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Studies on Some Factors Relating to Hardiness in the Strawberry

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FOREWORD

As the strawberry is an herbaceous perennial, and in the north usually is protected by a mulch during the winter, it is apparent that its ability to survive winter conditions involves factors other than resistance to low temperatures. The winter mulch provides a markedly modified environment for the entire plant. Little has been known, however, about the range of temperatures beneath the mulch, or whether at any time the temperature may fall to the point at which injury to the plants might occur. It is evident also that the degree of activity in the dormant plants may have a bearing upon their ability to withstand exposure to cold. Also, any marked changes in plant activity under such conditions may have an effect upon survival more or less independent of temperature. With these possibilities in mind, the results of these related studies are presented herewith.

W. G. Brierley

I. The Development of Cold Resistance in Strawberry Varieties[1]

Ernest Angelo

In selecting varieties of strawberries to be grown in Minnesota, the factor of winter hardiness must be given attention. According to Chandler (6) the strawberry is perhaps the most widely distributed of fruits, being grown in lower and in higher latitudes than are most other deciduous fruits. He points out that the plants may be covered easily and thus the coldness of winter is of little importance except where it is extremely cold and where there is little snow covering the soil. Many varieties of strawberries are grown successfully in Minnesota.

Dorsey and Bushnell (18) as well as Macoun (38) have shown that test winters, which seriously injure all but the hardiest varieties of fruits, have usually occurred not oftener than every 7 to 10 years. These test winters may not cause serious damage to the strawberry, yet at the same time tree fruits or bush fruits extending above the snow may be killed. A milder winter without snow cover may result in severe injury to strawberry plantings, while the tree and bush fruits are not injured. Further evidence of the importance of snow cover is given by Brierley and Hildreth (5), who show a relative lack of hardiness in three species of *Vaccinium* (blueberries). Although *V. pennsylvanicum* and *V. canadense* occur over a more northerly range than *V. corymbosum,* they found by means of freezing tests that the killing points of all three species as grown in Minnesota lie fairly close together. *V. pennsylvanicum* and *V. canadense,* being low-growing forms, survive by being protected by snow rather than by having a greater inherent hardening capacity. A similar condition was found in the relation of winterkilling of strawberries to snow cover during the winter of 1933-34 at the University of Minnesota Fruit Breeding Farm.

This study deals with laboratory tests of the hardiness of various strawberry varieties, and some factors relating to the development of hardiness in the strawberry plant.

REVIEW OF LITERATURE

Except for reports of frost injury to strawberry blossoms in the field by Wilcox (58), Schuster (52), Emery (20), Chandler (6), Shoemaker (53), Augur (1), and McClatchie and Coit (40), no exact information concerning the relative hardiness of strawberry varieties is available, as far as could be found. The relation of plants to low temperature, however, has been a subject for major investigation for two

[1] A thesis submitted to the faculty of the Graduate School of the University of Minnesota in partial fulfillment of the requirements for the degree of Doctor of Philosophy, June 1934.

centuries. As early as 1737 Duhamel and Buffon (19) presented a paper in which they advanced the theory that the death of plants from cold was due to rupture of the plant cells by ice formation within them. In 1830, Göppert (22), and later, in 1860, Sachs (51) showed this theory to be wrong. The latter was able to show that ice normally forms in the intercellular spaces and not inside the cells. He concluded that rapid thawing was the cause of death.

Hildreth (30), working with Wealthy apple shoots, found that rapid freezing and rapid thawing gave approximately equal amounts of injury and that both were markedly more severe than when the temperature changes were gradual. Potter (45) found with apple seedling roots that a very rapid temperature fall caused more injury than was caused by a slow fall to the same temperature. He found no appreciable influence of the rate of thawing on the amount of injury. Chandler (7) pointed out the practical importance of rapid temperature fall in connection with winter sunscald. He also found in working with many different tissues that, with few exceptions, the rate of thawing caused no perceptible difference in the amount of injury from a given temperature.

Müller-Thurgau (43) and Molisch (42) found that the rate of thawing exerted no influence on the amount of injury at a given temperature. Müller-Thurgau (43) believed injury from cold to be the result of desiccation by crystallization of the water of the cell. Wiegand (57) states that death of the plant tissue seems to be due to the actual withdrawal of water to form ice, not to the cold. Gorke (24) believed that death of the protoplasm results from concentration of the sap and protein precipitation in the same way that protein is precipitated from solution by increasing the concentration of salts. He also noted increased acidity on ice formation. Harvey (26) found increased hydrogen-ion concentration to result from freezing and thought this an additional factor in protein precipitation. He also found that the more easily injured midrib and petiolar tissues of the cabbage were less highly buffered than the remainder of the leaf and hence subject to greater fluctuations of actual acidity.

Since the completion of this study, Steele, Waldo, and Brown (55) have reported upon cold resistance in strawberries. Except for slight differences which might be due to the use of different varieties and to a different environment, the reports are in close agreement.

THEORIES OF COLD RESISTANCE IN PLANTS

Many of the early investigators of the subject of the winter survival of plants presented theories as to how the plant was enabled to endure very low temperatures. The older natural philosophers assumed that plants developed heat for protection just as animals do, and this idea remained prevalent until the experiments of Göppert (22) and others. Today nearly all workers in hardiness are agreed that killing is due to a withdrawal of water from the cell in the formation of ice. However, there is a disagreement as to how the cell is enabled to resist low temperatures. One group is of the opinion that the resistance is due to the ability of the cell to limit the amount of water that may be frozen out, while the other is of the opinion that the resistance is due to the immunity of the protoplasm to the effects of water loss.

Lidforss (36) concluded that an increase in sugar content in plants in autumn served as an adaptation to cold. Many workers have noted the presence of increased amounts of sugar in plants on exposure to low temperatures. Hooker (31) working with woody plants, and Rosa (49) with vegetables, thought that the pentosans in the protoplasm increase its resistance to freezing by increasing its ability to hold water by adsorption on colloids. Newton (44) found hardened wheat rather rich in colloidal substances and showed much greater resistance to low temperature as well as the ability to hold water more strongly against evaporation and against pressure than did unhardened tissue. Chandler (8) explains the protective effect of colloidal substances as being due to their increasing the stability of the protoplasm against irreversible changes, such as coagulation or disorganization, whether caused by freezing or in other ways. Harvey (26) found that a smaller percentage of the protein was precipitated from the sap of hardened than from that of tender cabbage plants by freezing at —4° C. for two hours. The hardened plants had more than twice as much amino nitrogen as the unhardened; this was taken as an indication of protein cleavage during hardening.

MATERIALS AND METHODS

All the freezing tests reported in this study were made in the temperature control rooms of the Section of Plant Physiology, University Farm. The temperatures of these rooms are maintained by automatically controlled mechanical refrigeration, with a variation of ±1° C. Temperature records were kept at all times by means of a Leeds and Northrup recording potentiometer. Illumination of a suitable intensity was supplied to the plants in the hardening rooms by electric lamps. An electric fan running at all times kept the air in circulation.

The strawberry plants used in these studies were, with the exception of one lot, runner plants dug in November and potted, one plant to a pot. Four- and six-inch pots were used. One lot of plants was received in February from the eastern shore of Maryland and potted as soon as received. The soil used in all the pots, except one lot, was from the strawberry field at the University of Minnesota Fruit Breeding Farm. One lot was potted in white sand and was used in the fertilizer test. The potted plants were kept in a greenhouse at about 20° C. With one exception, the plants received no artificial illumination while in the greenhouse. The plants received the regular greenhouse watering until selected for a particular test. When moved to the cold rooms the pots were placed on the floor in an area with uniform illumination. After receiving the hardening and freezing treatment, unless otherwise stated,

Table 1. Behavior of Varieties Held at 20° C. for Seven Days, Then Exposed to —10° C. for 24 Hours

Variety	State of recovery at end of 25 days
Dunlap	3 plants alive—making fair growth
Gibson	2 plants dead—1 making weak growth
Premier	2 plants dead—1 making weak growth
Alaska Seedling	All dead
Easy Picker	All dead
Mastodon	All dead
Progressive	All dead
Chesapeake	All dead

the plants were brought back to 0° C. for 24 hours before being returned to the greenhouse. The extent of injury was determined by noting the recovery of the plant some time after it had been brought back into the greenhouse. In some cases the crowns of the plants were sectioned to determine the amount and location of browned tissue.

PRELIMINARY TESTS

No accurate report on the killing temperature of strawberry plants was found in the literature. It was necessary, therefore, to make preliminary trials in order to obtain these data.

Eight Premier plants were dug from the field frozen in blocks of earth. Four of these plants were exposed at —7° C. for 24 hours and four were exposed for the same time at —13° C. The eight plants were then gradually brought to a higher temperature by keeping them at 0° C. for 24 hours and then planting the blocks in the greenhouse bench. The plants exposed at —7°C. gave no indication of being injured, while those exposed at —13° C. were entirely killed. This test indicated that the killing temperature is somewhere between —7° C. and —13° C. for plants hardened under normal field conditions. However, later tests show the killing temperature to vary according to the previous treatment received by the plant.

RATE AT WHICH VARIETIES ACQUIRE HARDINESS

Harvey (27) (28) has shown in his studies with cabbage and elm seedlings that these plants acquire their greatest hardiness when held at temperatures between 0° C. and 5° C., respectively, before being frozen. He speaks of the temperature 5° C. as the threshold value for hardening and points out that there is a close relation between the temperature at which growth ceases and the threshold value of temperature for evoking hardiness. He also suggests that since the temperature at which growth ceases is different for various plants, there seem likewise to be differences in the threshold value for hardening plants.

Table 2. Plants Held at 0° C. for Seven Days, Then Exposed to —10° C. for 24 Hours

Variety	State of recovery at end of 25 days	
Mastodon	Good new growth	Equal recovery
Dunlap	Good new growth	
Gibson	Good new growth	
Alaska Seedling	Good new growth	
Progressive	Fair new growth	
Easy Picker	Fair new growth	
Chesapeake	All dead	
Premier	All dead	

Eight varieties of strawberries listed below were used in a test to determine the varietal difference in hardiness as well as the rate at which this hardiness was acquired: Alaska Seedling, Chesapeake, Dunlap, Easy Picker, Gibson, Mastodon, Premier, and Progressive.

