GROWTH AND COMPOSITION OF THE STRAWBERRY PLANT IN RELATION TO ROOT TEMPERATURE

By

Alfred N. ATHAN Roberts

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
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DOCTOR OF PHILOSOPHY

Department of Horticulture

Year 1953

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Approved A. L. Kenworthy

Alfred N. Roberts

The possibility of correlating growth response of the strawberry plant to certain ecological conditions, namely, root temperature and concentration of the nutrient solution, with organic and nutrient-element composition was studied. The relationship between certain of these organic and ash components and their influence on the total production of dry matter in the root and aerial portions of the plant during its vegetative growth was considered.

Root temperature control was obtained by growing the plants in crocks of sand plunged in temperature control tanks designed especially for this purpose. Concentration of the nutrient solution was maintained by frequent renewal of sand cultures with various concentrations of Hoagland's standard nutrient solution. Growth measurements were based on the total production of dry matter and the number of runner plants produced. Organic and nutrient-element composition of the plant material produced was obtained by standard analytical procedures.

During the vegetative period of development, the growth of aerial portions of the strawberry plant was closely correlated with root temperature. Such a relationship was not present for root growth. Therefore, the top-root ratio increased with higher root temperature.

Maximum dry weight accumulation in both root and aerial portions of the strawberry plant occurred in nutrient solutions of relatively low salt concentration (0.5 Hoagland's solution). However, normal growth occurred in more concentrated solutions. On the basis of dry weight accumulation, maximum growth of all aerial parts of the plant during this vegetative phase of development occurred at root temperatures between 65° and 75° F, regardless of nutrient solution concentration. There was no significant difference in dry weight of roots within the range of root temperatures used in this study (45° to 75° F), regardless of nutrient solution concentration.

Although root temperature had a pronounced effect on the total growth of the aerial portions of the plant, the organic composition of the foliage was not significantly altered by differences in root temperature. However, there were significant changes in the organic composition of the roots with root temperature. Temperature effects upon organic components appeared to be more or less localized within the plant part subjected to differential temperature treatment.

Root temperature appeared to have very little, if any, appreciable effect on the nutrient-element composition of the aerial portions of the plant. Total ash of the roots was subject to greater influence from root temperature differences than was the foliage.

The total concentration of salts in the nutrient solution had no appreciable affect on the percentage of crude fiber and ether-extractable materials, but influenced the percentage of nitrogenous and metabolizable carbohydrate (N-free extract) components in both the leaf and root tissue.

The concentration of salts in the nutrient solution had a marked effect on both the total ash content and several of its components in root and leaf tissues.

A significant negative correlation was found to exist between the metabolizable carbohydrate (N-free extract) and nitrogenous (protein) fractions in the roots and foliage of the strawberry. A significant negative correlation was found also to exist between the content of ash and these metabolizable carbohydrate fractions in the roots and foliage. The same was true for these carbohydrate materials and the ash component, potassium.

The possible influence of root temperature and "luxury" absorption of nutrient elements on the efficient utilization of organic fractions and efficiency in dry weight production was considered.

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The author also wants to thank Dr. L. M. Turk of the Soils Department and Dr. W. B. Drew of the Department of Botany and Plant Pathology for serving on his guidance committee.

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INTRODUCTION

Studies of the effect of temperature on the growth and development of the strawberry plant have been confined to the relationship of atmospheric temperatures to photoperiodic responses. These observations have been concerned primarily with the growth of aerial parts of the plant. As with most other crops, comparatively little attention has been given to evaluating the importance of root temperature as a factor in the growth and phasic development of the strawberry plant.

There is a growing appreciation among plant scientists, particularly those who deal in the applied sciences, of the need for more systematic studies of the ecological factors, both individually and collectively, which bring about phasic development in plant growth along with the accompanying changes in plant structure and composition. The soil scientist is interested in more fully understanding the importance of the physical properties of soils in determining the growth and composition of plants. Until these two methods of approach receive sufficient simultaneous study, it may be impossible to accurately correlate either soil or plant analyses with growth responses of plants to various environmental conditions.

