level, the plants were stored in accordance with generally accepted storage conditions. Polyethylene films were used to prevent moisture loss, a critical element in storage success (28).

Literature Review

Mahlstede and Fletcher (26) made one of the first attempts to define proper handling and storage procedures for bare-root herbaceous perennials. They reported a 1953 study by Mr. George Rose of the Henry Field Seed and Nursery Company which examined the impact of several storage methods on the quality and regrowth ability of a number of herbaceous perennials. Bare-root plants were stored in polyethylene bags (sealed or unsealed) at one of three temperature regimes which included frozen storage at -2.2 to -1.1 ^{o}C, cold-room storage at 1.1 to 4.4^{o}C and common storage at 10 to 18.3^{o}C.

Following storage, each plant was rated on criteria such as keeping quality, appearance, presence of molds, need for trimming and presence of etiolated growth. The results showed a wide range of responses over the individual species tested but certain trends were delineated which applied to groups of species. For instance, *Ageratum* L., *Convallaria* L. and *Platycodon* DC had high ratings following storage in sealed bags under all of the temperature treatments while *Coreopsis* L., *Chrysanthemum coccineum* L. and *Aster* L. received low ratings regardless of treatment. The results, however, may have been influenced when the bare-roots were removed from storage for the initial rating and then were returned for additional storage prior to the final rating. If, in fact, the tissue was frozen, this may have allowed it to thaw before being refrozen which may have contributed to the decline in regrowth ratings for some species.

Mahlstede and Fletcher (26) developed a classification system for storage of herbaceous perennials based on groupings of plants with similar physical structure i.e. root type, and uniformity of response to handling and storage techniques. The system, however, was supported by limited data and included only a small percentage of the total number of species and varieties commonly stored as bare-roots (26).

Moisture Content at Harvest

Mahlstede and Fletcher (26) stated that successful storage of bare-root herbaceous perennials may be associated with the condition of the plants at the time of harvest. They reported that poor storage results were obtained when strawberry runners were "excessively succulent" at the time of packaging although this term was not defined. It was suggested that maturity and moisture content of the plants are key factors. However, limited attempts at artificially drying stock prior to storage were not successful (see 26). They estimated that a reduction in moisture content of between 12 and 54% did not reduce storage success although no supportive data was given (26)(27).

Reduced moisture contents for stored woody ornamentals may be achieved by cutting back on the irrigation of the crop in the field during late summer or early fall (10). This will presumably increase the level of hardiness but care must be taken to avoid stressing the plant (10). However, it seems unlikely that this technique could be utilized for herbaceous perennials grown under Michigan conditions where difficulties often arise due to excessive fall rainfall.

Physiological Status at Harvest

Several researchers have demonstrated that timing of harvest can influence storage success of strawberry (2), conifer seedlings (35) and deciduous plants (11). In red-osier dogwood, *Cornus sericea* L., the earliest harvestable stage of development has been defined as vegetative maturity i.e. that point at which plants may undergo chemical defoliation and still be expected to survive winter storage (11). *C. sericea* plants placed in cold-storage following this stage survived for long periods without injury (11).

Starch content at the time of harvest has been proposed as an indicator of physiological maturity for pine seedlings (18), roses (48) and strawberry runners

(9). Freeman and Pepin (9) found that several varieties of strawberry runners stored better when harvested after mid-November in the Pacific Northwest. They observed that the starch content of the root cortex was generally low in early fall, increased by mid-November and then declined throughout the winter.

Anderson and Gutteridge (3) found that mean maximum daily temperatures of less than 10^{o}C and minimums of less than 5^{o}C in the field 3 days prior to lifting improved the survival of fall harvested strawberry runners. They state that the later the lifting date, the better the survival rate after storage under climatic conditions in Great Britain. Maqbool, Richards and Cameron (unpublished) found similar results on herbaceous perennials grown in Michigan.

Ritchie et al (35) reported that Pacific Northwest nurserymen recognize a "window" during the fall harvest period in which bare-root conifer seedlings attain their optimum physiological condition for lifting and storage. Determining the timing of this optimum harvest period is complicated by the substantial physiological heterogeneity among seedlings of various seed lots and by climatic variations from year to year (35). They found that certain conifer seedlings' ability to withstand desiccation stress during storage appears to be linked to the degree of dormancy attained at lifting time (35).

To date, no reliable method has been developed to enable growers to quickly determine the earliest optimum date for lifting strawberry runners (2) or herbaceous perennials.

Rate of Cooling

For many horticultural commodities including strawberry runners (5), vegetables and fruits (49), the rate at which the material is brought to the desired storage temperature is an extremely important factor in successful storage. The heat of respiration must be removed by exposure to low temperatures and adequate air circulation around storage crates during the initial cooling period (22).

Mahlstede and Fletcher (26) harvested delphiniums in early fall at 25°C and packed them in polyethylene lined crates. Plants at the center of the crate took 14 hours to reach the storage temperature of 1.1°C while those near the outer edges reached the desired temperature in only 3 hours. Mahlstede (25) found that rotting was more apparent at the center of the crates of stored perennials which took 13-15 hours to cool from 25°C to 1.1°C. Under Michigan conditions where plants are often harvested from mid-October to December, initial cooling requirements may not be so great since soil temperatures are usually less than 5-10^{o}C (Richards, unpublished).

Storage Temperatures Levels

Few investigations have been published regarding the ideal storage temperatures for bare-root herbaceous perennials. Mahlstede and Fletcher (26) observed that most perennials are held commercially in refrigerated storage at a freezing temperature of -2.8 to -1.1^{o}C while some may be safely stored at refrigerated temperatures between 0.6 to 4.4^{o}C. Common storage at 10 to 18.3^{o}C was successfully used for short periods of time when plants were healed into sand or other material (26).

Maqbool (28) found no significant difference in regrowth quality of bare-root herbaceous perennials following 6 months storage at -2 or 0^{o}C. Many of the perennials tested did equally well following 6 months at -2, 2 and 5^{o}C. All plants attained poor regrowth quality following -5^{o}C storage and none survived storage at -10^{o}C.

Some species such as *Chrysanthemum maximum* appear to have quite specific temperature requirements. Bare-root plants of this species achieved acceptable regrowth quality only at the single temperature level of 2^{o}C. The current recommendation is to store bare-root perennials at or near 0^{o}C (28).

Low storage temperatures can minimize the rates of respiration, metabolic activity, mold development and other physiological reactions (28). Tree seedlings of many species are commonly stored at a range of temperatures between -2 and 2^{o}C since , survivability is reduced at -5^{o}C (1)(8). Asparagus plants are stored commercially at -2.2 to 0^{o}C (47). Most of the literature on storage of bare-root strawberry runners indicate an optimum temperature range of between -1.1 and 0^{o}C (2)(3)(5)(14)(44).

Rooted cuttings of the herbaceous perennial *Teucrium chamaedrys* stored well in closed polyethylene bags at 1.1^{o}C for 167 days but were unsatisfactory in terms of regrowth quality when stored at -0.6^{o}C (38). Worthington and Smith (47) found that no bud growth occurred in asparagus plants stored for 10 weeks at 0^{o}C. However, one week at 15.6^{o}C following cold storage resulted in bud growth on plants stored in polyethylene although the amount of this etiolated growth was not objectionable (47).

Temperature Fluctuations

Olien (31) found that winter killing of barley plants in Michigan involves direct freezing injury i.e. intracellular freezing. This occurred most commonly during winters in which there had been a midwinter thaw followed by a return to subfreezing temperatures.

Thomas and Lazenby (42) determined that repeated freezing and thawing could be expected to increase injury to Festuca arundinacea L. but only within a critical temperature zone specific to the plant and its physiological state. They determined that some grass varieties seem to be more sensitive to repeated freezing than were others.

Mader and Feldman (24) found that strawberry runners subjected to alternating freezing and thawing temperatures (-3 and 3°C) underwent a "physiological weakening" as indicated by decreasing levels of sugars and starches. These plants had a higher mortality rate when planted in the field compared to plants held at a constant storage temperature.

Gul and Allan (13) reported a higher survival rate for plants subjected to gradual rather than a rapid temperature change during freezing and thawing in winter wheat.

Water Relations

Fretz and Smith (10) suggested that the control of relative humidity is perhaps the single most important factor in successful storage of woody ornamental plants due to the difficulty in maintaining levels of 95-98% in commercial storage units. Robinson, et al (36) found that the reduction of temperature is the most important factor to successful storage of vegetables and soft fruits but it is followed closely by the need to minimize evaporative losses.

Shrinkage losses of vegetables are almost entirely due to evaporation from the surface (16). The amount of evaporation which can occur is limited by the amount of water which the air can hold. A reduction in water loss can be achieved by decreasing the temperature while maintaining a constant moisture content and/or by increasing the moisture in the environment at a constant temperature (36).

Mahlstede (25) found, however, that desiccation by controlled drying out of plant material prior to packaging for storage could improve the keeping quality of bare-root herbaceous perennials. If field conditions at harvest were excessively wet, allowing the plants to lose some moisture prior to storage would often result in improved field survival. This type of prestorage curing is also commonly used with tulips and other bulbs as recommended in the Holland Bulb Forcer's Guide.

Mahlstede and Fletcher (26) could not correlate moisture loss from fall harvested and stored bare-roots of carnations, delphiniums, strawberries and hybrid tea roses with their subsequent survival rate in the field.

Maqbool (28) found a highly significant inverse linear relationship between regrowth quality and water loss for a range of bare-root perennials. A mathematical model based on transpiration rates was developed by Cameron and Maqbool (6) which showed that, for Phlox subulata, the regrowth grade would be expected to drop to zero i.e. death, after 4 days of exposure to 15^{o}C with 50% relative humidity. It would take 11 days for the plants to drop to a zero rating if exposed to 0^{o}C at that humidity level. However, plants could be stored successfully for several months at 15^{o} C if the relative humidity were maintained at 98% or higher. Maqbool (28) recommended the use of 4 mil polyethylene films to provide a high relative humidity to provide high regrowth quality of bare-root herbaceous.

Free Moisture

Moistened packing materials such as shingletow, sawdust, peat moss or excelsior are often used to maintain the water content of stored bare-root plants (27). Worthington and Scott (46) and Duffield and Eide (8) found that if this material is excessively wet it may promote the development of molds on bare-roots.

Mahlstede and Kirk (27) attributed poor storage quality of strawberry runners to two factors: a) excessively succulent plants containing an abundance of moisture at the time of packaging; and b) a large quantity of free moisture in the package (27). Stuart (40) found that Easter lily bulbs stored in wet packing media resulted in a nearly 40% decrease in salable blooms compared to bulbs stored in dryer peat.

Polymeric Films

Anderson (2) stated that the use of polyethylene was one of the most significant advances to facilitate the cold storage of plant material. Polyethylene and other plastic wraps are used to prevent moisture loss in fruits and vegetables (15)(16)(17)(27), tree seedlings (1)(19), strawberry runners (5) and herbaceous perennials (28).

Polyethylene films are manufactured in thicknesses ranging from .001 to .005 inch and have differing permeabilities to water vapor, carbon dioxide, oxygen and ethylene. Thus, commodities packed in plastic may be subjected to conditions of higher humidity, higher concentrations of carbon dioxide and ethylene and lower concentrations of oxygen than those to which unpacked commodities are exposed (15)(17)(27)(40)(41).

Condensation on the inside of polyethylene films tends to encourage the development of molds on stored bare-root plants (46). Factors which contribute to condensation include high relative humidities caused by transpiration, heat produced by the plant material and inconsistent temperature control in the storage facility (43)(47).

Mahlstede and Fletcher (26) recommended the use of polyethylene bags for the storage of bare-root perennials to retard moisture loss. Maqbool (28) found that the beneficial effects of storing bare-root herbaceous perennials in 4 mil polyethylene bags exceeded any potentially negative effects from condensation, modified atmosphere or impaired rate of heat exchange.

Packing materials such as shingletow, peat moss, excelsior or sawdust have a dual purpose: 1) to retard moisture loss; and 2) to provide a cushioning effect to prevent injury to the plants during transit (20). Several studies have shown that sphagnum moss or similar packaging materials are not necessary for the storage of strawberry runners when poly bags are used (2)(46). Including root packing materials such as peat, hydromulch or sphagnum soaked in water provided no improvement over bare-root storage of Fraser fir seedlings (19). For Easter lilies, 20-30% moisture (considered dry) in peat packing materials in poly lined crates at -0.5^{o}C resulted in longer storage life (41).

Poly Bag Ventilation

Ryall and Werner (37) found that the presence of a limited number of holes in a sealed polyethylene bag would not allow air exchange to significantly decrease the internal humidity level. However, oxygen and carbon dioxide movement are greatly enhanced by the presence of a relatively small number of perforations (Shirazi, unpublished results).

Poly liners tend to retard heat exchange (26). Tomato seedlings shipped in poly lined crates averaged 1.2-1.8 degrees C warmer enroute and on arrival than did plants packed without film (29). Tomato seedlings which have a high rate of respiration survived best with ventilation holes in the poly liners while those without ventilation experienced excessive heating and poorer survival rates (29).

Mahlstede (25) stored several species of herbaceous perennials in ventilated or sealed poly bags and found that species varied in their response depending on the storage temperature. Those stored at subzero temperatures responded positively to sealed bags while either ventilated or sealed bags could be used in above-freezing storage. Sealed bags were recommended for _Alcea_, _Artemisia schmidtiana_ and _Platycodon_ which were prepackaged and stored at 4.4^{o}C.