Six plants of each variety were placed in a room held at a temperature of 20° C. A like number of each variety was placed at the same time in a room held at 0° C. The plants were in an active growing condition. At the end of seven days, three plants of each variety from each room were placed in a room at —10° C. where they were held for 24 hours. The plants were then moved into the 0° C. room for 24 hours and then into the greenhouse. After the plants had been in the greenhouse 25 days, the data were taken as shown in tables 1 and 2.

It may be concluded from these data that an exposure at 0° C. for seven days has hardened all the varieties. No doubt —10° C. was a little below the critical temperature for Chesapeake and Premier. At 20° C. for seven days the 8 varieties in this test were not sufficiently hardened to withstand —10° C. The injury to these plants was measured by the browning of the leaflets and the failure to produce new leaves. Harvey (28) found elm seedlings exposed continuously at 20° C. for five days killed at —5° C., while elm seedlings exposed for the same length of time at 0° C. were not killed and on only 10 per cent of the seedlings were the upper branches killed.

These data indicate that under the conditions of this experiment the varieties Mastodon, Dunlap, Gibson, and Alaska Seedling have a greater hardening capacity than the other four varieties studied. It may be pointed out also that the first three above-named varieties are commonly grown in the colder sections of the United States.

This test of the rate of acquiring hardiness was continued. At the end of 15 days one plant of each of six of the varieties from each of the two rooms (20° C. and 0° C.) was exposed for 24 hours at —10° C. and was then moved to the greenhouse by the usual procedure. By oversight, two of the varieties were left out of this longer period of hardening exposure. The data secured 25 days after the plants were moved into the greenhouse show those held at 0° C. for 15 days were in about the same stage of recovery as like varieties held at 0° C. for only seven days.

Table 3. Plants Held at 0° C. for 15 Days, Then Exposed to —10° C. for 24 Hours

Variety	State of recovery at end of 25 days
Progressive	Good growth
Easy Picker	Good growth
Gibson	Good growth
Alaska Seedling	Fair growth
Premier	Weak growth
Chesapeake	Dead

One variety, Premier, appeared to have acquired slightly greater hardiness during the longer exposure at 0° C. As only single plants of each variety were used in this test, probably not much confidence can be placed in the data.

All the plants held at 20° C. for the 15-day period were killed. The plants were less hardy after the long exposure at 20° C.

Table 4. Plants Held at 0° C. for 16 Days, Then Exposed to —15° C. for 24 Hours

Variety	State of recovery at end of 25 days
Alaska Seedling	Dead
Dunlap	1 plant dead, 1 making good growth
Easy Picker	Dead
Gibson	Dead
Mastodon	Dead
Premier	Dead

As it was thought possible for some of the plants to recover from a temperature lower than —10° C. at the end of 16 days, two plants of each variety from each room were exposed for 24 hours at —15° C. At the end of the 25 days, all the plants except one Dunlap from the 0° C. group were dead. Apparently —15° C. was below the killing temperature for these plants.

EFFECT OF LONGER EXPOSURE AT HARDENING TEMPERATURE

To test further the effect of a longer exposure of the plant at the hardening temperature, eight plants of each of three varieties, Mastodon, Progressive, and Dunlap, were placed at 0° C., and at the same time the same number were placed at 20° C. Five days later four plants of each variety were taken from each room and placed at —10° C. for 24 hours. The plants were then taken through the usual procedure into the greenhouse. After another five days the remaining plants in each room were given the same freezing temperature.

After the plants had been in the greenhouse for 21 days, it was found that all those held at 20° C. for both the 5- and 10-day period were dead.

Of those exposed for five days at 0° C., Mastodon and Dunlap were slightly injured, Mastodon showing slightly more injury than Dunlap. The injury was indicated by browning of the leaflets. The Progressive plants were killed. In the group held at 0° C. for 10 days, Mastodon and Dunlap were about equally injured and the injury was greater than in the case of those exposed for the shorter hardening period.

It appears that 10 days of continuous exposure at 10° C. had decreased the hardiness as compared to that acquired in the shorter five-day period. This may be due to an exhaustion of the food reserves as the photosynthetic rate is probably rather slow at the hardening temperature, even though the plants were supplied with light of sufficient intensity for this process.

RATE OF ACQUIRING AND LOSING HARDINESS

Tests were made with five varieties of strawberries to determine the effect of alternating long and short daily exposures at 0° C. and 20° C. upon the hardening of the plants. Four plants of each of the varieties, Chesapeake, Dunlap, Mastodon, Progressive, and Premier, were used in each treatment. The plants were exposed to alternating temperatures by changing them at intervals of two, four and 12 hours daily for 5 days between the 0° C. and the 20° C. rooms. They were then all frozen at −10° C. for 24 hours. The treatments were run in duplicate, one lot was started at the higher temperature and the other at the lower in order that one lot might enter the freezing room from the 0° C. exposure and the other from the 20° C. treatment.

Twenty-one days after the plants were placed in the greenhouse, all were dead. The short, alternating exposures at 0° C., as well as the

Table 5. Effect of Longer Exposure at 0° C. and Effect of Hardening at 0° C. Compared to 20° C.

Variety	Treatment		Condition after freezing
Mastodon	20° C. for 5 days	−10° C. for 24 hours	Dead
Progressive	" " " " "	" " " " "	"
Dunlap	" " " " "	" " " " "	"
Mastodon	20° C. for 10 days	−10° C. for 24 hours	Dead
Progressive	" " " " "	" " " " "	"
Dunlap	" " " " "	" " " " "	"
Mastodon	0° C. for 5 days	−10° C. for 24 hours	Slight injury
Progressive	" " " " "	" " " " "	Dead
Dunlap	" " " " "	" " " " "	Slight injury—more than Mastodon
Mastodon	0° C. for 10 days	−10° C. for 24 hours	Slightly greater than 5-day exposure
Progressive	" " " " "	" " " " "	Dead
Dunlap	" " " " "	" " " " "	Slightly greater than 5-day exposure

longer period of 12 hours, apparently were not sufficiently long to develop the hardiness necessary to withstand —10° C.

Since Harvey (27) (28), working with cabbage and elm seedlings, found that exposing the plants daily at temperatures between the threshold and higher temperatures for periods of five days produced as great hardiness as exposures at 0° C. continuously, it was thought advisable to run another test of the strawberry using a higher temperature for the freezing. The plants were runner plants shipped from Maryland and were potted as soon as received in February. In this test 10 varieties were used, and, in addition to the alternating temperature series, one set was run constantly at 20° C. and another at 0° C. All were run for six days and then frozen at —4° C. The per cent of injury after freezing was recorded for each variety for each treatment. The per cent of injury was estimated on the basis of the number of leaflets injured or killed. Four plants of each variety were used in each treatment.

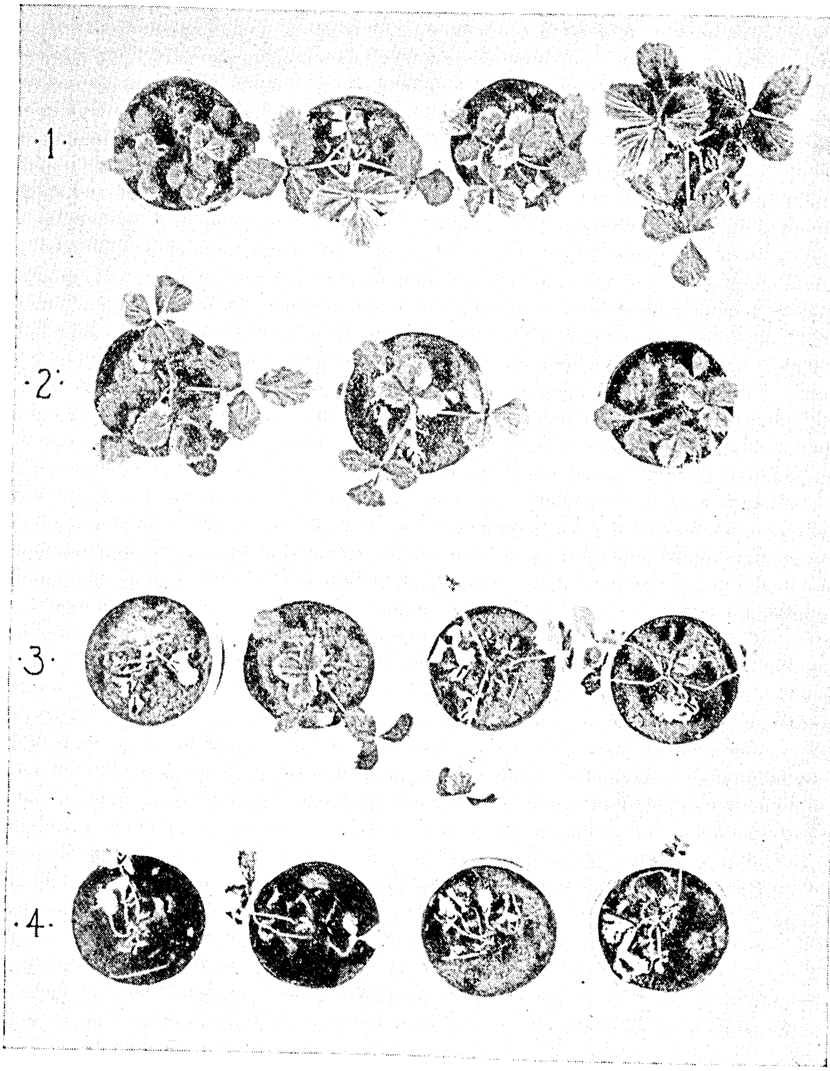
Table 6 gives a list of the varieties together with the per cent of injury under each treatment. The percentages of injury in each treatment were totaled for all the varieties and then divided by the number of varieties to obtain an average per cent of injury for each treatment.

It may be observed from these data that constant exposure at 0° C. gave an average of 24.5 per cent injury for all varieties studied, while the daily alternation of 12 hours at 20° C. and 12 hours at 0° C. gave an average of only 9.5 per cent injury. The duplicate of this latter treatment, except that the plants were exposed at the last period for 12 hours at the higher temperature (20° C.), gave an average of 48.2 per cent injury.

