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Title: FROST HARDINESS OF BUDS, FLOWERS, AND FRUIT OF PEAR (Pyrus communis L.)

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Spring frost damage to pears in the Pacific Northwest frequently results in substantial crop losses. This research was undertaken to investigate the effects of frost on pear buds, flowers, and fruit through controlled freezing tests and field studies in order to better understand the frost phenomenon and refine frost protection decisions.

Controlled freezing studies on 'Bartlett' pear (Pyrus communis L.) showed that the percent of florets injured by frost increased with decreasing temperature, advancing developmental stage, and increasing duration at minimum temperatures of -2, -3, and -4°C. Increases in injury occurred with exposures of 30 or 60 minutes at all stages except the small fruit stage, in which injury continued to

increase for 2 hours at -2°C. No significant effects of freezing rate were found at -2, -3, or -4°C. However, there was a significant effect of freezing rate at -5°C. No hardiness differences were found between comparable floral developmental stages from weak and vigorous trees. Bloom delay through evaporative cooling resulted in a loss of hardiness beyond that found earlier in the season on non-misted trees for similar stages of development. However, under field conditions a certain amount of frost protection was gained through bloom delay.

Simulated frost injury to small fruit ovaries at intervals after full bloom significantly increased fruit malformation, reduced fruit weight, and increased fruit drop of 'Bartlett', 'Bosc', and 'Comice' pear trees. Time of injury did not affect fruit weight and malformation in most cases, but early injury did significantly increase fruit drop. Significant positive correlations were found between fruit weight and seed content, while negative correlations were found between fruit malformation and seed content for all cultivars.

Crop density was correlated significantly with sum of percent floral injury from frost, orchard design, and height in the tree for 'Bartlett', 'Bosc', and 'Anjou' pear. Regression models for crop density, regressed on sum of the percent injury, orchard design, and height in the tree differed between cultivars indicating that one model cannot be used to estimate crop density at harvest for all

cultivars. Crop density was greater at low levels of frost injury in free standing than in hedgerow trees, and at greater elevations in the trees. Data suggest that 30 percent frost injury in hedgerow and 60 percent frost injury in free standing pear orchards are reasonable injury levels to accept without incurring crop losses.

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INTRODUCTION

Spring frost damage to pears in the Pacific Northwest continues to cost growers millions of dollars each year. In the past few years, frost protection has become increasingly more difficult as a result of: air pollution ordinances; rising labor, fuel and equipment costs; and the advent of high density orchards which are more prone to frost injury than taller standard orchards. It is estimated that frost protection accounts for 22.4 percent of the energy input in noncitrus fruit and nut production in the United States (206). Spring frosts are also responsible for many of the fluctuations in fruit supply, quality, and price, creating major problems in marketing.

In the Rogue River Valley of Oregon there is a 60-day period from mid-March to mid-May during which the night temperature may drop low enough to cause bud, blossom, or fruit damage. Frost protection measures employed by growers range from return stack heaters, overhead sprinklers, and wind machines to no protection at all and the hope that frost damage will be minimal (27).

Due to the complexities of floral development, critical temperatures or the lowest temperature that a bud, flower, or fruit will

withstand for 30 minutes without injury are often inaccurate. In many cases they are found to be too high, in order to guard against conditions in which the tissues are extremely susceptible to injury. Consequently, frost protection measures may be taken unnecessarily. Under different situations, it has been found that the critical temperatures are too low and injury has resulted (10). In order to refine frost protection decisions it is necessary to understand the factors affecting frost hardiness. In this way growers can develop increasingly successful risk strategies (27).

This study was undertaken to examine and understand some of the factors involved in spring frost hardiness, with the purpose of aiding pear growers in their frost protection decisions.

REVIEW OF LITERATURE

The Spring Frost Environment

There are basically two types of frosts, advective and radiation. The advective freeze is caused by the movement of a cold air mass into the region. Typically the air is dry and the cold lasts for several days. Winds are usually associated with the advective frost making it difficult to maintain orchard temperatures above the critical range with supplemental heat. Many of the factors involved in the radiation frost are also active during the advective frost (10). Fortunately,

advective frost is uncommon and usually occurs during winter.

The radiation frost generally occurs following a storm under conditions where a cool dry air mass remains relatively stationary for two or more days. On a calm clear night the ground is cooled due to radiation heat loss and the air in contact with it is also cooled. As a result, a temperature inversion is produced. An inversion is defined as an increase in temperature with increasing elevation (77). The magnitude or strength of the inversion depends upon the night temperature differential between the 15.2 or 18.3 meter height and the 1.0 or 1.5 meter height. Inversion strength varies from night to night and this accounts for the relative ease or difficulty in maintaining orchard temperatures (10). Thus, a 10-degree change in 15.2 meters indicates a strong inversion or low ceiling under which orchard heating is effective, while a 2-degree change in 15.2 meters denotes a weak inversion in which the vertical transport of heat is great and during which there is difficulty in holding orchard temperatures (53, 77).

On a radiation frost night, air cooled by contact with any radiating surface becomes denser (53). Level ground and depressions become progressively cooler than slopes as the denser air moves downhill and accumulates at lower elevations (19, 77). The downhill movement of air against rough surfaces produces a mixing of warm and cold air and reduces the rate of temperature fall. However, in

areas where trees block the downward movement of air or in depressions where the mixing of air is minimal, the rate of temperature fall is more rapid. Thus, pools of cold air develop in low areas and warm air layers are established above (77). Within the tree, lower branches are generally cooler than the upper branches due to this stratification (10, 209). The flow of air differs from that of water in that air is compressible and changes in density with changes in temperature.

The net radiation loss from the orchard on cold nights usually ranges from .05 to 0.2 lys. per minute (53) or approaches 900,000 BTU's per acre hour at its maximum (10). This loss varies with the humidity, cloud cover and air temperature and is usually at its maximum just prior to sunrise (10, 77). The bud, flower, or fruit surface is surrounded by a thin insulating boundary layer of air. The thickness of this air layer depends on the size, shape, surface orientation of the tissue, wind velocity and the temperature gradient between tissue and air (50). As the foliage develops it intercepts radiation from the ground and reduces heat loss (10).

Continuous monitoring of both tissue and air temperature has shown that tissue temperatures frequently fall below air temperatures due to radiation loss (87, 91, 111, 126, 166, 167). In fact, peach blossoms have been found to be as much as 2.5°C colder than the air temperature (91). More typically blossom temperatures

range between 0.5 and 0.7°C below that of the air (126). Schwintzer (166) in studying leaf orientation in soybeans found that the average differences between leaf and air temperatures were 1.0°C and 1.5°C for vertical and horizontal leaves respectively.

Winds mix the colder low level air with the warmer air aloft under inversion conditions and slow the rate of temperature fall or in some cases, actually raise the orchard temperature (10). Wind speeds of .88 m/s (87) are enough to destroy the boundary layer of air on a flower, increase the convective conductance, and maintain the tissue temperature near that of the air (10, 49). As the movement of air through the tree becomes turbulent, the conductive heat transfer rate becomes proportional to the wind velocity (49).

The quantity of moisture in the air affects the rate of heat loss to the sky (209). At night, water vapor helps to maintain or may raise the air temperature by absorbing outgoing radiation and reradiating the longer wavelengths. Thus, the more water vapor held in the air or the higher the dewpoint, the slower the temperature fall. Conversely, the drier the air or the lower the dewpoint, the more rapid the temperature fall (77).

Clouds of water vapor are effective at reradiating heat back to the ground. Generally, the lower and thicker the clouds, the greater the heating effect or the slower the temperature fall. However, if a break in the cloud cover occurs over an orchard a drop in

temperature usually occurs (209). High thin cirrus clouds of ice crystals have essentially no influence on orchard temperatures (10, 77).

Smoke has been shown to have no effect on slowing the temperature fall at night. The random sized carbon particles are unable to absorb and reradiate the longer wavelengths. However, particles 0.4-0.7 um are effective in scattering the visible shorter wavelengths of incoming solar radiation during the early morning hours and can prolong the low temperatures (10, 77, 196).

The Freezing Process

Dormancy and Deacclimation

Differential thermal analyses (DTA) is a technique which records the freezing process by measuring the difference in temperature between a dry reference and a tissue sample. Analyses using DTA conducted during the winter on dormant buds of rhododendron, apricot, plum, blueberry, peach, and cherry have shown that there are two points on a cooling profile at which freezing takes place (23, 52, 56, 146). The first exotherm occurs below -5°C following an initial lag and is associated with the freezing of water held in the bud scales (43, 52). A second exotherm or series of exotherms occurs upon death of the floral primordia (52, 56). The positions

of these exotherms shift with hardening and dehardening of the buds and in the spring rise to the temperature range of the first exotherm. Quamme (146) associates the multiple exotherms of peach flower buds in spring with freezing of the individual flower parts. Similar exotherms have not been found in pear and apple flower buds.

Experimental results using rhododendron flower buds suggest that flower primordia avoid freezing injury during dormancy by deep supercooling and support the theory that low temperature exotherms are produced by the freezing of cellular water. Deep supercooling appears to be possible only because of a barrier to freezing between the supercooled primordia and the frozen bud tissue, since primordia freeze readily when inoculated with ice crystals (51).

Evidence from dormant peach buds implies that two mechanisms are involved in primordia deep supercooling. The cuticle or primordium epidermis may act in inhibiting ice nucleation on the surface of the primordium, while a dry region at the base of the primordium could prevent ice propagation into the primordium. It is hypothesized that the dry region is produced by the movement of water into the bud scales as freezing begins (147). Other researchers (52, 116) point out that calculations on the minimum volume of cellular water necessary to prevent spontaneous nucleation correspond to cell and extracellular space volumes found in rhododendron flower primordia.

Studies on sweet cherry flower buds indicate that ice is propagated through the bud stem axis into the floral primordia when bud rest is broken. Cell division and the formation of large extracellular spaces within the primordia are thought to aid in ice nucleation and propagation throughout the tissue. Consequently, as the bud develops little difference exists between the freezing point of the primordia and other portions of the bud (52).

Dormant apple and pear flower buds which lack low temperature exotherms and do not deep supercool appear to survive low temperatures by tolerating a certain amount of extracellular freezing (56, 146).

Supercooling

In the spring as the buds and flowers develop, ice is usually not formed immediately upon subjecting a plant to temperatures below its cell sap freezing point. Tissues normally supercool and if supercooling persists for the duration of a low temperature exposure the plant escapes injury. On the other hand, if supercooling is only temporary, ice formation may take place in the extracellular and/or intracellular spaces (130). In the orchard factors favoring supercooling are normally weak (126). Rare instances of suspected supercooling in the field have been reported in which a branch or entire tree remains uninjured, while the surrounding

branches or trees fail to produce a crop (10, 138).

The degree of supercooling in both the lab and the field has been shown to be affected by a number of factors, especially those that influence the water supply to buds and flowers. Supercooling is usually decreased by spraying plants with water or by cutting floral spurs to be frozen under water (126), by increasing the size of the plant part to be frozen (23, 126), by reducing the freezing rate (115), and by selecting more advanced floral stages (23).

Even a slight loss of water from cells, cell walls and extracellular spaces favors supercooling. As a rule, the larger the plant part or quantity of water in or on the tissue, the greater the number of nucleation sites and the greater the possibility that spontaneous nucleation will occur (126). Increased supercooling followed by freezing may promote rapid freezing and an increase in the amount of injury (23, 115).

Nucleation

Salt (160) found temperature, time and what appeared to be chance to be the primary factors involved in the nucleation of supercooled insects and suggested that a number of tissue structures and substances could act as nucleators. Kaku (78) reported that ice nucleators were present within the mesophyll of Veronica and the midrib vascular tissue of Buxus, but that these were not present in

homogenized samples. MacKenzie et. al. (109) state that the cell cytoplasm acts like a dilute aqueous solution and that structures required for the heterogeneous nucleation of ice are not usually present within the cell.

Apparently in many plants ice nucleation occurs externally and that this ice then inoculates the internal tissues (78, 130). As a result, the morphological features of the plant play an important role in cellular freezing. Cuticular thickness and continuity have been shown to restrict movement of ice across the epidermis (179). Dew that freezes on the surface of the plant is thought to facilitate inoculation of the tissues by means of wounds such as cracks or damaged epidermal cells and trichomes (112, 130). The site of primary ice formation is likely to be a portion of the plant which has cooled below the air temperature due to radiation loss (130).

Attempts to collect airborne ice nuclei at temperatures just below $0^{o}C$ within the crop microclimate have not been successful (112), indicating that the freezing nuclei are possibly already present on the plant surfaces. Recent studies have revealed that the bacteria, Pseudomonas syringae, and P. florescens are active in ice nucleation on plant material (5, 96, 110, 163, 164, 165). Ice initiation has been observed to take place at temperatures as high as $-1.3^{o}C$ when these bacteria are present (164). In addition, both chemical and physical destruction of the bacteria destroy their ice nucleating

capacity (109, 164). Protection from freezing has been achieved in the field on corn, tomatoes, and potatoes by spraying with streptomycin (96, 164, 186), while frost susceptibility of corn, bean, and lettuce plants has been increased by spraying with suspensions of P. syringae (96).

Extracellular Freezing

Extracellular freezing usually takes place following nucleation and the introduction of ice crystals into the tissue. It is the result of an unstable thermodynamic situation in which the vapor pressure is greater on the inside than on the outside of the cell. In order to establish equilibrium, water can either pass through the plasmalemma and cell wall and freeze in the extracellular spaces or freeze intracellularly (116). The former will be discussed first.

Alden and Hermann (2) concluded that extracellular ice formation depends primarily on three factors, the permeability of the plasmalemma, the permeability of the cell wall, and the imbibitional capability of the protoplast, while the rate of water diffusion into the extracellular spaces depends on the degree of protoplast supercooling (113). Once extracellular ice is formed it is surrounded by water and often moves about (6).

Extracellular freezing is most often described as a protective mechanism against lethal intracellular freezing, but it has also been

implicated in both dehydration and mechanical damage (126). According to Mazur (117) extracellular freeze-induced dehydration results in the withdrawal of water, in an increase in solute concentration, in a reduction in both cell volume and macromolecule spatal separation, in solute precipitation and in pH changes. The desiccation can coagulate protoplasm, snap protoplasmic strands, rupture membranes, and produce toxic cell sap concentrations (126).

Studies on moss leaves reveal two types of extracellular dehydration. Peripheral dehydration occurs under conditions of slow cooling and involves the removal of water in such a way that the protoplasm shrinks around the nucleus. The nucleus which remains in the center of the cell is left connected to the cell walls only by thin protoplasmic strands. When exposed to excessively low temperatures or rapid dehydration, the protoplasmic strands may snap. Conversely, cytorrhesis occurs following rapid dehydration under which the cell wall collapses in the middle and forces the cell contents into a ring-shaped configuration. This type of injury often results in cell death (130).

Mechanical damage due to extracellular freezing occurs under conditions where the extracullular spaces are unable to accommodate the volume of water withdrawn from the cell. As water accumulates in the extracellular spaces, the cells are first separated along the middle lamella, and then, as freezing takes place, the cells may

be crushed or ruptured by expanding ice (126). In some cases the water that accumulates in the extracellular space may not only be from adjacent cells, but also from unfrozen cells that lie further away. Upon thawing, water is reimbibed by uninjured cells and the cavity formed by the extracellular freezing closes (131). Extracellular freezing frequently occurs in the field in both leaves and flowers (121).

Intracellular Freezing

Intracellular freezing in contrast to extracellular freezing always kills the cell (121, 126, 130, 131). It characteristically occurs under conditions of rapid cooling when the rate of water withdrawal from the protoplast fails to keep pace with the cooling rate (130). Samygin (161) has characterized three means of intracellular ice formation in turgid epidermal onion cells.

Intracellular ice formation in a single cell has been observed to move by means of the plasmodesmata from cell to cell. Under conditions in which the cell is plasmolyzed due to extracellular freezing, the protoplast is often divided into two or three sections. In these instances, freezing takes place in one section and is then propagated into other sections through the interconnecting protoplasmic strands. Ice penetration is delayed slightly by the tonoplast,

but following this crystallization takes place rapidly in the vacuole (131, 161).

In a second less frequent instance ice has been observed to propagate directly through cell walls that are bordered by extracellular spaces. Ice formation occurs first in the plasmolyte situated between the plasma and the cell wall and then in the plasma. However, under conditions of slow freezing ice forms in the reverse order. The passage of ice through cell walls adjacent to extracellular spaces is inhibited by a lack of protoplasmic connections and pores and also because of reduced pore sizes. In some cases, the pore size can be stretched enough to permit ice penetration by means of the pressure exerted by ice formation in the extracellular spaces (113, 131).

Finally intracellular ice is also formed by spontaneous nucleation which occurs first in the protoplasm and then in the plasmolyte. This may take place either slowly from a few nucleation points, or instantaneously from many nucleation sites under supercooled conditions.

The hypothesized mechanisms of cellular injury are numerous and varied. Excellent reviews on this subject have been written by Alden and Hermann (2), Burke et. al. (23), and Levitt (94).

The Freezing of Flowers and Fruit

The freezing of an apple or pear bud, flower, or small fruit can be broken down into two phases. In phase one under typical orchard conditions supercooling occurs until a temperature of -1.6 to -2.0°C is reached (42, 126, 129). At this point, ice innoculation from dew frozen on the coldest plant surface takes place through a wound and initiates extracellular freezing. Freezing occurs throughout the plant almost simultaneously via the vascular system (129). Within a flower, ice formation takes place extracellularly between the dense compact hypodermal cells four to six cells below the cuticle and the looser rounded cortical cells. In this process, water has been observed to be withdrawn from several cell layers in the surrounding tissues (131). Both tissues are thus protected from intracellular freezing and a layer of ice is formed which lifts the epidermus and hypodermis and separates them from the receptacle (42, 47, 48, 108, 126, 129, 130, 159, 176).

Recovery from this type of injury is fairly rapid and may occur within 2 or 3 days in apples under favorable growing conditions (174, 175), but normally takes about 2 weeks (159). Repair begins from both surfaces of the rupture by cell extension and the formation of chain-like bridges of callus cells which gradually fill in the cavity (42, 131). This type of injury is common and occurs

repeatedly during the winter in dormant flower primordia and leaves, and during the spring in buds, flowers, and fruit (42, 130). Researchers are confident that this type of injury is not lethal without further extracellular and intracellular freezing (48, 108, 159).

In phase two, intracellular freezing occurs causing cells to suddenly freeze and innoculate neighboring cells (130). This injury takes place as a sequence in apple and pear flowers. It begins at the base of the styles and then spreads to the cells in the area of the central vascular bundles, gradually taking over the entire placenta. Following this, intracellular freezing occurs in the ovules. Initially, the cell layers three to four cells below the ovule surface are destroyed; this is followed by killing of the remaining ovule cells (47). Meanwhile, freezing continues in the cortical area of the flower or fruit, and in some cases produces frost cracks which extend to the surface (109).

Survival of the flower or fruit is dependent upon the amount of damage sustained by the vital tissues and the capacity of the remaining cells to perform the necessary functions (130). For example, if the pistils are injured prior to fertilization there may be little chance for fruit set, while injury to the petals has little effect on survival. Generally, if the placenta is killed, the ovules fail to develop and the flower abscises (41, 124, 126, 176, 209). However,

if only part of the placenta and ovules are killed a fruit may still develop (42).

Recovery from non-lethal injury is thought to be favored by high humidity which aids in the replacement of cellular water, reduces dessication injury, and is conducive to cell growth and repair (130). Fruit malformation can result from both lack of seeds and extensive injury to the cortical area of the fruit (175, 176). Lack of seeds commonly causes a flattening of the fruit in the calyx area (178), however, an elongation of the fruit occurs in some cultivars (124). Cortical injury and cracking that result in a localized loss of cell meristematic activity lead to cork formation and distorted fruit growth (130, 175).

Frost Marking

Frost marking, frost russeting, or frost ringing are all caused by injury to the flower or fruit epidermis by low temperatures on pears and apples (42, 45, 172, 184). Frost marking results in a variety of blemishes and deformities ranging from small isolated coarse, woody, russeted blotches to complete russeting of the fruit. Both vertical and horizontal cracks may be formed as well as the characteristic irregular russeted rings that encircle the fruit and depress growth (41, 126, 171, 172, 208). Other researchers (15,

181) have noted an association between cultivars with thin cuticles and russet susceptibility.

Russeting is associated with cuticle cracking, reduced irregular cutical development, and tangential cell division (9, 172, 177, 184). Russet formation becomes apparent at 30 days after bloom (173, 174) while the maximum rate of tangetial growth is reached at 23 days after bloom in the apple (45). Sironval (180) believes that exposure of the hypodermis to oxygen is a key factor in initiating phellogen formation. However, it is apparent that 'skin' lifting during the first phase of freezing does not normally lead to russeting (41, 125, 175).

Following the initiation of phellogen beneath the injured area, both phellem and phelloderm are produced from a disorganized mass of cells and from a protective outer layer. Phellem continues to be produced and sloughed-off throughout the season (171, 172, 176) and as the fruit enlarges the russeted area enlarges proportionally. Mechanical injury to apples at intervals following fruit set indicate that increasingly serious malformations in cellular development occur with earlier fruit injury dates (177).

The stage of development and conditions under which the injury that eventually develops into frost russeting occur are difficult to determine. Young (208) after 10 years of field observations, concluded that marking may take place on pears both prior to and during

the bloom period. Peters and Rackham (134) after reviewing annual frost reports for a number of years claim that marking of pears can occur at any time between the green cluster and small fruit stages, but that it is less frequent during the earlier stages. Furthermore, it is suggested that marking is more liable to occur at a higher temperature especially if the bud or flower is covered with ice under high rather than low humidity conditions (208). Several studies indicate that a temperature of -3.3°C or lower prior to the bloom stage on a damp night produces substantial marking (134, 208). Simons (172) reports that a temperature of -3.9°C 3 days after full bloom creates considerable frost marking on several apple cultivars. Field observations have shown that 'Bartlett' and 'Anjou' show more russeting than most other pear cultivars for a given minimum temperature (134). However, severe russeting reportedly occurs on 'Seckel' following exposure to -1.7°C in the bloom stage (119).