In later studies, Maqbool (28) recommended the use of unsealed polyethylene bags or liners containing a few perforations for the long-term storage of bare-root herbaceous perennials. This allows for more rapid initial cooling and reduces condensation while maintaining a high humidity level inside the bag.

Pathogens

Fungal infections are a major cause of loss in the storage of strawberry runners (2) and Lockhart (22) found that rapid cooling to storage temperatures is important in minimizing mold development. According to Worthington and Scott (46), desiccated runners are more susceptible to decay but factors such as dormancy, soil on the plants and excessive moisture in packaging materials are also conducive to decay development (46).

Temperature is often a factor in mold development in conifer seedlings but Duffield and Eide (8) found that storage at 0 to 1.7^{o}C resulted in freedom from molds. A storage temperature of -3^{o}C inhibited mold development on Fraser fir seedlings even when the foliage was wet at the time of packing (19).

Maqbool (28) studied the effect of pre-storage fungicide application on the regrowth quality of a number of species of herbaceous perennials. Applications of fungicides always reduced the extent of mold coverage over 6 months of storage. However, fungicides had either no effect or were detrimental to the regrowth quality of the perennials tested. The most susceptible plants to this phytotoxic effect were those stored with green tops such as *Iberis sempervirens* and *Lavandula angustifolia*. On the basis of these experiments, he could not recommend the general use of fungicides for the control of storage molds.

Maqbool (28) also found that even when 50% of the surface of the bare-root plants were covered with surface molds, no direct impact on regrowth quality was observed. A higher degree of coverage or the presence of soft rotting molds, bacterial infections and, perhaps, physiological breakdowns did have a level of detrimental impact on cold-stored bare-root herbaceous perennials.

CHAPTER I

Post-Storage Handling of Bare-Root Herbaceous Perennials

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Introduction

Herbaceous perennials are often field-grown, harvested in the fall as bare-root plants and stored for varying periods of time by commercial growers. As orders are processed, the bare-root plants are removed from storage and shipped to the retail outlet where they are either held for future delivery or potted for sale.

Millions of bare-root herbaceous plants representing of thousands of species and varieties are successfully stored each year. Still, growers, wholesalers and retailers of herbaceous perennials report that a significant percentage of the plants harvested each fall lose quality before they reach the consumer (Walters Gardens, Wayside Gardens, personal communications).

It has been postulated that temperature fluctuations during the "post-storage period" i.e. between removal from long-term storage and delivery to the customer, may prove detrimental to the regrowth potential and ultimate quality of the plants. Temperatures during this period may reach 30-35°C with 20°C exposure being fairly common. Bare-root plants are also removed frequently from storage at -2°C, exposed to high temperatures and then returned to -2°C for additional storage or shipping (personal communications Wayside Gardens and Walters Gardens).

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It is well established that low temperatures can minimize processes such as respiration rate, metabolic activity, mold development and other physiological reactions which contribute to successful storage (28). Mahlstede and Fletcher (26) reported that bare-root perennials were routinely stored at temperatures ranging from -2.8 to 4.4^{o}C depending on the types involved. Maqbool (28) reported that -2 to 5^{o}C storage temperatures were optimum for many bare-root herbaceous perennials. The effects of elevated storage temperatures on this type of plant material have not been studied.

Maqbool (28) also established the paramount importance of the prevention of moisture loss during the storage period although this factor was not always considered in earlier storage temperature work. Bare-root plants in the experiments discussed here were kept in polyethylene films during storage in order to minimize desiccation and to isolate the effect of the temperature fluctuations independent of moisture loss. The specific intent was to determine how quickly and to what degree plant regrowth quality might decline in response to being held at elevated temperatures up to 30^{o}C during this post-storage period.

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Materials and Methods

Experiment 1

One year old plants were harvested in late November of 1984 and were stored through March, 1985. Eight species of herbaceous perennials were used including Aquilegia (*Aquilegia* 'McKana Hybrid)', Artemisia (*Artemisia schmidtiana* 'Silver Mound'), Asclepias (*Asclepias tuberosa*), Coreopsis (*Coreopsis grandiflora* 'Sunray'), Dicentra (*Dicentra spectabilis*), Geum (*Geum chiloense* 'Lady Strathden'), Lavandula (*Lavandula angustifolia* 'Hidcote Blue') and Phlox subulata (*Phlox subulata* 'Emerald Pink'). The plant material was taken to the campus in East Lansing following harvest and processing at Walters Gardens in Zeeland, Michigan.

The bare-root plants were divided into treatment units consisting of 6 plants from each of the eight species and placed in bulk-packed 4 mil polyethylene bags which were packed into wooden celery crates. The plant material was then stored for 5 months at -2^{o}C in controlled environment rooms.

Upon removal from storage, 39 crates were divided into 3 groups which were placed at 5, 10 or 20^{o}C for 3 days. This was intended to simulate conditions experienced during shipping from the wholesaler to the retailer.

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After 3 days of exposure to higher temperatures, one crate of plants from each temperature was planted in the greenhouse. The remaining 36 crates were divided equally between holding temperatures of -2, 5, 10 or 20^{o}C. After 1, 2 or 3 weeks of simulated holding period, one group of plants were removed from each treatment combination for planting.

The plants in one crate were planted in the greenhouse prior to the simulated shipping period. Three other crates of bare-root plants were kept at the long-term storage temperature (-2^{o}C). These controls were planted following 1, 2 and 3 week holding periods.

Experiment 2

Six species of one year old, fall dug herbaceous perennials including Achillea (Achillea filipendulina 'Coronation Gold'), Artemisia (Artemisia schmidtiana 'Silver Mound'), Phlox paniculata (Phlox paniculata 'Blue Boy'), Salvia (Salvia superba 'Blue Queen') and Sedum (Sedum spurium 'Dragon's Blood') were obtained from Walters Gardens in Zeeland, Michigan on December 14, 1985 for use in this experiment.

The procedures used to process the plant material was similar to that in Experiment 1 with the following changes. In Experiment 2, each replicate contained 10 plants per species. Following 5 months of storage at 0^{o}C, plant material was exposed to 0, 10, 20 or 30^{o}C a

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for 1, 2 or 3 weeks to simulated a holding period prior to marketing.

During both years, each root was inspected prior to potting and was rated for mold coverage and etiolation. Each plant was visually graded on the following scale: 1-No observable mold; 2- up to 25% coverage with molds; 3- 26-50% coverage; 4- 51-75% coverage; and 5- 76-100% coverage.

Regrowth Analysis

As the bare-root plants were removed from the treatments, they were planted with a peat-based, soiless media in five inch clay pots. The greenhouse was kept at a temperature of 10^{o} C during the night and 21^{o} C during the day. No supplemental lighting was used and the plants were not fertilized during the 4 week regrowth period.

In the greenhouse, each plant was rated for regrowth quality 4 weeks after planting. This time period was determined to be an ideal time to evaluate regrowth since treatment differences manifested at this time were indicative of future growth and developmental characteristics.

The rating was on a scale from 1 to 5 as follows: 1- No regrowth observed; 2- up to 25% of the regrowth potential expected; 3- 26-50% of the regrowth potential; 4- 51-75% of the regrowth potential; and 5-

76-100% of the regrowth potential. Factors considered in this subjective rating system included the number of shoots, length of shoots and overall vigor of the new growth.

Statistical Analysis

Experiment 1 - The analysis of variance was done on a species by species basis. The three-way analysis of variance consisted of 3 shipping temperatures x 4 holding temperatures x 3 holding periods with 6 replicates.

Experiment 2 - Shipping temperatures were not tested so the two-way analysis of variance included 3 holding temperatures x 3 holding periods and was run on a species by species basis. [Note: Data for week 3 at 30°C was not available so this temperature was not included in the AOV.]

Results

Experiment 1

Aquilegia

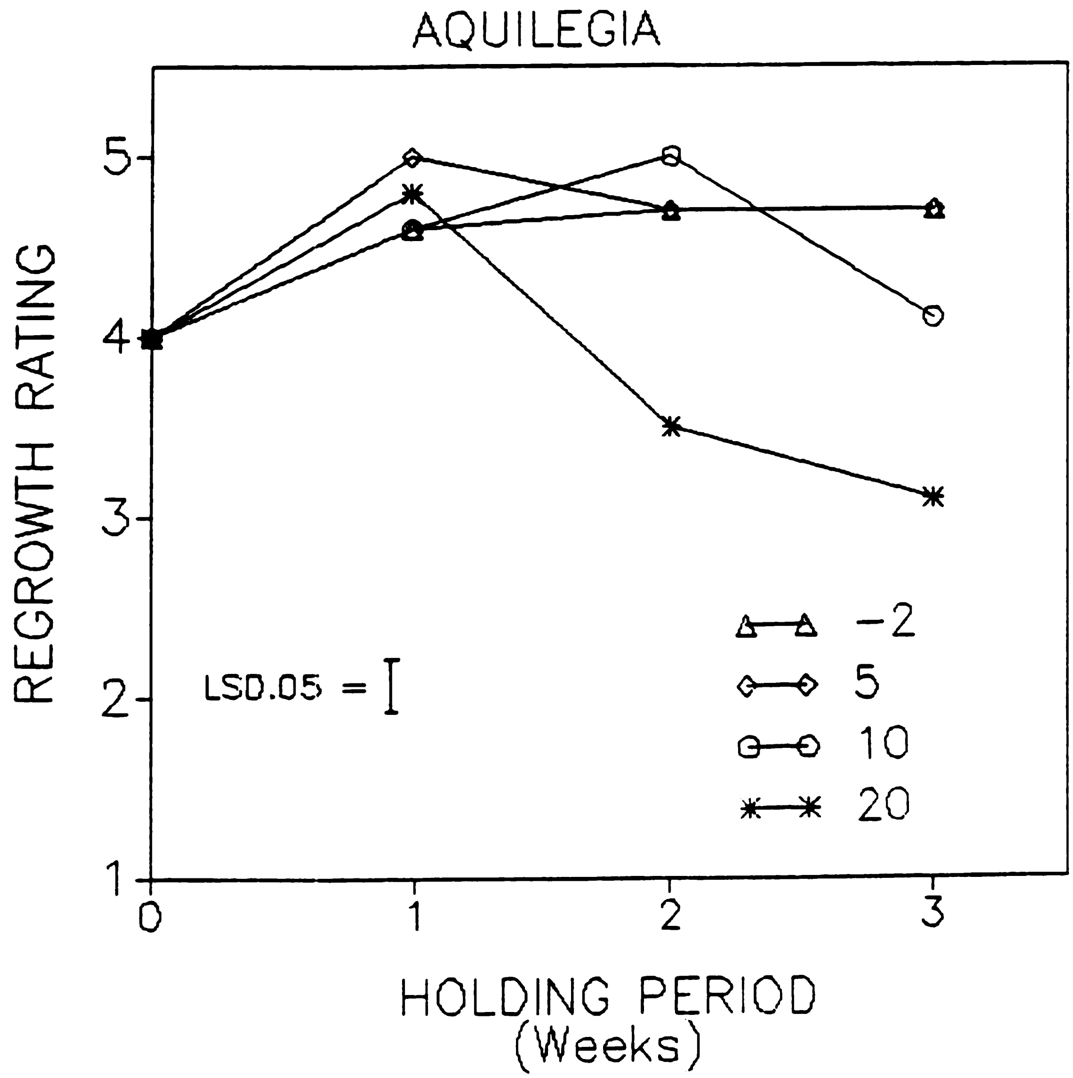
Exposure of bare-root Aquilegia to a holding temperature of 20°C for greater than one week reduced the subsequent plant regrowth rating (Figure 1.1). No significant differences in regrowth quality following exposure to holding temperatures of -2, 5 and 10°C over a 3 week period (Figure 1.1). Bare-root plants kept at 20°C for a three day simulated "shipping" period exhibited a reduction in subsequent regrowth rating independent of holding temperature or duration (Table 1.1). Overall, the regrowth quality of Aquilegia was very high reflecting rapid shoot growth by the majority of the treatment plants. The only exceptions were those held 2 or 3 weeks at 20°C (Figure 1.1).

Artemisia

The 3-way interaction among shipping temperature, holding temperature and holding time was significant at the .008 level. Overall, regrowth ratings for this species were very good with an average of 4.7 out of a possible 5.0. Three weeks at 20°C following shipping

Figure 1.1. Relationship between the 4 week regrowth rating of Aquilegia and length of exposure to different holding temperatures averaged over 3 shipping temperatures.

Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.


AQUILEGIA
REGROWTH RATING
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HOLDING PERIOD
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Table 1.1. Mean 4 week regrowth ratings[y] of Aquilegia as influenced by 3 days at various shipping temperatures and averaged over all holding temperatures and holding period.

Shipping Temperature (°C)	Mean Regrowth Rating
5	4.5
10	4.7
20	4.1

$LSD_{.05}$ = 0.3

y: Regrowth grades: 5 = 100% of regrowth potential; 4= 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

temperatures of 5 and caused a decline in regrowth quality for Artemisia (Figure 1.2). Plants held continuously at 20°C through both the shipping and holding periods did not decline significantly in 4 week regrowth rating compared to other treatments. Regrowth quality following holding times of 1, 2 or 3 weeks at -2, 5 or 10°C showed no significant decline regardless of shipping temperature (Figure 1.2).

Dicentra

Dicentra maintained an overall regrowth quality average of 4.8 out of a possible 5.0 (Table 1.2). A holding temperature of -2°C consistently resulted in a statistically significant decline of 6% in regrowth ratings compared to those plants held at 5, 10 and 20°C in all other combinations. Neither shipping temperatures nor weeks had a significant effect on regrowth quality of Dicentra.

