This pattern was repeated for many locations in Central Florida (2). The minimum temperature rose about 10°F from Dec. 16 to Dec. 18 and remained at 60°F until Dec. 23. Most locations in Central Florida reported slight rainfall (6) from Dec. 18 to Dec. 23, showing that there was general cloudiness over the region. An extended spatial and temporal cloud cover suppressed nocturnal radiative cooling and helped to maintain warm nocturnal temperatures. The extended cloudiness most likely contributed to the high minimum temperatures observed from Dec. 18-23 prior to the freeze. The high temperature and the slight rainfall are conducive to plant growth. Also, acquired cold hardiness may have been lost during the warm period.

Severe advective freezes have occurred in Florida in 1835, 1886, 1894-95, 1899, 1909, 1940, 1962, and 1983, on average, once each 20 to 22 yr. These freezes are a part of the climate of the northern part of the citrus producing area.

Conclusions

Radiant temperatures may be expected to be higher than air temperatures during advective freezes following warm, wet periods. Since advective freezes are infrequent in comparison with radiant frosts this is expected to be an infrequent adjustment to be considered.

The temperatures analyzed show that there were a large number of years within the last 30 yr which recorded below normal temperatures. In addition, the occurrence of extreme cold events have also increased. The data suggest declining minimum temperatures for December and January from North Central to South Florida. Citrus received more damage from the December 1983 freeze *not because* of low minimum temperature alone, but because of a combination of low minimum temperature, temperature behavior prior to the freeze, cloud cover, and rainfall. The 4 factors occurring in tandem caused this freeze to be labeled by many as the freeze of the century.

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REVIEW OF EFFECTS OF CULTURAL PRACTICES ON FROST HAZARD[1]

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Abstract. **Severe advective freezes, such as occurred December 1983, are experienced infrequently. Most damaging freezes are of the radiation type where temperatures develop which are only a few degrees below those lethal to citrus leaves and branches. Cultural practices can be, under certain conditions, manipulated to enhance the tree's warmth and cold hardiness and thereby avoid or reduce freeze damage. Principles involved are maintenance of weed-free, moist, compact soil to furnish a reservoir of heat for the night, enhancement of air drainage, maintenance of a thick leafy canopy to intercept heat radiated from the soil, and development of maximum hardiness to cold. Severely freeze damaged trees are colder and less cold-hardy than those not damaged. Certain modifications of cultural practices are suggested for trees severely freeze damaged; however, the basic principles involved remain the same.**

Damage of freezes to citrus in Florida is well documented. For example, a temperature of 22°F, the temperature often used as approximating the temperature at which leaf damage occurs, or lower, occurred on the average of every 3.1, 8.0, and 10.8 yr, respectively, at Ocala-Weirsdale, Orlando and Avon Park from 1894-1958 (2).

Occasional dry, windy (advective) freezes, such as occurred December 1983, are so severe almost no existing method of protection is economically feasible; however, most damaging freezes are of the radiation type that develop on calm nights and damage trees at temperatures only slightly lower than 22°F. Cultural practices can be, in some instances, manipulated to attain this much protection and it is our purpose in this paper to examine their role in doing this. Unfortunately, much of the evidence is not based on precise experimentation in the field because of the difficulty in making some of the physical measurements needed, the nonuniformity of freezes, the fact that temperatures of the various part of a tree differ from air temperature and are cyclic rather than static, and because tree hardiness to cold varies with even short periods of warm and cold weather preceding the freeze.

Principles Involved

A knowledge of the development of freezes, the microclimate of the tree and factors that induce maximum tree hardiness are necessary to determine how cultural practices can be used to lessen damage.

Freeze development. There are advective freezes and radiation frosts. An advective freeze develops from an invasion of cold polar air. Air temperatures are below freezing and wind speed is 3 mph or much more. The freezes

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of 1962 and 1983 were of this type. Wind speed in these freezes was high and the air extremely dry. Damage was worse on the tops and north sides of hills where trees were exposed to the full force of the cold, dry winds.