Factors Affecting Frost Injury

Minimum Temperature

The minimum temperature reached is a primary factor in frost injury (42, 63, 167). A number of critical temperature tables have been developed for pears (11, 101, 134, 208). A critical temperature is defined as the lowest temperature that a bud, flower, or fruit will

withstand for 30 minutes without injury (138). In order to designate the range over which injury may take place lethal temperature (LT) values are used (11, 26). These delineate the temperature at which a certain percentage of buds or flowers are killed in laboratory tests.

One problem in trying to determine critical temperatures is that hardiness levels may vary from day to day and from year to year because of environmental conditions (10, 145, 209). Another problem is the temperature difference between the air and blossom temperatures on high radiation nights. Since heating decisions are based on air temperatures, some critical temperature tables have been modified to take this into account and critical temperatures may appear to be unnecessarily high (91).

The layer of cold air near the ground is usually responsible for increased injury in the lower portion of the tree (62, 91, 209). Hamer and Collenette (60) noted a linear increase in injury with decreasing height below two meters in an apple tree. They also find there is a reduction in blossom injury with increased screening from the sky and that flowers facing downward tend to sustain less injury than those facing the sky. As a rule, the lowest orchard temperatures usually occur just prior to sunrise (77, 207).

Temperature Duration

Several researchers find that the degree of injury of dormant tissue increases with duration at a particular minimum temperature. Hildreth (73) claims that the amount of injury sustained by dormant apple twigs is directly proportional to the length of time at the minimum temperature, while Rollins et. al. (158) report that most of the increase in injury occurs during the first part of a 6 hour exposure. The latter result is also supported by studies on dormant peach buds in which a large portion of the injury took place during the first few hours of 13 and 16.5-hour exposure periods (167).

The degree of injury in apple flowers is dependent on both temperature and duration (47, 48, 126). Field (47, 48) shows that the amount of injury in several apple cultivars continues to increase up to 6 hours at -3.3 and -2.2°C, but takes 12 hours at -1.7°C. The degree of injury sustained during these exposure periods varies with both stage of development and cultivar tested. These results are supported by studies that show that it takes a considerably longer period to establish freezing equilibrium at -2°C than at -5°C (22).

Orchard heating recommendations based on field observations have also incorporated freezing duration. However, it is questionable that these are based on actual bud temperatures. According to

Young and Cate (209) all commercial pear cultivars show a slight amount of injury after an exposure to -3.6°C for 1 hour in the pink stage. While apples and pears in the small fruit stage are said to require protection if the temperature drops below -1.7°C or if the temperature remains below 0°C for more than 2 hours prior to sunrise (208).

Freezing Rate

Dormant buds and dormant terminal shoots of fruit trees are injured more at rapid freezing rates than at slow ones (25, 31, 73, 167). Chandler (25) noted that a rapid temperature fall during the early part of the freezing period produces more injury than a rapid drop in temperature later. On the other hand, others (56, 148) studying dormant apple twigs and rhododendron floretes using DTA find little or no relationship between the freezing rate and the amount of injury. George et. al. (52) also using DTA and dormant rhododendron buds indicate that there is an increase in the amount of injury between the rates of 8.5 and 18.8°C/hr, while little increase in injury occurs between the rates of 18.8 and 37°C/hr.

Studies on Eucalyptus seedings reveal that rapid cooling rates increase leaf damage more than slow cooling rates of 1.0°C/hr (7, 63). Furthermore, tests using apple blossoms also suggest that there is an increase in injury under rapid cooling rates (47,

48). However, other studies are inconclusive (25).

The rate of thawing has not been found to influence the degree of bud, flower, or small fruit injury (24, 25, 26, 47). There is also evidence that the application of a cold water spray immediately following does not affect the amount of injury (48).

Thus, it appears that the freezing rate has some effect during the dormant period and that the degree of this effect depends on the plant species. During the bloom period, the effect of the freezing rate may or may not be a factor in the injury response and there is little effect of the thawing rate on injury.

Tissue Hydration

Fruit trees subjected to partial water stress over a period of time usually show an increase in hardiness (25, 123). Modlibowska (123) notes that if water is withheld from potted apple trees so that tissue water content drops below 74%, supercooling of the flowers persists to -3.2°C. However, trees subjected to dry soil conditions for 2 to 4 weeks often produce many flowers with stunted styles, anthers, and yellowish-green petals. No correlation is found between blossom water content and the degree of frost injury at soil moisture levels above 15% (% dry wt.). Modlibowska concluded that dehydration results in an increase in the cell sap concentration, increased supercooling, a reduction in the freezing point, and reduced ice

formation. Furthermore, the ice that is formed is found primarily in the extracellular spaces and results in less injury. Scott and Cullinan (167) note that the buds on dormant peach branches that are cut and air dried for 24 hours are hardier than those brought directly from the field and that these are in turn hardier than buds on branches that are left for 24 hours with their basal ends in water. They also found that cultivars that take up the greatest quantity of water have the lowest bud survival when exposed to freezing temperatures.

Chandler (25) notes that rapid wilting just prior to freezing reduces the degree of injury in some plants, but not as much as the continued partial withholding of water over a period of time. This increased hardening has been attributed to an increase in the protoplasmic permeability (95, 126).

Water applied to the surface of the plant material just prior to freezing affects the degree of supercooling and in some cases the amount of injury (Modlibowska 126). She suggested that moisture on the surface of an apple flower suppresses supercooling in several ways. A wet blossom is cooled by evaporation below the air temperature which causes it to freeze and innoculate its internal water with ice crystals, while a dry blossom continues to supercool. In addition, the surface moisture may be partially taken up by the tissue, resulting in a reduction of the cell sap concentration and a

change in the internal water distribution. This difference between dry and wet tissues is less apparent in the pre-bloom stages (48). Other researchers (63, 185) have noted that water applied to the surface of Eucalyptus leaves prior to freezing increases leaf damage.

Studies by Modlibowska (126) concerning the consequences of misting different regions of apple flowers indicate that freezing injury to the styles and ovules is greatest in flowers misted from all sides. Less injury is found in flowers misted from beneath, while dry flowers and those misted from above are equally injured the least. Additional studies show that aqueous dyes of acid fuchsin placed into the calyx tube are not taken up by the tissue, while injections into spurs and leaf petioles can be traced to the flowers. Thus, it appears that water increases injury primarily through the receptacle.

Humidity has also been implicated in frost injury differences (126). Wet apple flowers are injured more than dry flowers, but tend to be damaged slightly more at a low humidity. While dry flowers are usually damaged more at a higher humidity. Possibly low humidity increases evaporation leading to a lower minimum temperature, while the high humidity promotes condensation and the presence of moisture increases the injury.

Bud and flower hardiness is highly correlated with tissue moisture content (47, 55, 63). Graham (55) notes that

rhododendron floret hardiness depends primarily on the capacity to rapidly lose water from the floret tissues during freezing. Hewett et. al. (69) indicate that there is no difference in hardiness between dry dormant buds and flowers of peach and those dipped in water just prior to freezing. However, buds and flowers that are misted with water for 24 hours before freezing are significantly more damaged. A subsequent study failed to indicate any differences in hardiness between the three treatments. These results are attributed to a physiological alteration of the tissue induced by drought stress. Similar studies using 'Concord' grape shoots in the second leaf stage show an increase in injury for both the dipped and misted treatments over that of the dry control. Another study indicates that dormant peach buds that have been misted for 12 hours and dried at air temperature for 3 hours show no significant differences in percent injury and percent moisture over unmisted buds. These data suggest that in some cultivars there is a lag period involved in tissue water uptake and that this directly affects bud and flower hardiness.

Developmental Stage

Usually as buds begin to deharden and advance into progressively later developmental stages, the temperature range between the ten and 90% injury levels becomes narrower and narrower (10, 11, 47, 138, 141, 145). In addition, the range of different

developmental stages within a tree is reduced. Consequently, the risk of crop loss increases, especially after first bloom (207). However, there are exceptions to these trends.

Controlled freezing tests by Hewett (68) support grower observations claiming that 'Roxburgh Red' apricot buds are more prone to frost injury at red calyx (pre-pink) than in the white stage. This increased hardiness is attributed to the insulating volume of air enclosed within the petals in the white stage. However, other tests (25) with peach buds fail to show a hardiness loss when the petals are removed. Exceptions also occur in apples. In the 'Court Pendu Plat' cultivar buds in the pink, white, and popcorn stages are injured more than flowers, and no correlation between tissue moisture content and hardiness is apparent (47).

Proebsting and Mills (139) attribute the loss of hardiness with the progessive changes in developmental stages to morphological development and protoplasmic changes. While others claim that this may in part be due to changes in the cell sap concentration (192).

Proebsting (138) cautions that one should not expect the same degree of hardiness each time a particular developmental stage is tested. He points out that bud and flower hardiness is continually changing and that a floral developmental stage is an arbitrary marker in the course of development. Richardson et. al. (154) and Anderson et. al. (3) have noted a correlation between the

accumulation of growing degree hours and floral developmental stages of peach and apple respectively.

Floral development is often more advanced on the south sides of pear trees than on the north sides, because of increased sun exposure (21). Jones (76) noted increased frost damage on the south sides of fruit trees, and attributed it to more advanced bud development.

Generally, in the small fruit stage as the fruit size increases the greater mass enables the fruit to withstand longer periods below $0^{o}C$ (134).

Cultivar

There are a variety of means by which fruit tree cultivars differ in hardiness. A variation in the bloom date may increase the chances of escaping injury for a later blooming cultivar (91, 101). For example, 'Anjou' pear may bloom as much as 1&1/2 weeks earlier than 'Bosc' (101). In addition, the degree of bud development within a tree varies between cultivars. 'Golden Delicious' apple buds born laterally on previous years shoots bloom later than terminal spur buds. Thus, a crop can be produced even if all the terminal spur buds are killed (10).

Hardiness differences are also found between comparable developmental stages due to an inherent capacity of the tissue to withstand the cold (91, 101, 132, 191) and to supercool (76). Young

(208) notes that 'Bosc' pear is more susceptible to frost than most other commercial pear cultivars at similar developmental stages, while 'Winter Nelis' tends to be hardier. Apples show no correlation between flower moisture content and hardiness at particular stages (48).

There are also cultivar differences in frost marking susceptibility and the ability to retain frost injured fruit on the tree. 'Bartlett', 'Anjou', and 'Seckel' cultivars have a greater susceptibility to frost marking that 'Bosc' and 'Comice' (99, 119, 208). On the other hand, 'Bartlett' and 'Bosc' have a greater tendency to maintain ovary-injured fruit on the tree than 'Anjou', 'Comice', and 'Winter Nelis' (208).

Preconditioning

Temperatures prior to a freeze are strongly implicated in bark, bud, and flower hardiness, especially during the dormant period. Controlled freezing studies indicate that during deacclimation apple bark tissue dehardens if it is exposed to temperatures above a particular level. Rehardening occurs at a slower rate and does not take place beyond a certain base level, which increases progressively with each day of dehardening (75).

High and low temperatures deharden and harden dormant buds respectively (118, 137, 138, 167). Peach and sweet cherry flower

buds are found to reharden when the temperature remains below -1.1 to -2.2°C in a manner similar to that of apple bark (137, 142). Temperature duration is apparently more important than the minimum temperature reached in the rehardening process (137). Other studies show a close relationship between the hardiness of peach twig tissue and that of the flower buds (68). Correlations also have been found between bud hardiness and the mean and $\frac{\max + \min}{2}$ temperatures for 2 and 7 days prior to freezing (68, 137).

As buds begin to swell and the bud scales separate the ability to reharden is reduced (10). During the bloom period Field (47, 48) notes that exposure to temperatures of 1.1 to 3.3°C do not induce hardening, while apple blossoms subjected to 6 hours at 0°C for four nights are slightly less damaged by freezing. Studies on sour cherry show no relationship between previous temperature exposure and the hardiness of unopened blossoms or flowers (38). Mellenthin (119) concluded that 'Anjou' pear flowers develop no frost hardiness if exposed to low daytime temperatures; however daytime temperatures of 26.7°C reduce hardiness. According to Head (67) a cool temperature regime for a week or more slows the rate of apple blossom development leading to a reduction in flower size and water content and an increase in both sugar content and hardiness.

Tree Vigor

Relationships between tree vigor, nutritional status and hardiness are found in the literature. Young (207, 208) claims that flowers and fruit on a weak tree are more subject to frost injury than are those on a vigorous tree. These results are also supported by field observations on peach trees (25); however 'Gano' apple trees failed to show hardiness differences between comparable floral stages on weak and vigorous trees.

Fertilization tests on peach trees using N (71) and K (25) produce no noticeable effect on bud, flower or fruit hardiness. However, K applications promote greater foliage hardiness on tulip poplar trees (199). Buican (21) notes that the uptake of K, P, Zn, and Co are proportional to the cold resistance of several corn cultivars and suggests that Zn increases membrane permeability leading to a reduction in intracellular ice injury (153). Additional studies concerning plant hardiness and nutrition may be found in reviews by Alden and Hermann (2) and Levitt (93).

Tree vigor may also influence the date of bloom. Vigorous trees often bloom later than weak trees in the spring, especially in southern areas. This is thought to be because they grow later in the fall and consequently end their rest period later than weak trees.

In one case vigorous peach trees are reported to have bloomed a month after weak trees in southern Missouri (25).

Repeat Freezes

Several investigators have noted that repeated freezing and thawing amplifies the degree of injury above that expected from an additive effect of freezing (23, 62, 133). Burke et. al. (23) note that hardy winter wheat is killed following two freezing and thawing cycles to -12°C, while similar plants are not injured when frozen once to -19°C. Eucalyptus seedlings are injured to a greater extent by two frosts than from what would be the additive effects of two individual frosts (63).

Mellenthin (119) states that 'Anjou' pear flowers exposed to temperatures of -2.2°C for two nights show a substantial increase in injury following the second night of freezing. However, Field (48) suggests that greater injury occurs in apple flowers that are frozen once to a particular minimum temperature for a certain duration than in flowers frozen repeatedly to the same minimum temperature for a cumulative total duration.

Biochemical Changes During Dehardening and Bloom

It is increasingly apparent that no single biochemical change or change in one class of compounds can fully explain the frost

hardiness phenomenon (117, 133). However, certain characteristic biochemical changes do take place within buds and flowers during the spring.

During the winter, reducing sugars are present at high levels in peach flower buds, although trace amounts of non-reducing sugars are found (88, 90). In general, hardy cultivars tend to accumulate larger quantities of soluble sugars than tender cultivars (90). Levels of the monosaccharides: galactose, glucose and xylose, decrease during the winter and increase in peach flower buds during the spring. Fructose levels increase slowly during the winter and increase rapidly in early March to a maximum in mid-March, then drop rapidly. The oligosaccharides: sucrose, stachyose, raffinose, and maltose, increase from January to mid-February and then drop to lower levels. However, sucrose increases rapidly in mid-March (89). Peach flower buds do not contain starch (88).

Amino acids (proline, serine, alanine, glutamic acid, aspartic acid and tyrosine) tend to increase markedly in both apricot and peach flower buds during March (44). Peach cultivars that are less hardy possess a higher free amino acid concentration in their flower buds during the winter than more hardy cultivars. In addition, the flower buds of tender peach cultivars show a lower protein content than hardy cultivars (88, 90). Flower bud protein increases to peak levels during the winter and drops rapidly during bud swell (88).

The organic acids also show an increase in flowers just prior to bloom. This is attributed primarily to fumaric, citric, pyruvic, succinic, and malic acids (44).

Lipid concentrations and composition change with changes in plant hardiness. Experiments on alfalfa indicate that total fatty acids, total linoleic acid, phosphatidylcholine, phosphatidylethanolamine mono- and digalactose diglycerides and triglycerides increase with hardening (58, 86), while phosphatidylglycerol, phosphatidylinositol, and sulfolipid decrease with hardening (86). De La Roche (33) points out that wheat seedlings grown at a lower temperature show an increased phospholipid concentration and a greater quantity of unsaturated fatty acids. Ketchie (80) also notes an increase in lipid unsaturation with hardening of peach tree bark. In contrast, studies of black locust bark show no increase in unsaturation of fatty acids. Furthermore, the major lipid compositional change with hardening appears to be an increase in the phospholipids at the expense of the neutral triglycerides (170). According to Willemot (201) during the hardening of winter wheat there is a trend toward phosphatidylcholine increases; however, it was concluded that phospholipid synthesis is not a prerequisite for hardening. On the other hand, phospholipid synthesis may be necessary for the maintenance of hardiness.

Waring et. al. (190) report that the proportions of phospholipid

classes and the acyl chain composition can be modified within a plant. By treating tomato seedlings with ethanolamine and Tween 85 (polyoxyethylene sorbitan trioleate, Sigma Chemical Co.) an increase in phosphatidylethanolamine and phosphatidylserine and a decrease in phosphatidylcholine is achieved.

Naturally occurring plant hormones also appear to undergo changes and influence bud, flower, and fruit hardiness. Several good reviews show growth regulator changes within the plant (Walker 188, Powell 135). Auxins are not found in apple and plum shoots (65), or apple (8), cherry, pear (16), or peach buds (17) during rest. However, there is an accumulation of auxins after a long exposure of buds to low temperature just prior to bud swell (8, 16). Following this Hatcher (65) notes a decline in diffusible auxin in shoots of both apple and plum. In contrast, others (152) were unable to find consistent auxin-like activity in a year-long study of apricot spur buds.

Cytokinins have been detected at low levels in apical buds of apple during dormancy, but in general show a gradual increase in the xylar sap and buds after dormancy is broken (39, 70, 107). Maximum levels are detected in buds shortly before the buds open in Betula and Populus according to Domanski and Kozlowski (39). Hewett and Wareing (70) claim that cytokinins reach their maximum level 2 weeks prior to bud break in the shoot and 1 week after bud

break in the buds of Populus x robusta. Luckwill and Whyte (107) report that cytokinins in the sap of apple trees reach their maximum concentration at full bloom. While Borkowska (18) claims that high cytokinin activity is present during March as apple buds swell and the level drops just prior to bud burst. It is generally agreed that the levels of cytokinin decrease after bud break (18, 39, 70, 107). The concentration then increases in Populus x robusta as shoots elongate (70).

Ramsay (152) associates the end of rest in apricot buds with an abrupt increase and decrease in gibberellin-like activity. Applications of gibberellic acid are known to break the rest period of black currants (122), and peach leaf buds (40, 189), but are not effective on peach flower buds (64) or apple buds. However, GA_3 applications prior to pollination and seed development on apple reduce the dormancy of mature seeds (195). Kinetin is known to break the rest period of both apple and peach fruit buds (188), suggesting variations in the rest mechanism between species. In peach GA levels increase up until the beginning of anthesis (29), while GA_3 activity decreases following the tight cluster stage in apples (157). GA appears to be synthesized in the young expanding leaves of the shoot and is present at fairly high concentrations in apple shoot apices, where it is responsible for shoot elongation (57).

Studies of inhibitor content indicate that there is a decrease

in what is thought to be abscisic acid (ABA) at the end of rest and then an increase in the concentration at bloom in apricot buds (152). In peach, ABA levels decrease with the beginning of bud swell (32). Studies of free and bound ABA by Wright (205) in black currant and beech suggest that free ABA decreases during the winter until just prior to bud burst, while bound ABA increases in the winter up to the middle of bud swell and then decreases. The highest bound/free ABA ratio occurs at bud break and then the value falls sharply. Kang and Lin (79) found that the application of the inhibitor naringenin in early spring stimulates bud break and flowering in Japanese apricot.

It seems apparent that the release from rest and subsequent bud, flower, fruit, and shoot growth are primarily controlled by changes in the balance of growth promoters and inhibitors (39, 135, 152, 188) and have some association with the loss of hardiness.

Bloom Delay

The use of evaporative cooling to reduce daytime bud temperatures and delay the bloom of fruit crops (155) has been studied by a number of researchers. The goal is to prolong the period of the normally hardier earlier developmental stages and avoid temperatures that would otherwise injure the flowers if they were not delayed. Bloom delays of up to 12, 14, and 15 days have been

achieved in peach and nectarine flowers (14, 20, 97, 182), 17 days in 'Red Delicious' apple flowers (4), 15 days in sweet cherry flowers (3), and 13 and 14 days in 'Bartlett' and 'Bosc' pear flowers (204).

In most evaporative cooling studies it is assumed that a delay in bloom will delay the loss of hardiness (3, 4, 20, 156, 182, 203, 204). Support for this assumption is found in studies by Lipe et. al. (97) in which a freeze during full bloom in 'Dixie Red' peach control plots led to a total crop loss, but left enough buds for an adequate crop in the bloom-delay plots, which were in 65% bloom at the time of the freeze. On the other hand, studies by Bauer et al., (14) in which bloom of 'Redhaven' peaches was delayed 15 days indicate that sprinkled flower buds tend to be hardier than non-sprinkled flower buds up until early March. At this point a reversal in hardiness begins to take place and by late March the non-sprinkled buds are hardier than the sprinkled or delayed flower buds.

The use of chemical applications to delay bud break and bloom have met with varying degrees of success. A few of the chemicals that are purported to produce some delay are: abscisic acid (98, 187); succinic acid-2, 2-dimethylhydrazide (diaminozide, SADH) (13, 129); daminozide and spray oil (149, 150, 151); (2-chloroethyl) trimethylammonium chloride (CCC) (129); lanolin emulsion and α-napthalene acetamide in a lanolin emulsion (168); napthaleneacetic acid; napthyl acetamide; and napthyl thioacetamide in 2% dioxane

and .003% Santomerse S (202); L-2-amino-4-[2'-aminoethoxyl] - trans-3-butenoic acid (210); 2-Chloreoethyl phosphonic acid (ethephon) (36, 140, 143, 144); and gibberellic acid (28, 139). The use of chemicals for bloom delay often produces undesirable side effects such as bud death (149, 150, 151, 168), reduced fruit set (36), gumosis (36, 143), and adverse affects on fruit quality (144).

Bloom delay has also been achieved by whitewashing buds and branches (200). This treatment reduces bud and branch temperatures on warm days and slows bud development. Bloom delays of 5 and 10 days have been obtained in Oregon and Idaho respectively (99). However, this technique does not consistently delay bloom every year (200).

Cryoprotectants

According to Ketchie and Murren (82) a cryprotectant is,

> "any agent added to living tissue that reduces susceptibility to cold injury, but does not act in a regulating capacity, such as a hormone in animals or a growth regulator in plants."