Asclepias

In contrast to other species tested, the regrowth rating of Asclepias increased following three days at 10 and 20°C shipping temperatures and at one week in a holding temperature of 20°C (Figure 1.3). The 3-way interaction among shipping temperature, holding

Figure 1.2. Mean four week regrowth rating of Artemisia following 3 days at different shipping temperatures and 1 to 3 weeks at different holding temperatures.

Regrowth grades: 5 - 100% of regrowth potential; 4 -75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

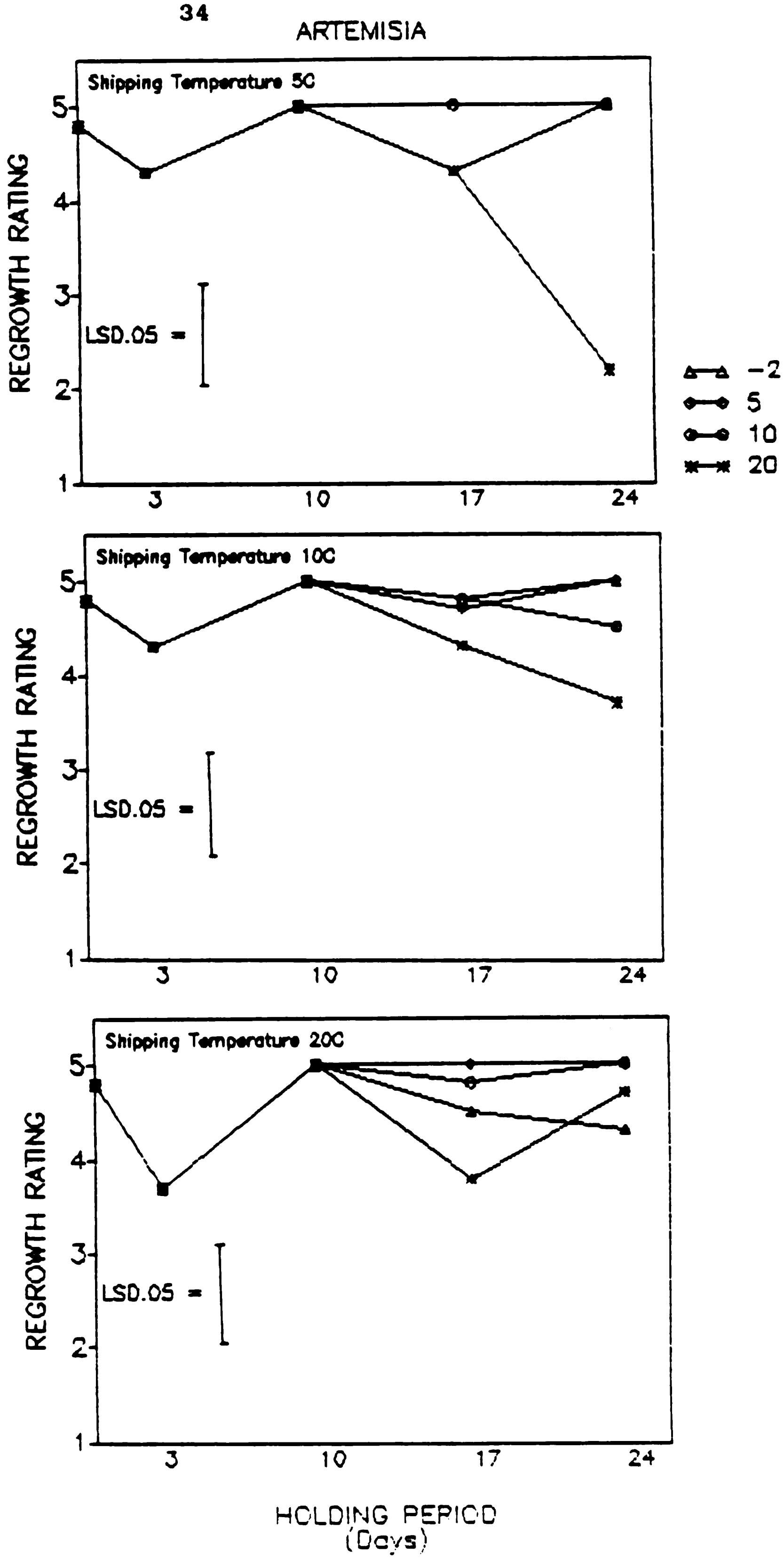

ARTEMISIA
Shipping Temperature 5C
Shipping Temperature 10C
Shipping Temperature 20C
REGROWTH RATING
LSD.05 =
1
2
3
4
5
3
10
17
24
−2
5
10
20
HOLDING PERIOD
(Days)

Table 1.2. Mean 4 week regrowth quality rating[y] for Dicentra as influenced by different holding temperatures.

Regrowth Rating of Dicentra

Holding Temp. (°C)	Regrowth Rating
-2	4.5
5	4.9
10	4.9
20	4.8
Avg.	4.8

LSD.05 = 0.3

y: Regrowth grades: 5 = 100% of regrowth potential; 4 = 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

temperature and time was significant at the .000 level. The results following exposure to other shipping and holding temperatures were variable.

The mean survival percentage of Asclepias was 76.7% but was 90% for plants held at 20^{o}C. No plants survived following a shipping temperature of 5^{o}C and one week at -2^{o}C (Figure 1.3b). When the 5^{o}C shipping temperature was followed by a holding temperature of 20^{o}C, all plants survived in all three weeks (Figure 1.3b).

Phlox subulata

Shipping temperature did not significantly effect the subsequent regrowth of Phlox subulata. The 2-way interaction between holding temperature and weeks was significant at the .000 level. Following 2 or 3 weeks at a holding temperature of 20^{o}C, there was a significant decline in regrowth quality (Figure 1.5). All plants died after 2 and 3 weeks at 20^{o}C following a shipping temperature of 20^{o}C and after 3 weeks at 20^{o}C following shipping at 10^{o}C. Holding temperatures of -2 and 5^{o}C showed no decline in regrowth quality but there was a significant decline after 3 weeks at 10^{o}C (Figure 1.5).

Coreopsis

The 3-way interaction among shipping temperature, holding temperature and time was significant at

Figure 1.3. Four week regrowth rating of Asclepias following 3 days at different shipping temperatures and 1 to 3 weeks at different holding temperatures.

Regrowth grades: 5 = 100% of regrowth potential; 4 = 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

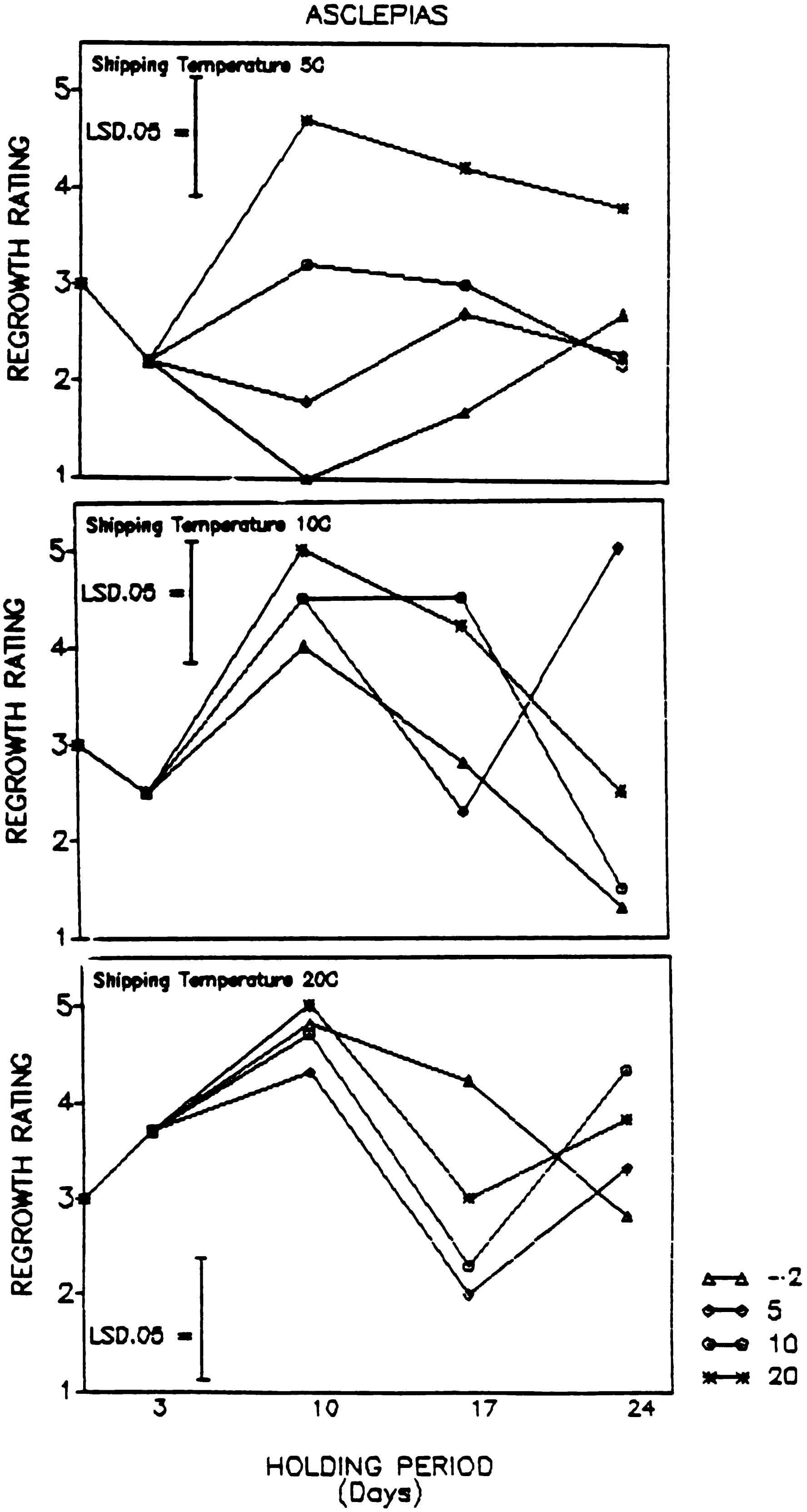
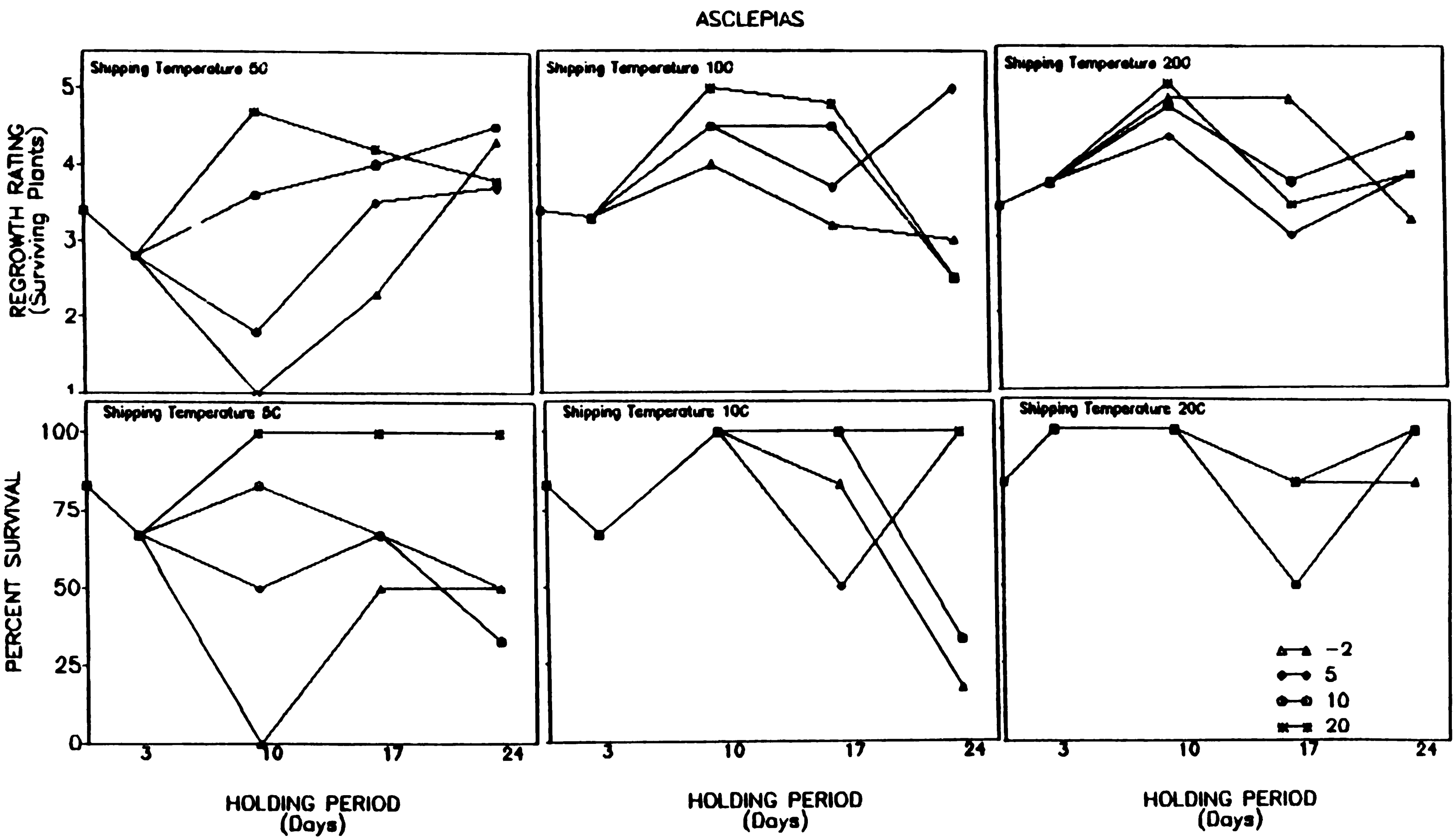

ASCLEPIAS
Shipping Temperature 5C
LSD.05 =
Shipping Temperature 10C
LSD.05 =
Shipping Temperature 20C
LSD.05 =
REGROWTH RATING
1
2
3
4
5
3
10
17
24
HOLDING PERIOD
(Days)
-2
5
10
20

Figure 1.4a. Four week regrowth rating of surviving plants of Asclepias following 3 days at different shipping temperatures and 1 to 3 weeks at different holding temperatures.