In order to accomplish the objectives desired by the plant and soil scientists, a series of studies would be necessary. This series of studies should involve controlled root temperatures and nutritional conditions as they influence growth and phasic development of the plant in relation to organic and ash composition. Both the roots and aerial parts of the plant should be considered in such an evaluation of plant growth during the several phases of development. The results of such a series of studies should furnish information concerning the desirable temperature and nutritional conditions that would promote the most efficient utilization of the products of photosynthesis in growth and production of the plant under a given set of environmental conditions.

The objective of this initial investigation was limited to the exploration of the possibility of correlating growth response of the strawberry, as influenced by root temperatures and concentration of the nutrient solution, with organic and ash composition. The methods and results obtained could then be used in an expanding program of evaluating the relationship of ecological factors to plant growth and composition.

REVIEW OF THE LITERATURE

Physiology of the Strawberry

Gardner (1923) and Mann (1927) observed that the strawberry plant behaves like a biennial, in that it stores large quantities of nitrogen and carbohydrates in the summer and fall for use in production of foliage and fruit the following spring. Long (1935) established the fact that fruit production of the strawberry plant was determined by the food reserves that accumulate during the growing season and are made available in the spring.

Whitehouse (1928) suggested that the carbohydrate-nitrogen status of the plant might be an important factor in fruitfulness of the strawberry plant. The importance of an efficient leaf surface in facilitating the accumulation of the products of photosynthesis and compounds derived largely from them for adequate fruit-bud differentiation and fruiting the following spring was established by Sproat and Darrow, G. M. (1935) and Morrow and Darrow, G. M. (1939).

The work of Greve (1936) showed that flower-bud differentiation in the strawberry was directly associated with the photoperiod under which the plant was grown. The photoperiod in turn influenced the chemical composition of the plant and Greve concluded that C/N relations were particularly affected and thus flower-bud formation was dependent upon a nutritional condition within the plant. Darrow, G. M. (1936), Darrow, G. M. and Waldo (1934) and Hartmann (1947), showed that a reduction in atmospheric temperature may be as important in inducing flower formation in the strawberry as a short photoperiod. They concluded that at low atmospheric temperatures flower buds may form in the strawberry under long photoperiods.

Temperature as a Factor in Growth Processes

Richards, Hagan and McCalla (1952) have made a comprehensive review of this subject.

Weiss (1949) called attention to the difficulty of studying the influence of environmental factors on plant development because of the complex nature of growth processes. However, he considered that the final result of growth can usually be measured as an increase in dry weight and very often in volume.

Through effects on physical and chemical reactions, temperature controls numerous physiological processes. It was outside the scope of this paper to discuss the literature available on all these processes, but since some of these physiological processes had a direct bearing on the results obtained from manipulations of root temperatures they have been considered more fully.

Absorption of Water

Kramer (1949) has reviewed the literature on the subject of the influence of root temperature on water absorption. It has been demonstrated by Brown (1939) with Bermuda grass and by Bailey and Jones (1941) with cultivated blueberries that low soil temperature decreased the ability of the plant to absorb water and resulted in wilting of the plants when transpiration was sufficiently high. Döring (1935), Rouschal (1935) and Kramer (1942) showed that the rate of water absorption by warm weather crops or plants native to warm climates was more closely correlated with soil temperature than are plants adapted to cooler seasons or climate.

Clements and Martin (1934) and Ellis and Swaney (1947) found that while water absorption appeared to increase with temperature up to a certain point, a level was reached where further increases in temperature resulted in a lesser rate or quantity of water absorption. Kramer (1949) reviewed and discussed the possible explanations for the relationship of root temperature to water absorption, but this literature was beyond the scope of this investigation.

Absorption of Nutrients

While the literature contained many data indicating that nutrient intake was less at low temperatures, Hagan (1952) was of the opinion that it was very difficult if not impossible to separate the effects of low temperature on the absorption process from those on translocation and assimilation.

Kramer and Currier (1950) reviewed the concept of permeability and its relation to water and mineral absorption. Hoagland and Broyer (1936) showed that the accumulation of nutrient salts by plants was not merely a matter of cell permeability but that energy exchange was necessary for the root to absorb nutrients against a concentration gradient. They observed that within certain temperature ranges (6^{o} - 24^{o} C) there were high temperature coefficients (2.5 - 5.0) for salt accumulation.