Cryoprotective agents may be divided into two classes consisting of penetrating agents, and non-penetrating agents.

Penetrating cryoprotectants are most effective at comparatively high concentrations under slow freezing conditions and are thought to function within the cell on a colligative basis. They resist

cellular dehydration from extracellular ice and prevent intracellular freezing by means of their strong water binding capacity (103, 120). In addition, by being taken up by the cell they reduce the ionic concentration and protect against the build up of toxic compounds. A penetrating cryoprotectant must have the capacity to penetrate the cell and be non toxic at relatively high concentrations. Glycerol and dimethyl sulfoxide (DMSO) are examples of this type of cryoprotectant.

Non-penetrating agents are effective at low molar concentrations and protect against rapid freezes. Little is known about the mode of action of non-penetrating cryoprotectants, but it is thought that they increase membrane permeability, allow solute flow in both directions and thus aid in reducing the osmotic gradient. Sugars, sugar alcohols, and polyvinylpyrrolidone (PVP) are known to act in this capacity (117, 120).

Glycerol has been found to confer some protection on: apple buds (25), flowers (25, 48), and bark (81); peach flowers, and small fruit; wild goose plum (25), and blackberry blossoms (47). There is some evidence that glycerol is almost completely metabolized within the plant (82).

Kuiper (84) claims that decenylsuccinic acid (DSA) protects apple and peach blossoms from frost, however, Hilborn (72) was unable to obtain consistent protection on either blueberry or apple

flowers. Studies on strawberry flowers show no protection from DSA, but applications of decenyldimethylsuccinamic acid, decenylsuccinichydrazide, and decenyl-NN-dimethylsuccinichydrazide seem to increase survival (85). Lee et. al. (92) found that DSA changes the water permeability of Allium and Rhoeo epidermal cells and that permeability appears to be related to the concentration of undissociated DSA. However, they were unable to induce frost resistance through DSA applications.

Ketchie and Murren (82) point out that applications of PVP glycerol, ethylene glycol, and DMSO increase the cold resistance of apple and pear trees during dormancy, but that the degree of protection varies with cultivar. Fennema et. al. (46) provide an excellent review of freezing injury and cryoprotectants in addition to a listing of compounds that are known to confer protection from freezing.

Several compounds don't fit the definition of a cryoprotectant, but do appear to provide some blossom frost protection when applied the previous growing season. Daminozide reduces frost damage to apple blossoms and causes a delay in bloom. However, bloom delay is not considered to be the primary factor responsible for the increased hardiness. A spray of CCC is effective in reducing frost injury to 'Bartlett' pear flowers prior to bloom and in some cases often advances floral development (128, 129). Microscopic examination of the flowers shows that CCC markedly reduces both

vessel (34%) and parenchymatos (19%) cell sizes suggesting a reduction in the probability of spontaneous nucleation and water supply. GA applications tend to increase frost damage especially the incidence of frost cracking. In general, the protection from exogenous growth regulators is inconsistent from year to year (129).

Fruit Set

Factors Affecting Fruit Set

In most cases it is possible for a fruit tree to lose 50 to 90% of its blossoms and still produce a substantial crop (191, 207). However, crop forecasts made following a freeze by determining the number of buds that are injured are usually far from the actual yield obtained at harvest (192). Much closer approximations of yield are possible following the final drop (42). This is because there are many factors besides frost injury that are involved in fruit set and in the ultimate yield.

Several of the variables that affect fruit set are pollination (44, 178), tree vigor (42), fruit thinning (197), rootstock (195), nitrogen fertilization (194), pruning (136), limb girdling (196), and the ability to set fruit parthenocarpically (124). In addition, carry-over effects influence fruit set. Poor mite control (102), early defoliation due to fungus diseases (37), and lack of seeded fruits

(198), all reduce fruit set the following year.

Fall sprays of ethephon (83), and late sprays of lime-sulfur and oil (30) decrease set on apples and pears respectively. Conversely, sprays of dormant oil (102) and both spring and fall sprays of boron (12) and 2, 4, 5-trichlorophenoxypropionic acid (2, 4, 5-TP) (198) increase fruit set in pears. Spring applications of GA increase the parthenocarpic set of pears (59), while 1-Napthaleneacetic acid (NAA) and 1-Napthaleneacetamide (NAD) are used to thin 'Bartlett' pears commercially (100, 193).

Endogenous Hormonal Changes Involved in Fruit Set

The fruit set mechanism is still unexplained. It is thought to involve GA, auxin, cytokinin, ethylene, and ABA and appears to be affected by any treatment that alters the levels of these growth regulators (193, 197). In general, following pollination and fertilization it is believed that GA synthesis by immature seeds (34) increases auxin levels and induces set (162).

Early work by Luckwill (104) on apples suggests a relationship between auxins produced by the seeds and the end of fruit drop. Subsequent studies implicate intervals of reduced fruit drop with intervals of active hormone synthesis (105). Addicott (1) points out that auxin translocated to the pedicel abscision zone from the fruit is the primary factor inhibiting abscision. Studies of

abscising apple fruits show a low unidientified promoter and a high ABA content (74). GA activity in apple fruits is relatively low after bloom. It then rises following June drop and falls rapidly (35). There are also indications that the tissues surrounding the seeds may synthesize GA_3 (66).

Seedless 'Bartlett' pear fruits contain a greater quantity of promoter than seeded fruits during the period between 25 and 70 days after full bloom. During this period ABA contents are very similar between seeded and seedless fruits (54). No difference in GA content is noted between seeded and seedless 'Bartlett' pear fruits up to 25 days after full bloom. Following this the GA level rises abruptly in seeded fruits, but little change is found in seedless fruits. There are two peaks in ABA content, one occurring at 40 and the other at 85 days after full bloom. The ABA level in the seedless fruit is much higher than that in the seeded fruit at 85 days after full bloom (114).

Promoting Fruit Set After A Frost

Applications of 2, 4, 5-TP and 2, 4, 5-trichlorophenoxyacetic acid (2, 4, 5-T) at bloom on 'Bartlett' pear are known to reduce fruit drop after a frost (60). GA sprays also increase the percentage of seedless frost injured pears that remain on the tree to harvest (106, 124, 125, 127). In general, cultivars with a greater natural

ability to set fruit without pollination have a greater tendency to respond to GA treatments.

The optimum GA concentration for a particular cultivar and stage of development needs to be high enough to induce the development of a good crop of marketable fruit, yet not so high that an excessive crop of low quality fruit is set (124). In one case a spray of 100 ppm GA at full bloom on 'Bartlett' produced a four-fold increase in marketable pears. On the other hand, excessive levels of GA induce the production of smaller abnormally shaped fruits (106) and inhibit fruit bud initiation for the following year's crop, especially if applied at petal fall or later (125). Frost injured GA treated fruit are often tapered towards the calyx (124), slightly thickened in the neck region and have hard stony cores (124). Spraying is effective at increasing set at all developmental stages and is particularly effective immediately after a frost where injury facilitates GA penetration. It is unlikely that GA applications are needed following frosts that kill up to 50% of the flowers, since enough undamaged blossoms usually remain to provide a good crop (127).

Directions For Additional Research

After reviewing the literature it is apparent that there are many unanswered questions in the complex field of frost protection.

For example, little is known about the influence of frost duration, freezing rate, and tissue hydration in relation to the degree of injury sustained by buds, flowers, and fruit of pear. Controlled studies are needed to examine the effects of tree vigor on pear frost hardiness. In addition, the question of whether pear bloom delay by means of evaporative cooling provides the degree of hardiness anticipated remains untested.

There is a need to develop methodology for the prediction of yield in order to determine the amount of frost damage that can be tolerated. In addition, a study is needed to investigate the time of frost injury following bloom as it relates to fruit drop, malformation, and size.

There are only a few of the gaps in our knowledge of frost hardiness. The following research effort will attempt to add to our understanding in these areas.

EFFECT OF FREEZING DURATION, RATE, AND TISSUE HYDRATION ON 'BARTLETT' PEAR BUDS, FLOWERS, AND SMALL FRUIT[1]

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Abstract. Freezing studies were made on 'Bartlett' pear (Pyrus communis L.) bouquets of buds, flowers, and small fruit. Injury increased with decreasing temp, increasing developmental stage, and increasing duration at the min temp up to 30 and 60 minutes of exposure in all stages except the small fruit stage where injury at -2°C increased for up to 2 hours. The effect of freezing rate was dependent on min temp, and dry florets were injured slightly more than florets misted just prior to freezing.

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Introduction

Spring frosts frequently injure pear flowers and small fruit causing major production losses. In the past, critical temp tables have been developed for pears based on floral developmental stages and critical temp (1, 10, 13, 21). A critical temp is defined as the lowest temp that can be endured for 30 min or less, an interval derived from field observations, without injury (20). Field (5) found increasing floral injury up to 6 hr at -2.2 and -3.3°C, and increasing injury for up to 12 hr at -1.7°C in several apple cultivars during controlled freezing tests.

Effects of freezing rate on apple blossoms by Chandler (3) were inconclusive, while subsequent studies (5, 6) noted an increase in injury at rapid freezing rates. Moisture applied to the surface of apple flowers (12) and Eucalyptus leaves (7, 19) just prior to freezing increased the amount of injury. Hewett et. al. (8) found a significant increase in injury when apple flowers were kept wet for 24 hr before freezing, but that there was little difference in injury between dry control flowers and flowers that had been wet just prior to freezing. Desiccation studies on apple flowers (6, 11) and fruit (3) indicate that dehydration increases hardiness.

This investigation was undertaken to study the relationships between temp duration, freezing rate, water application prior to

freezing, stage of development, and frost injury to buds, flowers and fruit of pear.

Materials and Methods

Effects of freezing duration and hydration. Spurred branches or bouquets containing at least 10 flower clusters each were collected from 41-year-old trees of 'Bartlett' pear on Old Home x Farmingdale seedling rootstock with Old Home interstock during the spring of 1976 and 1977. The basal portion of each branch was recut under water, and 3 branches were set into a vacuum flask of water to prevent supercooling of the flowers (12). Air and blossom temp were monitored with 28-gauge copper constantan thermocouples. A thermocouple was inserted into the receptacle of a flower or small fruit at either the proximal or distal end of each set of 3 branches. The thermocouple position was alternated between the 2 heights from flask to flask within the freezing chamber.

The controlled freezing apparatus consisted of a 0.48 m^3 freezer lined with black fiberboard perforated on the bottom and top for vertical air flow from a squirrel cage fan. Additional mixing of the air within the freezing chamber was obtained by a 10-inch fan with its motor located outside the freezer. A heating coil with the voltage supplied through a variac and positioned at one end of the freezer outside the liner above the squirrel cage fan was controlled

by a programmable Data-Trak system independent of the freezer. Specific freezing rates were programmed and controlled by the Data-Trak, while constant freezer temp were maintained through the use of the 640 Process Controller.

In 1976, bouquets were sprayed with water to run off prior to placing them in the freezer. The period between collecting bouquets and the initiation of the freezing test was never longer than 45 min. Five flasks of branches were placed in the freezer and the sixth was left out as a control. Branches were positioned so that flowers were not in contact with the liner and the flasks were placed around the periphery to facilitate air circulation. The freezing methodology was developed during a year of trials.

The rate of temp fall was 2.5°C/hr after an equilibrium temp of 1°C to -2, -3, or -4°C. Upon reaching the min temp, a flask of 3 branches was removed after 1, 15, 30, 60, and 120 min duration. Bouquets were allowed to warm to room temp and placed outside overnight for injury evaluation the following day. Freezer runs to each of the 3 min temp were made for the pink, white, bloom, and small fruit developmental stages (Fig. 1).

Injury evaluations were based on the individual floral developmental stages, rather than on the cluster developmental stages, due to the wide variation in floral stages found within each cluster. A flower or fruit was considered injured if any internal tissue

browning was apparent. Lifting of the receptacle epidermis was not considered as injury (5, 12) and no attempt was made to determine whether flowers or small fruit were dead or alive.

Percent injury values for one developmental stage for the freezing tests conducted on one date (date-stage) were calculated for each branch, and SD were computed for each set of 3 branches. A combined % injury value for each set of 3 branches was then calculated, and a split-split-plot analysis of variance was conducted. The control and small fruit developmental stage data were not included in the statistical analysis due to the large no. of zero values in the former and the preponderance of 100% injury values in the latter.

In a second experiment conducted in 1977, the above procedure was repeated using dry branches with the addition of the closed sepals developmental stage.

Effects of freezing rate and hydration. In a third study conducted in 1977, branches were collected as previously noted and replicated freezing tests were made using freezing rates of 1.0 and 2.5^{o}/hr for both dry branches and branches that had been misted just prior to freezing. A flask of 3 branches were removed from the freezer at -2, -3, and -4^{o}C for the closed sepals, white, and bloom floral stages (Fig. 1). Bouquets were also removed at -5^{o}C for the closed sepals and white stages of the wet branches, but only

for the closed sepals stage of the dry branches. In all experiments a flask of unfrozen branches was maintained as a control. Since 8 separate freezer runs were involved in testing each floral stage, freezer tests were run over a period of several days. Injury evaluations were conducted as before. Unfrozen control and -2°C temp data were not included in the statistical analyses due to a lack of injury. Standard deviations were calculated and based on the mean % injury from 2 freezer runs.

Results and Discussion

Freezing duration. The freezing duration studies on both wet and dry branches showed significant increases in injury (5% level) with decreasing temp and with increasing duration (1% level) in the critical injury range (Tables 1 and 2). No significant interactions were found. Data points for unfrozen control branches were not included on any of the tables or figures in these experiments since there was little or no field injury during both seasons. The large SD (Tables 1 and 2) were caused in some cases by a lack of large no. of flowers on a branch in the desired developmental stage and the resultant wide ranging % values.

In both years (Fig. 2-6) it was apparent that injury usually increased up to either 30 or 60 min of exposure in the critical temp range. There was little subsequent increase in injury for longer

durations. This was true at all stages except the small fruit stage at -2°C (Fig. 2 and 4). In this case the % injury continued to increase up to 120 min exposure. These results agree with those of Field (5) in which it took 12 hr to attain max injury at -1.7°C but only 6 hr at -2.2 and -3.3°C in apple flowers and those of Dr. Michael Burke (unpublished) who noted that it took longer to establish freezing equilibrium at -2°C than at -5°C. Apparently the period required to attain max injury differs between apples and pears. It also appears that the 30-min exposure period used in the established critical temp tables for pears (1, 10, 13, 19) is a realistic value.

Most of the increase in injury occurred during the first part of the 2 hr exposure period. These results are consistent with studies on dormant apple twigs (16) and peach buds (17), but disagree with earlier research on dormant apple twigs (9), roots (14), and flowers (5) which claimed a direct relationship between the amount of damage and duration of exposure. In the present experiments there appears to be a relationship such that a reduction in temp necessitates a reduction in duration in order to prevent further tissue injury.

A visual comparison between wet (Table 1) and dry (Table 2) branches indicates that brief wetting prior to placing the branches in the freezer had little or no effect on increasing the amount of injury sustained by the flowers, especially in the white, bloom, and small fruit stages. There does appear to be an increase in injury

of the wet flowers over dry flowers in the pink stage (Tables 1 and 2). This could have been caused by the branch hydration, but was probably due to the difference in environmental conditions that the flowers were exposed to prior to freezing because of differential sampling dates. Proebsting and Mills (15) also noted a large variation in the % kill for a particular temp in this developmental stage over a 12-year period. They found that critical temp were not biological constants, but varied considerably, especially in the earlier developmental stages. Thus, both dry flowers and those misted just prior to freezing would be expected to incur approximately the same amount of injury with 30 min of exposure at a given critical temp.

A comparison of the injury levels obtained in these experiments after 30 minutes exposure (Tables 1 and 2) with those obtained by other investigators (1, 15) indicates that our injury levels generally tend to be higher but fall within the ranges found by Proebsting and Mills (15). For example in the white or full white cluster developmental stage our data (Tables 1 and 2) show that 96 and 100% injury were obtained at -4°C in 1976 and 1977 respectively. Data of Ballard et. al. (1) indicate an average critical temp for 90% kill of -5.6°C, while Proebsting and Mills (15) show an average critical temp of -6.4°C for this level of injury.

An examination of field injury data explains the apparent

critical temp difference. Field data presented by Proebsting and Mills agree closely with their own (1, 15) controlled freezing tests. Similarly, the injury levels found in the present study correspond to the field data of Lombard et. al. (10). Thus, it appears that accurate hardiness measurements are achieved through both controlled freezing techniques, but that substantial hardiness differences exist between the two locations due to climatic and microclimatic preconditioning variations.

Freezing rate. In the freezing rate study the effects of temp and date-stage were significant at the 5% level in all analyses. There was a significant effect of freezing rate at the 5% level for the wet branches in the closed sepals and white date-stages and for the dry branches in the closed sepals date-stage in those analyses including the -5°C temperature (Table 3). In addition, the analysis of freezing rate for the dry bouquets in the closed sepals, white, and bloom developmental stages showed a significant rate x temp interaction at the 1% level and rate x temp x date-stage interaction at the 5% level. Thus, the effect of rate was dependent on temp. The temp x date-stage interaction on injury was significant at the 5% level in all split-split-plot analyses using -3 and -4°C temp data indicating the importance of stage and date of sampling. Tests for the degree of hydration showed significance at the 5% level for the 2.5°C/hr freezing rate in the closed sepals, white, and bloom

developmental stages in tests to -4°C, and for the 1.0°C/hr freezing rate in the closed sepals stage in tests to -5°C. However, tests were inhibited by interactions.

Table 3 and Fig. 7-9 show the effects of freezing rate, flower hydration, stage of development, and temp on % floral injury. The increased injury sustained in tests to -5°C using the more rapid (2.5°C/hr) freezing rate are supported by studies of dormant peach (3, 9) cherry, apple, and plum (9) buds. Additional support is found in studies by Daniel and Crosby (5) who found greater differences in dormant peach tree injury between slow (2.8°C/hr) and rapid (11.1°C/hr) freezing rates when trees were removed at lower temp (-9.4, -12.2, and -15°C) as compared to higher temp (-6.6°C). Our studies disagree with those of Field (5, 6). He showed that greater percentages of apple blossoms were injured by a rapid freezing rate, while our studies did not find this to be true at bloom. This difference could be explained by the freezing rate, since the rapid freezing rates used in the studies on apple blossoms far exceeded those possible under orchard conditions. Thus, it appears that the temp x rate interaction occurs not only at -5°C, but extends over a range of temp and developmental stages.

These studies also provide an explanation for the effectiveness of wind machines under conditions where orchard temp drop into the critical range without corresponding injury (2). The added

protection may be gained by a reduction in the rate of temp fall.

The effect of surface applied water, though not significant in most cases showed a consistent trend for the closed sepals (Fig. 7) and white (Fig. 8) date-stages in which the dry florets were slightly more injured than the wet florets at a given freezing rate. However, in the bloom stage (Fig. 9) the reverse was true. More wet flowers were injured than dry flowers. Examination of rainfall data for the season showed that the tests conducted at 1.0 and 2.5°C/hr on wet flowers in the bloom stage were performed on a day that it had rained. Thus, the increase in injury in wet flowers (Fig. 9) probably was due to increased hydration of the flowers. This agrees with data of Hewett et. al. (8) who found significant increases in apple blossom injury following prolonged misting.

We attribute the slightly increased injury of the dry buds and florets in Fig. 7 and 8 to a difference in the freezing rate. Wet florets tend to freeze slower than dry florets due to a lag in the freezing profile caused by the freezing of a large quantity of water.

The freezing rate study substantiates the significance of the effect of the developmental stage on frost injury. Examination of all the frost injury figures supports the concept of a progressive loss of hardiness with increasing developmental stages (Tables 1, 2, and 3).

These data illustrate the importance and interrelationships

between freezing duration, freezing rate, stage of development, min temp and tissue hydration with respect to 'Bartlett' pear frost injury. Results concerning the effects of tree vigor and bloom delay on floral hardiness are discussed in another paper (18).

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Table 1. Effect of freezing duration on injury of wet 'Bartlett' pear buds, flowers, and fruit.

		Percent buds, flowers, or fruit injured			
	Date:	4/10/76	4/19/76	4/25/76	5/6/76
Duration (min)	Stage: Temp °C	3 (pink)	4 (white)	6 (bloom)	9 (small fruit)
1	-2	0[z] ± 0[y]	0 ± 0	0 ± 0	26 ± 26
15		3 ± 1	0 ± 0	9 ± 9	27 ± 12
30		6 ± 5	0 ± 0	5 ± 2	36 ± 2
60		19 ± 5	6 ± 7	16 ± 8	76 ± 7
120		17 ± 11	12 ± 5	7 ± 8	100 ± 0
1	-3	6 ± 6	25 ± 4	83 ± 5	100 ± 0
15		17 ± 9	42 ± 30	92 ± 7	100 ± 0
30		45 ± 25	61 ± 5	93 ± 6	100 ± 0
60		47 ± 31	69 ± 13	88 ± 4	100 ± 0
120		65 ± 15	71 ± 18	96 ± 4	100 ± 0
1	-4	64 ± 12	95 ± 5	77 ± 12	100 ± 0
15		86 ± 5	79 ± 20	89 ± 11	100 ± 0
30		97 ± 3	96 ± 3	81 ± 8	100 ± 0
60		93 ± 3	100 ± 0	88 ± 10	100 ± 0
120		89 ± 3	93 ± 4	93 ± 6	100 ± 0

[z]Values shown are means of % injury from 3 branches that were misted prior to freezing.

[y]Standard deviations.

Table 2. Effect of freezing duration on injury of dry 'Bartlett' pear buds, flowers, and fruit.