Regrowth grades: 5 = 100% of regrowth potential; 4 = 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

Figure 1.4b. Percent survival of Asclepias following 3 days at different shipping temperatures and 1 to 3 weeks at different holding temperatures.


ASCLEPIAS
Shipping Temperature 5C
Shipping Temperature 10C
Shipping Temperature 20C
Shipping Temperature 5C
Shipping Temperature 10C
Shipping Temperature 20C
REGROWTH RATING (Surviving Plants)
PERCENT SURVIVAL
5
4
3
2
1
100
75
50
25
0
3
10
17
24
HOLDING PERIOD (Days)
HOLDING PERIOD (Days)
HOLDING PERIOD (Days)
−2
5
10
20

the .001 level. Bare-root plants of Coreopsis held at $20^{o}C$ had an average regrowth rating of only 1.9 out of 5.0 as averaged over all 3 weeks (Data not shown).

Coreopsis had an overall survival rate of 57.3% and no plants survived 2 or 3 weeks at $20^{o}C$ shipping and holding temperatures (Figure 1.7). The survival pattern of this species was erratic and the only obvious trend was the observed loss in plant viability after 2 and 3 weeks at $20^{o}C$. The regrowth ratings of the surviving plants, however, were nearly all above 3.5 (Figure 1.6b). The exceptions were those plants stored in the $20^{o}C$ holding temperature for 3 weeks following shipping at 5 and $10^{o}C$ although $10^{o}C$ was not consistently detrimental. (Figure 1.6b).

Geum

The overall average regrowth rating was very low (2.0) and the ratings exhibited a high level of variability throughout. No trends were noted in the results (Data not shown). The 3-way interaction for regrowth quality among shipping temperature, holding temperature and time was significant at the .000 level.

Survival rate for Geum overall was 34.9% and this data was also highly variable among treatments. No clear trends could be delineated in the data or in regrowth ratings of surviving plants which had an

Figure 1.5. Relationship between 4 week regrowth rating and time in holding temperatures of *Phlox subulata* averaged over the 3 shipping temperatures.

Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

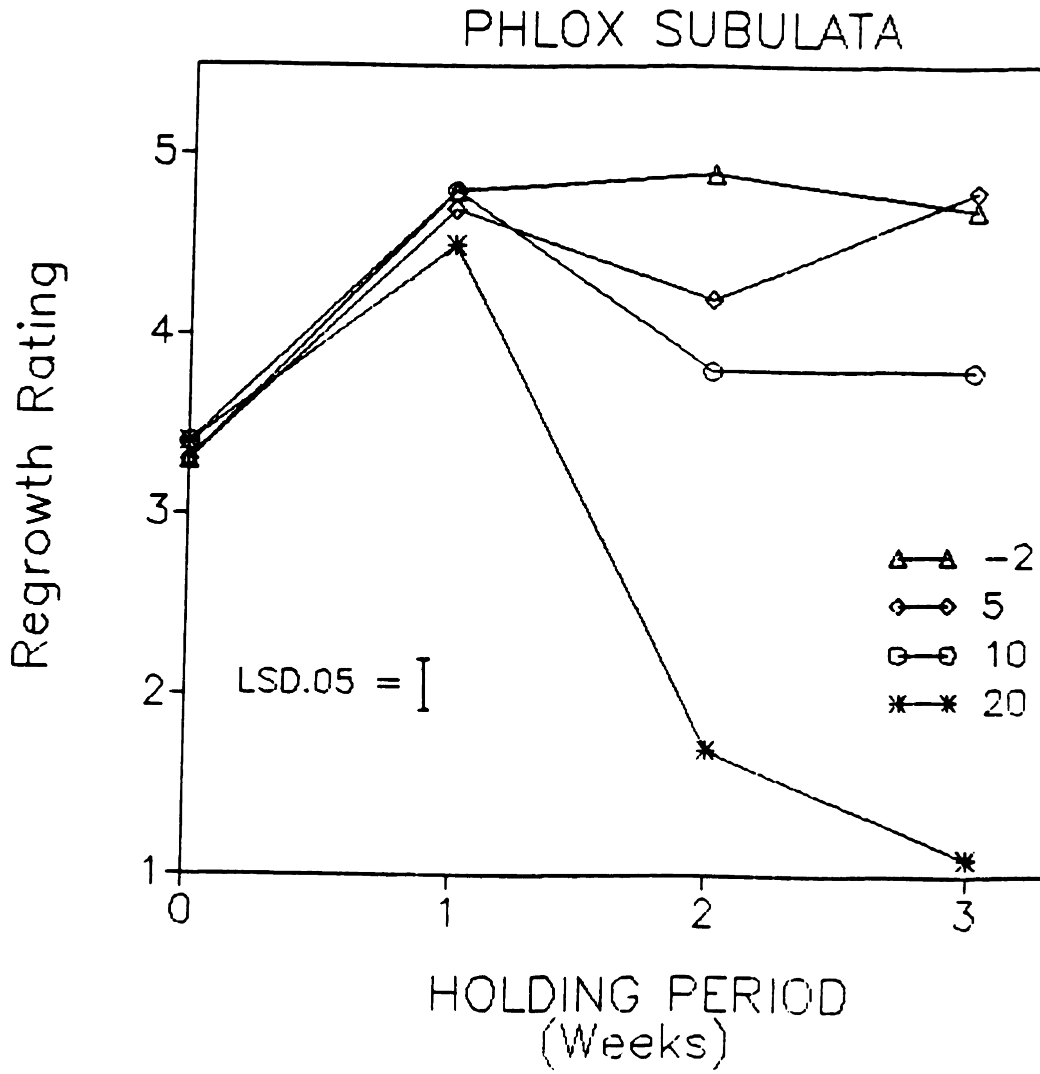

PHLOX SUBULATA
Regrowth Rating
5
4
3
2
1
0
1
2
3
LSD.05 =
-2
5
10
20
HOLDING PERIOD
(Weeks)

Figure 1.6a. Four week regrowth rating of Coreopsis following 3 days at different shipping temperatures and 1 to 3 weeks at different holding temperatures.

Regrowth grades: 5 = 100% of regrowth potential; 4 = 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

Figure 1.6b. Four week regrowth rating of surviving plants of Coreopsis following 3 days at different shipping temperatures and 1 to 3 weeks at different holding temperatures.

Regrowth grades: 5 = 100% of regrowth potential; 4 = 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

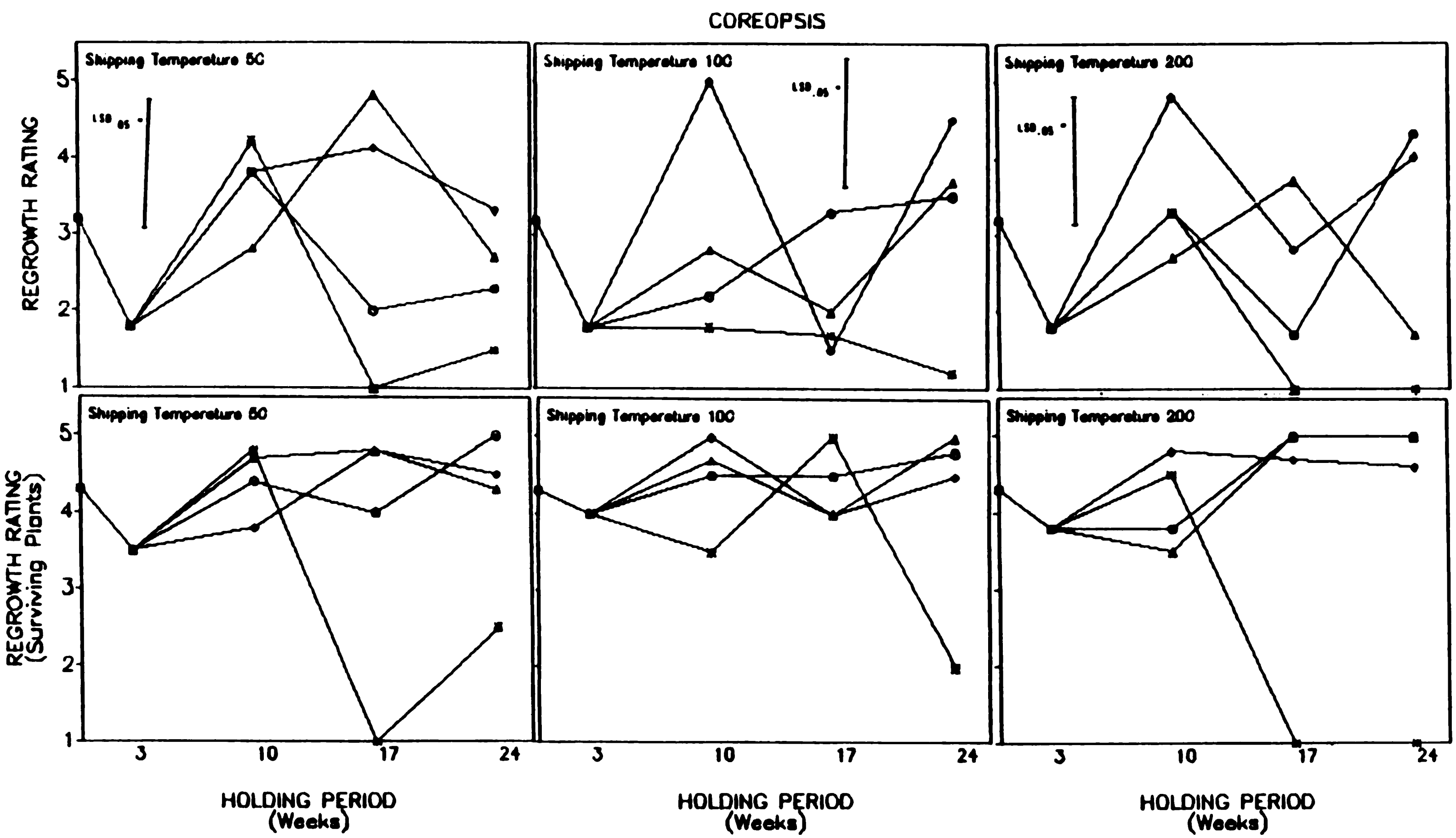
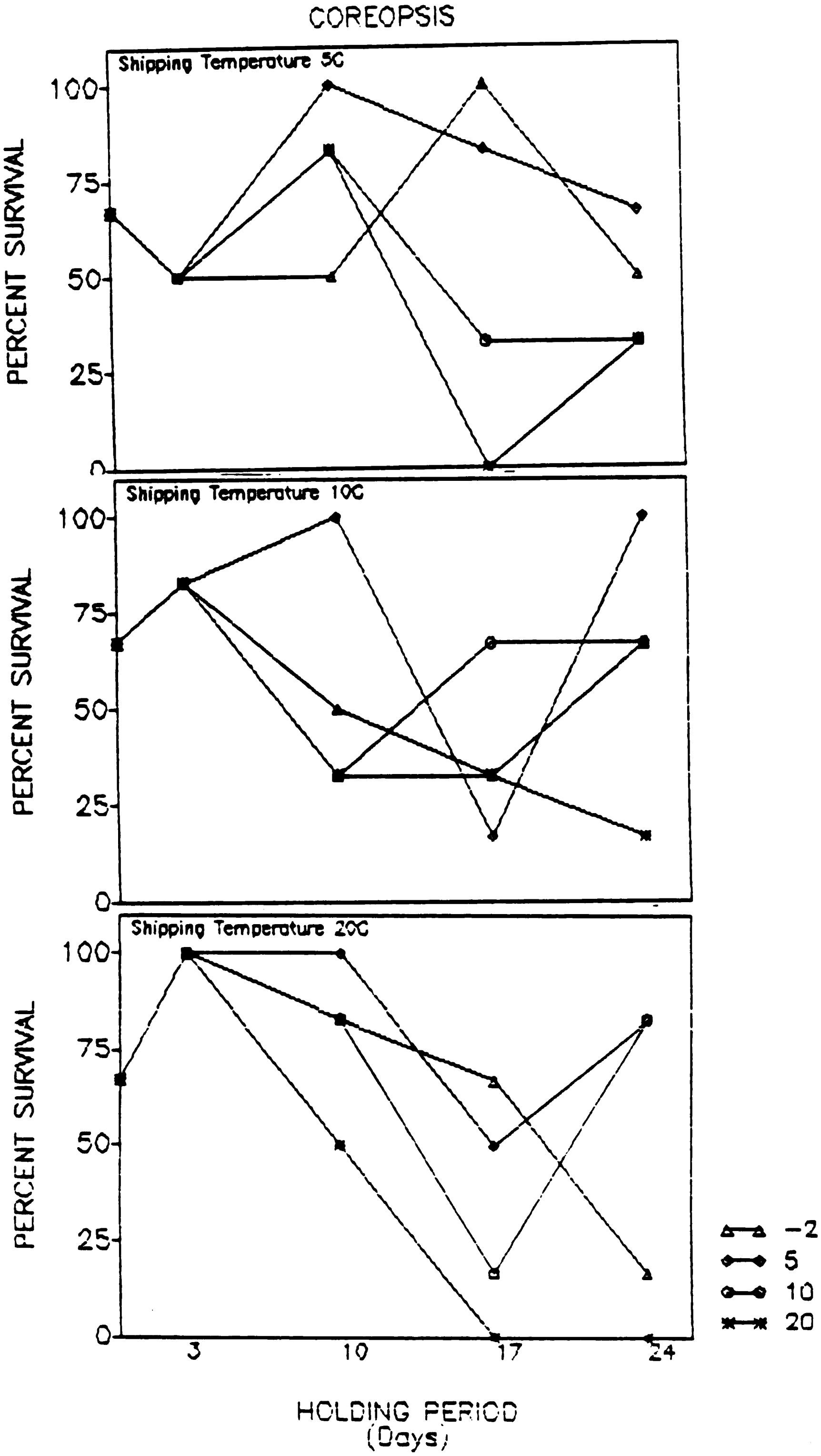

COREOPSIS
Shipping Temperature 5C
Shipping Temperature 10C
Shipping Temperature 20C
LSD .05 =
REGROWTH RATING
REGROWTH RATING (Surviving Plants)
1
2
3
4
5
3
10
17
24
HOLDING PERIOD (Weeks)

Figure 1.7. Percent survival of Coreopsis following 3 days at different shipping temperatures and 1 to 3 weeks at different holding temperatures.