Evidently an exposure of 12 hours per day is sufficient time for the strawberry plant to acquire considerable hardiness (Plate I). It is also

Table 6. Per Cent Injury to Ten Strawberry Varieties Exposed Daily for Six Days to Varying Alternating Temperature Treatments (Plants Frozen at —4° C.)

	0° C. 24 hours	20° C. 24 hours	20° C. 12 hours 0° C. 12 hours	0° C. 12 hours 20° C. 12 hours	20° C. 20 hours 0° C. 4 hours	0° C. 4 hours 20° C. 20 hours	20° C. 22 hours 0° C. 2 hours	0° C. 2 hours 20° C. 22 hours	Average
Aroma	5	98	20	90	100	100	100	100	76.6
Chesapeake	90	50	5	55	50	65	85	60	57.5
Dunlap	40	100	5	90	75	100	100	100	76.0
Gibson	5	25	5	5	20	55	85	10	26.0
Klondike	10	100	5	25	100	100	100	100	67.5
Mastodon	0	95	0	2	35	60	98	25	39.0
Missionary	5	100	5	35	80	95	100	100	70.5
Premier	75	80	5	75	85	80	100	100	75.0
Progressive	5	100	0	35	90	95	100	100	65.6
Wm. Belt	10	35	45	25	30	85	85	20	42.0
Average injury	24.5	78.3	9.5	48.2	66.5	83.5	95.3	71.5	



CONDITION OF STRAWBERRY PLANTS OF THE VARIETY PROGRESSIVE AFTER HARDENING TREATMENTS

(1) 0° C. for 6 days. (2) 0° C. for 12 hours. (3) 0° C. for 4 hours. (4) 0° C. for 2 hours. All lots were exposed to —4° C. for 24 hours immediately after hardening treatment.

evident that this hardiness may be lost rather rapidly. These results are quite similar to those obtained by Harvey (28) in working with elm seedlings.

VARIETAL DIFFERENCES IN HARDINESS

By taking the average per cent of injury of all treatments for each variety in the test above, an indication of the comparative rank in hardiness of these varieties may be obtained. As a further check on the hardening capacity of these 10 varieties, four plants of each were held at 0° C. for five days and then exposed at —5° C. for 24 hours. The data calculated from Table 6, together with the injury notes taken from the exposure at —5° C. and field notes taken in the springs of 1931 and 1932, are given in Table 7.

From a study of Table 7, it may be concluded that the laboratory and field results do not conform. Hildreth (30) calls attention to the fact that the proof of the efficacy of any artificial test for hardiness must be the conformity of its results to field experience. He was enabled to compare his artificial tests of the hardiness of apple varieties with the hardiness as determined by the experiences of practical fruit growers and professional horticulturists. Unfortunately, no such determinations are available for the strawberry. The field notes taken in 1931 and 1932 may be no indication of the hardiness of the varieties as under field conditions because there are so many uncontrolled variables. For instance, some varieties may have had a heavier mulch of straw or snow than others. Further controlled field studies must be made before these two methods may be accurately compared.

Table 7. Varietal Hardiness as Indicated by Laboratory and Field Notes

Variety	Per cent injury		
	Average for all treatments in Table 6	24 hours at —5° C. after hardening at 0° C. for 5 days	In field spring of 1931
Gibson	26.0	20.0	90.0
Mastodon	39.0	30.0	90.0
Wm. Belt	42.0	85.0	Not grown
Chesapeake	57.5	85.0	100.0
Progressive	65.6	75.0	15.0
Klondike	67.5	95.0	Not grown
Missionary	70.5	95.0	Not grown
Premier	75.0	80.0	25.0
Dunlap	76.0	95.0	90.0
Aroma	76.6	100.0	Not grown

EFFECT OF CHEMICAL TREATMENT

Plants of the variety Premier were treated with various combinations of potassium chloride, calcium phosphate, and sodium nitrate. The plants were growing in pots filled with a black soil of good fertility. Three weeks after treatment with the chemicals the plants, together with checks of untreated plants, were hardened for five days at 0° C. and frozen 24 hours at —10° C. The amount of injury was practically the same for all plants including the checks. No doubt there was a sufficient supply of these chemical elements present in the soil, and the plant made no use of those added in the treatment.

Another set of plants was dug from the field in November and potted in pure white sand. By the middle of December these plants were making new growth as evidenced by new leaflets. The plants were then treated with calcium acid phosphate, calcium nitrate, and potassium chloride. Four plants were used in each treatment as well as in the check. The chemicals were made up in stock solutions of 0.5 M. concentration. Treatments were made by adding the designated amount (1, 3, or 6 cubic centimeters) of the stock solutions to 50 cubic centimeters of tap water which was then applied every third day to the plants in place of the usual greenhouse watering.

The different treatments were as follows: (1) Tap water alone, (2) one, three, and six cubic centimeters of each salt solution alone, (3) all possible combinations of two different salt solutions in the three concentrations, and (4) all three salt solutions in the three concentrations. The plants were treated in this manner for three weeks, when those that had received six cubic centimeters of the chemicals showed signs of considerable injury by turning reddish brown at the margin of the leaflets. These were discarded from the test. Evidently this was too concentrated an application of the chemicals. In all the treatments where nitrogen was lacking, there was a distinct reddening of the foliage. Davis and Hill (14), studying the nutrition of the strawberry in sand, describe the same reddening effect.

At the end of the three-week treatment, the plants were hardened and frozen at —9° C. This temperature had always caused considerable injury to Premier in previous treatments, but there was practically no evidence of freezing injury in any of the treatments of this group, including the check. In searching for an explanation of this additional hardiness, it was found that a large electric light had been burning in the greenhouse a part of every night while the plants were being treated. It may be that with the additional light, the plants were able to carry on a greater amount of photosynthesis with practically no additional respiration, and therefore there was an accumulation of reserves. After remaining in the greenhouse for one week the plants were again hardened at 0° C. and frozen at —12° C. Unfortunately, this temperature was a little too low as all the plants were severely injured. At the end of three weeks all plants were dead except the four which had received the one cubic centimeter treatment of calcium acid phosphate. These four plants continued alive until the plants were discarded several weeks later.

Chandler (9), using heavy applications of potash fertilizers on cabbage plants, tobacco plants, and peach trees, was unable to influence hardiness. Crane (13), in a study of the effects of fertilizing peach trees, found a larger percentage of the fruit buds were killed in winter on the trees receiving nitrogen and there was no evidence of any effect from potassium or phosphorus.

EFFECT OF DRYING ON HARDINESS

Chandler (9) says: "What evidence we have indicates that woody tissues will withstand lower temperatures if they are partly dried before being frozen. With seeds it is rather well known that dryness greatly increases resistance to low temperature." Chandler (11) also found that peach buds on trees that were ringed through the sapwood in early winter were more resistant to freezing than buds on normal trees of the same variety. He thought the slow wilting might bring about changes in the protoplasm making it more resistant. Potter (45) found that at the same freezing temperature roots were injured more in moist than in dry soil.

Eight plants of the variety Premier were placed in an office window where they were kept for three weeks in February. During this time four of the plants were kept well watered while the other four were watered only enough to prevent wilting. At the end of the three weeks, the plants were placed at 0° C. for five days and were then frozen at −10° C. The four plants that had been well watered died, while the four that had received very little water were only slightly injured.

As stated above, Potter (45) found roots were injured more in moist soil than in dry soil when the temperature was the same. In this test the temperature was the same in both the wet and drier soil, as indicated by thermometers placed in the pots. Craig (12) found during the winter of 1899 that tree roots were injured most in sandy soil, least in loam, and to an intermediate degree in clay. No doubt the soil temperatures varied according to the amount of moisture present, being lowest in the sandy soil with the least water supply.

LIGHT AND HARDINESS

In studying the hardiness of Minhardi wheat, Dexter (16) found little or no hardening took place in the dark. In the case of alfalfa he found plants in darkness hardened less completely than those in the light.

To test the effect of light on the hardening of the strawberry plant, four Premier plants were placed under a cardboard box in the 0° C. room while at the same time four others were placed in the same room in the light. The plants were kept in this way for 15 days and then were frozen at —9° C. for 24 hours. After the plants had been removed to the greenhouse, the plants kept in darkness showed plainly that they had been entirely killed while those that had been in the light were yet alive. It was evident that the plants exposed to the light had hardened perceptibly more than those kept in the dark.

AGE OF PLANT IN RELATION TO HARDINESS

Gardner, Bradford, and Hooker (21) say: "The most generally recognized and most potent single factor influencing killing by cold, particularly in tissues withstanding a fair amount of freezing, is the degree of maturity attained at the time of exposure." Strawberry plantings are made early in the spring in most sections of the country, but occasionally plantings are made in August. Late-formed runner plants would not be expected to reach so advanced a stage of maturity as plants formed early in the season.

Eight plants each of the varieties Progressive and Dunlap, which were potted in November, and eight plants of each of the same varieties potted in February were hardened at 0° C. for five days and then exposed for 24 hours at —5° C. The plants were then thawed gradually and placed in the greenhouse. The plants potted in November were dug from a planting at the University Fruit Breeding Farm, while the plants potted in February were from Maryland. The November-potted plants were called old plants, and the February-potted plants were called new plants.