Concentration of the nutrient solution: Hoagland and Broyer (1936) demonstrated the importance of the concentration of the external solution in determining the ash composition of the plant. They expressed this relationship of concentration in the cell sap to that in the solution as accumulation ratios. These values were dependent upon the concentration of the culture solution. Hoagland (1944) called attention to the fact that the amount of selective absorption of ions by plants varied with temperature. Wanner (1948a, 1948b) studied the influence of temperature on anion and cation absorption and also linked such absorption to the concentration of the external solution. He found the temperature coefficients for absorption of anions were higher than those for absorption of cations and that these temperature coefficients were lower with higher external concentrations. He suggested that salt absorption from higher concentrations was less dependent upon temperature than from lower concentrations because less energy was required.

Since, salt absorption was dependent upon the metabolic activity of the roots, Hoagland and Broyer (1936) emphasized that coefficients for salt accumulation increased indirectly. Kramer (1949), and Haber (1945) pointed out the importance of the physical factors involved in salt accumulation, such as viscosity and ion mobility. Jacobson (1946) and Jacobson and Overstreet (1947) found that certain ions were absorbed at temperatures as low as 0° C.

Hagan (1952) after reviewing the subject concluded that there was not sufficient evidence available to prove that a reduced rate of nutrient absorption was responsible for the slow growth of plants at low root temperatures.

Nitrogen status: Nightingale (1933, 1935) observed that nitrate was absorbed by the tomato, apple and peach at temperatures near the minimum for growth. He and Blake (1934a, 1934b) suggested that nitrogen uptake by apple and peach was greater at higher temperatures. Darrow, R. A. (1939) working with bluegrass was in agreement with this viewpoint. These studies with various crops indicated that low temperatures did not greatly affect the absorption of nitrate but did seriously limit the ability of the roots to metabolize this nitrate to organic nitrogenous materials necessary for growth.

Nightingale and Blake (1934a, 1934b) found evidence in peaches that the translocation of these elaborated nitrogenous materials to other parts of the plant was controlled to considerable extent by temperature. In greenhouse studies with apple trees, Batjer, *et al* (1943) verified the conclusions of Nightingale and Blake. Similar results were also reported by Aldrich (1931) and by Smith (1935).

Translocation of Organic Materials

Went, *et al* (1944b, 1946, 1949) found that the amount of sugar translocated in the tomato decreased as the temperature was increased from 8° to 26° C. This was contrary to the opinion of Curtis (1929) and Curtis and Herty (1936) that there was a positive rather than negative temperature coefficient in translocation. Brown (1939) working with grasses and Hewitt and Curtis (1948) with bean plants found the same negative temperature coefficient for translocation. Batjer, *et al* (1939) obtained similar results with apple trees.

Respiration of Organic Materials

Most physiological texts are agreed that the temperature coefficient (Q_{10}) for respiration will average between 2.0 and 2.5 in a temperature range of 0° to 35° C. Gerhart (1940) stated that the temperature coefficient for respiration in the fruit of the strawberry was 2.5 for temperatures below 25° C. Brierley and Landon (1937) found that respiration of the strawberry plant could be measured even when the plants were in a frozen condition and plant activities at a low ebb. They found that in general the respiratory rate at 0° C for the strawberry was higher than investigators had found for woody plants.

The work of Hewitt and Curtis (1948) showed increasing rates of respiration for most plants with increasing temperatures.

The depletion of organic reserves in the plant as a result of higher respiration and growth rates with higher temperatures has been demonstrated by several investigators. Benedict (1950) working with quayule plants found the percentage of free sugars, levulins and inulin in the roots dropped rapidly as the soil temperature was increased to 65° F. Nightingale and Blake (1934a, 1934b) working with fruit trees and Decker (1944) with pine found that carbohydrate reserves decreased with increasing temperature. Brown (1939) and Sullivan and Sprague (1949) observed the same condition in forage grasses. Weinman (1948) reviewed the effects of temperature on the reserve substances in grasses and concluded that under normal growing conditions the carbohydrate content of these plants decreased as temperature increased.