COREOPSIS
Shipping Temperature 5C
Shipping Temperature 10C
Shipping Temperature 20C
PERCENT SURVIVAL
0
25
50
75
100
3
10
17
24
HOLDING PERIOD
(Days)
-2
5
10
20

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average rating of 3.0. Even exposure to 20^{o}C did not consistently reduce regrowth quality compared to the other temperatures (Data not shown).

Lavandula

Lavandula had an overall average regrowth rating of only 2.0 and only 45% of the plants survived. The data for regrowth ratings and survival rate for this species exhibited a high degree of variability (Data not shown). Exposure to the 20^{o}C holding temperature for 3 weeks resulted in 100% mortality after all shipping temperatures, however, there were no consistent detrimental effects at 10^{o}C (Data not shown). The 3-way interaction for regrowth quality among shipping temperature, holding temperature and time was significant at the .000 level.

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Experiment 2

Achillea

The regrowth data for Achillea was displayed a high degree of variability (Figure 1.8a). Regrowth quality at 10 and 20^{o}C declined after two weeks but then increased after week 3. This effect, however, was not so evident when only surviving plants were considered (Figure 1.8b). The 2-way interaction for regrowth quality between holding temperature and weeks was significant at the .000 level.

Nearly one-third of the plants did not survive (Data not shown). All plants were dead after 2 weeks at the holding temperature of 30^{o} (Figure 1.8).

Phlox paniculata

Overall, this species did very well with an average regrowth rating of 4.3. There were no problems evident at holding or shipping temperatures of 0 and 10^{o}C. Ratings declined significantly following 2 weeks at 20^{o}C but returned to high levels after the third week. At 30^{o}C, the regrowth ratings decline after 2 weeks (Figure 1.9). The 2-way interaction between holding temperature and weeks was significant at the .005 level.

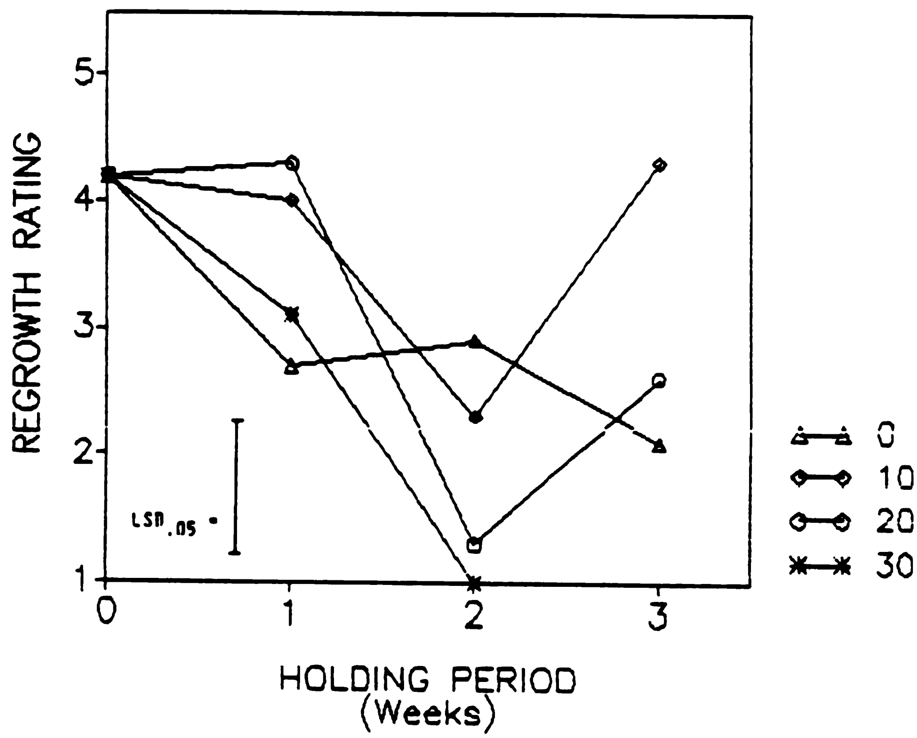
Figure 1.8a. Relationship between 4 week regrowth rating and time in holding temperatures for Achillea.

Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

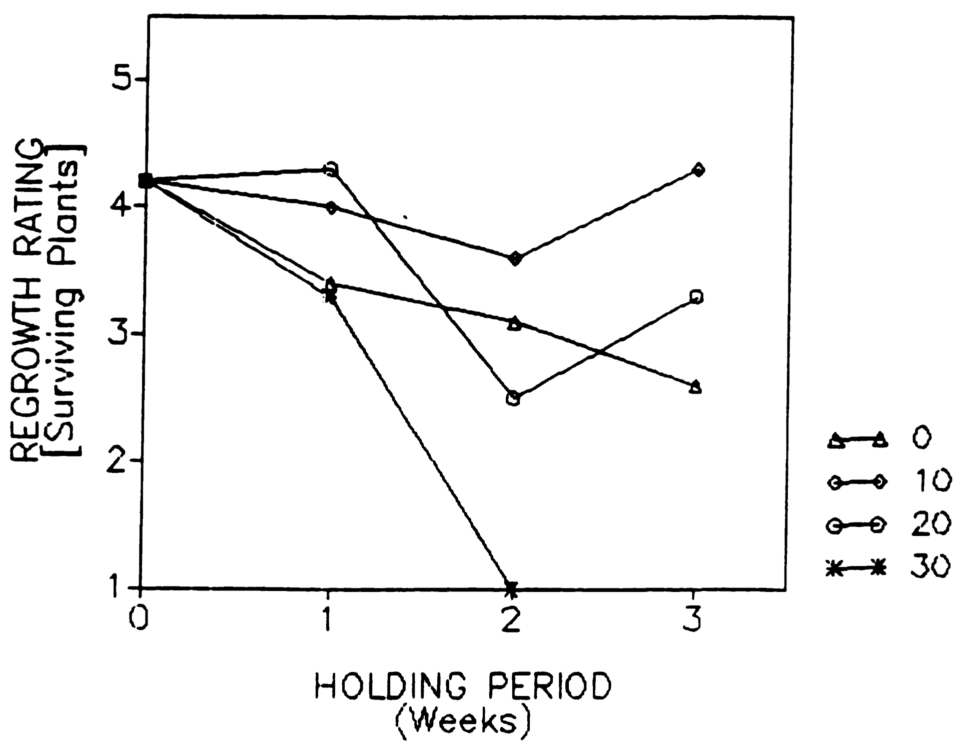
Figure 1.8b. Relationship between 4 week regrowth rating of surviving only and time in holding temperatures for Achillea.

Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

ACHILLEA



REGROWTH RATING
5
4
3
2
1
LSD.05 =
0
1
2
3
HOLDING PERIOD
(Weeks)
0
10
20
30



REGROWTH RATING
[Surviving Plants]
5
4
3
2
1
0
1
2
3
HOLDING PERIOD
(Weeks)
0
10
20
30

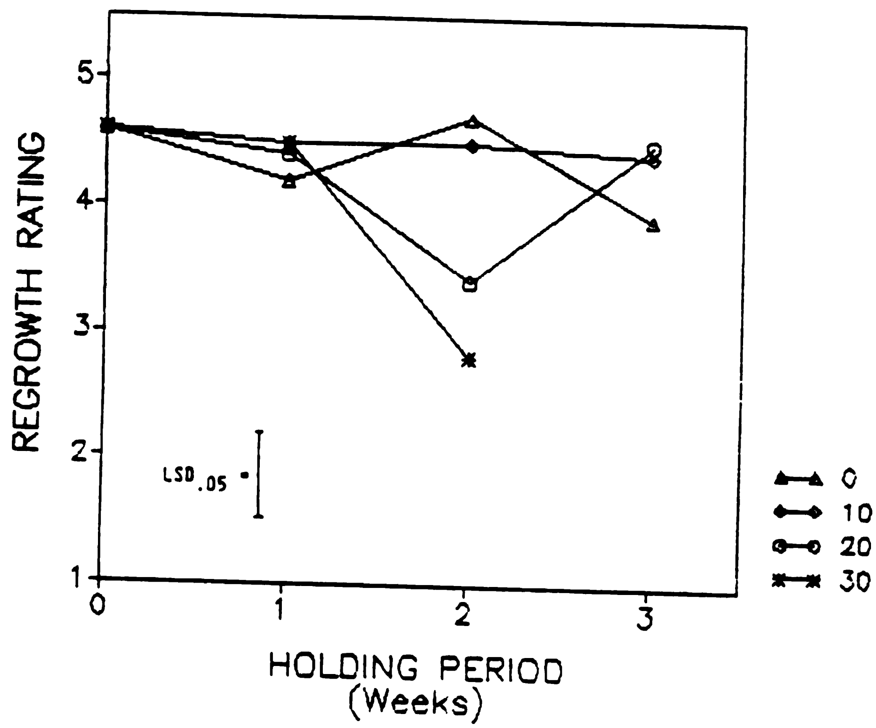
Figure 1.9a. Relationship between 4 week regrowth rating and time in holding temperatures of for _Phlox paniculata_.

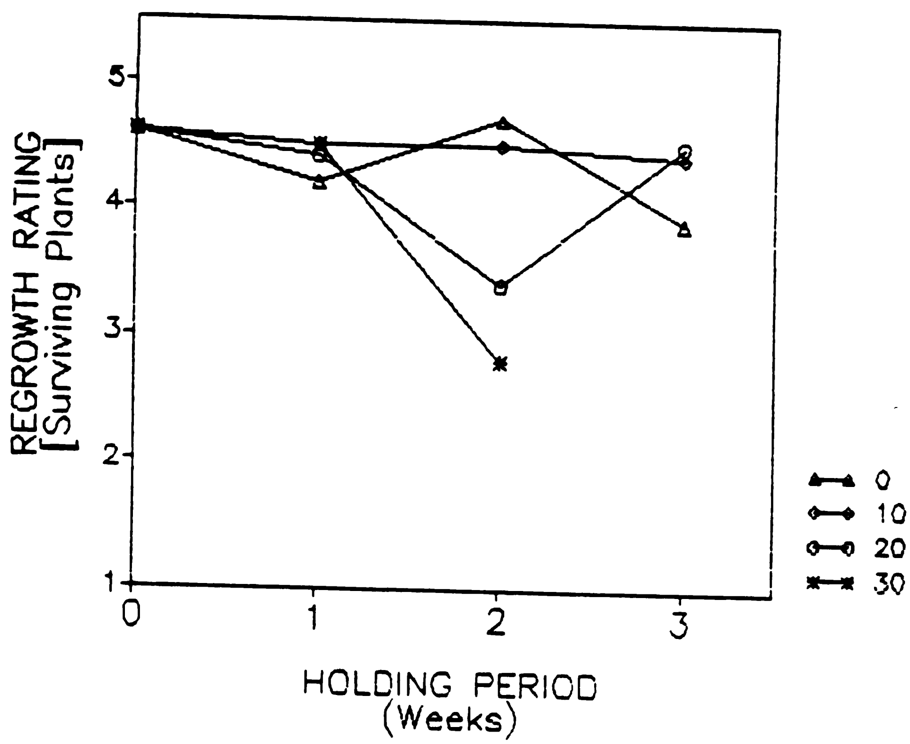
Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

Figure 1.9b. Relationship between 4 week regrowth rating of surviving only and time in holding temperatures for _Phlox paniculata_.

Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

PHLOX PANICULATA





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Sedum

Overall, Sedum did very well with an average regrowth rating of 4.1 and a range of 3.4 to 4.7 ($LSD_{.05}$=1.0). Even 2 weeks at 30°C did not cause significant problems. No trends in treatment response were obvious in the data although some slight statistical differences occurred after the first week (Figure 1.7). The 2-way interaction between holding temperature and weeks was significant at the .027 level.