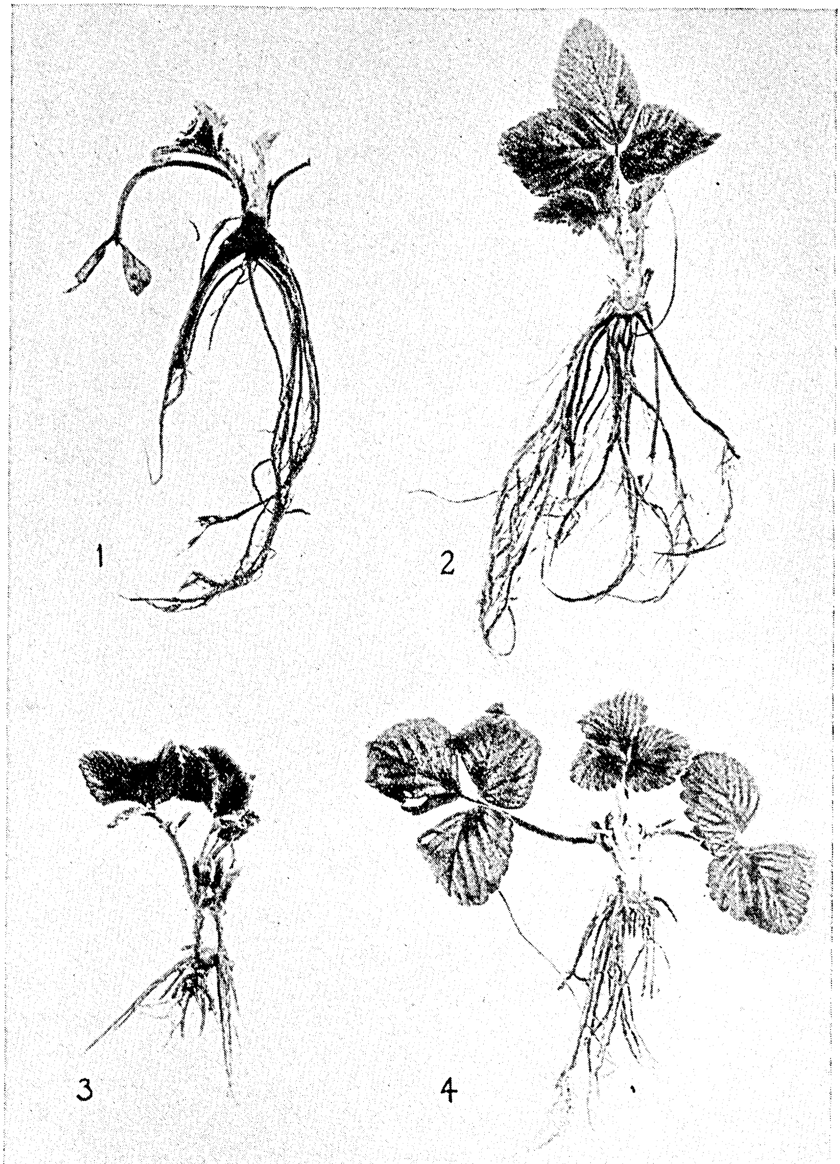
Table 8. Effect of Potting at Different Times of Year Upon Freezing Injury at —5° C.

Variety	Potted	Per cent injury
Progressive	November	20
Progressive	February	85
Dunlap	November	20
Dunlap	February	98

Table 8 shows the relative amount of injury to the two types of plants. The old plants were injured only 20 per cent, while the new plants showed 85 per cent injury in the case of Progressive and 98 per cent for Senator Dunlap.

NUTRITION AND HARDINESS

Many workers in the field of hardiness have found increases in sugar content upon exposure to low temperatures, and it has been thought that this offered protection against freezing injury. Dexter (17) found that by placing freshly severed stems of cabbage plants in 2½ per cent and 10 per cent sucrose solutions for 40 hours more water was left unfrozen in the plants kept in the higher concentration and the amount of total sugars in the plants in the 10 per cent sucrose solution was more than double that in the plants kept in the lower concentration.



LONGITUDINAL SECTIONS THROUGH CROWNS OF STRAWBERRY PLANTS INJURED BY FREEZING

All plants held for seven days at higher temperatures followed by 24 hours at −10° C. (1) Easy Picker, from 20° to −10° C. (2) Easy Picker, from 0° to −10° C. (3) Alaska, from 20° to −10° C. (4) Alaska, from 0° to −10° C. Note the area of browning; also the greater amount of browning in plants 1 and 3.

Several Premier strawberry plants were set in the greenhouse bench in a fertile soil where they might have the best of growing conditions. As soon as runner plants formed they were placed in pots filled with soil. The plants remained attached to the mother plant until well rooted in the pot. The runner was then cut from the mother plant and the free end of the runner was placed in a bottle of sucrose solution. Three concentrations of sucrose were used in water, 2 per cent, 5 per cent, and 10 per cent. Two runner plants were used in each of the concentrations. The runners remained in the sugar solutions for seven days. The plants were then hardened for five days and frozen at —10° C. The injury was quite severe and was equal in all treatments. It is possible that the plants did not take up any of the sugar solution through the runners.

INJURY IN RELATION TO SIZE OF POT

Since some of the plants used in these studies were in four-inch pots and others in six-inch pots, it was thought advisable to determine whether or not size of pot influenced the results.

Four plants of each variety, Progressive and Dunlap, were potted in four-inch pots and a like number were potted in six-inch pots. When the plants had become well established they were hardened and frozen at —5° C.

Table 9. Size of Pot in Relation to Injury When Frozen at —5° C.

Variety	Size of pot	Per cent injury
Dunlap	4-inch	100
Dunlap	6-inch	98
Progressive	4-inch	85
Progressive	6-inch	85

From Table 9 it may be seen that size of pot had no effect on the degree of injury. These results are as might be expected since the temperature of the soil within pots of either size soon became the same as that of the room in which the plants were exposed.

LOCATION OF INJURY

Chandler (11), in discussing injury of trees from freezing, points out the fact that in the woody tissues above ground the pith is the most likely to be killed. He further points out that sapwood is less resistant than bark and that when wood is well matured the cambium is one of the most resistant of tissues.

Injured strawberry plants were sectioned and studied for location of injured tissue. The medulla is found to be dark brown in plants badly injured (Plate II). Those plants which failed to recover after freezing were found to have most of the large roots badly browned, and the tip of the medulla just below the apex of the crown was dark brown.

Plants that did not show so much injury were often found to be browned in the medulla at the base of the crown, but there was no browning at the apex.

DISCUSSION

Actively growing strawberry plants can be hardened by short exposures of five days at 0° C. to such an extent that they will recover from freezing at temperatures of —5° to —10° C. Longer periods of exposure at 0° C. do not increase the hardiness but decrease it slightly. Strawberry plants growing at 20° C. are not resistant to —5° C. and may be said to show no considerable hardiness. Hardiness acquired by strawberry plants exposed to 0° C. for short periods of time is likewise lost during short exposures at 20° C. Strawberry plants growing in pots and hardened at 0° C. for 10 days have a killing temperature of about —10° C. There is a varietal difference in degree of hardiness in strawberry plants as determined by freezing tests. It is not determined whether laboratory freezing tests of the strawberry are indicative of their hardening capacity under field conditions.

Strawberry plants growing in a drier soil were injured less than those growing in wet soil when the pots were exposed to freezing temperatures. No doubt this would not be the result under field conditions where the soil temperature would vary according to the amount of moisture present in the soil. Strawberry plants are enabled to harden to a greater extent in the presence of light at 0° C. than without light. This may have a practical application as, while a mulch may be beneficial to strawberry plantings, too heavy an application may reduce the light to such an extent as to limit the hardening of the plants. Within certain limits, size of containers has no influence on the hardiness of strawberry plants frozen under controlled conditions. Strawberry plants frozen to such an extent as to be badly browned throughout the medulla or especially if browned in this tissue at the apex of the crown are not likely to recover.

SUMMARY

Potted strawberry plants were exposed to controlled low temperatures in tests of the rate of acquiring and losing hardiness.

1. Strawberry plants of several varieties were found to harden at 0° C. to resist freezing at —5° C.

2. The low-temperature killing point for strawberry plants growing in pots was found to be about —10° C. after hardening 10 days at 0° C.

3. Exposure at 0° C. for a period of more than seven days does not increase the hardiness.

4. Exposure at a constant temperature of 20° C. does not harden strawberry plants.

5. Daily alternations of temperatures of 12 hours at 0° C. and 12 hours at 20° C. for six days produced greater hardiness than continuous exposure at 0° C., provided the 12-hour exposure at 0° C. immediately preceded the hardiness test.

6. When exposed for six days to treatments alternating between 12 hours at 0° C. and 12 hours at 20° C., hardiness was gained at 0° C. and lost at 20° C. More hardiness appeared to be gained at 0° C., however, than was lost at 20° C. so that the alternating treatments resulted in a net gain in hardiness.

7. There is a varietal difference in hardiness of strawberry plants. The order of hardening capacity is Gibson, Mastodon, Wm. Belt, Chesapeake, Progressive, Klondike, Missionary, Premier, Dunlap, and Aroma.

8. The size of pot, whether four or six-inch pots were used, had no influence on the hardiness of plants growing in them.

9. Plants watered abundantly were not so hardy as plants watered sparingly.

10. Plants with runners held in solutions of sucrose and water for several days gave no indication of the treatment having affected the hardiness.

11. Runner plants potted in November hardened better than plants potted in February.

12. The degree of freezing injury in the strawberry plant can be estimated by the amount of browning in the medulla.

II. Winter Soil Temperatures as a Factor in the Environment of the Strawberry and Some Other Herbaceous Plants in Minnesota

V. E. Iverson

The general subject of winter injury of cultivated plants is of great importance in Minnesota and other northern states because of extreme winter conditions. Injury during the winter may be due to low temperatures, to desiccation, or perhaps to smothering. These factors may operate alone or in combination.

The object of this study was to determine the relative effects that various types of ground covers commonly used for plant protection in the north have upon soil temperatures and upon plant survival.

REVIEW OF LITERATURE

No attempt was made to review all of the extensive literature dealing with the subject of hardiness. Only papers directly relating to the present study are cited.

Many workers have studied the various factors affecting the temperature of the soil. Li (35) published a very exhaustive study of the literature as well as research data on this subject. He summarizes the factors affecting soil temperatures as follows: (a) Factors affecting soil temperature, considering the source of heat and the factors modifying its intensity and duration, including duration and intensity of sunshine, air temperature, wind velocity, moisture content of the soil, humus content of the soil, color of the soil, structure of the soil, shade of the living cover, and litter. (b) Factors determining the specific heat and the power of heat absorption by the soil, including soil type and soil texture, cloudiness, latitude, altitude, exposure, and slope.