A radiation frost, often called a freeze when it is particularly damaging, results from a series of heat transfers following cooling of the earth by movement of a mass of cold air into the state. This air is not itself sufficiently cold to damage trees. During the day, even while the earth is being cooled by the cold air moving into the state, the soil absorbs heat via the sun's rays and radiates part of it back to the sky; however, much more is absorbed than radiated so the soil becomes a reservoir of heat. Air in contact with the warmer earth absorbs heat by conduction, conduction being heat transfer by molecular excitation of movement; i.e. the "warmer" more excited molecules of the earth are conducted to the less excited molecules of the cooler air. The warmed air near the soil rises and this movement of a hot gas (the air) is heat transfer by convection.

At night there is loss of heat from earth to sky by radiation. Little heat is returned unless a cover exists, such as clouds, which absorb and radiates heat back. Air in contact with earth loses heat to it by conduction as the earth cools by radiation. If the wind ceases, a cold layer of air develops next to the earth. Even a light wind will mix the warm air aloft with the colder layer and prevent or delay development of damaging low temperatures. If the land is sloping, the heavier cold air will drain into lower adjacent areas which become lakes or pockets of cold air and the slopes are left relatively warm.

If loss of heat to the sky from the soil by radiation and loss of heat from the air to the soil by conduction continues without replacement of heat, and without mixing of air by wind or removal of cold air by drainage, a deep layer of air that is below the freezing point of water develops. This is termed a radiation freeze.

The dew point is the temperature of which moisture in the air condenses on plant parts and other objects. When the temperature falls to or below dew points that are below freezing, ice crystals form on plant surfaces. This is called a white frost. No ice crystals are formed during periods of freezing temperature if the dew point is not reached. This is often termed a black frost. The higher the dew point the more moisture there is in the air and the less chance that temperature will fall low enough to do severe damage.

Tree microclimate. Ambient or air temperature in a grove is usually used as a measure of its coldness. During an advective freeze air and tree temperatures are essentially the same.

During a radiant frost, however, exposed leaves lose heat by radiation and the warmer air surrounding them is cooled through conduction, causing a cold layer of air to develop on the exposed side of the leaf; however, this heavier cold air drains off (10) (Fig. 1). Thus, while leaves may become much warmer than air during the day (12) they usually are no more than 3.3°F colder than the air at night.

The small branches and leaves forming the tree canopy shield an area of soil that is continuously radiating heat. The canopy absorbs as much as 95% of this heat and in turn radiates heat back to the soil and other plant parts (12). Air temperatures under the canopy and temperatures of inner leaves and twigs are about the same. The trunk and large limbs, however, are warmer than air temperature under the canopy and the soil remains warmer still. The framework branches and inner leaves and air under the canopy are, of course, warmer than the outside air.

Soil between the trees also radiates heat, part striking the tree sides and part being lost to the sky. The leaves in turn radiate heat, part going to other trees. Thus, trees warm each other to some extent in which might be termed a community effect.