		Percent buds, flowers, or fruit injured				
	Date:	3/26/77	3/31/77	4/6/77	4/11/77	4/24/77
Duration (min)	Stage: Temp °C	2 (closed sepals)	3 (pink)	4 (white)	6 (bloom)	9 (small fruit)
1	-2	0[z] ± 0[y]	0 ± 0	0 ± 0	0 ± 0	7 ± 9
15		0 ± 0	0 ± 0	0 ± 0	1 ± 1	51 ± 13
30		0 ± 0	0 ± 0	0 ± 0	0 ± 0	50 ± 4
60		0 ± 0	0 ± 0	0 ± 0	6 ± 7	74 ± 11
120		0 ± 0	0 ± 0	10 ± 9	4 ± 3	98 ± 3
1	-3	0 ± 0	0 ± 0	12 ± 5	0 ± 0	94 ± 7
15		0 ± 0	0 ± 0	29 ± 8	85 ± 8	100 ± 0
30		0 ± 0	0 ± 0	54 ± 23	62 ± 18	100 ± 0
60		0 ± 0	1 ± 2	32 ± 13	84 ± 18	100 ± 0
120		0 ± 0	7 ± 4	60 ± 39	98 ± 4	100 ± 0
1	-4	0 ± 0	25 ± 22	85 ± 13	91 ± 17	100 ± 0
15		1 ± 3	60 ± 35	98 ± 3	100 ± 0	100 ± 0
30		14 ± 13	68 ± 16	100 ± 0	100 ± 0	100 ± 0
60		15 ± 15	73 ± 9	98 ± 3	100 ± 0	100 ± 0
120		14 ± 19	79 ± 10	100 ± 0	100 ± 0	100 ± 0

[z]Values shown are means of % injury from 3 dry branches.

[y]Standard deviations.

Table 3. Effect of freezing rate, min temp, and level of hydration (dry and misted just prior to freezing) on injury of 'Bartlett' pear buds and flowers.

		Percent buds or flowers injured					
		1.0°C/hr rate			2.5°C/hr rate		
	Temp	Developmental stages			Developmental stages		
Hydration	°C	2	4	6	2	4	6
Dry	-2	0[z] ± 0[y]	0 ± 0	1 ± 0	0 ± 0	0 ± 0	0 ± 0
	-3	1 ± 1	7 ± 3	11 ± 6	1 ± 1	9 ± 5	9 ± 10
	-4	6 ± 1	35 ± 25	45 ± 13	3 ± 1	80 ± 28	100 ± 0
	-5	9 ± 2	-	-	70 ± 19	-	-
Wet	-2	0 ± 0	1 ± 1	10 ± 15	0 ± 0	1 ± 2	3 ± 1
	-3	0 ± 0	10 ± 10	47 ± 30	0 ± 0	18 ± 11	80 ± 6
	-4	0 ± 0	19 ± 6	82 ± 5	4 ± 6	45 ± 13	100 ± 0
	-5	0 ± 0	16 ± 11	-	22 ± 7	56 ± 17	-

[z]Values shown are based on the mean % injury of 2 freezer runs, with each mean composed of the sum injury from 3 branches.

[y]Standard deviations.

Fig. 1. 'Bartlett' pear bud, flower, and small fruit developmental stages: 1, tight cluster; 2, closed sepals; 3, pink; 4, white; 5, popcorn; 6, bloom; 7, petal fall; 8, calyx; 9, small fruit.

Fig. 2. Effect of duration at a min temp of -2°C on injury of wet 'Bartlett' pear buds, flowers, and fruit.

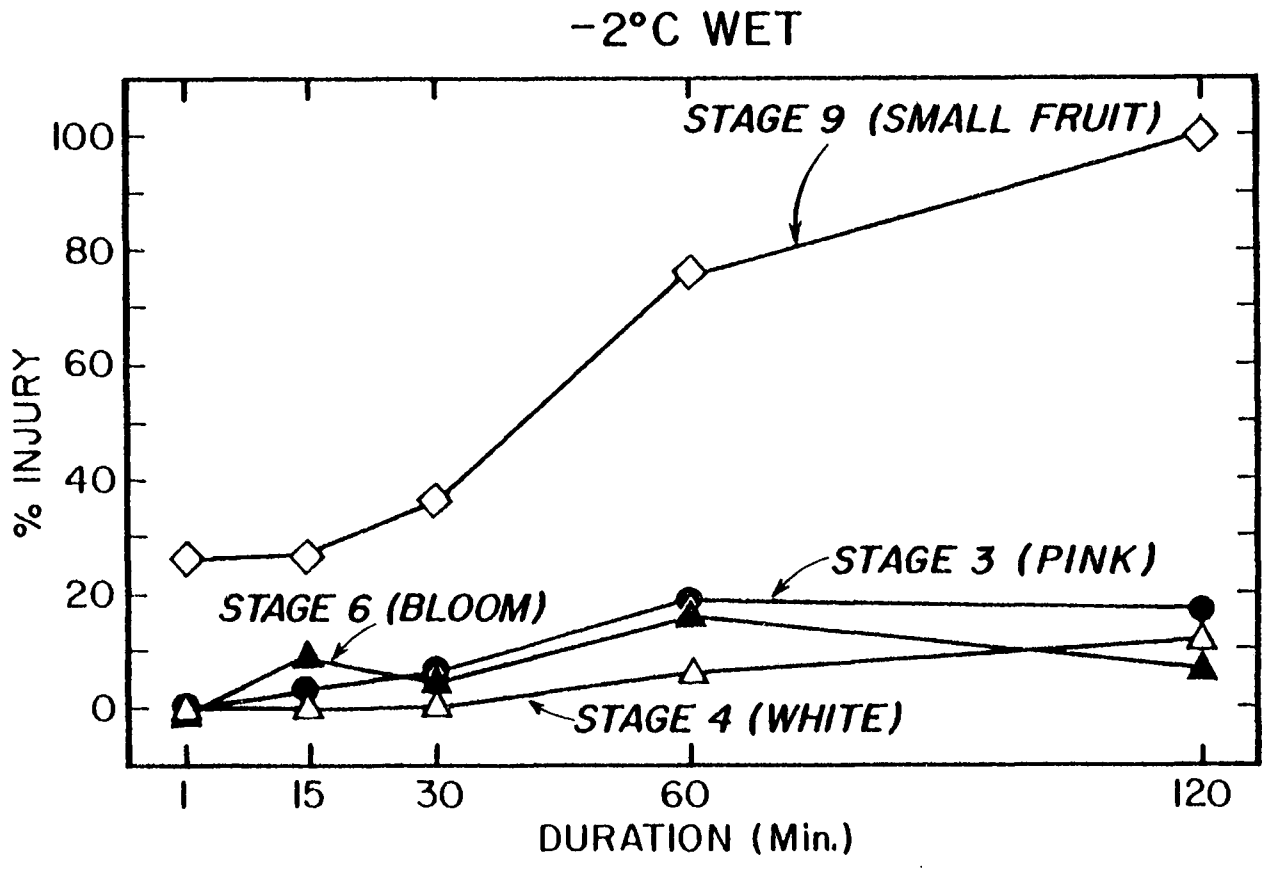

-2°C WET
STAGE 9 (SMALL FRUIT)
STAGE 3 (PINK)
STAGE 6 (BLOOM)
STAGE 4 (WHITE)
% INJURY
100
80
60
40
20
0
1
15
30
60
120
DURATION (Min.)

Fig. 3. Effect of duration at a min temp of -3°C on injury of wet 'Bartlett' pear buds, flowers, and fruit.

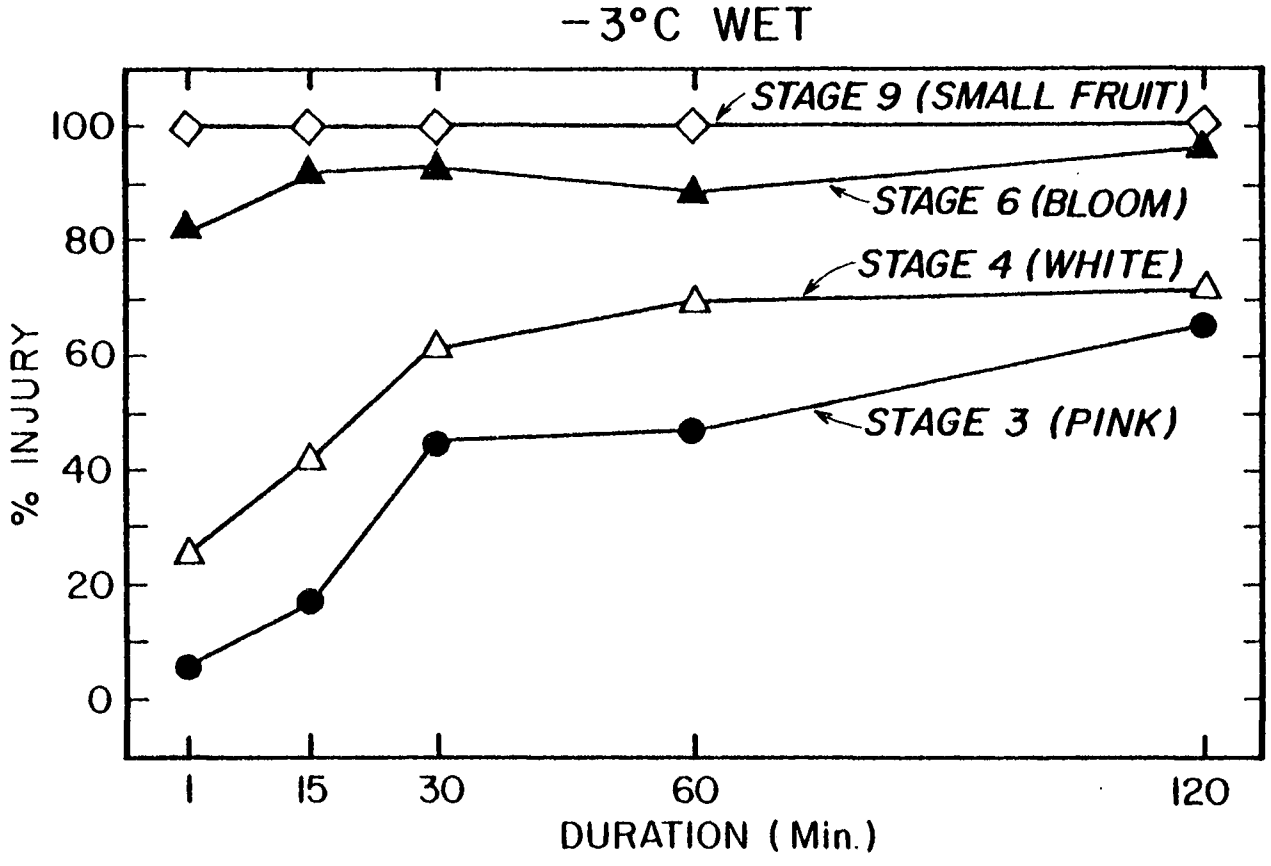

-3°C WET
STAGE 9 (SMALL FRUIT)
STAGE 6 (BLOOM)
STAGE 4 (WHITE)
STAGE 3 (PINK)
% INJURY
100
80
60
40
20
0
1
15
30
60
120
DURATION (Min.)

Fig. 4. Effect of duration at a min temp of -2°C on injury of dry 'Bartlett' pear flowers and fruit.

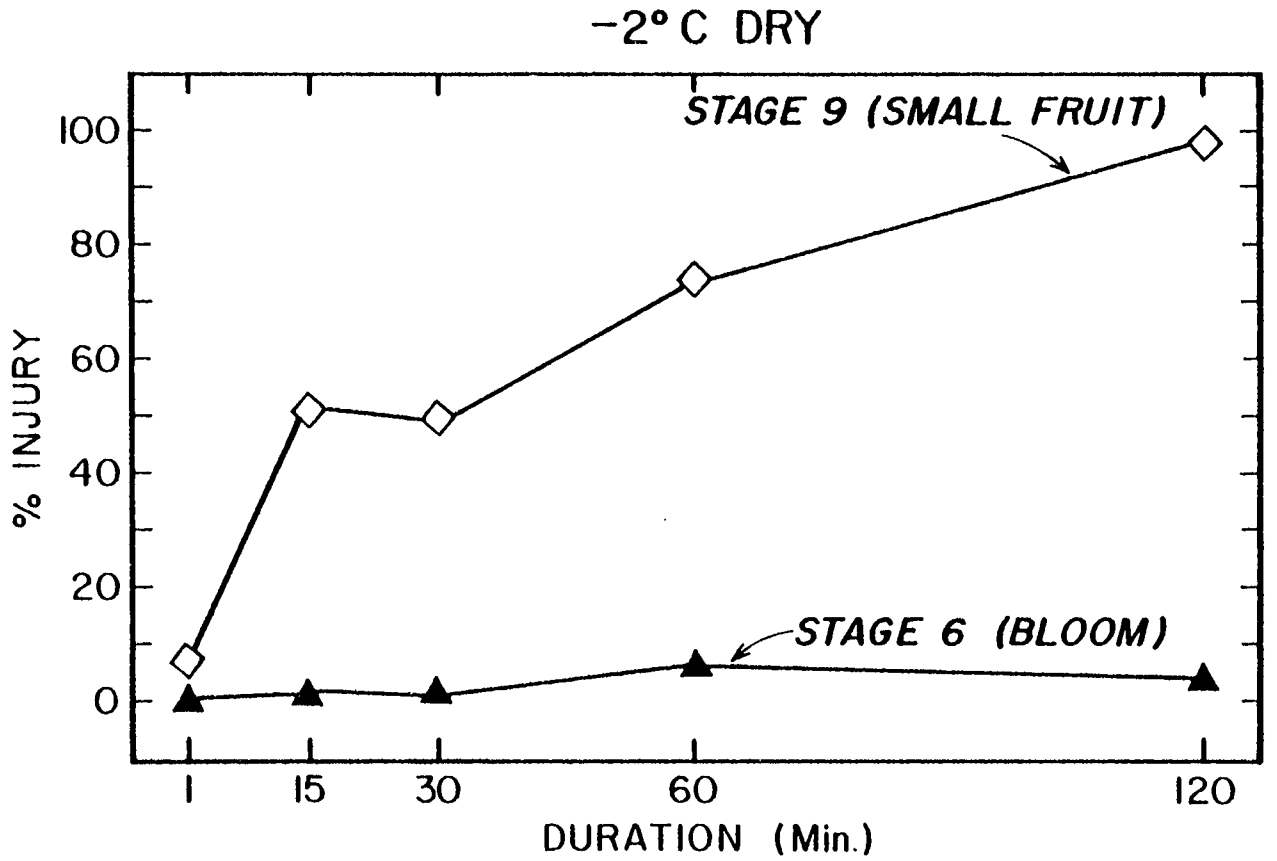

-2° C DRY
STAGE 9 (SMALL FRUIT)
STAGE 6 (BLOOM)
% INJURY
100
80
60
40
20
0
1
15
30
60
120
DURATION (Min.)

Fig. 5. Effect of duration at a min temp of -3°C on injury of dry 'Bartlett' pear buds, flowers, and fruit.

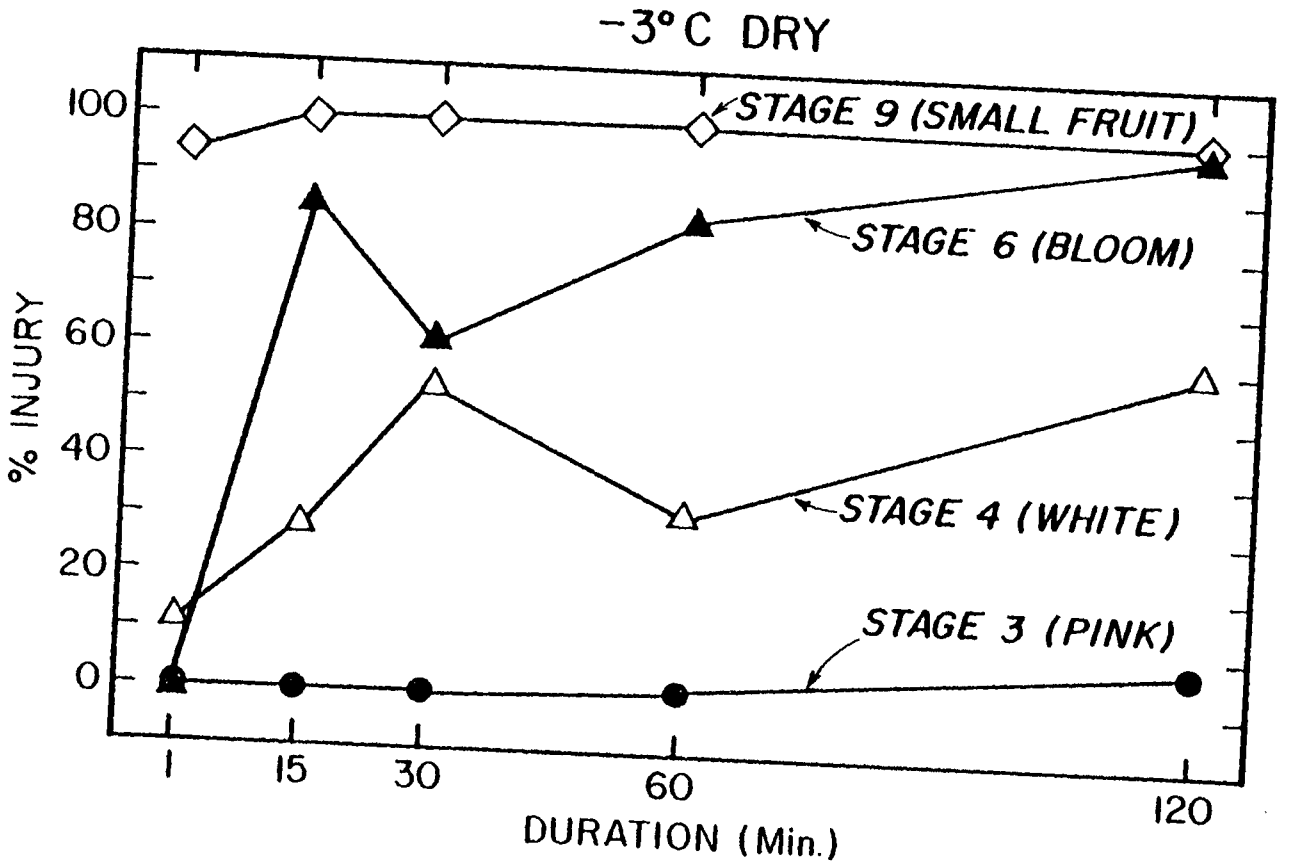

-3° C DRY
100
80
60
40
20
0
% INJURY
STAGE 9 (SMALL FRUIT)
STAGE 6 (BLOOM)
STAGE 4 (WHITE)
STAGE 3 (PINK)
1
15
30
60
120
DURATION (Min.)

Fig. 6. Effect of duration at a min temp of -4°C on injury of dry 'Bartlett' pear buds, and flowers.

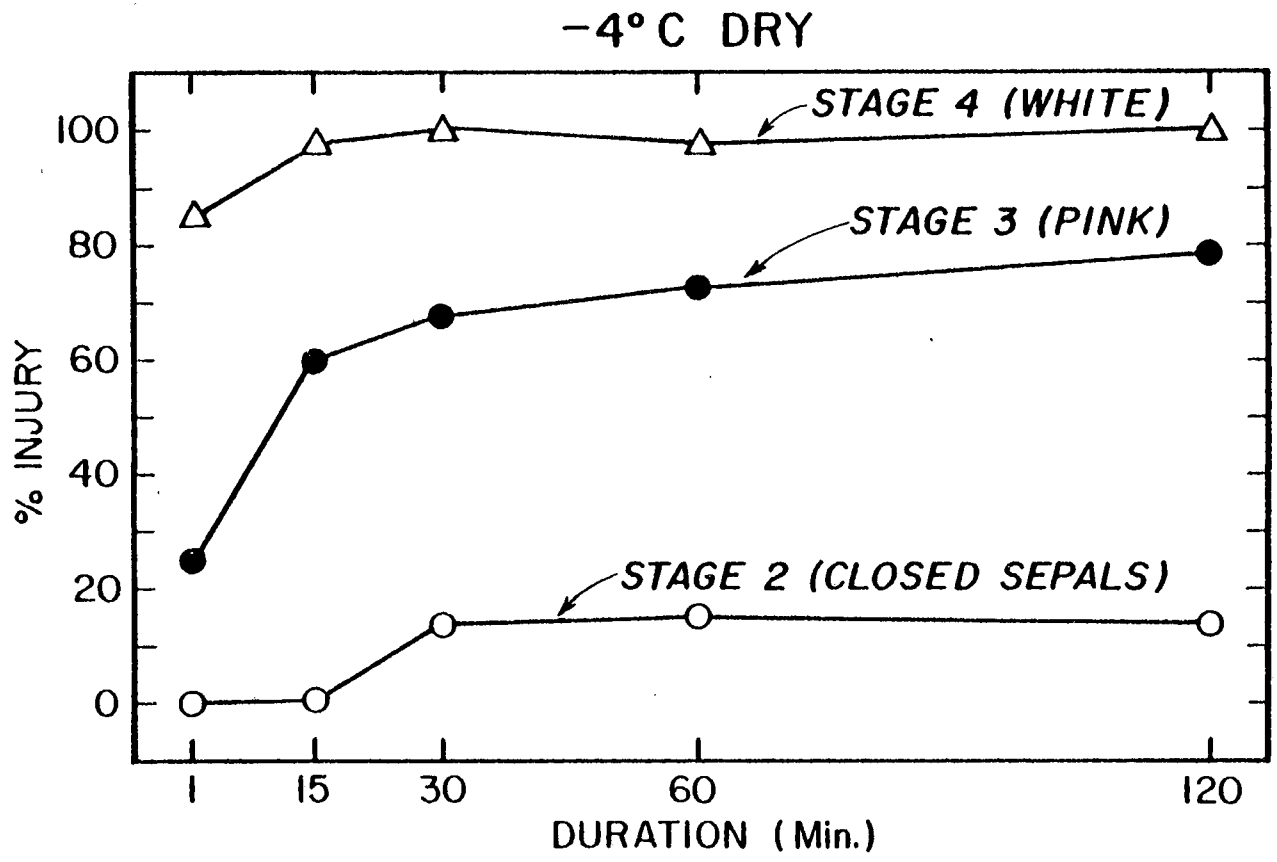

-4° C DRY
STAGE 4 (WHITE)
STAGE 3 (PINK)
STAGE 2 (CLOSED SEPALS)
% INJURY
100
80
60
40
20
0
1
15
30
60
120
DURATION (Min.)