Artemisia

The regrowth ratings for Artemisia declined significantly over the three weeks in storage when averaged over all holding temperatures (Table 1.3). The results for holding temperature were also significant, with 10°C resulting in a significantly higher average regrowth rating than either 0 or 20°C (Table 1.4). The 2-way interaction was not significant.

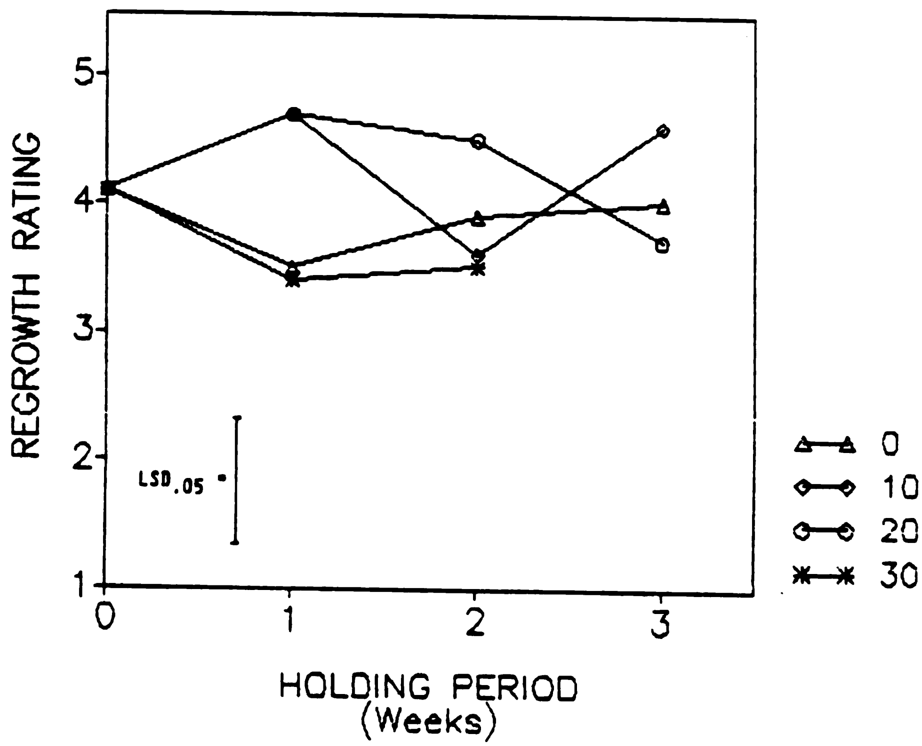
Figure 1.10a. Relationship between 4 week regrowth rating and time in holding temperatures for Sedum.

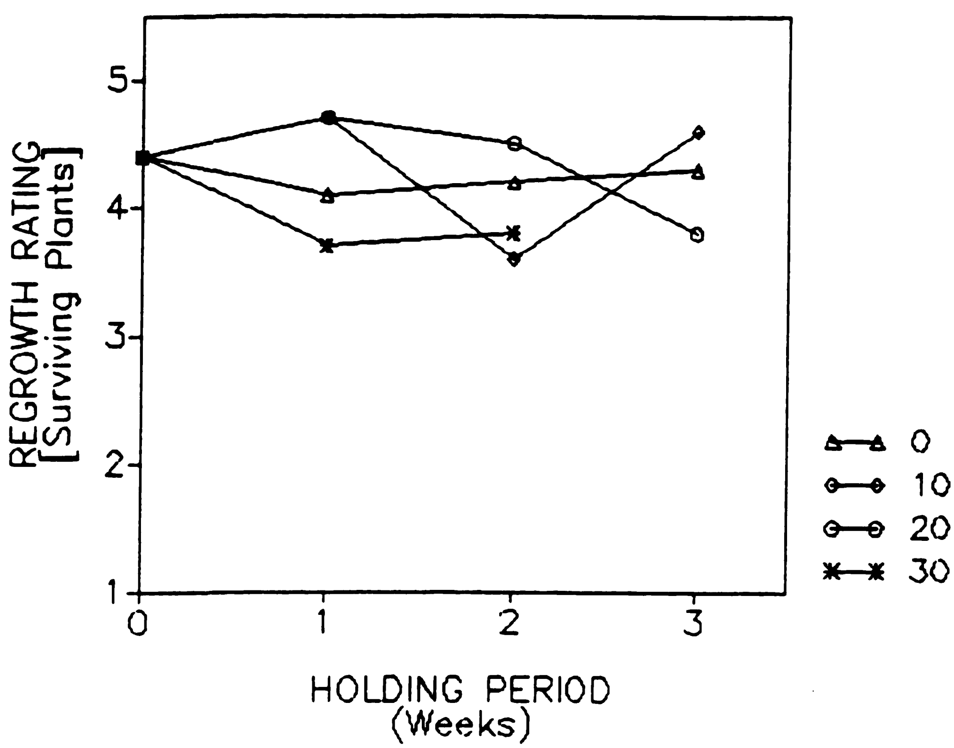
Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

Figure 1.10b. Relationship between 4 week regrowth rating of surviving plants only and time in holding temperatures for Sedum.

Regrowth grades: 5 - 100% of regrowth potential; 4 - 75%; 3 - 50%; 2 - 25%; and 1 - No observable growth.

SEDUM


5
4
3
2
1
REGROWTH RATING
LSD.05 =
0
1
2
3
HOLDING PERIOD
(Weeks)
0
10
20
30


5
4
3
2
1
REGROWTH RATING
[Surviving Plants]
0
1
2
3
HOLDING PERIOD
(Weeks)
0
10
20
30

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2

Table 1.3. Mean 4 week regrowth ratings[y] of Artemisia as influenced by 1 to 3 weeks post-storage duration averaged over shipping and holding temperatures. The main effect was significant at the .000 level and the 2-way interaction was not significant.

Holding Period (Weeks)	Regrowth Rating
1	4.6
2	3.7
3	3.3
LSD.05 = 0.2	

y: Regrowth grades: 5 = 100% of regrowth potential; 4= 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

Table 1.4. Mean 4 week regrowth ratings[y] of Artemisia as averaged over weeks and shipping temperatures. The main effect was significant at the .000 level and the 2-way interaction was not significant.

Holding Temperature (^{o}C)	Regrowth Rating
0	3.5
10	4.4
20	3.7
LSD.05 = 0.2	

y: Regrowth grades: 5 = 100% of regrowth potential; 4= 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

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Salvia

Salvia had an average overall regrowth rating of only 2.4 and a survival rate of 64%. Regrowth ratings for the third week of holding prior to planting were significantly lower than those in the first two weeks (Table 1.5). The 20^{o}C holding temperature, which resulted in an overall mean rating of only 1.9, was significantly lower than the other treatment temperatures tested (Table 1.6). The 2-way interaction was not significant.

Table 1.5. Mean 4 week regrowth ratings[y] of Salvia as influenced by time over 0, 10 and 20^{o}C holding temperatures. The main effect was significant at the .041 level and the interaction was not significant.

Holding Period (Weeks)	Regrowth Rating
1	2.9
2	2.4
3	2.1

$LSD_{.05}$ = 0.6

y: Regrowth grades: 5 = 100% of regrowth potential; 4= 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

Table 1.6. Mean 4 week regrowth ratings[y] of Salvia as influenced by temperatures averaged over 1, 2 and 3 weeks in holding. The main effect was significant at the .013 level and the interaction was not significant.

Holding Temperature (^{o}C)	Regrowth Rating
0	2.6
10	2.8
20	1.9

$LSD_{.05}$ = 0.6

y: Regrowth grades: 5 = 100% of regrowth potential; 4= 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

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Etiolation

Prior to potting, each bare-root was examined for evidence of etiolated growth. Over 72% of the bare-root Achillea, Aquilegia and Phlox paniculata exhibited etiolated growth of 2.5 to 5 cm in length (see Table 1.7 and 1.10). Artemisia, Salvia, Sedum and Lavandula showed little or no etiolated growth prior to potting (Tables 1.7 and 1.9). Generally, there was an increase in the percentage of bare-root plants with etiolated growth as the temperature increased in both the shipping and holding phases of Experiment 1 (Tables 1.7 and 1.8).

Following 3 days in the different shipping temperatures, Asclepias and Coreopsis showed an increase in etiolation percentage as temperatures increased. At 10 and 20°C, all or nearly all the bare-roots of Aquilegia showed signs of etiolated growth (Table 1.7).

Over the 4 holding temperatures, Coreopsis showed a definite trend toward an increase in etiolation with an increase in temperature while Aquilegia had a high percentage of etiolated bare-root plants throughout all the holding temperatures. Geum and Dicentra showed an increase in etiolation as temperatures increased from -2 to 10°C but then declined after 20°C (Table 1.8).

Table 1.7. Mean percentage of bare-root plants exhibiting etiolated growth upon visual inspection prior to potting as effected by shipping temperatures during Experiment 1.

Plants Exhibiting Etiolated Growth (%)

SPECIES:	Shipping Temperature (°C) 5	10	20
Aquilegia	65.3	100.0	95.8
Artemisia	0.0	0.0	8.3
Asclepias	5.6	11.0	25.0
Coreopsis	19.5	38.9	69.4
Dicentra	52.7	45.8	54.1
Geum	22.2	18.0	29.1
Lavandula	0.0	0.0	0.0
Phlox sub.	19.4	5.6	13.8
AVG.	23.1	27.4	36.9

Table 1.8. Mean percentage of bare-root plants exhibiting etiolated growth upon visual inspection prior to potting as affected by holding temperatures during Experiment 1.

Plants Exhibiting Etiolated Growth (%)

SPECIES:	Holding Temperatures (°C) -2	5	10	20
Aquilegia	72.2	83.3	96.3	96.3
Artemisia	0.0	0.0	11.1	0.0
Asclepias	0.0	0.0	14.8	40.8
Coreopsis	22.2	35.2	51.9	61.1
Dicentra	27.8	50.0	77.8	48.1
Geum	5.6	31.6	37.0	18.6
Lavandula	0.0	0.0	0.0	0.0
Phlox sub.	3.7	0.0	9.2	38.9
AVG.	16.4	25.0	37.3	38.0

Table 1.9. Mean percentage of bare-roots exhibiting etiolated growth upon visual inspection prior to potting as affected by weeks in holding temperatures during Experiment 1.

Plants Exhibiting Etiolated Growth (%)

	Duration of Holding Period (Weeks)			
	1	2	3	AVG.
SPECIES:				
Aquilegia	76.4	91.7	93.1	87.0
Artemisia	8.3	0.0	0.0	2.8
Asclepias	0.0	8.3	33.3	13.9
Coreopsis	40.3	48.6	39.0	42.6
Dicentra	41.7	62.5	48.6	50.9
Geum	22.3	25.0	22.3	23.2
Lavandula	0.0	0.0	0.0	0.0
Phlox sub.	0.0	31.9	6.9	12.9
Avg.	23.6	33.5	30.4	29.2

Table 1.10. Mean percentage of bare-roots exhibiting etiolated growth upon visual inspection prior to potting as effected by weeks in storage during Experiment 2.

Plants Exhibiting Etiolated Growth (%)

	Duration of Holding Period (Weeks)		
	1	2	3
SPECIES:			
Achillea	87.5	75.0	87.0
Artemisia	2.5	12.5	20.0
Phlox paniculata	60.0	70.0	100.0
Salvia	0.0	0.0	0.0
Sedum	0.0	0.0	0.0
AVG.	30.0	31.5	41.4

Table 1.11. Mean percentage of bare-roots exhibiting etiolated growth upon visual inspection prior to potting as effected by holding temperatures during Experiment 2.

Plants Exhibiting Etiolated Growth (%)

	Holding Temperatures (°C)			
	0	10	20	30
SPECIES:				
Achillea	63.3	73.3	100.0	100.0
Artemisia	0.0	10.0	16.7	20.0
Phlox paniculata	46.7	93.3	83.3	75.0
Salvia	0.0	0.0	0.0	0.0
Sedum	0.0	0.0	0.0	0.0
AVG.	22.1	35.3	37.3	35.3

Mold Ratings

Each bare-root plant was visually inspected prior to potting and was given a rating based upon the percentage of the surface area covered by molds. All species in both experiments had a mean rating of less than 2.0, i.e. 1-25% coverage by molds, except Coreopsis, Lavandula and Geum which had averages of 2.9, 2.4 and 2.3, respectively.

There were no obvious effects of the treatments on the amount of mold coverage with the exception of Phlox subulata which tended to have increased levels of mold in 5, 10 and 20^{o}C as compared to -2^{o} (results not shown). In addition, no correlation could be made between the presence of mold coverage and the 4 week regrowth rating of the bare-root plants (results not shown).

Discussion

Following long-term storage, bare-root herbaceous perennials are often subjected to elevated temperatures during shipment and again as they await potting or delivery to the retail markets. Based on typical responses of many horticultural crops to high temperatures following harvest, it would seem likely that exposure to non-refrigerated conditions for extended periods would cause a decline in regrowth quality or survival of bare-root plants.

In the experiments reported here, which were conducted over a 2 year period, 12 species of bare-root herbaceous perennials were remarkably tolerant of post-storage exposure to elevated temperatures. It should be noted that the 12 species used are considered to be average to poor in their ability to survive storage (Wayside Gardens, personal communications).