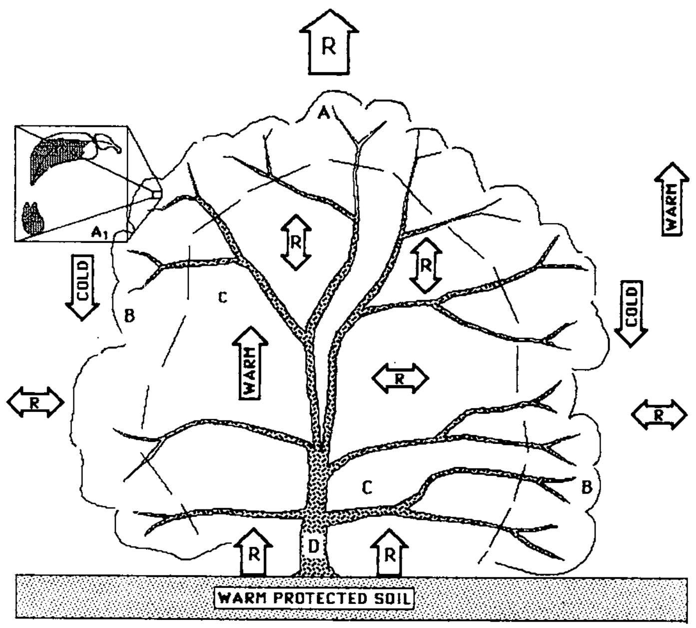

Fig. 1. Exposed leaves (A) on a mature citrus tree are colder than the exterior air temperature due to radiation A_1. Cold air plows off them to ground level causing a circulation of warmer air upward. Leaves at (A) are coldest; side leaves (B) receive heat from soil and adjacent trees and are warmer; air inside canopy (C) is warmer than exterior air and similar to inside canopy leaves, due to absorption of radiant heat from soil by the canopy and warming of air by conduction; trunk (D) is still warmer due to its mass. Cold air flowing off exposed outer leaves (cold arrow), pushes up warmer air (warm arrow) to cause a diffusive eddy.

The tree is over 50% water and so the mass of leaves, limbs, and trunks contain considerable heat. It is the large mass of the trunk that results in a lag in its drop in temperature at night. Small, young trees do not have effective canopies and their mass is much less than older ones. Thus, they are colder than larger trees and less energy loss is required to cool them (13).

Tree hardiness. Our understanding of why some trees withstand more cold than others and why the freezing point of a given tree or part of a tree varies within a given winter is incomplete, despite much research. It suffices for this discussion to recognize that cool periods result in maximum storage of carbohydrates and other metabolites, dormancy and maximum hardiness to cold (1, 3, 11).

Dormancy and cold hardiness can vary in various parts of the tree at any given time. Sun striking the trunks of young trees, for example, can cause the sunny side of the trunk to become active and susceptible to cold. A period of warm weather at any time during the winter can result in a loss of hardiness to cold, just as cool weather can induce hardiness.

Effects of Cultural Practices

The relation of cultural practices to freeze damage will refer to radiation frosts unless otherwise stated.

Soil management. The texture and color of soils affect their ability to absorb, store, and radiate heat; however, such characteristics cannot be manipulated in an established grove so they are not considered here. On the other hand, soil management offers a major means of passive protection.

Much more heat can be stored and conducted in moist than in dry soil (Fig. 2). Also, compact soil that forms a firm surface is a better conductor of heat than loose soil resulting from recent cultivation.

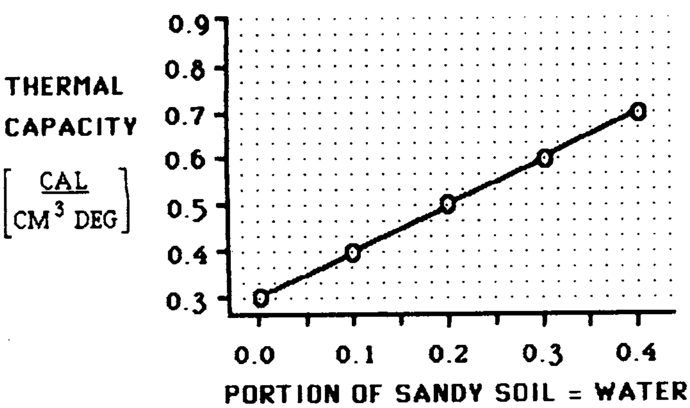

Fig. 2. The thermal capacity or heat storage capability of a sandy soil increases directly with the addition of water (indicated as a fraction of the soil mass). (Data from table 9, (6))

Weeds, sod and heavy leaf litter are effective heat insulators. They reduce both the heat absorbed during the day and that emitted at night. Weeds, particularly high weeds between trees, impede the flow of cold air down slopes and are therefore deleterious. Turrell (12) observed a freeze during which wind machines over bare ground effectively protected trees from frost but not when used over cover crops.