Assimilation and Growth

Hagan (1952) in his review of plant growth processes in relation to temperature called attention to the complexity and lack of knowledge concerning the mechanism whereby growth results from the assimilation of basic materials. He cited the reviews of Barron (1949) and Kramer and Currier (1950) as support for this conclusion. However, the results of respiratory energy transfer studies by Bonner (1949) and Van Niel (1949) emphasized the role of metabolic processes in plant growth and these in turn have been shown to be temperature sensitive.

Wilson (1949) pointed out that expressions pertaining to the relationship between temperature and growth (temperature coefficient and Van Hoff's Law) were of doubtful value in predicting the influence of temperature in relation to such complex phenomena as growth. MacDougal (1920) stated that it was impossible mathematically to link variations of growth with temperature variations, because growth was modified by any one of many mechanisms dependent on prevailing temperature. Hagan (1952), Went (1944a, 1944b) and Weiss (1949) also supported this earlier line of reasoning.

Temperature as a Factor in Root Growth and Composition

The literature on the subject indicated that growth, development and composition of the root were influenced directly by soil temperature and indirectly by the supply of carbohydrates to the roots translocated to them from the photosynthetic parts of the plant. While data on the effect of root temperature on the growth and development of the strawberry plant were not available, considerable information was available for other crops which should be useful in evaluating the responses that might occur in the case of the strawberry.

Stuckey (1941) and Brown (1943) found in general that root growth in forage grasses was greater during the early spring and fall when temperatures were lower and that there was little or no development of the roots during the heat of summer. Darrow, R. A. (1939) verified these observations under controlled greenhouse air temperatures. He attributed the low root weights obtained at higher temperatures to a lack of available carbohydrates associated with excessively high respiration. Stuckey (1942) investigating the root growth of several grasses in nutrient solutions under controlled temperatures found similar trends in root growth with temperature.

Brenchley and Singh (1922) noted the importance of root temperatures in determining the tolerance of pea seedlings to high air temperatures. Jones, F. R. and Tisdale (1921) called attention to the influence of light intensity and plant age on plant responses to soil temperature.

In the case of cereal crops, Dickson (1923) observed that spring and winter wheat made their greatest root growth at relatively low soil temperatures. Wort (1940) found the dry weights of roots of Marquis wheat were less as soil temperatures increased under the conditions of his experiments. Dickson (1923) determined that corn roots irrespective of the age of the plant made their greatest growth at higher soil temperatures than that for most crops studied.

The research of Jones, F. R. and Tisdale (1921) has been interpreted by Earley and Cartter (1945) as showing some interesting relationships of light to the influence of soil temperature on root development in the soybean. They observed that, in a general way, root growth increased with increasing temperature from 2° to 25° C, but light intensity determined the amount of root growth response relative to increases in root temperature. Under low light conditions, root growth was affected to a lesser degree by soil temperature.

The investigations of Johnson and Hartman (1919), Arndt (1932), Tavernetti (1944) and Pierce and Wood (1946) showed close correlations between soil temperature and root development for numerous other agronomic crops. However, the results obtained in many of these studies were conditioned by environmental factors other than soil temperature.

Growth responses of vegetable crops to soil temperatures also vary with species and environmental conditions. Burkholder (1920), Richards (1921), Bushnell (1925) and Hoagland (1944) have reported the response of some of these crops to soil temperatures.

The effect of temperature on the growth of apple roots was studied by Collison (1935), who found some root growth at temperatures near the freezing point. Nightingale (1934, 1935) made extensive studies of the effects of temperature on the roots of apple trees. He observed that the presence or absence of a well-developed, fibrous root system influenced growth of the roots at low temperatures. Batjer, et al (1939) obtained similar results with dormant apple trees.

Rogers (1939) by means of observation trenches noted that apple trees in an orchard developed increasingly more new roots at soil temperatures from 7° to 21° C. Proebsting (1943) made similar observations.

Woodruff and Woodruff (1934) working with pecans and Girton (1927) with citrus also reported close relationships between temperature and root growth in these crops.

Shanks and Laurie (1949) observed that the fresh weight of the roots of greenhouse roses was proportionately less as the temperature of the roots increased. The appearance of the roots grown at various temperatures corresponded closely to those described by Nightingale for apple.

The only study to be found in the literature regarding the influence of soil temperature on strawberry root development was that of Gray (1941). This study was concerned with the effects of excessively high root temperatures on the growth of strawberry roots.