Post-storage exposure to 20^{o}C for 2 and/or 3 weeks caused a significant decline in regrowth quality for only 4 of the 12 species tested (Table 1.12). One of these, Salvia, showed a negative response to all temperatures including 0^{o}C. No species showed a significant decline in regrowth after 1 week at 20^{o}C or up to 3 weeks at 10^{o}C. In fact, all species survived one week at 30^{o}C although 3 of the 5 species tested had a moderate decline in regrowth quality (Table 1.13). Sedum did well following 2 weeks at 30^{o} and Phlox paniculata had only a moderate decline in regrowth quality. Three of the 5 species exposed to 30^{o}C for 2 weeks did experience an extreme decline in regrowth quality.

Asclepias actually appeared to show some positive effects from a brief exposure to elevated temperatures following long-term storage. This plant is known as a late emerging species in the garden (39) which may indicate a need for exposure to elevated soil temperatures before it resumes active growth in the spring. A third experiment had been designed to test this response under a wider range of temperatures. Unfortunately, the bare-root plants to be used molded severely during storage and failed to survive. Further study of this phenomenon might prove valuable in defining proper post-storage handling for this species.

Table 1.12. Relative sensitivity of herbaceous perennials to exposure to holding temperatures of 10 and 20°C for 2-3 weeks[x] based on regrowth quality following storage.

Degree of Impact on Regrowth	Holding Temperature 10°C	20°C
Slight or None	Achillea Aquilegia* Artemisia Asclepias Coreopsis* Dicentra Phlox paniculata Phlox subulata Sedum	Aquilegia* Dicentra* Phlox pan. Sedum
Moderate		Artemisia
Extreme	Salvia	Achillea Coreopsis* Phlox sub* Salvia+
Inconsistent and/or Inconclusive	Geum* Lavandula	Asclepias* Geum Lavandula

x There was no effect following one week at these temperatures in most cases.
* Species sensitive to promotion of etiolated growth at elevated temperatures.
+ Species responded negatively to all temperatures over time.

Table 1.13. Relative sensitivity of herbaceous perennials to exposure to holding temperatures of 30^{o}C for 1-2 weeks based on regrowth following storage.

Degree of Impact	Weeks 1	2
Slight or None	Phlox paniculata Sedum	Sedum
Moderate	Achillea	Phlox pan. Artemisia Salvia
Extreme		Achillea Artemisia Salvia

Extreme = Overall average rating of 1-2; Moderate =2-3; Slight or None = 3-5.

Geum, Coreopsis and Lavandula exhibited variable responses to the treatments with regrowth ratings failing to show any definite trends due in part to erratic plant survival rates. Coreopsis generally achieved a good regrowth rating in almost all cases where growth occurred but its main problem was in surviving the storage treatment. All 3 of these species are considered difficult-to-store and are frequently the subject of consumer complaints (Wayside Gardens, Inc. and Walters Gardens, Inc. personal communications). These species also require additional study to define the factors responsible for their unreliability as stored bare-root herbaceous perennials.

In Experiment 1, there was an attempt made to test the effect of a simulated shipping temperature over a 3 day period. Artemisia, Coreopsis, Dicentra and Phlox subulata were not significantly effected by shipping temperatures. Significant negative effects of the three day shipping period were found for Aquilegia at 20°C, Asclepias at 5°C, Geum at both 5 and 20°C, and Lavandula at both 10 and 20°C. No single, clear trend could be delineated. This factor was not tested the second year because of this lack of an apparent trend during the holding period and since even 1 week at 10 or 20°C did not cause a significant decline in regrowth quality for any of the species.

Maqbool (28) found that storage temperatures of 2°C or higher tended to encourage etiolated growth on stored bare-root herbaceous perennials. In Experiment 1, the percentage of bare-root plants which exhibited etiolated growth after post-storage holding tended to increase as the shipping temperature increased. However, there did not appear to be a direct correlation between the presence of etiolated growth and subsequent regrowth quality. For instance, over 72% of the Aquilegia plants had etiolated growth prior to potting but they maintained an overall regrowth rating of 4.3 of a possible 5.0.

It should be noted that the experimental plants were planted in potting media, watered regularly and grown in a climate controlled greenhouse set for cool daytime temperatures. If the tender, etiolated growth found on these bare-root plants were subjected to harsher conditions often encountered in the garden, the results may be less favorable.

The objective of this study was to determine the impact of elevated post-storage temperatures on the regrowth quality of bare-root herbaceous perennials. Therefore, efforts were made to minimize other potential stresses such as desiccation by storing all plants inside bulk-packed polyethylene bags. The bags were loosely sealed to facilitate the exchange of oxygen and carbon dioxide while minimizing moisture loss. Also, the plants were not tightly packed into the crates which allows for air circulation and the avoidance of heat build-up.

The practical implications of these results are that bare-root herbaceous perennials which are wrapped properly to avoid desiccation and to allow gas and heat exchange, can withstand at least temporary exposures to elevated temperatures. Generally, most bare-root herbaceous perennials should be able to withstand as much as 2 to 3 weeks at $10^{o}C$ or one week at $20^{o}C$ without significant loss of regrowth quality. Some species, especially those generally considered easy-to-store, may even withstand prolonged periods at 20^{o}.

Storage at these elevated temperatures certainly cannot be generally advocated but, if unavoidable conditions force such exposure, the probability is good that most of the plants will survive.

CHAPTER II

Influence of Successive Freeze/Thaw Cycles on Regrowth Performance of Bare-Root Herbaceous Perennials

Introduction

Herbaceous perennials are often field-grown, harvested in the fall as bare-roots and stored for varying periods of time by commercial growers. As orders are processed, the bare-root plants are removed from storage and shipped to the retail outlet where they are either held for future delivery or potted for sale. It is recommended that most bare-root herbaceous perennials be stored at a constant temperature in the range of 0 to -2^{o}C (26)(28). At times, mechanical malfunctions in refrigeration systems or temporary interruptions in storage during shipping and handling may allow temperatures to fluctuate. Frozen bare-roots may temporarily thaw when temperatures rise and unfrozen material may freeze if temperatures drop too low.

At present there is no published information available to help growers and retailers identify those species which will not tolerate such fluctuations. This experiment was designed to test the effects of successive cycles of temperatures of -3^{o}C and 1^{o}C on 6 bare-root herbaceous perennial species which had been been packaged and stored. Plant response was monitored by evaluating subsequent regrowth potential following exposure to one or more cycles.

Materials and Methods

Six species of one year old herbaceous perennials of were used: Coreopsis (Coreopsis grandiflora 'Sunray'),Geum (Geum chiloense 'Lady Strathden'),Hemerocallis (Hemerocallis fulva 'Tawny'), Hosta (Hosta 'Honeybells'), Lupine (Lupinus 'Russell Hybrids') and Monarda (Monarda didyma 'Croftway Pink'). The plant material was taken directly from processing at Walters Gardens in Zeeland, Michigan on November 8, 1984, to the campus in East Lansing. Five plants of each of the 6 species were placed into a 4 mil polyethylene bag. Each bag represented one replicate and two bags were placed inside a wooden celery crate prior to storage. The bags were folded over but not completely sealed.

The crates were placed in a controlled environment storage room at $1^{o}C$ for one week followed by a week at $-3^{o}C$ in a second room. Following exposure to the subzero temperature, the crates were shifted back to the $1^{o}C$ room to start another cycle. Thermocouples were placed in the crates during the exposure to $-3^{o}C$ to determine the rate of equilibration with the surrounding air temperature. After one day to allow the plants to thaw, one crate of plants was removed for potting and regrowth analysis in the greenhouse. Six cycles were completed during the experiment.

The plants in the greenhouse were evaluated each week for 4 weeks following planting and were rated individually for regrowth quality. The rating was on a scale of 1 to 5 as follows: 1- No regrowth observed; 2- up to 25% of the regrowth potential expected after 4 weeks in the greenhouse; 3- 26-50% of the regrowth potential; 4- 51-75% of the regrowth potential; 5-76-100% of the regrowth potential.

Factors considered in this subjective rating system included the number of shoots, length of shoots and overall growth rate. After observing the different growth rates attained by varieties used in this and other experiments (Klobucher and Cameron, unpublished), it was determined that the 4 week rating was most indicative of a plant's regrowth potential.

The data were analyzed as a completely randomized, 1-way design with 2 replicates and 5 observations per replicate.

Results

All plants of Hemerocallis, Hosta and Monarda survived each of the 6 freeze/thaw cycles and Lupine was only slightly affected, losing one plant in each of the final 3 cycles (Figure 2.2).

Hemerocallis, Hosta, Lupine and Monarda had very high regrowth ratings throughout the experiment with overall averages of 4.0 or greater (Figure 2.1). Monarda's regrowth ratings were, however, somewhat variable but generally improved over the 6 cycles.

Lupine attained a high regrowth rating following each of the first 3 cycles before experiencing a slight but statistically significant decline after each of the final 3 cycles (Figure 2.1) Much of the decline could be attributed to the death of 10% of the plants during that period since the surviving plants continued to achieve a very high rating (data not shown).

Following the first cycle, only one of the bare-root Coreopsis plants died while all of the Geum survived (Figure 2.2). After subsequent cycles, the survival rates for these two species were somewhat variable, however. The trend was for a decline in survival as the number of cycles increased. Overall, only 55% of the Coreopsis and 36.7% of the Geum survived six freeze/thaw cycles (data not shown).

When considering only those plants which survived, Geum maintained an average regrowth rating of 3.9. The surviving plants of Coreopsis maintained an average rating of 4.9 after the first 4 cycles but then declined to 2.8 and 2.0 respectively during the final two cycles (Table 2.1).

Table 2.1. Mean 4 week regrowth ratings[y] of surviving Coreopsis and Geum as influenced by storage in alternating temperature cycles consisting of one week at 1°C and one week at -3°C.

REGROWTH RATINGS

	CYCLES					
SPECIES:	1	2	3	4	5	6
COREOPSIS	5.0	4.8	4.8	5.0	2.8	2.0
GEUM	4.0	4.0	---	3.5	4.0	4.0

y: Regrowth grades: 5 = 100% of regrowth potential; 4= 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

The regrowth ratings for Coreopsis were variable but generally, declined over time. After each of the final two cycles, the ratings dropped to very low levels of 1.7 and 1.1 respectively (Figure 2.1).

The regrowth rating of the Geum was high (4.0) following the first cycle but declined significantly over the following cycles with an overall average of only 2.1 (Figure 2.1). All plants died after the third cycle (Figure 2.2).

Figure 2.1. Effect of exposure to freeze/thaw cycles ($1^{o}C$ for one week; $-3^{o}C$ for one week) during storage on the 4 week mean regrowth ratings[y] of Coreopsis, Geum, Hemerocallis, Hosta, Lupine and Monarda.

Regrowth grades: 5 = 100% of regrowth potential; 4 =75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.

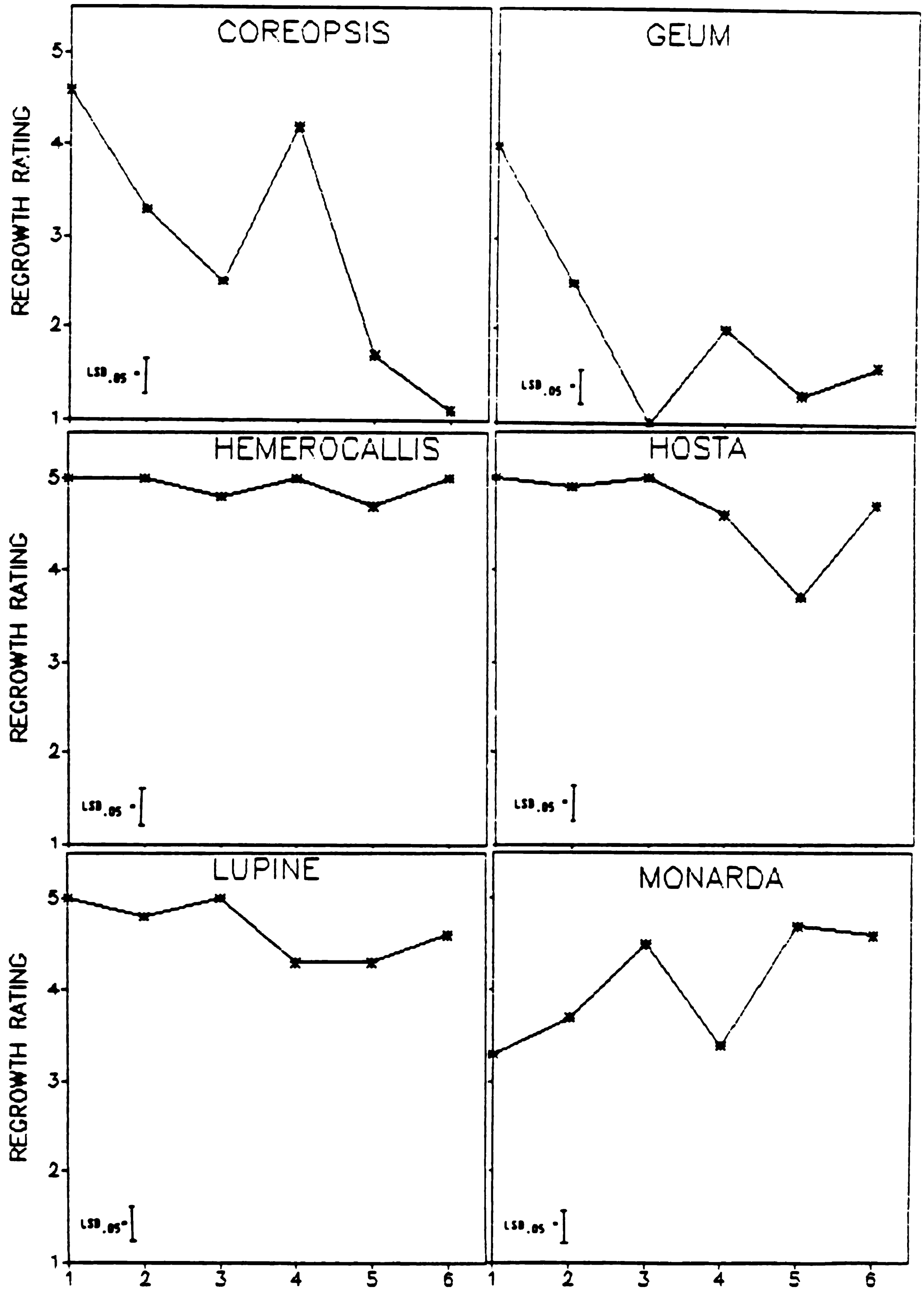
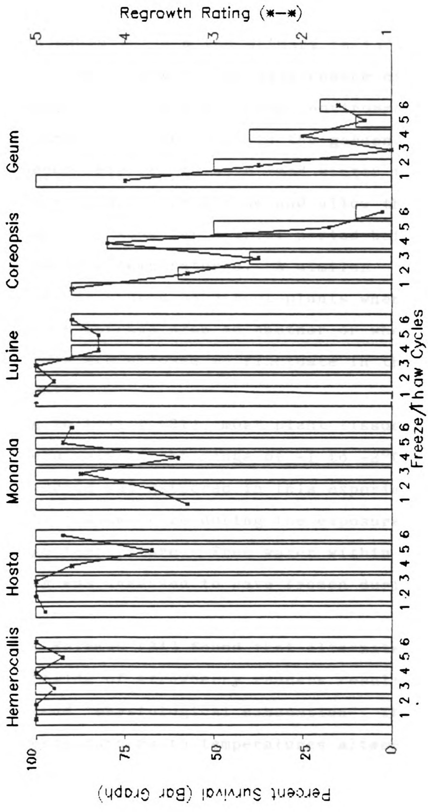