Thus, soil should be kept as free from weeds and litter as possible, moist and compact. Data as to the degree of effectiveness are sparse; however, Leyden and Rohrbaugh (9), in Texas, showed striking differences in damage to citrus trees due to temperature related to weed control. Temperatures 1 ft above the ground over chemical weed control with no tillage averaged 3.8°F and 1.8°F warmer than over sod and clean cultivation with tillage respectively. Temperature differences between sod and other weed control systems were smallest when grass was closely mowed and greater when height of weeds increased. Recently cultivated soil resulted in lower temperatures than that tilled early enough to let rain compact it.

Many Florida growers herbicide the tree row but not spaces between them, which is either mowed or cultivated. Also, many growers are shifting to low volume irrigation that wets only part of the soil surface. Herbiciding the entire grove floor and using a system that wets as much of the soil area as possible should enhance protection in a radiant frost.

Impeding air drainage. Good air drainage is recognized as a major factor determining the warmth of a site. The harmful effect of weeds between trees on slopes has been mentioned (see Soil Management).

Also, dams of brush and trees on a slope can appreciably change the temperature by blocking the flow of cold air to lower lying land. Removing the brush and trees or the refuse entirely, or cutting a broad swath through them will alleviate the problem.

Tree spacing and row orientation. It has been established (6) that a given site will be coldest as a meadow or pasture and warmest as a forest. This is due to the canopy effect of trees that intercept radiant heat from the soil and maintain a microclimate (see Tree Microclimate) warmer than that outside the tree.

A grove is comparable to a forest and the more canopy the warmer it is. Plantings with wide spaces between trees are colder than those spaced more closely because there is more canopy to intercept radiant heat from the soil and because trees warm each other through radiant heat transfer.

Trees planted on a rectangle should have the rows run up and down the slope and the trees should be kept pruned by hedging for maximum air drainage. This is, at times, in conflict with the benefits of running rows north and south to provide maximum light on tree sides. The cold hazard usually outweighs any benefits of added light.

If trees are planted so close in the row that a solid hedge is mandated, then occasional lines of trees running down the slope should be removed to provide air drainage. Some growers feel "lifting tree skirts" (lower branches) will permit the cold air to flow under the trees, and it will. This, however, reduces the beneficial effect of the canopy and is not recommended.

Pruning. A hedged and topped grove is probably slightly colder than a completely canopied one; however, growers have no choice but to hedge tree sides and top in order to facilitate harvesting and pest control and to maintain maximum yield.

Severely topping trees just prior to or during the freeze season is a mistake because it destroys the canopy and all its attendant advantages. Hedging during this period is also likely to reduce the effectiveness of the canopy. On the other hand, hedging and topping well before the freeze season can stimulate growth of a thicker canopy and be advantageous.

There are no research data to confirm the above views, only observations and logic based on principles of physics. Turrell (12), in California, observed, for example, large recently topped grapefruit trees were killed while nearby untopped trees were only slightly damaged.

Pest and disease control. The objectives of pest and disease control in protecting against freeze damage are to maintain a dense canopy and avoid debilitation of the tree. Virus damaged trees have been reported to be more susceptible to freeze damage. Garnsey, in Florida, (5), for example, reported oranges [*Citrus sinensis* (L.) Osb.] citrange [*Poncirus trifoliata* (L.) Raf. x *C. sinensis* on Carrizo] rootstock inoculated with severe strains of citrus exocortis viroid (CEV) were badly damaged by cold and some were killed. Trees inoculated with mild strains were moderately damaged and only minor twig damage occurred on trees free of CEV.

The primary pests and diseases that cause leaf drop and thereby tend to reduce the warmth of the microclimate under the canopy are greasy spot and mites. Severe leaf drop could also debilitate the tree.

The extent to which varying degrees of leaf loss reduces the canopy effect and debilitates the tree is unknown. Slight leaf loss probably has little or no effect; however, growers in chronically cold areas would be well advised to maintain as dense a canopy as is feasible.