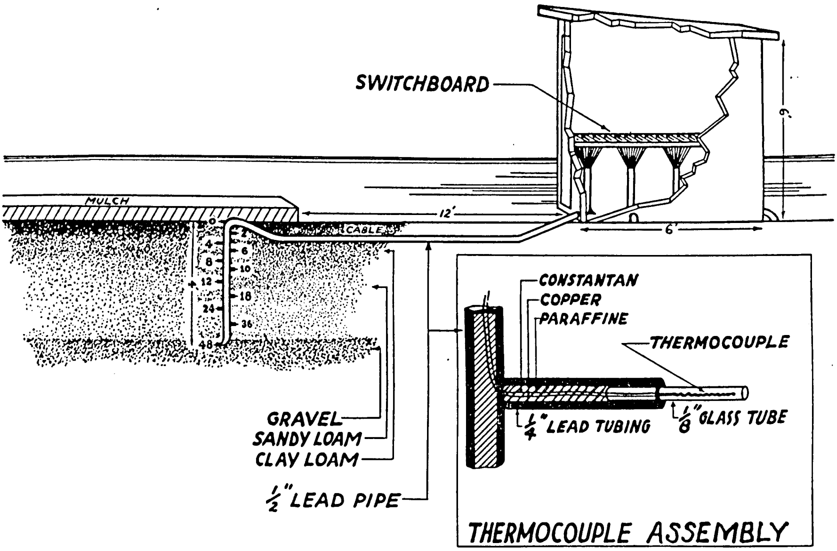


FIG. 1. DIAGRAM OF APPARATUS USED FOR MEASURING SOIL TEMPERATURES

Other summaries on this subject were published by Bouyoucos (2) (3) (4) and Russell (50). Smith (54) states that "the moisture content of the soil has a great influence in determining the temperature of the soil because of the higher specific heat of wet soil which is close to 1 where that of dry soil is approximately 0.2." Bouyoucos (3) found that the water-holding capacity of soils and the rate of flow of air through soils decreases with the rise in temperature, indicating that temperature has a great influence upon the aeration of soils. Mail (39) stresses the importance of rain in affecting the temperature of frozen soils. To DeSaussure (1700) as mentioned by Göppert (23): ". . . . we owe the first observations on the temperature of snow at various depths." Mail (39) found that a snow covering of a few inches makes a remarkable difference in the temperature of the soil.

The periods in the spring and fall when the gradients of the soil temperatures are reversed are known as the periods of soil temperature inversion. They are sometimes spoken of as the thermostatic points or periods of overturn. Harrington (25) found overturns of soil temperatures in Saskatchewan at the two-foot level about April 14 and October 10. The process of reversing the temperature gradients throughout the eight feet under observation required about six weeks (from April 14 to May 27). Kimball, Ruhnke, and Glover (33) found overturns in May and September in a light sandy soil in southern Ontario. Thomson (56) found that the overturns in soil temperatures in Winnipeg, Manitoba, during 1931, 1932, and 1933 began about March 27 and were completed to a depth of 66 inches by April 27, 9 feet by May 19, and 15 feet by July 3. Fourteen weeks were required for the complete overturn. The fall overturn started on August 28 and was complete to a depth of 66 inches by October 3, 9 feet by November 3, and 15 feet by December 24, requiring a total of nearly 17 weeks.

Mail (39) states that in the spring "a complete inversion only occurs when the mean air temperature is above the freezing point." During the winter of 1927-28, the inversion began in Minnesota on February 6, when the mean air temperature reached 0° C.

The effect of changes in air temperatures on the lag in soil temperature penetration varies with soil conditions. Kimball, Ruhnke, and Glover (33) found a temperature lag of six to seven hours for every four inches of light, sandy soil in Southern Ontario. McColloch and Hayes (41) report a temperature lag in Kansas of much longer duration than that reported in Ontario. This was probably due to differences in soil conditions, as the Ontario soil is much lighter than that in Kansas. Mail (39) determined the lag of soil temperature in ice-filled soils. "A rise in air temperature from —23° C. to —6° C., that is, 17° C. through 5 days, resulted in a corresponding rise in the 24-inch level of only .75° C. 5 days after the commencement of the upward movement."

Although these earlier contributions have presented valuable data relative to soil temperatures, none of them has shown what temperatures are likely to be found under the various mulches and ground covers commonly utilized in horticultural practice.

MATERIALS AND METHODS

The thermocouple method of measuring soil temperatures is well described by Robinson (48). The method of measuring soil temperatures in this study was essentially the same as that given by Robinson and that used by Mail (39) at Minnesota with the exception of some minor differences in the construction of the apparatus. The thermocouple method is probably the simplest and most accurate way of measuring soil temperatures. It was the purpose of this experiment to record accurately the temperature of the air and the temperatures of the soil under various types of ground coverings at the following depths: ground level, 2, 4, 6, 8, 10, 12, 18, 24, 36, and 48 inches. A diagram showing the arrangement of the apparatus is shown in Figure 1.

The mulches tested for the two winters 1934-35 and 1935-36, in addition to check plots, were as follows:

1934-35	1935-36	
3-inch oat straw	3-inch oat straw	3-inch mixed leaves
6-inch oat straw	6-inch oat straw	6-inch mixed leaves
6-inch snow	3-inch marsh hay	3-inch snow
3-inch International peat	3-inch International peat	6-inch snow
	3-inch nutria peat	3-inch ice
	6-inch nutria peat	

The peat mulches used in this experiment consisted of the following types: (a) A slightly decomposed brown acid peat obtained from the International Peat Products Company of Eveleth, Minnesota, designated as International peat, and (b) a well decomposed, black, basic peat obtained from the Northwest Terminal of Minneapolis, Minnesota, designated as nutria peat.

The ice mulch tested in 1935-36 was obtained by ridging a plot with soil and applying water with a fine spray several times during sub-zero weather. The proper thickness of ice was also maintained in this way.

Each plot had an area of at least 100 square feet. They were located in a field ideally free from local differences in wind effects. In this area a small fieldhouse was erected for the protection of instruments and apparatus used for recording the soil temperatures.

Snow was kept off the mulched plots to the mulch level and removed entirely on the bare ground plot. In no case was this snow removal delayed as long as 24 hours. Temperature readings were begun a week after the mulches were applied. They were not taken on the days of snow removal because of a possible upset of soil temperatures owing to the temporary blanket of snow. By means of cables leading from the several plots, the individual temperature readings were made inside the fieldhouse with a Leeds-Northrup potentiometer with zero adjustment which was connected to the various thermocouples by means of a switchboard. Records were taken daily at approximately 10 a.m. except Sundays for the following periods: 1934-35, January 3 to April 1; 1935-36, November 15 to February 1. Temperature readings were discontinued early in the spring of 1936 because difficulties were encountered with the temperature-reading apparatus.

All mulches except snow and ice were maintained for the entire periods mentioned above. Snow and ice were maintained only when materials were available and the temperatures below freezing. At other times temperatures were not recorded from these plots.

ANALYSIS OF DATA

Weather data.—Temperature and precipitation data for the periods of this experiment are given in Table 10.

Variability of soil temperatures.—The relative values of the ground coverings as a protection against fluctuating soil temperatures are shown in tables 11 and 12. The standard deviations from the mean

Table 10. Temperature and Precipitation Data Taken from the Monthly Weather Review of the United States Department of Agriculture Weather Bureau, for Minneapolis, for the Periods of This Experiment

Season and month	Mean maximum plus mean minimum ÷ 2 in degrees F.	Departure from normal in degrees F.	Minimum in degrees F.	Total precipitation in inches	Deviation from normal in inches
1934-35					
December	15.0	−4.6	−19	1.23	+.2
January	11.0	−1.7	−31	1.44	+.6
February	25.5	+9.6	− 3	.21	−.7
1935-36					
December	17.6	−2.0	−12	1.04	+.1
January	3.8	−8.9	−34	.77	−.1
February	0.0	−15.9	−26	1.55	+.6

temperatures are given for each set of conditions. The means calculated on the basis of the entire data are not given because they have no significance here.

The variability of temperatures under a given mulch uniformly decreases as the depth increases to a certain point (underlined in the tables). Beyond this point the uniformity ceases and the temperature fluctuations become much more erratic. These points could not be determined in the case of the bare ground plots as fluctuations become progressively less at each station down to the 48-inch level. This is easily explained on a purely physical basis. The depth of temperature

Table 11. Standard Deviations in Degrees Fahrenheit of the Temperatures Recorded During the Winter of 1934-35 at the Several Depths for Each Treatment

Depth	Six-inch oat straw	Three-inch oat straw	Bare ground	Three-inch International peat	Six-inch snow
Inches			Degrees Fahrenheit		
0	4.63	3.87	11.56	3.19	3.56
2	3.42	3.37	9.63	2.30	3.19
4	3.19	2.93	8.99	1.90	2.46
6	2.52	2.39	8.19	1.43	1.95
8	2.39	2.06	6.94	1.24	1.92
10	1.93	1.68	5.48	1.08	1.57
12	1.81	1.48	5.56	1.07	1.36
18	1.24	1.19	3.65	0.93	1.23
24	1.36	1.60	3.19	1.60	1.35
36	1.34	1.28	1.55	1.37	1.56
48	1.35	1.38	1.38	1.40	1.59

variations in the soil is principally a function of the amplitude of oscillation of temperature at the ground level. However, it is also affected by differences in soil texture, organic matter, frost penetration, and soil-moisture conditions. Variability in soil temperature is a function of soil type to a certain extent. Greater variations and more rapid changes are found in the lighter soils. The changes in soil structure, from a heavy clay loam to that of a light, gravelly texture with a decrease in organic matter as the depth increases, is clearly illustrated in the diagram of the apparatus (Fig. 1).

The formation of ice in the upper layers also results in greater uniformity of soil temperatures, since the heat of fusion of ice is 80.02 calories per gram. Ice formation causes an accumulation in the upper layers of soil of the moisture vaporized from lower warm layers. This, together with melting snows during periods of high temperatures and precipitation moisture, narrows the spread of the soil temperatures in the upper levels. This was shown by Smith (54), Bouyoucos (2), and Mail (39). All of these factors seem to contribute to the results presented in tables 11 and 12.

The results given in Table 11 indicate that the efficiency of the mulches in protecting the soil against temperature variations for the season of 1934-35 was as follows: Three-inch International peat was best, followed in order by three inches of oat straw, and six inches of oat straw. The six-inch snow mulch can not be compared with the others since it could not be maintained during the entire period of experimentation.

High air temperatures were recorded during the early part of January, and fermentation was probably taking place in the straw mulches, especially in the six-inch mulch. This may have been responsible for the high temperatures which were recorded for these mulches during this period.