Fig. 7. Percent 'Bartlett' pear bud injury at various temp for 2 freezing rates (1.0 and 2.5°C/hr) and 2 levels of hydration (dry and misted just prior to freezing) for stage 2 (closed sepals) on 3/26 - 3/30/77.

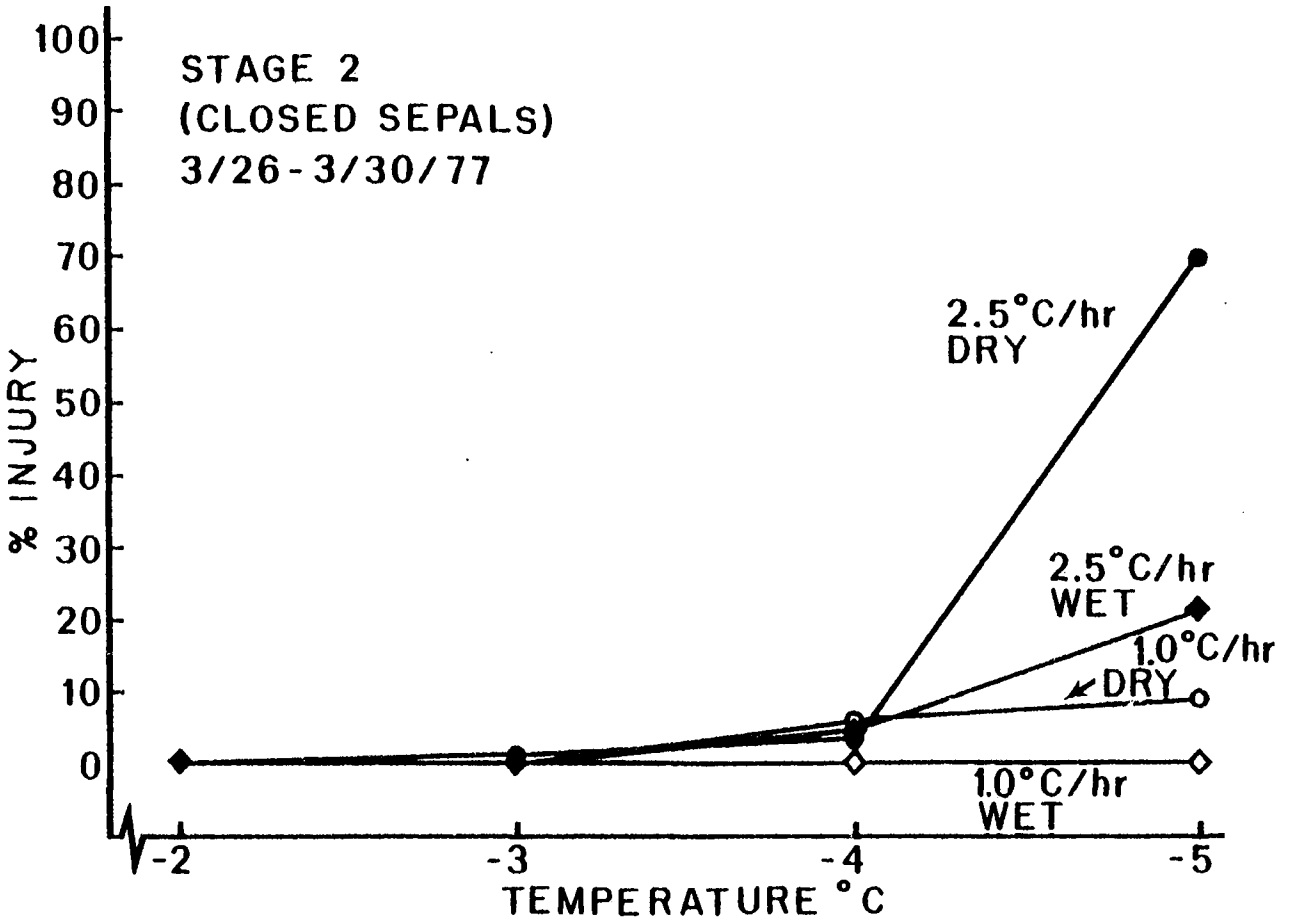

STAGE 2
(CLOSED SEPALS)
3/26-3/30/77
% INJURY
100
90
80
70
60
50
40
30
20
10
0
2.5°C/hr
DRY
2.5°C/hr
WET
1.0°C/hr
DRY
1.0°C/hr
WET
-2
-3
-4
-5
TEMPERATURE °C

Fig. 8. Percent 'Bartlett' pear bud injury at various temp for 2 freezing rates (1.0 and 2.5°C/hr) and 2 levels of hydration (dry and misted just prior to freezing) for stage 4 (white) on 4/3 - 4/6/77.

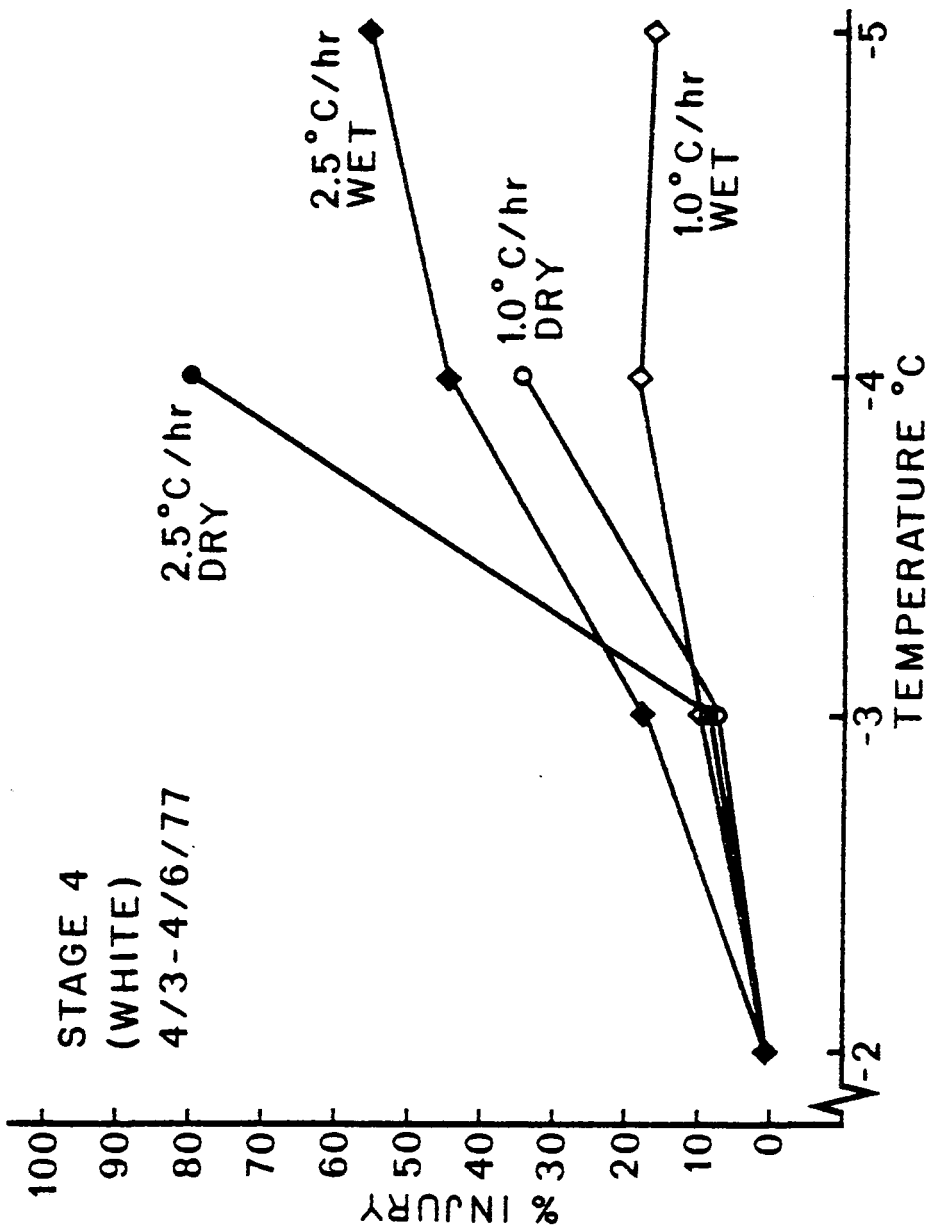
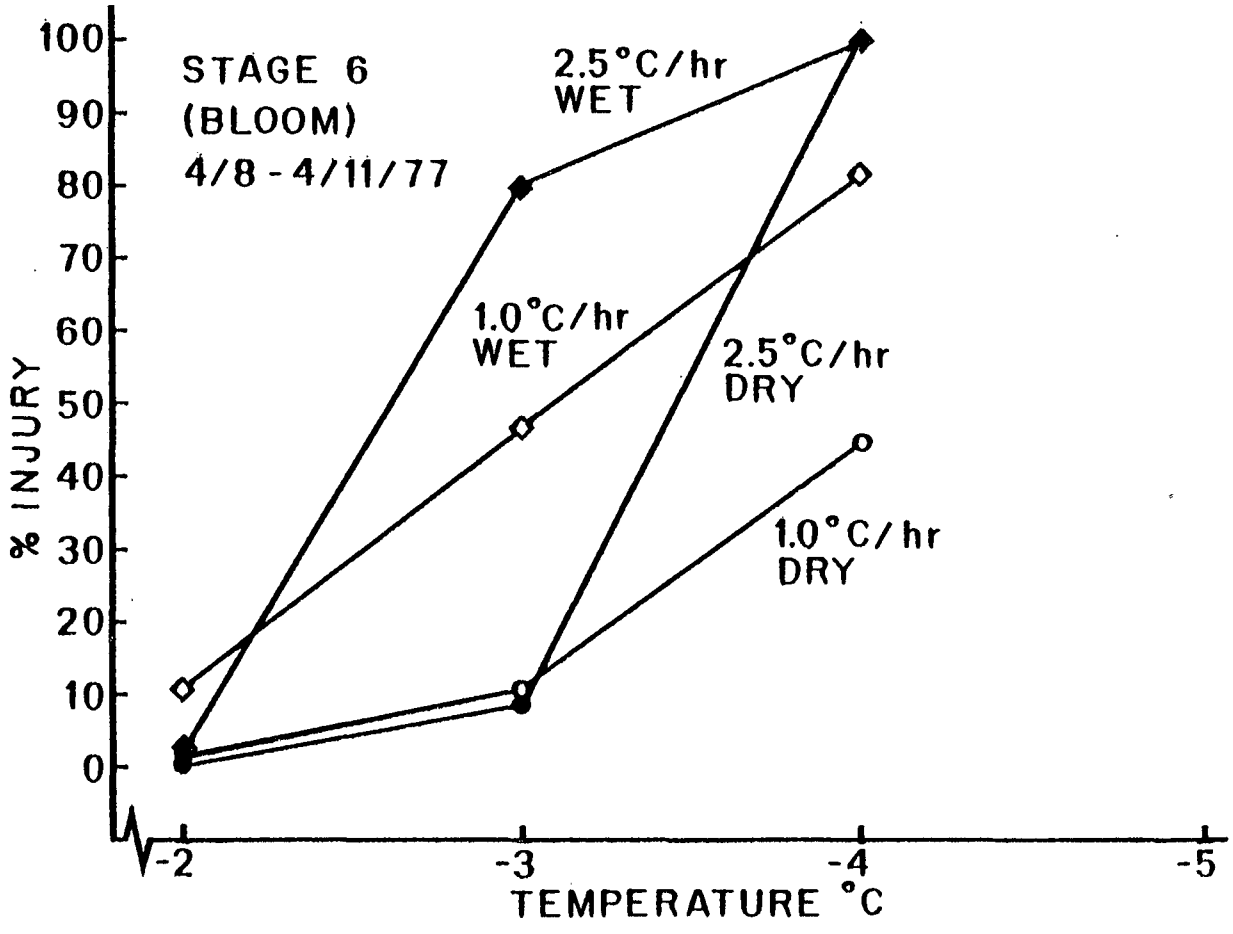

STAGE 4
(WHITE)
4/3-4/6/77
% INJURY
100
90
80
70
60
50
40
30
20
10
0
-2
-3
-4
-5
TEMPERATURE °C
2.5°C/hr
DRY
2.5°C/hr
WET
1.0°C/hr
DRY
1.0°C/hr
WET

Fig. 9. Percent 'Bartlett' pear flower injury at various temp for 2 freezing rates (1.0 and 2.5°C/hr) and 2 levels of hydration (dry and misted just prior to freezing) for stage 6 (bloom) on 4/8 - 4/11/77.


STAGE 6
(BLOOM)
4/8 - 4/11/77
2.5°C/hr
WET
1.0°C/hr
WET
2.5°C/hr
DRY
1.0°C/hr
DRY
% INJURY
100
90
80
70
60
50
40
30
20
10
0
-2
-3
-4
-5
TEMPERATURE °C

EFFECTS OF TREE VIGOR AND EVAPORATIVE COOLING FOR BLOOM DELAY ON FROST HARDINESS OF 'BARTLETT' PEAR BUDS, FLOWERS, AND SMALL FRUIT[1]

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Abstract. Controlled freezing tests showed no hardiness differences between comparable floral developmental stages on weak and vigorous 'Bartlett' (Pyrus communis L.) pear trees. Bloom delay through evaporative cooling resulted in a loss of hardiness beyond that found earlier in the season on non-misted trees for similar stages of development. However, some frost protection was gained through bloom delay.

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Introduction

Indentification of the reasons for hardiness variability in developing flower buds is necessary to establish valid critical temperatures (15). Tree vigor, nutritional and frost hardiness studies have often yielded inconsistent results. Young (23, 24) and Chandler (6) observed that flowers and fruit on weak trees were more subject to injury by frost than those on vigorous trees. However, subsequent studies on apple by the latter investigator were unable to confirm this. Fertilization tests with N (11) and K (6) have not affected the hardiness of developing peach flowers or fruit, while greater foliage hardiness has been produced in tulip poplar trees through K applications (20). High tree vigor has also been associated with bloom delay in the spring (6).

Evaporative cooling for bloom delay and frost protection is currently receiving much attention. Many researchers have assumed a certain degree of protection in apples (1, 2, 16), peaches (1, 5, 16, 17), nectarine (5), and pears (21, 22) based on developmental stages and critical temp tables. This assumption was supported in field studies by Lipe et. al. (12) in which a frost, while peach control plots were in full bloom eliminated the crop, but left an adequate crop in the bloom delay plots, which showed 65% bloom. However, Bauer et. al. (4) found that by late March, non-sprinkled

'Redhaven' peach buds and flowers were hardier than those that were sprinkled.

These studies were conducted to determine the hardiness of 'Bartlett' pear developing flowers as affected by tree vigor and bloom delay through evaporative cooling.

Materials and Methods

Tree vigor. Foliar analyses were conducted on 5 weak and 5 vigorous 41-year-old 'Bartlett' pear on Old Home x Farmingdale seedling rootstock with Old Home interstock in August of 1976 and 1977. During the spring of 1977, 25 terminal shoots from the previous season's growth were measured on each tree and dates of first bloom were recorded.

Replicated hardiness tests were conducted for each of 5 date-stages during the season. Four flasks of weak branches and 4 flasks of vigorous branches, with each flask containing 3 branches, were used in every freezer run. Each branch contained at least 10 flower clusters. All bouquets were sprayed with water and 3 flasks of both weak and vigorous branches were placed in the freezer. The remaining 2 flasks of bouquets were left out as controls. The temp was decreased at 2.5°C/hr and a flask of both weak and vigorous bouquets were removed at -2, -3, and -4°C. Descriptions of the

freezing apparatus, floral stages of development and frost injury evaluation have been reported previously (18).

Evaporative cooling for bloom delay. Replicated freezing tests were performed on 'Bartlett' pear branches during the spring for the closed sepals, white, bloom, and calyx date-stages. Three flasks, each containing 3 dry branches with 10 flower clusters per branch, were placed in the freezer. A fourth flask of bouquets was retained as an unfrozen control. The freezer temp was reduced at 1°C/hr and a flask of branches was removed at -2, -3, and -4°C.

Identical freezing tests were conducted on bouquets from similar 'Bartlett' pear trees on which bloom had been delayed for 18 days with a high pressure fogging system. Hardiness tests were run for the closed sepals and white stages when the majority of each tree was in the bloom stage.

The high pressure fogging system was started on January 31, 1977, and set at a base initiation temp of 7.0°C. It was operated at a pressure of 0.60 megapascals (90 psi) and shut off on April 15. Additional information concerning the fogging system has been published recently (7, 22).

Results and Discussion

Tree vigor. The effects of tree vigor, temp, and date-stage are shown in Table 1 and Fig. 1. Data for unfrozen control flowers

were not included, since there was little or no field injury. Standard deviations for injury values (Table 1) showed considerable variation in several cases; however, mean injury values were relatively close between weak and vigorous trees.

The effects of temp, date-stage, and temp x date-stage were significant at the 1% level for the -3 and -4°C data as in previous studies (18). No significant differences in injury were found between flowers and small fruit in comparable developmental stages on weak and vigorous trees.

These experimental results agree with those of Chandler (6), but do not agree with the observations of Young (23, 24). This apparent inconsistency could be attributed to floral developmental stage differences between weak and vigorous trees in the studies by Young. In the present study, little difference was found in the date of first bloom between weak and vigorous trees (Table 2). However Chandler (6) has reported one case in which vigorous peach trees bloomed a month later than weak trees. The wide variation in floral developmental stages would be more than enough to account for substantial hardiness differences.

Our study shows a significant difference in terminal shoot

growth (1% level), but no differences in leaf nutrient-element concn between weak and vigorous trees (Table 2). In general, N, P, and Mn levels were below average, while those of Zn were above average. Differences in tree vigor in these experiments have been attributed to variations in seedling rootstock performance, not to pear decline.

Evaporative cooling for bloom delay. The use of evaporative cooling delayed bloom, but resulted in a significant (5% level) loss of bud and flower hardiness beyond that found earlier in the season for comparable developmental stages (Table 3 and Fig. 2). Statistical analysis of the -3° and -4°C data showed a significant effect of both temp and stage of development on bud and flower injury at the 1% level. There were no significant interactions, unlike the tree vigor and freezing rate (18) studies in which a significant temp x date-stage interaction was apparent. This indicates that the interaction was confounded by the effects of bloom delay.

These data disagree with the assumptions of previous investigators (1, 2, 5, 16, 17, 21, 22) that inferred certain levels of hardiness based on developmental stages and critical temp tables. However, the study does suggest that a fair degree of protection is

gained through evaporative cooling in pears (Fig. 2), in contrast to studies on peaches (4). In the present study, a frost of -2.6°C on April 18, 1977 produced 10% injury on open bloom in the control plot, but produced no injury on flower buds in the closed sepals stage in the bloom delayed trees.

The hardiness levels found in the bloom delay treatments lie in the upper portions of the known hardiness ranges for particular developmental stages, according to Proebsting and Mills (15). This implies that the min hardiness level possible for a given stage of development may be achieved under conditions of evaporative cooling in pears. In addition, a comparison of the standard deviations (Table 3) between non-misted and bloom delay treatments shows larger values for the bloom delayed treatments at -3° and -4°C. Thus, a greater range in hardiness was present in the pink and white stages of the bloom delay treatments.

Since the fogging system was turned off 6 days prior to the first hardiness tests, and since tests were not conducted during or immediately following rain, the possibility of water absorption from the environment prior to the tests and consequent hardiness loss was precluded (8, 10, 14). However, the possibility of an inherently high tissue moisture content due to prolonged growth under high moisture conditions exists. Hardiness might have been lost through the leaching of compounds from the buds (7, 19), from growth

regulator changes, or from exposure to elevated temp and subsequent rapid flower development following the termination of misting (3, 9, 13).

The sampling intervals used in the bloom delay portion of the experiment, which were possible, because of differential cooling of the mist, might have accentuated the hardiness differences found in the closed sepals and white stages. It is not known whether the more advanced portions of the tree influenced the hardiness of the less advanced portions.

The findings of these studies suggest that tree vigor does not affect floral hardiness, unless it induces a delay in bloom. On the other hand, bloom delay through evaporative cooling tends to produce max hardiness loss in the closed sepals, white, and bloom stages.

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Table 1. Effect of tree vigor, date-stage, and min temp on 'Bartlett' pear bud, flower, and small fruit injury, 1977.

Tree vigor	Date	Developmental Stage	Percent buds or flowers injured, Temp °C: -2	-3	-4
Vigorous	3/25	2 - closed sepals	0[z] ± 0[y]	1 ± 1	8 ± 9
	4/3	4 - white	0 ± 0	7 ± 4	38 ± 22
	4/7	6 - bloom	0 ± 0	34 ± 45	100 ± 0
	4/14	8 - calyx	0 ± 1	27 ± 27	97 ± 1
	4/29	9 - small fruit	0 ± 0	98 ± 3	100 ± 0
Weak	3/25	2 - closed sepals	0 ± 0	0 ± 0	13 ± 12
	4/3	4 - white	0 ± 0	1 ± 1	24 ± 3
	4/7	6 - bloom	0 ± 0	45 ± 35	100 ± 0
	4/14	8 - calyx	0 ± 0	44 ± 6	99 ± 0
	5/26	9 - small fruit	0 ± 0	81 ± 27	100 ± 0

[z]Values shown are based on the mean % injury from 2 freezer runs, with each mean consisting of a summation of the injury from 3 branches.

[y]Standard deviations.

Table 2. Relationship between tree vigor, date of first bloom, terminal shoot length, and leaf nutrient concn for 'Bartlett' pear.

Tree vigor	Avg date first bloom	Terminal[y] shoot length (cm)	Leaf nutrient-element concn[z] N (%)	K (%)	P (%)	Ca (%)	Mg (%)	Mn (ppm)	Fe (ppm)	Cu (ppm)	B (ppm)	Zn (ppm)
Vigorous	4/5/77	30.6[x]	2.15	1.09	.13	1.58	.28	23	55	8.8	35	130
Weak	4/4/77	13.0	1.97	1.11	.13	1.65	.33	23	71	8.6	34	140
Significance at	NS	1%	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[z]Means based on 2 seasons data (1976, 1977) for each of 5 weak and 5 vigorous trees.

[y]Means based on 25 observations in 1977 on each of 5 weak and 5 vigorous trees.

[x]Mean separation within columns by student's t test.