Mineral nutrition. The bulk of evidence indicates freeze damage is not influenced by any mineral element as such. Maximum cold hardiness comes from maintaining a dense canopy of leaves that are not deficient in any mineral element. Deficiencies of magnesium (Mg) caused severe leaf loss several decades ago and gave rise to the suggestion Mg was directly related to cold hardiness; however, its influence on hardiness appears to be through leaf drop and tree debilitation, and not to a given level of Mg in the leaves. Late applications of nitrogen (N) that cause excessive growth and delay the development of winter dormancy reduce cold hardiness and should be avoided.

Irrigation. Cooper (2, 4) has reported reducing irrigation in the fall and early winter can induce dormancy and increase cold hardiness; however, water deficiency sufficiently severe to cause leaf drop and weaken the tree reduces cold hardiness. Thus, it would appear reasonable to withhold water sufficiently in fall and early winter to enhance development of dormancy, or at least, not delay its development; however, water stress should not be developed to the point a rain would force new growth and destroy dormancy.

Later in the winter, when dormancy and cold hardiness are controlled by low temperatures, water should be maintained to provide a maximum reservoir of heat (see soil management) and optimum conduction of heat into the soil during the day and out at night.

Managing freeze-damaged plantings. Factors that influence warmth and cold hardiness of uninjured trees in a radiant frost are the same for those which are damaged; however, certain factors become less or more important. Where the extent of damage is sufficiently limited that an effective canopy develops by the following winter, emphasis should be placed on repairing the canopy through optimum water, fertilizer and pest and disease control during the summer, not delaying dormancy through withholding late applications of fertilizer and by restricting water use as much as feasible in the fall. Weed-control, maintenance of adequate soil moisture and avoidance of dams of brush or pruning refuse at the foot of slopes should be emphasized during the winter.

Killing back to framework branches creates a different situation. Lack of canopy reduces tree mass and the canopy's role as a cover is destroyed. Some growers leave long, undamaged framework branches when pruning freezed damaged trees. It would appear to be better to cut back more severely to force out a protective canopy sooner; however, no pruning practices will develop an adequate canopy by the winter following the freeze. Emphasis on those factors described for moderately damaged trees holds as well for those severely damaged; however, one cannot expect to keep a severely damaged tree as warm or as dormant as one with a good canopy.

Large limbs with sparse foliage absorb much heat and the bark is likely to be more active and susceptible to freezes than shaded ones. Turrell (12) has reported temperatures as high as 50°F above ambient for exposed citrus limbs. Little attention has been given to this situation for citrus. Deciduous fruit growers, however, recognize the problem and refer to freeze damage of exposed bare trunks and branches as "winter sun scald," even though dead tissues or cankers that develop are due to freeze damage (8, 11). Spraying whitewash or white paint on citrus trees has been used to prevent sun damage to bare citrus branches in the spring and summer but not to induce or maintain dormancy in the fall and winter following a freeze. In Florida, where summer sun damage is unlikely, whitewashing delays new growth and canopy development as much as 2 weeks if applied in the spring. Applying white wash sprays to bare limbs in fall and winter, however, should enhance hardiness to cold by reducing bark temperature and thereby, growth; however this has not been investigated with citrus. White latex paint applied to the trunks of peach trees during winter both lowered trunk temperatures greatly and reduced severe freeze damage to them (7, 8, 11).

Modification of cultural practices to maximize tree warmth and cold hardiness will undoubtedly be contrary to other management objectives at times. For example, small or even modest-sized trees might be subject to damage from blowing sand if soil is completely bare from tree to tree, making it necessary to leave strips of mowed cover. Such factors must always be taken into account and an appropriate compromise reached.

Multiple factors affect the degree to which given cultural practices modify tree warmth and hardiness. Moreover, a given freeze may be so severe that protection is not immediately noticeable. Thus, it is often difficult for growers to assess the effectiveness of their cultural program; however, observations over many years and a body of research rather conclusively indicate the importance of cultural practices in reducing cold damage.

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