The effectiveness of a mulch in protecting the soil against low temperatures is largely governed by the condition of the mulch at times of temperature drop. Some types of mulches are affected by their physical conditions to a larger extent than are others. High air temperatures during the first and second weeks in January melted the snow in the straw mulches and changed the condition of the snow mulch. The six-inch straw mulch contained much more snow than the three-inch straw mulch and was affected to the greater extent by this change. The high-temperature period was followed by low temperatures, reaching a minimum of —21° F. about 10 a.m. on January 23. This low temperature stopped any fermentation which may have been taking place and caused a rather thick layer of ice to form in the six-inch straw mulch, with very little ice in the three-inch straw mulch. The six-inch snow mulch was changed to a rather thick icy layer upon which more snow was added to compensate for the loss.

These factors completely changed the relative values of the mulches tested. The six-inch straw mulch became less effective following the high-temperature period, especially during the week of January 24. This explanation accounts for the greater variability of soil temperatures under the six-inch straw mulch than under the three-inch straw mulch. It suggests a possibility that if the six-inch snow mulch had been maintained in a more uniform, loose condition it, too, would have been much more effective.

Table 12. Standard Deviations in Degrees Fahrenheit of the Temperatures Recorded During the Winter of 1935-36 at the Several Depths for Each Treatment

Plot depth	Bare ground	Three-inch marsh hay	Three-inch oat straw	Three-inch mixed leaves	Three-inch snow	Three-inch ice	Three-inch International peat	Three-inch nutria peat	Six-inch oat straw	Six-inch snow	Six-inch nutria peat	Six-inch mixed leaves
Inches						Degrees Fahrenheit						
0	12.42	6.40	8.05	6.18	8.45	10.87	12.26	13.05	5.87	6.23	9.16	5.67
2	11.94	5.95	7.71	5.63	6.95	10.45	11.94	12.40	4.81	5.76	8.65	5.42
4	11.63	9.23	7.35	5.50	6.77	10.01	11.47	12.26	4.92	5.56	8.46	5.21
6	11.21	5.42	6.74	5.08	5.74	9.57	11.14	12.15	4.55	5.32	8.22	5.00
8	10.95	5.02	6.19	4.64	6.70	9.16	10.48	11.01	4.09	5.16	7.81	4.76
10	10.11	4.79	5.82	4.34	6.42	8.82	9.71	10.24	4.52	5.26	7.55	4.35
12	9.79	4.74	5.57	3.85	6.20	8.65	9.08	9.59	4.52	4.85	7.34	4.46
18	8.46	3.66	4.71	2.96	5.11	7.74	7.73	7.48	4.52	4.85	6.71	4.06
24	7.48	3.33	3.73	2.64	4.91	6.96	6.89	7.38	4.53	4.31	5.91	4.08
36	6.48	4.49	3.32	2.05	4.33	6.29	6.73	5.29	4.60	3.95	5.27	4.21
48	5.47	3.37	3.48	3.29	4.20	5.87	6.13	5.19	5.61	4.22	5.07	4.23

Minimum temperatures.—In any study of low-temperature injury to plants, the minimum temperature of the immediate environment of the plants must be considered. Tables 13 and 14 illustrate the effect of various mulch treatments on the minimum soil temperatures in the root areas for most herbaceous plants. The minimum temperatures are highly significant in view of the data presented by Angelo (Part I), by Roberts (47), and by Steele, Waldo, and Brown (55). These workers point out the temperatures at which injury to strawberry plants might be expected during periods of low temperature. They show that injury occurs in most varieties of strawberries at temperatures of about 15° to 20° F. It is quite possible that, with some of the mulch treatments applied, temperatures below 15° to 20° F. might occur in the soil during severe winters.

From the data for the season of 1934-35, it is evident that the three-inch International peat mulch was extremely effective as an insulation material. During that season it was maintained in a dry, flaky condition. The data presented for the season of 1935-36 indicate that the peat mulches tested were considerably less effective. This can be explained by considering the physical condition of the mulches. A considerable drop in effectiveness followed a period of light rains during which the peat mulches became saturated with water. A sudden drop in temperature caused ice to form so that for the greater part of the season all of the peat mulches behaved much like the ice mulch. This was particularly true with the nutria peat. It seemed to pack more and form a more solid structure than did the International peat.

Soil-temperature inversion.—Data on soil-temperature inversion are presented only for the season of 1934-35. Temperature readings for the season 1935-36 were not continued far enough into the spring to include this period of overturn. However, in the spring of 1935 it was found that the type of ground cover did not appreciably affect spring

Table 13. Minimum Temperatures in Degrees Fahrenheit at Different Depths in the Soil Under Various Mulch Treatments for the Winter 1934-35

Depth	Six-inch straw	Three-inch straw	Bare ground	Three-inch International peat	Six-inch snow
Inches			Degrees Fahrenheit		
0	19	22	—7	22	21
2	24	24	—2	27	22
4	25	25	2	28	25
6	27	27	5	30	28
8	28	28	10	31	28
10	29	29	11	32	32
12	30	30	13	33	33
18	33	33	20	34	34
24	34	34	26	35	35
36	36	36	33	37	37
48	37	37	36	38	38

Table 14. Minimum Temperatures in Degrees Fahrenheit at Different Depths in the Soil Under Various Mulch Treatments for the Winter 1935-36

Depth	Bare ground	Three-inch marsh hay	Three-inch oat straw	Three-inch mixed leaves	Three-inch snow	Three-inch ice	Three-inch International peat	Three-inch nutria peat	Six-inch oat straw	Six-inch snow	Six-inch nutria peat	Six-inch mixed leaves
Inches						Degrees Fahrenheit						
0	—7	15	9	16	7	—1	—2	—6	25	17	9	18
2	—6	16	10	18	9	2	0	—4	27	18	11	20
4	—5	18	12	20	11	4	2	—2	28	19	13	22
6	—2	20	15	21	13	6	4	1	29	21	15	23
8	0	21	18	23	15	9	7	4	30	21	16	25
10	3	22	19	24	17	11	9	6	31	22	17	26
12	5	24	21	25	19	14	12	12	32	23	19	27
18	12	27	25	29	24	18	19	15	33	26	21	32
24	16	30	29	32	27	22	24	19	33	29	26	33
36	22	35	34	35	34	28	30	27	35	33	31	35
48	28	37	36	37	36	34	34	33	37	35	34	37

overturn and inversion of soil temperatures. A difference of only a few days was noted in the extreme cases.

Soil-temperature inversion in bare ground began about March 13 and was completed to a depth of 24 inches by March 17. The data on time of soil-temperature inversion to the 24-inch level under the mulches tested are presented in Table 15.

Table 15. Time of Temperature Inversion Under Certain Mulch Treatments as Compared to that Under Bare Ground to 24 Inches During the Spring of 1935

Treatment	Started	Completed to 24 inches
Bare ground	March 13	March 17
Three-inch International peat	March 15	About March 27
Three-inch oat straw	March 14	About March 25
Six-inch oat straw	March 14	About March 21

The effectiveness of a ground cover in preventing high soil temperatures early in the spring is very important. If the soil temperatures rise to a point where growth activity begins in plants (about 41° F.) and this high-temperature period is followed by freezing temperatures, considerable injury to plants is likely to occur. This injury may be prevented by the proper use of an effective mulch treatment.

Plant tests.—During the season of 1935-36, in addition to temperature studies, 10 species of herbaceous plants were tested under the various mulch treatments. These species covered a considerable range in hardiness, but owing to the fact that only a small number of plants of each species were tested and only one season's data obtained, no definite conclusions can be drawn. Some differences in plant survival occurred, however, which are worthy of mention. In October of 1935 the plants to be tested were set out in the various plots. Each plot contained the following numbers and sizes of plants of each species.

Campanula carpatica, two one-year-old plants
Aquilegia canadensis, two one-year-old plants
Delphinium grandiflorum, four one-year-old plants
Althaea rosea, six large plants
Chrysanthemum maximum, eight one-year-old plants
Campanula medium, four one-year-old plants and four large plants
Digitalis purpurea, four one-year-old plants and four large plants
Chrysanthemum coccineum, six medium-sized plants
Iris germanica, six large seedling iris selections
Fragaria sp. (variety Senator Dunlap), one 10-foot row

In March, 1936, the plants were checked for winter survival. These results are presented in Table 16.

SUMMARY

1. Soil-temperature data for the season of 1934-35 as compared with those for the season of 1935-36 indicate that the physical condition of a mulch is far more important than mulch type.

Table 16. Average Condition of Plants in the Spring of 1936 as Affected by Mulch Treatments*

	Bare ground	Three-inch marsh hay	Three-inch oat straw	Three-inch mixed leaves	Three-inch snow	Three-inch ice	Three-inch International peat	Three-inch nutria peat	Six-inch oat straw	Six-inch snow	Six-inch nutria peat	Six-inch mixed leaves
						Degrees Fahrenheit						
Campanula carpatica	3.00	3.00	2.00	2.00	2.50	3.00	2.50	3.00	1.00	2.00	2.00	2.00
Aquilegia canadensis	1.50	3.00	2.00	3.00	3.00	3.00	2.00	3.00	3.00	2.00	3.00	2.00
Delphinium grandiflorum	2.75	2.00	1.25	1.50	2.00	2.00	1.50	1.25	2.50	2.00	2.50	1.00
Althaea rosea	2.83	2.83	2.83	3.00	3.00	2.66	2.83	3.00	3.00	2.66	3.00	3.00
Chrysanthemum maximum	3.00	3.00	2.75	2.75	3.00	3.00	1.87	2.00	3.00	2.75	3.00	3.00
Campanula medium	3.00	3.00	3.00	2.75	2.75	3.00	2.75	3.00	2.75	2.50	3.00	2.75
Digitalis purpurea	2.00	2.37	2.37	1.50	2.37	2.37	1.50	1.62	2.25	1.50	2.25	1.50
Chrysanthemum coccineum	3.00	3.00	3.00	2.66	2.66	2.83	2.33	3.00	2.33	2.33	2.66	2.33
Iris germanica	2.66	2.83	3.00	3.00	2.83	2.83	3.00	3.00	3.00	3.00	2.83	3.00
Fragaria sp. (strawberry, variety Senator Dunlap)	1.00	2.00	2.50	2.50	2.50	1.50	1.50	1.50	2.00	3.00	2.75	2.00
Average	2.474	2.703	2.470	2.466	2.661	2.619	2.178	2.437	2.483	2.374	2.699	2.258

* Condition index: 1—poor; 2—fair; 3—good.