Table 3. Effect of bloom delay through evaporative cooling, stage of development, and min temp on 'Bartlett' pear bud and flower injury.

Floral development	Date 1977	Developmental stage	Percent buds or flowers injured, Temp °C: -2	-3	-4
Normal	3/29	2 - closed sepals	0[z] ± 0[y]	1 ± 1	6 ± 1
	4/5	4 - white	0 ± 0	7 ± 3	34 ± 25
	4/10	6 - bloom	1 ± 0	11 ± 6	45 ± 13
	4/20	8 - calyx	0 ± 1	96 ± 0	100 ± 0
Delayed bloom	4/21	2 - closed sepals	0 ± 0	41 ± 34	56 ± 49
	4/22	4 - white	5 ± 7	55 ± 51	72 ± 14
	4/23	6 - bloom	1 ± 1	67 ± 22	82 ± 13
	4/28	8 - calyx	1 ± 1	87 ± 5	99 ± 1

[z]Values shown are based on the mean % injury from 2 freezer runs, with each mean consisting of a summation of the injury from 3 branches.

[y]Standard deviations.

Fig. 1. Effect of date, stage of development, temp, and tree vigor on % 'Bartlett' pear bud and flower injury. Branches were cooled at 2.5°C/hr. Stages of development tested were: 2 - closed sepals, 4 - white, 6 - bloom, 8 - calyx, and 9 - small fruit.

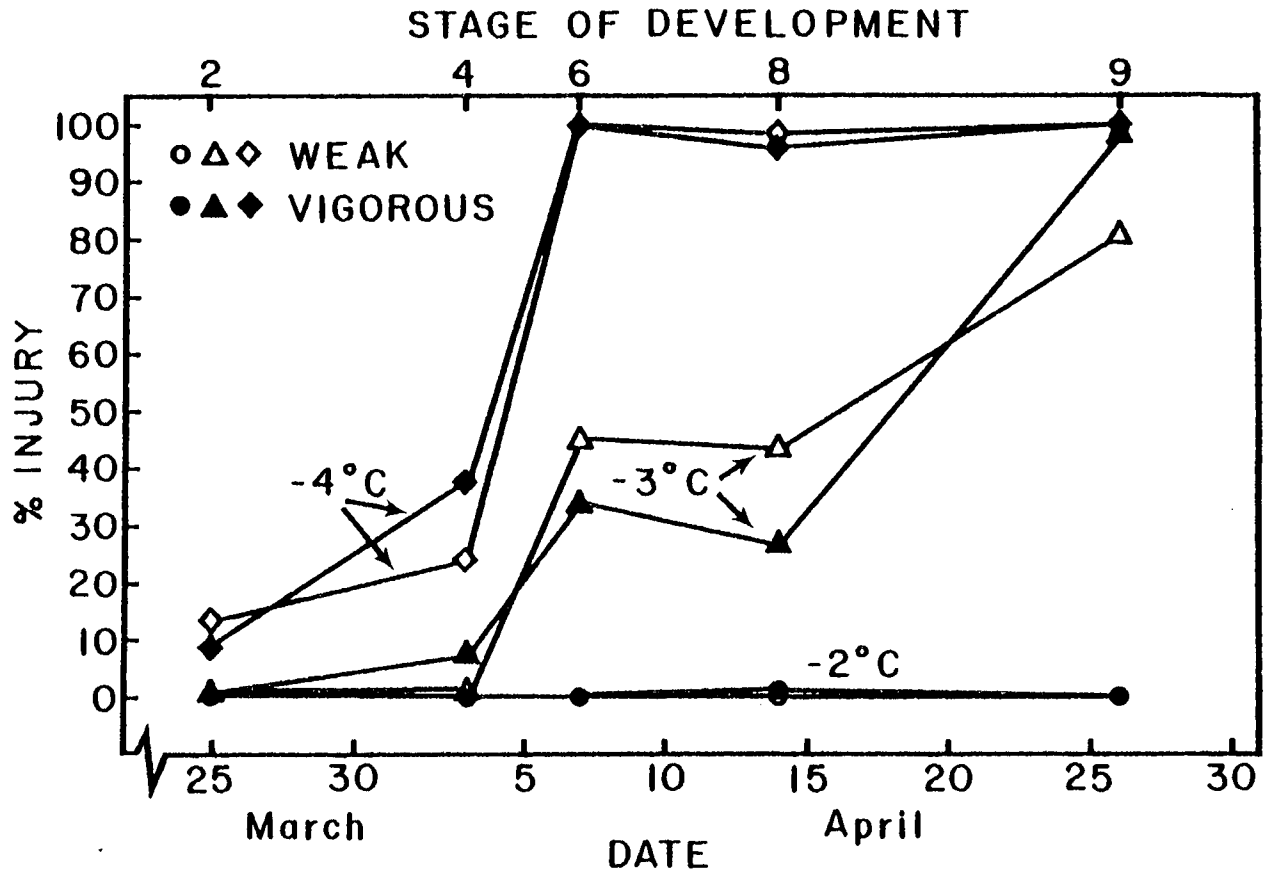
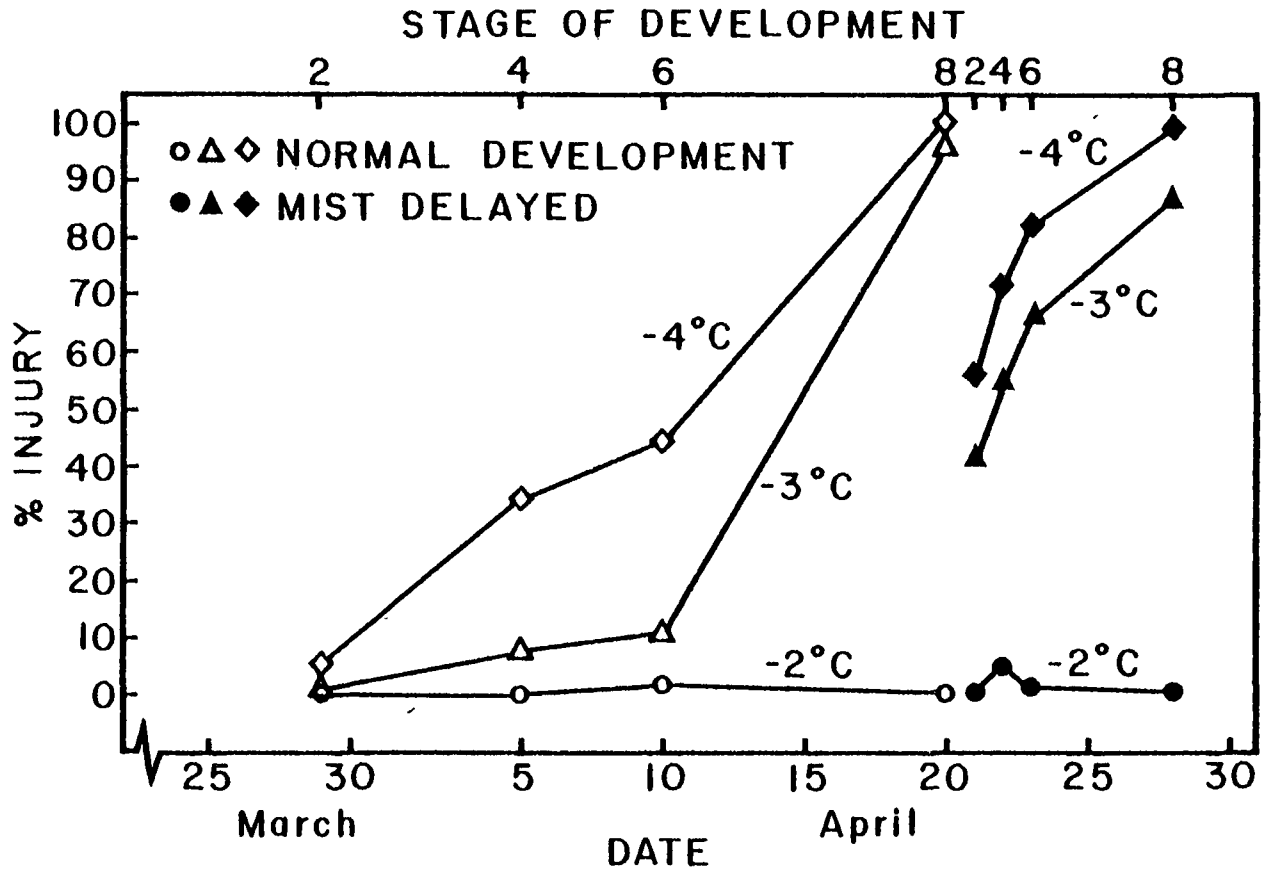

STAGE OF DEVELOPMENT
2
4
6
8
9
100
90
80
70
60
50
40
30
20
10
0
% INJURY
o Δ ◇ WEAK
● ▲ ◆ VIGOROUS
-4°C
-3°C
-2°C
25
30
5
10
15
20
25
30
March
April
DATE

Fig. 2. Effect of date, stage of development, temp, and bloom delay through evaporative cooling on % 'Bartlett' pear bud and flower injury. Branches were cooled at a rate of 1°C/hr. Stages of development tested were: 2 - closed sepals, 4 - white, 6 - bloom, and 8 - calyx.


STAGE OF DEVELOPMENT
2
4
6
8
2
4
6
8
100
90
80
70
60
50
40
30
20
10
0
% INJURY
NORMAL DEVELOPMENT
MIST DELAYED
-4°C
-3°C
-2°C
-4°C
-3°C
-2°C
25
30
5
10
15
20
25
30
March
April
DATE

EFFECT OF SIMULATED FROST INJURY ON FRUIT DEVELOPMENT IN THREE PEAR CULTIVARS[1]

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Additional index words. Pyrus communis, fruit set, fruit size, fruit malformation

Abstract. Simulated frost injury to ovaries at intervals after full bloom significantly increased fruit malformation, reduced fruit wt, and increased fruit drop in 'Bartlett', 'Bosc', and 'Comice' pear (Pyrus communis L.). Time of injury did not affect fruit wt and malformation in most cases, but did significantly affect fruit drop. Significant positive correlations were found between fruit wt and seed content, while negative correlations were found between fruit malformation and seed content for all cultivars.

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Introduction

Survival of a flower or fruit following a frost depends upon the amount of damage to the vital tissues and the capacity of the remaining intact cells to perform the functions of growth and development (9). If the flower placenta is killed, ovules cease development and abscission usually occurs (2, 6, 7, 8, 11, 16), however, if only a portion of the placenta and ovules are killed the fruit may survive (3). On the other hand, a small pear fruit that has had its ovules completely killed often develops to maturity (7). 'Bartlett' and 'Bosc' pear cultivars have a greater tendency to maintain ovary injured fruit to harvest than 'Anjou', 'Comice', and 'Winter Nelis' (15).

Fruit malformation results from extensive injury to the fruit cortex (10, 11). Frost injury usually causes a flattening of the fruit calyx in apple (12), but may cause neck thickening or fruit elongation in pear (6). Distorted fruit growth, cracking, and cork formation are the result of cortical injury and restricted meristematic activity (9, 10).

This investigation was undertaken to study the effect of simulated fruit frost injury period on fruit drop, size, and malformation.

Materials and Methods

Paired limb units were selected on the south sides of five 9-year-old 'Bartlett', 'Bosc', and 'Comice' hedgerow trees on P. communis (OPR-1) rootstocks in 1976. Ten clusters on one limb were thinned to the largest fruit in every cluster to promote max fruit set (14). Each fruit was injured with a needle inserted through the calyx in order to destroy the placenta and ovules and simulate frost injury. Ten clusters on the other limb were similarly thinned but not injured and fruit were tagged. Treatments were repeated on 5 different trees of each cultivar at approximately 10-day intervals after full bloom. 'Bartlett' and 'Bosc' fruit were injured on 5 separate occasions beginning at 9 and 10 days after full bloom, respectively, while 'Comice' fruit were injured on 3 separate occasions beginning at 21 days after full bloom in 1976. An additional study was conducted with the 'Comice' cultivar in 1977 in which fruit were injured on 5 occasions, beginning at 10 days after full bloom.

Data were collected on fruit wt, seed no., percent drop, and malformation on each limb unit during the normal cultivar harvest period.

Results and Discussion

Statistical analysis of fruit wt data showed simulated frost

injured fruit of 'Bartlett', 'Bosc', and 'Comice' to be significantly smaller than uninjured fruit (Table 1). Injured fruit averaged 22, 12, 13, and 46% smaller by wt than uninjured fruit of 'Bartlett', 'Bosc', 'Comice' (1975), and 'Comice' (1977) respectively. Time of injury did not significantly affect fruit wt in 'Bartlett', 'Bosc', and 'Comice' (1977), however, 'Comice' (1976) fruit injured at 21 days after full bloom were significantly larger than those injured at 40 days after full bloom (Table 2). The larger size of 'Comice' fruit injured earlier in the season may have resulted from a lack of competition since few fruit remained on the branches after injury (4). No significant condition x time of injury interactions were found in fruit wt analyses.

A significant positive correlation was found between seed content and fruit wt for all cultivars, although correlation coefficients were low (Table 3). These results agree with correlations found between seed content and fruit diam by Lombard et. al. (5).

Injured fruit were significantly ($F > 0.01$) more malformed than uninjured fruit (Table 1, Fig. 1). Fruit malformation was not significantly affected by time of injury in 'Bartlett', 'Bosc', and 'Comice' (1976). However, 'Comice' fruit in 1977 showed a significant ($F > 0.05$) effect of time of injury and a significant ($F > 0.05$) condition x time of injury interaction. Thus, fruits injured at 40 days after full bloom were more malformed than those

injured at 50 days after full bloom. The differences between the 1976 and 1977 'Comice' results are hard to explain and warrant further study. Correlations between seed number and fruit malformation were significant for all cultivars (Table 4). The correlation coefficients for 'Bosc' tended to be lower than those for other cultivars (Tables 3 and 4), suggesting that fruit wt and malformation were less affected by seed no.

Statistical analysis of arcsin $\sqrt{\%\ \text{drop}}$ showed a significant ($F = > 0.01$) increase in fruit drop following ovary injury for 'Bartlett', 'Bosc', and 'Comice' 1977, but no significant increase in fruit drop was found for 'Comice' (1976) (Table 1).

Time of injury significantly ($F = > 0.05$) affected fruit drop in all cultivars. Since, fruit drop was not uniform for all periods of injury, due to the natural occurrence of fruit drop in waves, further analysis was not carried out. No significant condition x time of injury interactions were found.

Ovary injury appears to exert little influence on 'Bosc' fruit drop following 18 days after full bloom, while the effect on 'Bartlett' extends up to 30 days after full bloom (Table 5). This may reflect the greater tendency for 'Bosc' to set seedless fruit (5). Percent fruit drop for injured 'Comice' was higher at 10 and 20 days after full bloom, than that found for 'Bartlett' and 'Bosc'.

These results agree with those of others (5, 13), in which seedless 'Comice' set less than 'Bartlett' and 'Bosc'.

Injury to 'Comice' in 1977 reduced fruit wt and increased fruit drop more than in 1976 (Table 1). This emphasizes the variability in cropping found with young 'Comice' trees on P. communis root-stocks by Lombard (unpublished).

In general, the increased set of injured fruit with increasing time after full bloom agrees with results of Modlibowska (7) and Abbot (1) on pears and apples respectively.

Results of these studies emphasize the detrimental effects of frost injury on fruit wt, malformation, and drop.

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Table 1. Effect of simulated frost ovary injury at various periods after full bloom on fruit wt, fruit malformation, and % drop of 3 pear cultivars.

Factor	Cultivar	Year	Avg[z] at all injury periods: Injured	Avg[z] at all injury periods: Not injured
Fruit wt (g)	Bartlett	1976	93.7	119.8**[y]
	Bosc	1976	141.3	160.0**
	Comice	1976	131.6	151.7*
	Comice	1977	101.9	187.7**
Fruit malformation[x]	Bartlett	1976	3.3	1.2**
	Bosc	1976	2.6	1.3**
	Comice	1976	2.9	1.3**
	Comice	1977	3.6	1.1**
Percent drop[w]	Bartlett	1976	54.2	16.6**
	Bosc	1976	39.8	16.4**
	Comice	1976	36.8	37.3
	Comice	1977	96.8	49.9**

[z]Avg of 5 observations from 5 branches at all injury periods.

[y]Means within rows significantly different at the 5% (*) and 1% (**) level.

[x]Index scale: 1 = normal shaped, 2 = slight calyx flattening, 3 = slight calyx flattening and malformation (Federal regulations would cull fruit indexed 3 to 5), 4 = moderate malformation, 5 = very malformed and contorted.

[w]Statistical tests were conducted on arscin $\sqrt{\%\ \text{drop}}$ data and back transformed to % drop for table values.

Table 2. Effect of interval of simulated frost ovary injury on 'Comice' fruit wt, 1976.

Days after full bloom	Avg[z] fruit wt (g) over condition
21	159.0 a[y]
31	136.7 ab
40	129.3 b

[z]Avg of 5 injured and 5 uninjured branches of fruit.

[y]Mean separation by LSD 5% level.

Table 3. Coefficient (r) and linear regression equations for correlation between fruit wt (g) and seed no. for 3 pear cultivars.

Cultivar	Year	n	r	S.E.[z]	Linear equation[y]
Bartlett[x]	1976	260	.35	.53	Fruit wt = 99.64 + 3.22 (seed no.)
Bosc	1976	341	.18	.69	Fruit wt = 146.72 + 2.25 (seed no.)
Comice	1976	178	.35	.93	Fruit wt = 119.53 + 4.61 (seed no.)
Comice	1977	149	.59	.91	Fruit wt = 124.38 + 7.99 (seed no.)

[z]Standard error of the estimate.

[y]The model for the regression equations in which the independent variable correlates linearly with the dependent variable takes the form: $Y = \alpha + b X$ where Y is the estimated fruit wt, α is the Y intercept, b is the regression coefficient or slope, and X is the independent variable, seed no.

[x]Significant (1% level) regression relationship for all cultivars and years.

Table 4. Coefficient (r) and linear regression equations for correlation between fruit malformation[z] and seed no. for 3 pear cultivars.

Cultivar	Year	n	r	S.E.[y]	Linear equation[x]
Bartlett[w]	1976	260	-.68	.02	Fruit mal. = 3.07 - .25 (seed no.)
Bosc	1976	341	-.46	.02	Fruit mal. = 2.15 - .15 (seed no.)
Comice	1976	178	-.65	.02	Fruit mal. = 2.77 - .22 (seed no.)
Comice	1977	149	-.59	.02	Fruit mal. = 2.49 - .20 (seed no.)

[z] Index scale: 1 = normal shaped, 2 = slight calyx flattening, 3 = slight calyx flattening and malformation, 4 = moderate malformation, 5 = very malformed and contorted. (Federal regulations would cull fruit indexed 3 to 5).

[y] Standard error of the estimate.

[x] The model for the regression equations in which the independent variable correlates linearly with the dependent variable takes the form: $Y = \alpha + b X$ where Y is the estimated fruit malformation, α is the Y intercept, b is the regression coefficient or slope, and X is the independent variable, seed no.

[w] Significant (0.1% level) regression relationship for all cultivars and years.

Table 5. Effect of interval of simulated frost injury on % fruit drop for 3 pear cultivars.

Cultivar	Year	Days after full bloom	Avg % fruit drop[z] Injured	Not injured
Bartlett	1976	9	90 ± 17[y]	34 ± 13
		20	66 ± 23	28 ± 31
		24	64 ± 29	28 ± 13
		30	34 ± 21	6 ± 6
		35	14 ± 21	10 ± 12
Bosc	1976	10	56 ± 32	6 ± 6
		18	62 ± 39	36 ± 43
		21	28 ± 22	14 ± 15
		33	40 ± 16	48 ± 15
		40	16 ± 16	10 ± 12
Comice	1976	21	84 ± 15	84 ± 15
		31	34 ± 24	10 ± 7
		40	8 ± 13	22 ± 16
Comice	1977	10	100 ± 0	58 ± 19
		20	100 ± 0	58 ± 27
		30	100 ± 0	60 ± 32
		40	88 ± 16	54 ± 13
		50	16 ± 31	20 ± 14

[z]Avg % fruit drop from 5 branches.

[y]Standard deviations.

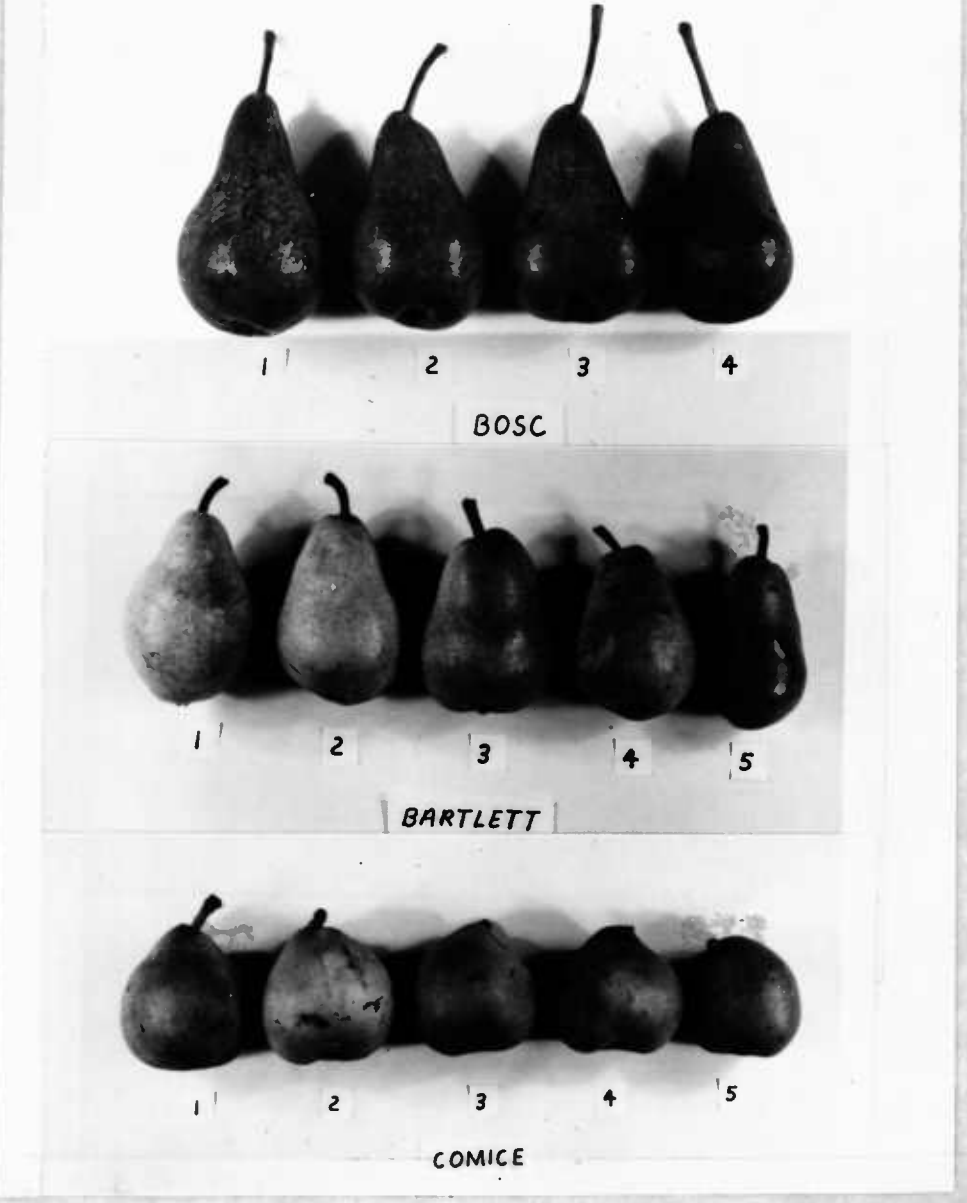

Fig. 1. 'Bosc', 'Bartlett', and 'Comice' malformation scale: 1 = normal shaped, 2 = slight calyx flattening, 3 = slight calyx flattening and malformation, 4 = moderate malformation, 5 = very malformed and contorted. (Federal regulations would cull fruit indexed 3 to 5).