COREOPSIS
GEUM
HEMEROCALLIS
HOSTA
LUPINE
MONARDA
REGROWTH RATING
LSD.05 =
1
2
3
4
5
6
FREEZE/THAW CYCLES

Figure 2.2 Effect of exposure to Freeze/Thaw Cycles (1^oC for one week; -3^oC for one week) on the mean regrowth ratings[y] and percent survival of Coreopsis, Geum, Hemerocallis, Hosta, Lupine and Monarda.

Regrowth grades: 5 = 100% of regrowth potential; 4 =75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.


Regrowth Rating (*—*)
5
4
3
2
1
Hemerocallis
Hosta
Monarda
Lupine
Coreopsis
Geum
1 2 3 4 5 6
Freeze/Thaw Cycles
100
75
50
25
0
Percent Survival (Bar Graph)

Discussion

The control of desiccation during the storage period has been shown to be a the primary factor in storage success (28), however, the maintenance of a steady temperature level in the storage environment is also of great importance (26)(28). In the garden, a natural phenomenon referred to as a "mid-winter thaw" occurs when winter temperatures rise and allow the soil to thaw into the root zone for a brief period before a return to subfreezing temperatures. A similar situation occurs for stored bare-root plants when they are moved from one storage area to another or when temperature levels are allowed to fluctuate in the refrigeration unit.

According to Levitt (21), most plant tissues freeze at temperatures in the range of -1 to -2^{o}C. However, no evidence was gathered in this experiment to confirm that the tissue froze during the exposure to the -3^{o}C storage temperature. Free water within the polyethylene bag was observed to have frozen during the week in -3^{o}C.

Mader and Feldman (24) found that alternate freezing and thawing of strawberry runners resulted in a condition termed "physiological exhaustion". They exposed strawberry runners to temperatures alternating between 3 and -3^{o}C. Following 24 days, roots of plants treated in this manner had 9% less starch while the tops had 15% less total sugars as compared to plants held at a constant 3^{o}C. Also, 50% of the plants exposed to alternating temperatures died during greenhouse regrowth but only 10% of the plants stored at 3^{o}C failed to survive. Seventy percent of plants from the constant temperature were described as "vigorous" compared to 10% of the plants from the alternating group.

Alternating freezing and thawing temperatures did not negatively effect all species tested in this experiment. In fact, Hemerocallis, Hosta, Lupine and Monarda showed little if any decline in regrowth rating or survival following such treatments. The results for Coreopsis and Geum were variable although the trend was for a decline in both survival and regrowth rating. When considering only those plants which survived, Coreopsis showed a trend toward a declining regrowth rate as the number of cycles increased and the surviving plants of Geum maintained an acceptable level of regrowth quality (data not shown).

The practical implications of the results of this experiment are that some species of bare-root herbaceous perennials appear to be able to withstand exposure to variable temperatures with little effect on either survival or regrowth quality. Other species, however, may be effected but the response may be highly variable due to an interaction or influence of other environmental or physiological factors.

Coreopsis and Geum are generally considered to be difficult-to-store under even ideal conditions (Wayside Gardens and Walters Gardens, personal communications). However, they would usually be expected to survive 12 weeks of storage as in this experiment if they are not stressed by alternating temperatures. Ultimately, more research is needed to determine if exposure to alternating periods of freezing and non-freezing temperatures is a problem for other bare-root herbaceous perennials.

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APPENDIX

Table 1.9

Experiment 1

Analysis of Variance

Aquilegia

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	13.0	6.5	7.83	0.000	0.3
Hold Temp.	3	31.2	10.4	12.52	0.000	0.3
HT x ST	6	7.9	1.3	1.59	0.148	
Weeks	2	14.0	7.0	8.48	0.000	0.3
HT x WKS	6	23.6	3.9	4.74	0.000	0.6
ST x WKS	4	7.4	1.9	2.23	0.065	
HT x ST x WK	12	14.8	1.2	1.49	0.124	
ERROR	180	149.5	0.8			

Artemisia

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	1.2	0.6	0.94	0.999	
Hold Temp.	3	16.9	5.6	9.23	0.000	
HT x ST	6	5.1	0.9	1.40	0.213	
Weeks	2	9.8	4.9	8.07	0.000	
HT x WKS	6	13.9	2.3	3.79	0.001	
ST x WKS	4	1.7	0.4	0.71	0.999	
HT x ST x WK	12	17.0	1.4	2.32	0.008	0.9
ERROR	180	109.8	0.6			

Asclepias

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	41.7	13.9	9.19	0.000	
Hold Temp.	3	36.6	18.3	12.08	0.000	
HT x ST	6	41.8	7.0	4.60	0.000	
Weeks	2	42.5	21.3	14.04	0.000	
HT x WKS	6	25.3	4.2	2.78	0.012	
ST x WKS	4	43.2	10.8	7.13	0.000	
HT x ST x WK	12	66.2	5.5	3.63	0.000	1.4
ERROR	180	272.7	1.5			

Coreopsis

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	101.4	33.8	13.66	0.000	0.6
Hold Temp.	3	2.9	1.4	0.58	0.999	0.5
HT x ST	6	9.2	1.5	0.62	0.999	1.0
Weeks	2	31.0	15.5	6.26	0.002	0.5
HT x WKS	6	57.4	9.6	3.87	0.001	1.0
ST x WKS	4	21.2	5.3	2.14	0.075	0.9
HT x ST x WK	12	82.9	6.9	2.79	0.001	1.8
ERROR	180	445.3	2.5			

Dicentra

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	8.0	2.7	4.09	0.007	0.3
Hold Temp.	3	1.0	0.5	0.76	0.999	0.3
HT x ST	6	6.9	1.1	1.74	0.110	0.5
Weeks	2	3.4	1.7	2.63	0.073	0.3
HT x WKS	6	2.7	0.5	0.70	0.999	0.5
ST x WKS	4	1.9	0.5	0.72	0.999	0.5
HT x ST x WK	12	9.4	0.8	1.19	0.281	0.5
ERROR	180	118.0	0.7			

Geum

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	42.0	14.0	8.73	0.000	0.5
Hold Temp.	3	22.5	11.2	6.98	0.001	0.4
HT x ST	6	29.3	4.9	3.04	0.007	0.8
Weeks	2	17.1	8.5	5.31	0.005	0.4
HT x WKS	6	19.9	3.3	2.07	0.057	0.8
ST x WKS	4	8.3	2.1	1.30	0.271	0.7
HT x ST x WK	12	104.2	8.7	5.40	0.000	1.4
ERROR	180	289.5	1.6			

Lavandula

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	21.8	10.9	8.34	0.000	0.4
Hold Temp.	3	29.1	9.7	7.43	0.000	0.4
HT x ST	6	36.4	6.1	4.65	0.000	0.8
Weeks	2	5.6	2.8	2.13	0.120	0.4
HT x WKS	6	53.2	8.9	6.79	0.000	0.8
ST x WKS	4	10.3	2.6	1.97	0.098	0.7
HT x ST x WK	12	62.6	5.2	4.00	0.000	1.3
ERROR	180	235.0	1.3			

Phlox subulata

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Ship Temp.	2	1.1	0.5	0.71	0.999	0.3
Hold Temp.	3	186.1	62.0	81.11	0.000	0.3
HT x ST	6	9.0	1.5	1.96	0.071	0.6
Weeks	2	60.8	30.4	39.70	0.000	0.3
HT x WKS	6	77.2	12.9	16.82	0.000	0.6
ST x WKS	4	5.0	1.2	1.63	0.166	0.5
HT x ST x WK	12	11.1	0.9	1.21	0.271	1.0
ERROR	180	137.7	0.8			

Experiment 2

Analysis of Variance

Achillea

FACTOR	DEG. OF FREEDOM	MEAN SQUARE	F VALUE	PROB.	LSD.05
HOLDING TEMPERATURE	2	8.01	5.12	0.008	0.7
HOLDING TIME	2	16.94	10.83	0.000	0.7
TIME X TEMPERATURE	4	9.53	6.09	0.000	1.1
Error	81	1.56			

Artemisia

FACTOR	DEG. OF FREEDOM	MEAN SQUARE	F VALUE	PROB.	LSD.05
HOLDING TEMPERATURE	2	6.93	4.76	0.011	0.2
HOLDING TIME	2	12.03	8.26	0.000	0.2
TIME X TEMPERATURE	4	2.12	1.45	0.224	----
Error	81	1.46			

Phlox paniculata

FACTOR	DEG. OF FREEDOM	MEAN SQUARE	F VALUE	PROB.	LSD.05
HOLDING TEMPERATURE	2	1.01	1.54	0.221	----
HOLDING TIME	2	0.21	0.32	0.999	----
TIME X TEMPERATURE	4	2.58	3.92	0.005	0.7
Error	81	0.66			

Salvia

FACTOR	DEG. OF FREEDOM	MEAN SQUARE	F VALUE	PROB.	LSD.05
HOLDING TEMPERATURE	2	6.70	4.54	0.013	0.6
HOLDING TIME	2	4.90	3.32	0.041	0.6
TIME X TEMPERATURE	4	2.35	1.59	0.184	----
Error	81	1.48			

Sedum

FACTOR	DEG. OF FREEDOM	MEAN SQUARE	F VALUE	PROB.	LSD.05
HOLDING TEMPERATURE	2	2.50	2.23	0.114	----
HOLDING TIME	2	0.70	0.62	0.999	----
TIME X TEMPERATURE	4	3.25	2.89	0.027	1.0
Error	81	1.12			

Freeze/Thaw Experiments

Coreopsis

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Total	59	213.4				
Treatment	5	95.8	19.2	8.73	0.015	1.7
Error	54	117.6	2.2			

Geum

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Total	59	142.8				
Treatment	5	59.7	11.9	7.73	0.015	1.6
Error	54	83.1	1.5			

Hemerocallis

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Total	59	13.0				
Treatment	5	1.3	0.3	1.18	0.999	
Error	54	11.7	0.2			

Hosta

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Total	59	37.0				
Treatment	5	8.7	1.7	34	0.075	
Error	54	28.3	0.5			

Lupine

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Total	59	61.3				
Treatment	5	5.1	1.0	0.9	0.999	
Error	54	56.2	1.0			

Monarda

Source	Deg. of Freedom	Sum of Squares	Mean Square	F Value	Prob.	LSD.05
Total	59	57.9				
Treatment	5	20.3	4.1	5.8	0.030	0.3
Error	54	37.6	0.7			

Table 1.11. Overall mean 4 week regrowth ratings[y], percentage survival and error mean square for species of bare-root herbaceous perennials used in Experiments 1 and 2.

Species:	Average Regrowth Rating	Overall Percent Survival
Experiment 1		
Aquilegia	4.5	94.2
Artemisia	4.7	96.5
Asclepias	3.3	76.7
Coreopsis	2.9	57.3
Dicentra	4.8	96.1
Geum	2.0	34.9
Lavandula	2.0	45.0
Phlox sub.	4.0	88.3
Experiment 2		
Achillea	2.9	67.1
Artemisia	3.9	87.9
Phlox pan.	4.3	94.2
Salvia	2.4	64.2

y: Regrowth grades: 5 = 100% of regrowth potential; 4= 75%; 3 = 50%; 2 = 25%; and 1 = No observable growth.