2. During the winter of 1934-35, peat was very effective as a mulch because it remained in a dry, loose condition. In 1935-36 it lost much of its effectiveness when it became wet, packed, and frozen.

3. The data for the season of 1935-36 indicate that, of the organic mulches tested, mixed leaves would be the most consistently effective mulch material because it was the least affected by physical conditions.

4. Ice had little value as a mulch in protecting the soil against low temperatures, and when it was present in organic mulch materials the value of such materials was reduced proportionately.

5. During severe winters, plant injury generally attributed to smothering by a covering of ice might be explained on the basis of low-temperature injury. The investigations of Roberts (47), Steele, Waldo, and Brown (55), and Angelo (Part I) relative to cold resistance of strawberries show that strawberry plants may be injured at relatively high temperatures—about 15° to 20° F. Temperatures considerably lower than this were recorded beneath ice and icy mulches.

III. The Respiratory Rate of Dormant Strawberry Plants[1]

W. G. BRIERLEY and R. H. LANDON

It is generally recognized that in the northern part of the United States the strawberry enters its winter rest period about the time of the first frosts. The plants remain dormant beneath the winter mulch, usually in a frozen condition, until the advent of spring temperatures. During this time respiration continues even though all plant activities are at a low ebb. Since information concerning the respiration of the dormant strawberry plant is of interest in connection with certain phases of strawberry culture, this study was undertaken.

In the fall of 1933 an attempt was made to determine the respiratory rate of potted strawberry plants that were in a dormant condition. Because of the nature of the strawberry crown that prevented sealing, neither ice nor paraffin was found to be satisfactory for this purpose. The results also were considered inconclusive because of the small size of the samples and lack of information relative to the movement of gases through frozen soil. Later, material was obtained by digging plants from frozen ground and washing them free from adhering soil. This procedure was unsatisfactory in that it was impossible to avoid injuring the plants.

To eliminate the difficulties previously encountered, a somewhat different method was adopted in the fall of 1936. For the samples used on October 6 and October 23, plants were dug in the field, washed free from

[1] A preliminary report of this study was published in the Proc. Am. Soc. Hort. Sci., 35:480-482.

soil, and used immediately. For all the samples used later, the method of handling was as follows.

On October 28, before the ground was frozen, a sufficient number of well-developed plants of the Dunlap variety were dug and washed free from soil. An attempt was made to select plants that were uniform in size. After washing, the plants were tied in bunches of 25. The bunches were then packed in boxes of moist peat with the leaves of the plants projecting above the surface. After this the boxes were placed in a deep coldframe and mulched with 12 to 15 inches of straw. With the approach of cold weather, the frame was covered with tight doors that excluded snow but allowed access to the plants. Temperatures in the peat in the boxes were recorded daily throughout the winter. From the beginning of cold weather until the middle of January the temperature remained very close to —1° C., with minor fluctuations that tended to follow changes in the air temperatures. During a period of severely cold weather the temperature in the peat fell to —3° C. but soon rose again and remained at slightly below freezing until April 14, 1937, when 0° C. was recorded. These temperatures correspond very closely with those recorded by Iverson (Part II) in his study of soil temperatures beneath mulch in the field. To ascertain the effects of the method of handling, all of the plants used were set in the field in May. Of these plants, 98 per cent made a satisfactory growth. From this it is evident that the

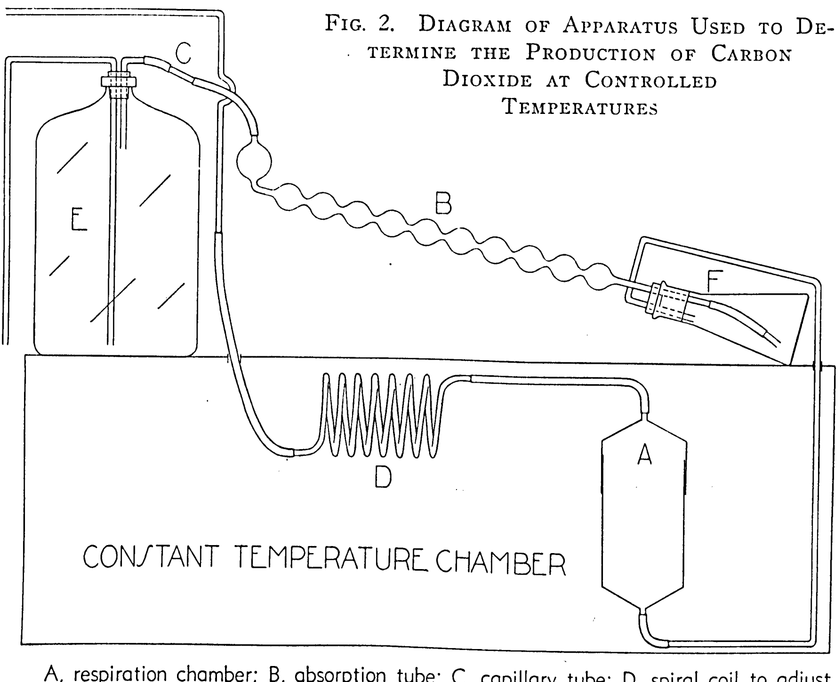


FIG. 2. DIAGRAM OF APPARATUS USED TO DETERMINE THE PRODUCTION OF CARBON DIOXIDE AT CONTROLLED TEMPERATURES

A, respiration chamber; B, absorption tube; C, capillary tube; D, spiral coil to adjust temperature of outside air; E, aspirator; F, flask.

plants remained in good condition during the winter and it can be assumed that the data relating to respiratory activity may be considered representative of the behavior of plants subjected to ordinary field conditions in winter. The high percentage of living plants is of interest in view of the fact that many were used a number of times in making determinations and were usually in a frozen condition when handled.

The apparatus described by Landon and Brierley (34) and shown in Figure 2 was used in ascertaining the amount of carbon dioxide given off by the dormant strawberry plants. The respiration chamber was a tin can of such shape and size that it was well filled by a bunch of 25 strawberry plants. The chamber had a capacity of 1,650 cc. When determinations were made, the chamber was kept in a small freezing box in which a thermoregulator held temperatures within ±0.5° F. Normal air brought from outdoors and adjusted to the temperature of the freezing box before passing into the respiration chamber was used. Blank determinations were made at frequent intervals and deducted from the results obtained with plants in the chamber. The rate of air flow through the respiration chamber was such that it was emptied three times in an hour.

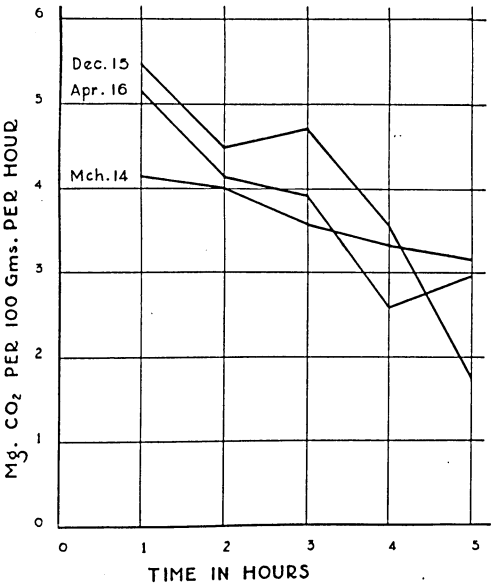


Fig. 3. Production of Carbon Dioxide by Three Samples of Dormant Strawberry Plants at 0° C., Showing the Decline in Respiratory Rate at Successive Hourly Intervals

When the respiratory rate of a bunch of plants was to be ascertained, the bunch was removed from the coldframe and taken to a cold cellar where adhering particles of peat were brushed off and the bunch weighed. It was then placed in the respiration chamber as quickly as possible and the chamber placed in the freezing box which was already at the desired temperature. Air was passed through the chamber for 30 minutes before the first determination was made. Four or five determinations were made at hourly intervals, after which the plants were returned to the coldframe. The production of carbon dioxide was found to decline at each succeeding hourly interval as shown in Figure 3. Because of this, the initial rates were used in comparing the performance on different dates since they were considered to be more representative than an average of the several determinations.

The determination of October 6 was made at 25° C., corresponding to field temperatures at that time. From October 23 until April 16 the determinations were made at 0° C., as this temperature closely paralleled that of the coldframe and that of the soil surface in the field beneath

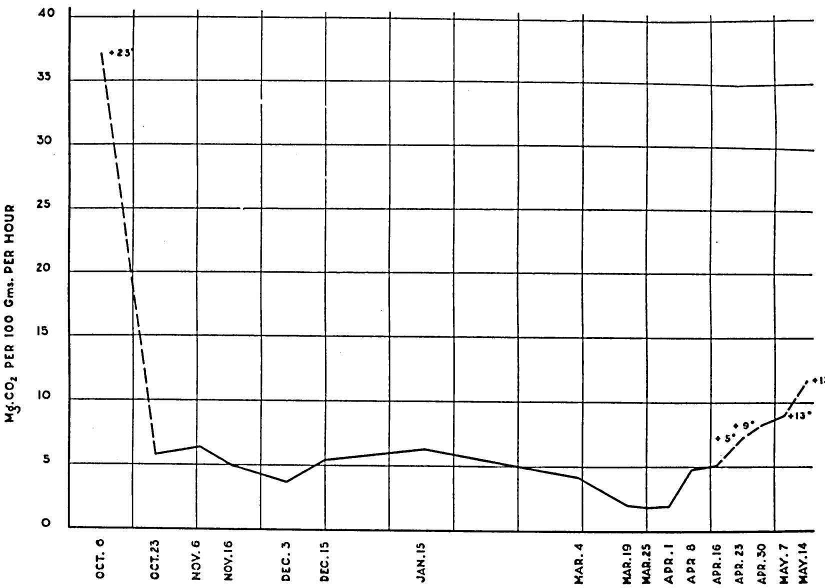


FIG. 4. RESPIRATORY RATE OF STRAWBERRY PLANTS THROUGHOUT THE DORMANT SEASON

Solid line indicates determinations made at 0° C.

mulch and snow found by Iverson (Part II). From April 23 until the end of the study, the temperatures used were those of the coldframe on the several dates.