EFFECT OF FROST INJURY, ORCHARD DESIGN, AND HEIGHT IN THE TREE ON CROP DENSITY OF THREE PEAR CULTIVARS[1]

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Additional index words. Pyrus communis

Abstract. Crop density was correlated significantly with sum of % floral injury from frost, orchard design, and height in the tree for 'Bartlett', 'Bosc', and 'Anjou' pear (Pyrus communis L.). Regression models differed between cultivars indicating that one model cannot be used to estimate crop density for all cultivars. Crop density was greater at low frost injury levels, in free standing trees in contrast to hedgerow trees, and at greater elevations in the trees. Data suggest that 30% injury in hedgerow and 60% injury in free standing pear orchards are reasonable injury levels to accept without incurring crop loss in an attempt to refine frost protection decisions.

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Introduction

It has been estimated that most pear and apple cultivars can lose from 50 to 90% of the flowers on a tree and still mature a substantial crop (2, 12, 17). However, crop forecasts made following a freeze are usually far from the yield obtained at harvest (12). Dorsey (3) reported that closer yield approximations were possible following the final drop.

The objectives of this study were to predict harvest crop density at the calyx and small fruit stages from frost injury level, height in the tree, orchard design, and side of the tree.

Materials and Methods

Frost injury evaluations were made after the last spring frost which occurred on the morning of April 21st on 10 clusters in the calyx or small fruit stages (11) at 2 levels (1.5 and 3.0 m) on 2 sides (north and south) of 5 mature pear trees in close proximity. Unsampled limb units on each tree in the 4 specified positions with 2-4 cm basal diam were tagged for later crop density evaluation. Each orchard design (free-standing or hedgerow) sampled consisted of a group of 5 trees located at the Southern Oregon Experiment Station. Data were collected from 2 hedgerow and 3 free standing 'Bartlett', 1 hedgerow and 3 free-standing 'Bosc', and 1 hedgerow and 3 free standing 'Anjou' orchard designs.

Fruit were cut and evaluated for frost injury at harvest. Crop density (harvested fruit without frost injured ovaries per basal cross-sectional area of limb unit) was calculated for each limb unit.

Results and Discussion

Multiple regression analysis on 'Bartlett', 'Bosc', and 'Anjou' showed that independent variables (sum of the % injury, height in the tree, orchard design, and side of the tree) were added in the same order to the models, but that side of the tree did not contribute significantly to any model (Table 1). Sixty-one, 56, and 43% of the variation in crop density were explained by variation in sum of the % floral injury, orchard design (free standing or hedgerow), and height in the tree in 'Bartlett', 'Bosc', and 'Anjou', respectively. Multiple coefficients of determination were comparatively lower, possibly due to a greater influence of other factors on fruit set and crop density in 'Anjou' (14).

Final models based on significance tests are presented in Table 2. Regression equations are similar between 'Bartlett' and 'Bosc', however, the equation for 'Anjou' differs considerably. Thus, the same regression equation cannot be used to estimate crop density at harvest for all cultivars.

Linear regression analysis of crop density and sum of the % floral injury for each orchard design (free standing, hedgerow)

showed a negative correlation and a progressive reduction in the Y-intercept for comparable cropping systems in the order: 'Bartlett' > 'Bosc' > 'Anjou' (Fig. 1-3). Stephen (10) found that fruit set capacity decreased in the following order: 'Bosc' > 'Bartlett' > 'Anjou' in a 3-year cross-pollination study. Our study was based on crop density, which is a function of bloom density and fruit set, while Stephen's study was based on fruit set alone. Lombard (personal communication) has found that 'Bartlett' tends to bloom heavier than 'Bosc', while 'Bosc' usually sets heavier than 'Bartlett'. Rootstock (8, 15), nutritional (13), vigor (15), pollination (9), and hormonal level (16) differences are additional factors to be considered in determining reasons for crop density differences between cultivars.

A comparison of linear regression equations between free standing and hedgerow orchard designs showed significant differences for 'Bartlett' (5% level), 'Bosc' (1% level), and 'Anjou' (1% level) (Fig. 3). Similar comparisons of regression slopes between orchard designs showed no significant differences for 'Bartlett' and 'Anjou', but marginally significant differences (5% level) for 'Bosc'. Thus, crop density was greater in free standing than in hedgerow trees for all cultivars and at all levels of injury for 'Bartlett' and 'Anjou'. Crop density differences found between orchard designs could be attributed to differences in pruning and bloom density, however, further investigation is warranted.

The failure of regression lines to terminate at 100% injury and a crop density of 0 (Fig. 1-3) may be due to several factors. Experimental error could have arisen in the process of assessing injury levels for each limb unit by sampling too few flower clusters from an adjacent branch. Visual floral injury determinations may not have been 100% accurate. In addition, the 'Bartlett' cultivar often produces late bloom, which were not assessed for injury. Examination of Fig. 1-3 indicates that a polynomial function would probably not improve the relationships significantly.

Figures 2 and 3 show a greater disperson of data points for 'Bosc' and 'Anjou' at lower levels of injury, than at higher levels. This suggests that a large number of variables influence crop density at low levels of injury, while frost is the primary influence at high levels of injury. This trend is less apparent in 'Bartlett' (Fig. 1).

The significance of height in the tree in our study (Table 1) is supported by others (4, 5, 7, 18) in which less floral injury was found in the upper portions of trees than in lower portions, because of temp inversions.

The results of this study disagree with observations of Jones (6), in which greater frost damage to flowers was noted on the south sides of pear trees. We did not find side of the tree to be significant in regression models, although a slight trend was found

for greater crop density on the south side in 'Bartlett' and 'Bosc' and on the north side in 'Anjou'.

Lombard (personal communication) found that average crops were produced by 'Bartlett' and 'Bosc' at a crop density of 3 and by 'Anjou' at a crop density of 1.5. Crop densities below these values resulted in less than a full crop. Using these values, our data on free standing trees indicate that frost injury levels greater than 90, 60, and 80% resulted in crop losses in 'Bartlett', 'Bosc', and 'Anjou' respectively (Fig. 2-4). On the other hand, 'Bartlett', 'Bosc', and 'Anjou' hedgerow orchards showed a crop loss at injury levels greater than 40, 32, and 30%, respectively.

Thus, frost injury is more liable to produce a crop loss in hedgerow than in free standing trees and the degree of crop loss is influenced by cultivar, indicating that hedgerows should be planted on frost free sites or given frost protection. Ballard and Proebsting (1) also noted a greater susceptibility of high density hedgerow trees to frost injury.

Conklin et. al. (2) estimated from grower observations that crop losses occurred with bud losses greater than 50%. However, the present study suggests that crop losses may result from floral injury levels as low as 30-40% in hedgerow orchards, or may not occur until injury levels of 60-90% are attained in free standing orchards.

Studies were also conducted on 'Seckel' and 'Comice', but were not presented because of insufficient data and low r values. However, cultivar crop densities based on complete models at 0% injury were rated in the following order: 'Bartlett' > 'Bosc' > 'Seckel' > "Anjou' > 'Comice'.

Results of these studies provide models for the prediction of crop density at harvest for 3 pear cultivars. Findings suggest a need for testing additional variables such as: temp during pollination with respect to bee activity and effective pollination period (9), rootstock (8, 15), and the influence of previous seasons seeded fruit (16), in the models.

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Table 1. Stepwise multiple coefficients of determination for crop density[z] and 4 variables on 3 pear cultivars.

Variable	Multiple coefficient of determination (R^2)		
	Bartlett	Bosc	Anjou
Sum % floral injury	0.52**[y]	0.51**	0.25**
Orchard design[x]	0.57**	0.55**	0.36**
Height in tree[w]	0.61**	0.56**	0.43**
Side of tree[v]	0.61[NS]	0.56[NS]	0.43[NS]

[z]Crop density = harvested fruit without frost injured ovaries per basal cross-sectional area of limb unit.

[y]Stepwise coefficients were not significant (NS); and significant (**) at the 1% level between each consecutive step.

[x]Orchard design = Hedgerow or free standing.

[w]Height in tree = 1.5 or 3.0 m.

[v]Side of tree = North or south.

Table 2. Multiple regression equations for crop density of 3 pear cultivars (harvested fruit without frost injured ovaries per basal cross-sectional area of limb unit) as dependent on sum % floral injury (I), orchard design (D), and height in tree (H).

Cultivar	Equation[z]
Bartlett	Crop density = 4.802 - .049(I) - .977 (D) + .856 (H)
Bosc	Crop density = 4.058 - .045(I) - .500 (D) + .452 (H)
Anjou	Crop density = 1.814 - .031(I) - .699 (D) + .705 (H)

[z]The model for multiple regression equations in which the independent variables correlate linearly with the dependent variable takes the form: $Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 \ldots B_N X_N + E$ where in our models Y is the estimated crop density, B_0 is the Y intercept, $B_1 \ldots . B_N$ are partial regression coefficients, $X_1 \ldots . X_N$ are the independent variables, sum % floral injury, orchard design, and height in the tree, and E is the residual error.

Fig. 1. Correlation between crop density (harvested fruit without frost injured ovaries per basal cross-sectional area of limb unit) and sum of % 'Bartlett' pear floral injury for free standing and hedgerow orchards.

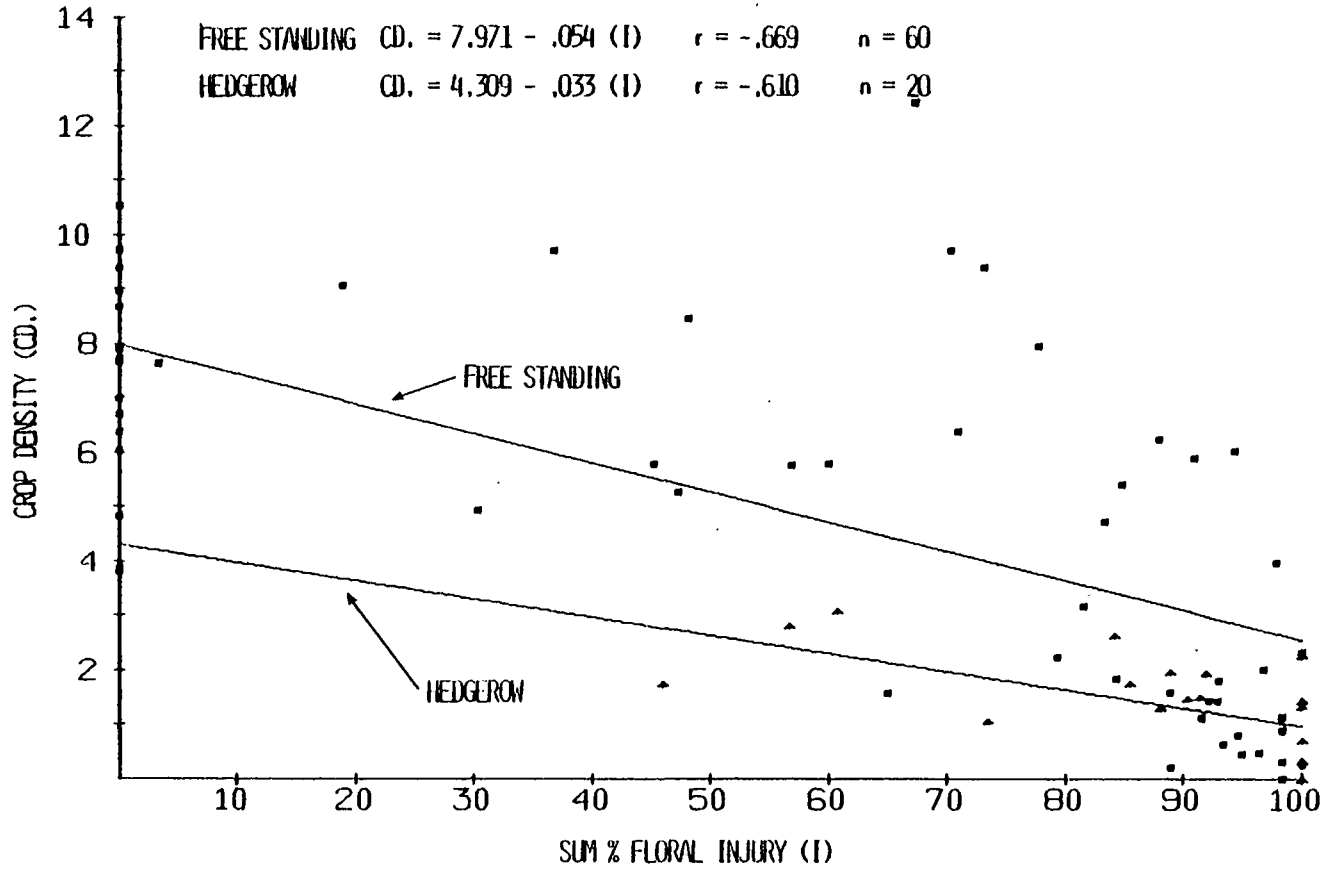

FREE STANDING CD. = 7.971 - .054 (I) r = -.669 n = 60
HEDGEROW CD. = 4.309 - .033 (I) r = -.610 n = 20
CROP DENSITY (CD.)
SUM % FLORAL INJURY (I)
FREE STANDING
HEDGEROW
14
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90
100

Fig. 2. Correlation between crop density (harvested fruit without frost injured ovaries per basal cross-sectional area of limb unit) and sum of % 'Bosc' pear floral injury for free standing and hedgerow orchards.

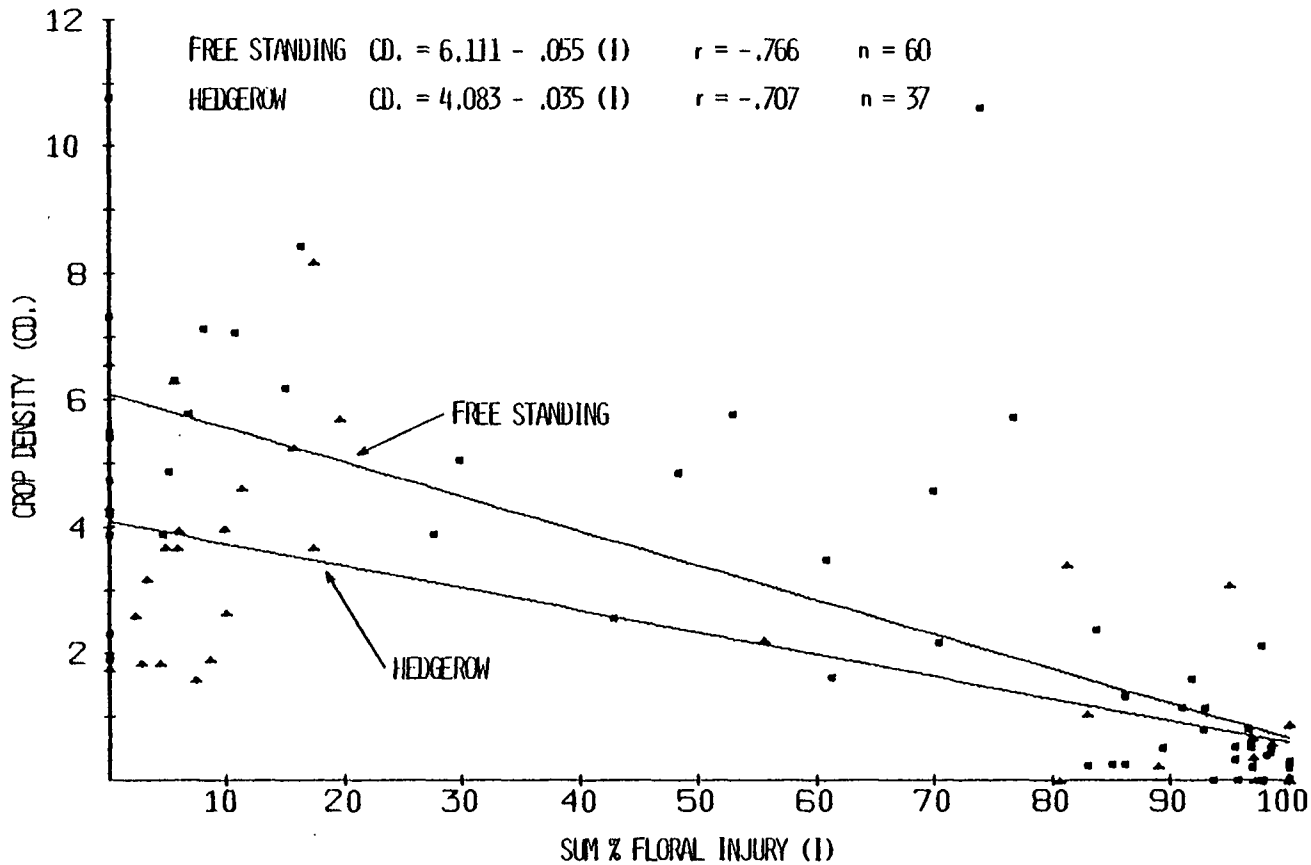
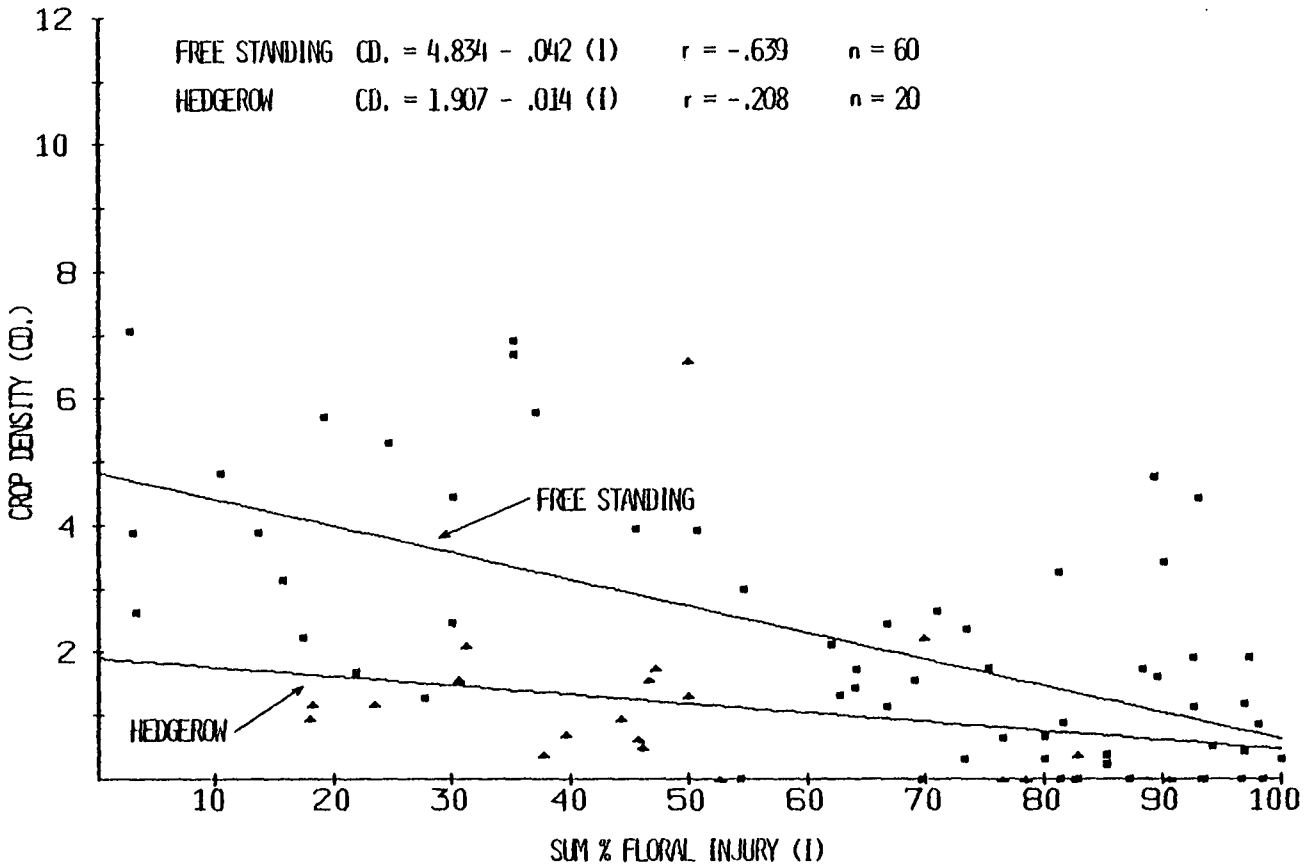

FREE STANDING CD. = 6.111 - .055 (I) r = -.766 n = 60
HEDGEROW CD. = 4.083 - .035 (I) r = -.707 n = 37
CROP DENSITY (CD.)
SUM % FLORAL INJURY (I)
FREE STANDING
HEDGEROW
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90
100

Fig. 3. Correlation between crop density (harvested fruit without frost injured ovaries per basal cross-sectional area of limb unit) and sum of % 'Anjou' pear floral injury for free standing and hedgerow orchards.


FREE STANDING CD. = 4.834 - .042 (I) r = -.639 n = 60
HEDGEROW CD. = 1.907 - .014 (I) r = -.208 n = 20
CROP DENSITY (CD.)
SUM % FLORAL INJURY (I)
FREE STANDING
HEDGEROW
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90
100

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APPENDICES

Table 1-A. Analysis of variance of percent wet 'Bartlett' pear bud and flower injury as affected by date-stage (Ds) (pink, white, and bloom), temp (Te) (-2, -3, and -4°C), and duration (Du) (1, 15, 30, 60, and 120 min), split-split-plot design.

ANOVA	df	MS	F
Ds (Main-plots)	2	1064.8	
(Error a)			
Te (Sub-plots)	2	25178.7	16.7*[z]
Te x Ds (Error b)	4	1511.7	
Du (Sub-sub-plots)	4	780.1	10.4**
Te x Du	8	130.3	1.7[NS]
Du x Ds	8	119.7	1.6[NS]
Te x Du x Ds (Error c)	16	75.1	
Total	44		

[z] Significant difference at the 5% (*) and 1% (**) level.

Table 2-A. Analysis of variance of percent dry 'Bartlett' pear bud and flower injury as affected by date-stage (Ds) (closed sepals, pink, white, and bloom), temp (Te) (-2, -3, and -4°C), and duration (Du) (1, 15, 30, 60, 120 min), split-split-plot design.

ANOVA	df	MS	F
Ds (Main-plots)	3	9143.0	
(Error a)			
Te (Sub-plots)	2	20659.3	7.5^{*z}
Te x Ds (Error b)	6	2775.0	
Du (Sub-sub-plots)	4	826.3	4.5**
Te x Du	8	202.8	1.1^{NS}
Du x Ds	12	110.9	0.6^{NS}
Te x Du x Ds (Error c)	24	184.6	
Total	59		

[z] Significant difference at the 5% (*) and 1% (**) level.

Table 3-A. Analysis of variance of percent wet 'Bartlett' pear bud and flower injury as affected by freezing rate (Ra) (1.0 and 2.5°C/hr), date-stage (Ds) (closed sepals, white, and bloom), and temp (Te) (-3 and -4°C), split-split-plot design.

ANOVA	df		MS	F
Reps		1		
Ds	2	2	12212.8	159.8**[z]
Reps x Ds (Error a)	3		76.4	
Ra	1		1345.7	4.9[NS]
Ra x Ds	2		280.7	1.0[NS]
Reps x Ra		1		
Reps x Ra x Ds (Error b)	3	2	273.8	
Te	1		1537.4	27.1**
Te x Ds	2		334.8	5.9*
Te x Ra	1		10.4	0.2[NS]
Te x Ds x Ra	2		134.9	2.4[NS]
Reps x Te		1		
Reps x Te x Ra		1		
Reps x Te x Ds		2		
Reps x Te x Ra x Ds (Error c)	6	2	56.8	
Total	23			

[z] Significant difference at the 5% (*) and 1% (**) level.

Table 4-A. Analysis of variance of percent dry 'Bartlett' pear bud and flower injury as affected by freezing rate (Ra) (1.0 and 2.5°C/hr), date-stage (Ds) (closed sepals, white, and bloom), and temp (Te) (-3, and -4°C), split-split-plot design.

ANOVA	df		MS	F
Reps		1		
Ds	2		3266.7	49.0**[z]
Reps x Ds (Error a)	3		66.7	
Ra	1		1618.7	5.1[NS]
Ra x Ds	2		453.6	1.4[NS]
Reps x Ra		1		
Reps x Ra x Ds (Error b)	3	2	319.5	
Te	1		8887.3	92.2**
Te x Ds	2		1903.2	19.7**
Te x Ra	1		1623.0	16.8**
Te x Ds x Ra	2		498.7	5.2*
Reps x Te		1		
Reps x Te x Ra		1		
Reps x Te x Ds		2		
Reps x Te x Ra x Ds (Error c)	6	2	96.4	
Total	23			

[z] Significant difference at the 5%(*) and 1%(**) level.

Table 5-A. Analysis of variance of percent wet 'Bartlett' pear bud injury as affected by freezing rate (Ra) (1.0 and 2.5°C/hr), date-stage (Ds) (closed sepals and white), and temp (Te) (-3, -4, and -5°C), split-split-plot design.

ANOVA	df		MS	F
Reps		1		
Ds	1	1	3124.3	225.8**[z]
Reps x Ds (Error a)	2		13.8	
Ra	1		1653.2	63.9*
Ra x Ds	1		380.1	14.7[NS]
Reps x Ra		1		
Reps x Ra x Ds (Error b)	2	1	25.9	
Te	2		551.3	5.2*
Te x Ds	2		133.2	1.3[NS]
Te x Ra	2		350.7	3.3[NS]
Te x Ds x Ra	2		25.0	0.2[NS]
Reps x Te		2		
Reps x Te x Ra		2		
Reps x Te x Ds		2		
Reps x Te x Ra x Ds (Error c)	8	2	105.2	
Total	23			

[z] Significant difference at the 5%(*) and 1%(**) level.

Table 6-A. Analysis of variance of percent dry 'Bartlett' pear bud injury as affected by freezing rate (Ra) (1.0 and 2.5°C/hr), and temp (Te) (-3, -4, and -5°C), for the closed sepals date-stage, split-plot design.

ANOVA	df		MS	F
Reps		1		
Ra	1		1165.9	21.2*[z]
Reps x Ra (Error a)	2		55.0	
Te	2		1815.2	29.7**
Te x Ra	2		1273.5	20.9**
Reps x Te		2		
Reps x Te x Ra (Error b)	4	2	61.0	
Total	11			

[z] Significant difference at the 5%(*) and 1%(**) level.

Table 7-A. Analysis of variance of percent 'Bartlett' pear bud and flower injury as affected by date-stage (Ds) closed sepals, white, and bloom, hydration (H) (dry and wet just prior to freezing), and temp (Te) (-3 and -4°C) when frozen at 1.0°C/hr, split-split-plot design.

ANOVA	df		MS	F
Reps		1		
Ds	2		4053.6	21.5*[z]
Reps x Ds (Error a)	3	1	188.7	
H	1		473.8	1.9[NS]
H x Ds	2		1140.6	4.7[NS]
Reps x H		1		
Reps x H x Ds (Error b)	3	2	245.4	
Te	1		2023.5	21.8**
Te x Ds	2		510.1	5.5*
Te x H	1		81.1	0.9[NS]
Te x Ds x H	2		49.7	0.5[NS]
Reps x Te		1		
Reps x Te x H		1		
Reps x Te x Ds		2		
Reps x Te x H x Ds (Error c)	6	2	93.0	
Total	23			

[z] Significant difference at the 5% (*) and 1%(**) level.

Table 8-A. Analysis of variance of percent 'Bartlett' pear bud and flower injury as affected by date-stage (Ds) (closed sepals, white, and bloom), hydration (H) (dry and wet just prior to freezing), and temp (Te) (-3 and -4°C) when frozen at 2.5°C/hr, split-split-plot design.

ANOVA	df		MS	F
Reps		1		
Ds	2		9766.1	33.7** [z]
Reps x Ds (Error a)	3	2	289.8	
H	1		331.8	26.7*
H x Ds	2		1253.5	100.8**
Reps x H		1		
Reps x H x Ds (Error b)	3	2	12.4	
Te	1		7832.3	129.9**
Te x Ds	2		1634.4	27.1**
Te x H	1		2121.4	35.2**
Te x Ds x H	2		677.4	11.2**
Reps x Te		1		
Reps x Te x H		1		
Reps x Te x Ds		2		
Reps x Te x H x Ds (Error c)	6	2	60.3	
Total	23			

[z] Significant difference at the 5% (*) and 1%(**) level.

Table 9-A. Analysis of variance of percent 'Bartlett' pear bud injury as affected by hydration (H) (dry and wet just prior to freezing), and temp (Te) (-3, -4, and -5°C) for the closed sepals date-stage frozen at 2.5°C/hr, split-plot design.

ANOVA	df		MS	F
Reps		1		
H	1		776.8	9.5[NS z]
Reps x H (Error a)	2	1	81.6	
Te	2		2534.5	37.8[**]
Te x H	2		777.9	11.6[**]
Reps x Te		2		
Reps x Te x H (Error b)	4	2	67.1	
Total	11			

[z] Significant difference at the 1% (**) level.

Table 10-A. Analysis of variance of percent 'Bartlett' pear bud injury as affected by hydration (H) (dry and wet just prior to freezing) and temp (Te) (-3, -4, and -5°C) for the closed sepals date-stage frozen at 1.0°C/hr, split-plot design.

ANOVA	df		MS	F
Reps		1		
H	1		75.6	88.0*[z]
Reps x H (Error a)	2	1	0.9	
Te	2		18.0	20.7**
Te x H	2		18.0	20.7**
Reps x Te		2		
Reps x Te x H (Error b)	4	2	0.9	
Total	11			

[z] Significant difference at the 5%(*) and 1%(**) level.

Table 11-A. Analysis of variance of percent 'Bartlett' pear bud, flower and fruit injury as affected by date-stage (Ds) (closed sepals, white, bloom, calyx, and small fruit) tree vigor (V) (weak and vigorous), and temp (Te) (-3 and -4°C), split-plot design with a factoral arrangement in the sub plots.

ANOVA		df		MS	F
Reps			1		
Ds		4		11402.9	26.4^{**z}
Reps x Ds	(Error a)	5	4	432.5	
V		1		0.8	0.004^{NS}
Te		1		11651.0	53.1**
V x Te		1		11.7	0.1^{NS}
V x Ds		4		152.6	0.7^{NS}
Te x Ds		4		1335.4	6.1**
V x Te x Ds		4		90.1	0.4^{NS}
Reps x V			1		
Reps x Te			1		
Reps x V x Te			1		
Reps x V x Ds			4		
Reps x T x Ds			4		
Reps x T x V x Ds	(Error b)	15	4	219.6	
Total		39			

[z] Significant difference at the 1% level.

Table 12-A. Analysis of variance of percent 'Bartlett' pear bud injury as affected by bloom delay through evaporative cooling (Bd) (not delayed and mist delayed), date-stage (Ds) (closed sepals, white, bloom, and calyx), and temp (Te) (-3 and -4°C), split-plot design with a factoral arrangement in the main plots.

ANOVA	df		MS	F
Reps		1		
Bd	1		8406.8	10.0*[z]
Ds	3		7137.7	8.5**
Bd x Ds	3		1236.0	1.5[NS]
Reps x Bd		1		
Reps x Ds		3		
Reps x Bd x Ds (Error a)	8	3	838.9	
Te	1		2074.8	15.0**
Te x Bd	1		16.2	0.1[NS]
Te x Ds	3		139.6	1.0[NS]
Te x Bd x Ds	3		96.4	0.7[NS]
Reps x Te		1		
Reps x Te x Bd		1		
Reps x Te x Ds		3		
Reps x Te x Bd x Ds (Error b)	8	3	138.4	
Total	31			

[z] Significant difference at the 5% (*) and 1% (**) level.

Table 13-A. Factoral (2 x 2) analysis of variance of 'Bartlett' (1976) fruit wt as affected by condition (C) (ovary injured and not injured) and time (T) (9, 20, 24, 30, and 35 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	8502.1	14.5**[z]
T	4	1202.2	2.0[NS]
C x T	4	709.8	1.2[NS]
Error	37	588.3	
Total	46		

[z] Significant difference at the 1% (**) level.

Table 14-A. Factoral (2 x 2) analysis of variance of 'Bosc' (1976) fruit wt as affected by condition (C) (ovary injured and not injured) and time (T) (10, 18, 21, 33, and 40 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	4380.5	8.6**[z]
T	4	133.9	0.3[NS]
C x T	4	175.9	0.4[NS]
Error	38	509.9	
Total	47		

[z] Significant difference at the 1% (**) level.

Table 15-A. Factoral (2 x 2) analysis of variance of 'Comice' (1976) fruit wt as affected by condition (C) (ovary injured and not injured), and time (T) (21, 31, and 40 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	3040.1	4.8^{*z}
T	2	2390.2	3.8^{*}
C x T	2	925.6	1.4^{NS}
Error	22	632.2	
Total	27		

[z] Significant difference at the 5% (*) level.

Table 16-A. Factoral (2 x 2) analysis of variance of 'Comice' (1977) fruit wt as affected by condition (C) (ovary injured and not injured), and time (T) (40 and 50 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	36749.0	66.7**[z]
T	1	660.2	1.2[NS]
C x T	1	207.6	0.4[NS]
Error	14	551.2	
Total	17		

[z] Significant difference at the 1% (**) level.

Table 17-A. Factoral (2 x 2) analysis of variance of 'Bartlett' (1976) fruit malformation[z] as affected by condition (C) (ovary injured and not injured) and time (T) (9, 20, 24, 30, and 35 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	58.1	119.3**[y]
T	4	0.8	1.6[NS]
C x T	4	1.2	2.4[NS]
Error	37	0.5	
Total	46		

[z] Index scale: 1 = normal shaped, 2 = slight calyx flattening, 3 = slight calyx flattening and malformation, 4 = moderate malformation, 5 = very malformed and contorted.

[y] Significant difference at the 1% (**) level.

Table 18-A. Factoral (2 x 2) analysis of variance of 'Bosc' (1976) fruit malformation[z] as affected by condition (C) (ovary injured and not injured) and time (T) (10, 18, 21, 33, and 40 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	21.5	282.0**[y]
T	4	0.2	2.8[NS]
C x T	4	0.1	0.9[NS]
Error	38	0.1	
Total	47		

[z] Index scale: 1 = normal shaped, 2 = slight calyx flattening, 3 = slight calyx flattening and malformation, 4 = moderate malformation.

[y] Significant difference at the 1% (**) level.

Table 19-A. Factoral (2 x 2) analysis of variance of 'Comice' (1976) fruit malformation[z] as affected by condition (C) (ovary injured and not injured) and time (T) (21, 31, and 40 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	1.95	162.45**[y]
T	2	0.12	0.97[NS]
C x T	2	0.03	0.25[NS]
Error	22	0.12	
Total	27		

[z] Index scale: 1 = normal shaped, 2 = slight calyx flattening, 3 = slight calyx flattening and malformation, 4 = moderate malformation, 5 = very malformed and contorted

[y] Significant difference at the 1% (**) level.

Table 20-A. Factoral (2 x 2) analysis of variance of 'Comice' (1977) fruit malformation[z] as affected by condition (C) (ovary injured and not injured) and time (T) (40 and 50 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	30.5	144.2**[y]
T	1	1.1	5.2*
C x T	1	1.5	7.2*
Error	14	0.2	
Total	17		

[z] Index scale: 1 = normal shaped, 2 = slight calyx flattening, 3 = slight calyx flattening and malformation, 4 = moderate malformation, 5 = very malformed and contorted.

[y] Significant at the 5% (*) and 1% (**) level.

Table 21-A. Factoral (2 x 2) analysis of variance of 'Bartlett' (1976) fruit drop[z] as affected by condition (C) (ovary injured and not injured) and time (T) (9, 20, 24, 30, and 35 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	2.08	26.82**[y]
T	4	0.88	11.30**
C x T	4	0.16	2.09[NS]
Error	40	0.08	
Total	49		

[z] Statistical tests were conducted on transformed data arcsin $\sqrt{\%\ \text{drop}}$.

[y] Significant difference at the 1% (**) level.

Table 22-A. Factoral (2 x 2) analysis of variance of 'Bosc' (1976) fruit drop[z] as affected by condition (C) (ovary injured and not injured) and time (T) (10, 18, 21, 33, and 40 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	0.88	7.58**[y]
T	4	0.40	3.48*
C x T	4	0.21	1.76[NS]
Error	40	0.12	
Total	49		

[z] Statistical tests were conducted on transformed data arcsin $\sqrt{\%\ \text{drop}}$.

[y] Significant difference at the 5% (*) and 1% (**) level.

Table 23-A. Factoral (2 x 2) analysis of variance of 'Comice' (1976) fruit drop[z] as affected by condition (C) (ovary injured and not injured) and time (T) (21, 31, and 40 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	0.0001	.0021[NS y]
T	2	2.3604	37.0115[**]
C x T	2	0.2025	3.1751[NS]
Error	24	0.0638	
Total	29		

[z] Statistical tests were conducted on the transformed data arcsin $\sqrt{\%\ \text{drop}}$.

[y] Significant difference at the 1% (**) level.

Table 24-A. Factoral (2 x 2) analysis of variance of 'Comice' (1977) fruit drop[z] as affected by condition (C) (ovary injured and not injured) and time (T) (10, 20, 30, 40, and 50 days after full bloom), completely randomized design with five observations per treatment.

ANOVA	df	MS	F
C	1	4.59	90.22**[y]
T	4	0.55	10.71**
C x T	4	0.03	0.62[NS]
Error	40	0.05	
Total	49		

[z] Statistical tests were conducted on the transformed data arcsin $\sqrt{\%\ \text{drop}}$.

[y] Significant difference at the 1% (**) level.

Table 25-A. Conditions and dates under which frost marking[z] is thought to have taken place on 'Bartlett' pear at the Southern Oregon Branch Experiment Station in 1977.

Date	Flower temp. °C 2.0 m.	Air temp. °C 2.0 m.	Wind speed m./s.	Total opaque sky cover	Dew point °C[y]	Time	Net radiation (langlies/min.)	Developmental stage
Apr. 10	-2.4	-1.8	.17	0	-1.7	4:20 AM	-.063	Full bloom
Apr. 11	-2.0	-1.7	.24	0	-5.0	4:55 AM	-.065	Petal fall

[z]Fifty-three percent of the fruit at the 2.0 m height showed frost marking at harvest, while the fruit on similar trees on which bloom had been delayed for 18 days through evaporative cooling showed no frost marking.

[y]Readings obtained from the National Weather Service Station at the Medford airport located 10 km. from the orchard.

Table 26-A. Effect of streptomycin sulfate on dry 'Bartlett' pear flower injury. Bouquets were cooled at a rate of 2.5°C/hr in a controlled freezing chamber to -3°C and left for a duration of 15 minutes.

Streptomycin[z] concentration (ppm)	Freezing treatment	Freezing test	Average percent flowers injured[y]	
			Bloom	Petal fall
0	Unfrozen	-	0 ± 0[x]	0 ± 0
100	Unfrozen	-	0 ± 0	4 ± 5
200	Unfrozen	-	0 ± 0	1 ± 2
0	Frozen	1	36 ± 10	37 ± 11
100	Frozen	1	53 ± 13	63 ± 10
0	Frozen	2	70 ± 26	82 ± 13
200	Frozen	2	100 ± 0	86 ± 16

[z]Streptomycin sulfate was applied at 3 day intervals for a total of ten applications between the blossom buds exposed and bloom developmental stages.

[y]Averages are based on the sum of the percent floral injury on two branches from each of three trees.

[x]Standard deviations.

Table 27-A. Effect of ethanolamine and Tween 85[z] on dry 'Bartlett' pear flower injury. Bouquets were cooled at a rate of 2°C/hr in a controlled freezing chamber to -3°C and left for a duration of 15 minutes.

Ethanolamine concentration (mM)	Freezing treatment	Freezing test	Average percent flowers injured[y]	
			Bloom	Petal fall
0	Unfrozen	-	0 ± 0[x]	0 ± 0
5	Unfrozen	-	0 ± 0	1 ± 1
10	Unfrozen	-	1 ± 1	2 ± 3
0	Frozen	1	79 ± 23	83 ± 21
5	Frozen	1	70 ± 36	84 ± 18
0	Frozen	2	89 ± 10	94 ± 7
10	Frozen	2	84 ± 14	85 ± 11

[z]Ethanolamine and .005% Tween 85 (polyoxyethylene 20 sorbitan trioleate) were applied at the blossom buds exposed developmental stage.

[y]Averages are based on the sum of the percent floral injury on two branches from each of three trees.

[x]Standard deviations.

Table 28-A. Effect of glycerol on dry 'Bartlett' pear flower injury. Bouquets were cooled at a rate of 2°C/hr in a controlled freezing chamber to -3°C and left for a duration of 15 minutes.

Glycerol[z] concentration (%)	Freezing treatment	Freezing test	Average percent flowers injured[y]	
			Petal fall	Calyx
0	Unfrozen	-	0 ± 0[x]	1 ± 2
10	Unfrozen	-	0 ± 0	0 ± 0
25	Unfrozen	-	0 ± 0	2 ± 4
0	Frozen	1	90 ± 5	86 ± 1
10	Frozen	1	87 ± 4	77 ± 5
0	Frozen	2	97 ± 6	78 ± 8
25	Frozen	2	74 ± 25	73 ± 11

[z]Glycerol was applied on the day prior to the hardiness tests.

[y]Averages are based on the sum of the percent floral injury on two branches from each of three trees.

[x]Standard deviations.

Table 29-A. Effect of dodecyl ether of polyethylene glycol (WK) on dry 'Bartlett' pear flower injury. Bouquets were cooled at a rate of 2°C/hr in a controlled freezing chamber to -3°C and left for a duration of 15 minutes.

WK[z] concentration (%)	Freezing treatment	Average percent flowers injured[y]	
		Petal fall	Calyx
0	Unfrozen	0 ± 1[x]	0 ± 0
0.25	Unfrozen	0 ± 0	0 ± 0
0	Frozen	84 ± 12	80 ± 21
0.25	Frozen	89 ± 6	94 ± 5

[z]WK was applied on the day prior to the hardiness tests. Severe burning of leaves, petals, and pedicels occurred following WK application.

[y]Averages are based on the sum of the percent floral injury on two branches from each of three trees.

[x]Standard deviations.