The data obtained in these studies are shown in Figure 4. The first determination was made on October 6, a few days after the first killing frost, at the field temperature of 25° C. Although growth had ceased, the respiratory rate was found to be relatively high at that temperature. On October 23, after a series of light frosts when a determination was made at 0° C., the rate was found to have declined sharply. From October 23 until April 1, although fluctuations appeared, there was a gradual downward trend in the respiratory rate. It may be that the decline was due to a reduction in the amount of reserve material available for utilization in respiration. Long (37), working with the Aroma variety of strawberry in Missouri, has shown that the total sugars, although fluctuating in amount, tend to remain at the same average level throughout the dormant season. During the same time, however, there was a decline in starch and hemicellulose which he believed were converted to sugar and used in respiration. On April 8, before any indications of growth were evident, an upward trend in the respiratory rate was noted, which became more pronounced at later dates after the temperature of the coldframe had started to rise. As long as the plants were dormant, the rate was low. At higher temperatures, and the beginning of growth, the respiratory rate increased rapidly.

On October 30 and December 1, the respiratory rate was determined at 5° C. At both times the rate was found to be higher than at 0° C., on somewhat comparable dates. These results were anticipated in view of the known effect of higher temperatures in increasing the production of carbon dioxide by plants. On December 3, January 21, and February 18, the rate at a temperature of —5° C. was found to be consistently lower than at 0° C., as might be expected. In general, the rate at 0° C. was higher than other workers have shown for woody plants. It may be that this is the case when the respiratory rates of dormant herbaceous and woody plants are compared.

When the respiratory rate observed at 0° C. is used as an index of plant activity, it appears safe to conclude that there are no abrupt changes in the activity of dormant strawberry plants from mid-October until the beginning of growth in early April. Plant activity is low in late October. From these data it appears that no undesirable effects are likely to result from early mulching in the field in the north, a practice now recommended in order to avoid injury from severe, early freezes.

LITERATURE CITED

1. Augur, P. M., and others. 1885. The best method of preventing frost. Am. Pom. Soc. Proc. 20:54.
2. Bouyoucos, G. J. 1913. An investigation of soil temperature and some of the most influential factors influencing it. Mich. Agri. Exp. Sta. Tech. Bul. 17.
3. ——————. 1915. Effect of temperature on some of the most important physical processes in soils. Mich. Agri. Exp. Sta. Bul. 22.
4. ——————. 1916. Soil temperatures. Mich. Agri. Exp. Sta. Tech. Bul. 26.
5. Brierley, W. G., and Hildreth, A. C. 1928. Some studies on the hardiness of certain species of *Vaccinium*. Plant Phys. 3:303-308.
6. Chandler, William Henry. 1925. Fruit growing, 619-620. Houghton-Mifflin Company, New York.
7. ——————————————, 539-542.
8. ——————————————, 551.
9. ——————————————, 536.
10. ——————————————, 509.
11. ——————————. 1913. The killing of plant tissue by low temperature. Mo. Agri. Exp. Sta. Res. Bul. 8.
12. Craig, J. 1900. Observations and suggestions on the root-killing of fruit trees. Iowa Agri. Exp. Sta. Bul. 44.

13. Crane, H. L. 1924. Experiments in fertilizing peach trees. W. Va. Agri. Exp. Sta. Bul. 183.

14. Davis, M. B., and Hill, H. 1928. Nutritional studies with *Fragaria.* Sci. Agri. **8**(11) :681-692.

15. Dexter, S. T. 1932. Studies of the hardiness of plants; a modification of the Newton pressure method for small samples. Plant Phys. **4**:721-726.

16. ————. 1933. Effect of several environmental factors on the hardening of plants. Plant Phys. **8**:123-139.

17. ————. Growth, organic nitrogen fractions, and buffer capacity in relation to the hardiness of plants. (Unpublished.)

18. Dorsey, M. J., and Bushnell, J. W. 1920. The hardiness problem. Proc. Am. Soc. Hort. Sci. **17**:210-224.

19. Duhamel, du Monceau, H. L., and Buffon, G. L. L. 1737. Observations des different effects que produisent sur les végétaux les grandés gelées d'hiver et les petites gelées du printemps. Mem. Math. et Phys. Acad. Roy. Soc. Paris 233-298. Cited by Göppert.

20. Emery, S. M. 1898. Mont. Agri. Exp. Sta. Ann. Rept. Bul. 16, pp. 69-82.

21. Gardner, V. R., Bradford, C. F., and Hooker, H. D., Jr. 1922. The fundamentals of fruit production, p. 260. McGraw, Hill Book Co., New York.

22. Göppert, H. R. 1830. Ueber die Wärme-entwickelung in den Pflanzen; deren Gefrieren und die Schutzmittel gegen dasselbe, 1-273. Breslau.

23. ————. 1883. Pflanzen Gefrieren und Erfrieren.

24. Gorke, H. 1907. Ueber chemische Vorgänge beim Erfrieren der Pflanzen. Landw. Versuch. Sta. **65**:149-160.

25. Harrington, E. L. 1928. Soil temperatures in Saskatchewan. Soil Sci. **25**:183.

26. Harvey, R. B. 1918. Hardening processes in plants and developments from frost injury. Jour. Agri. Res. **15**:83-112.

27. ————. 1930. Time and temperature factors in hardening plants. Am. Jour. Bot. **17**:187-196.

28. ————. 1930. Length of the period of exposure to low temperature as a factor in the hardening process of tree seedlings. Am. Jour. For. **28**:50-53.

29. ————. 1935. An annotated bibliography of the low temperature relations of plants. Burgess Publ. Co., Mpls.

30. Hildreth, A. C. 1926. Determination of hardiness in apple varieties and the relation of some factors to cold resistance. Minn. Agri. Exp. Sta. Tech. Bul. 42.

31. Hooker, H. D. 1920. Pentosan content in relation to winter hardiness. Proc. Am. Soc. Hort. Sci. **17**:204-207.

32. Keen, B. A., and Russell, E. J. 1921. The factors determining soil temperature. Jour. Agri. Sci. **11**:211-240.

33. Kimball, D. A., Ruhnke, G. H., and Glover, M. P. 1934. A comparison of temperatures in air and at various depths in a light sandy soil in southern Ontario. Sci. Agri. **14**:353-359.

34. Landon, R. H., and Brierley, W. G. 1934. An apparatus for the measurement of respiratory rate. Sci. **80**:75.

35. Li, Tsi Tung. 1926. Soil temperature as influenced by forest cover. Yale Univ. Bul. 18.

36. LIDFORSS, B. 1896. Die wintergrüne Flora. Eine biologische Untersuchung. Abs. Bot. Centralb. 68:33-44.

37. LONG, J. H. 1935. Seasonal changes in nitrogen and carbohydrate content of the strawberry plant. Proc. Am. Soc. Hort. Sci. 33:386-388.

38. MACOUN, W. T. 1918. Winter injury in Canada. Proc. Am. Soc. Hort. Sci. 15:13-17.

39. MAIL, G. ALLEN. 1930. Winter soil temperatures and their relation to subterranean insect survival. Jour. Agri. Res. 41 (8):571-600.

40. MCCLATCHIE, A. J., and COIT, J. E. 1909. Relation of weather to crops and varieties adapted to Arizona conditions. Ariz. Agri. Exp. Sta. Bul. 61.

41. MCCOLLOCH, J. W., and HAYES, W. P. 1923. Soil temperature and its influence on white grub activities. Ecology 4:29.

42. MOLISCH, H. 1897. Untersuchungen über das Erfrieren der Pflanzen. 1-73.

43. MÜLLER-THURGAU, H. 1880. Ueber das Gefrieren und Erfrieren der Pflanzen. Landw. Jahrb. 9:133-189.

44. NEWTON, R. 1924. The nature and practical measurement of frost resistance in winter wheat. Univ. Alberta Res. Bul. 1.

45. POTTER, G. F. 1924. Experiments on the resistance of apple roots to low temperatures. New Hampshire Agri. Exp. Sta. Tech. Bul. 27.

46. ——————. 1922. Winter injury of apple roots. New Hampshire Agri. Exp. Sta. Bul. 203, 14-16.

47. ROBERTS, R. H. 1933. Strawberry "black root" injury. Proc. Am. Soc. Hort. Sci. 30:295.

48. ROBINSON, W. 1927. The thermocouple method of determining temperatures. Ann. Soc. Ent. Am. 20:513-521.

49. ROSA, J. R., JR. 1920. Pentosan content in relation to hardiness of vegetable plants. Proc. Am. Soc. Hort. Sci. 17:207-210.

50. RUSSELL, E. J. 1937. Soil conditions and plant growth. 7th edition. Longmans, Green and Co., New York and London.

51. SACHS, J. 1860. Krystallbildungen bei dem Gefrieren und Veränderung der Zellhäute bei dem Aufthauen saftiger Pflanzentheile. Math. Phys. Cl. 12:1-50. Bericht. Konig, Sachs, Gesell. Wiss. Leipzig.

52. SCHUSTER, C. E. 1920. Ore. Agri. Exp. Sta. Bien. Crop Pest and Hort. Rept. 3:44.

53. SHOEMAKER, J. S. 1934. Small fruit culture 159:19. P. Blakiston's Sons and Co., Philadelphia.

54. SMITH, ALFRED. 1926. A contribution to the study of interrelations between the temperature of the soil and of the atmosphere and a new type of thermometer for such study. Soil Sci. 22:447.

55. STEELE, T. A., WALDO, G. F., and BROWN, W. S. 1934. Conditions affecting cold resistance in strawberries. Proc. Am. Soc. Hort. Sci. 32:434-439.

56. THOMSON, W. A. 1934. Soil temperatures at Winnipeg, Manitoba. Sci. Agri. 15:209-217.

57. WIEGAND, K. M. 1906. Some studies regarding the finding of bugs in twigs in winter. Bot. Gaz. 41:373.

58. WILCOX, E. V. 1899. The resistance of strawberries to frost and 12 other subjects. Mont. Agri. Exp. Sta. Bul. 22.

59. WINKLER, ALBERT. 1913. Ueber den Einfluss der Aussenbedingungen auf die Kälteresistenz ausdauernder Gewächse. Jahrb. für Wissenschaft. Bot. 52:467-506.