Temperature as a Factor in Shoot Growth and Composition

Cannon (1917) early recognized that under unfavorable atmospheric conditions shoot growth could be increased by maintaining favorable root temperatures for growth.

The influence of root temperature on the growth of the aerial portions of forage crops has been studied by Darrow, R. A. (1939), Stuckey (1942), Jones, F. R. and Tisdale (1921) and Earley and Cartter (1945). Although, the temperature at which maximum dry weight production occurred varied with species and variety, there was a tendency in all cases for top growth to be less at both excessively low or high temperatures.

Dickson (1923) and Wort (1940) observed that the optimum root temperature for maximum top growth of wheat was lower for later stages of plant growth than for the early stages during plumule development. Dickson (1923) found a similar shift in optimum root temperature for shoot growth with physiological age of the corn plant but in the opposite direction to that observed for wheat and most other crops studied.

Jones, F. R. and Tisdale (1921) called attention to the importance of incident radiation in determining the response of soybean plants to increases in soil temperature. The so-called optimum temperature increased with greater light intensity. Camp and Walker (1927) also pointed out the importance of other environmental factors in determining the response of shoot growth of cotton to soil temperature.

Nightingale (1935), Proebsting (1943) and Batjer, et al (1939) observed the top growth of apple and peach trees to be closely correlated with the volume of roots produced at the different temperatures. Halma (1935) and Haas (1936) studied the growth of citrus at various soil temperatures and found considerable difference in response with the various species used in commercial production.

Shanks and Laurie (1949) found the fresh and dry weight of shoots of Better Times roses increased directly with soil temperatures. High root temperatures favored high top-root ratios. The effects of soil temperature on shoot growth of Rubel blueberries studied by Bailey and Jones (1941) followed a similar pattern. In both the above studies high root temperatures resulted in tall upright plants, as compared with low spreading plants at low root temperatures.

STATEMENT OF PROBLEM

The purpose of the following study was to explore the possibility of correlating the growth response of the strawberry plant to certain ecological conditions, namely, root temperature and concentration of the nutrient solution, with its organic and mineral composition. Also considered was the relationship between certain of these organic and mineral constituents and their influence on the total production of dry matter in the root and aerial portions of the plant. By this means, an attempt was made to evaluate the effects of both root temperature and concentration of the nutrient solution on the accumulation of these organic and ash constituents in the plant and their bearing on the efficiency of dry weight production.

METHODS

Equipment

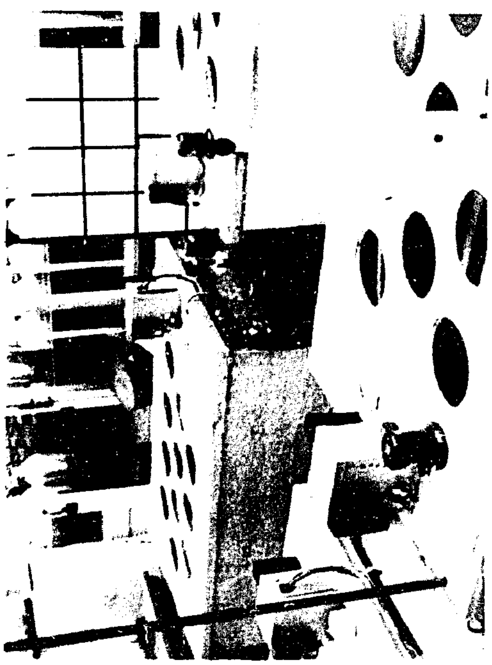
Root temperature control was obtained by means of a series of temperature control tanks designed after those described by Mellenthin (1951), assembled at Michigan State College (Figure 1). These tanks, four in number, were constructed by enclosing 300-gallon, round-end stock tanks in insulated plywood boxes, which were strongly reinforced to support the weight of the water they were to contain. A

Figure 1. Construction and arrangement of temperature control tanks

A -- General view of tanks after completion and before plant containers were added

B -- Close-up showing three of the plant containers in place. Crocks in the background are being drained of excess solution in a rack designed for this purpose

C -- Close-up showing one of the tanks with all plant containers in place



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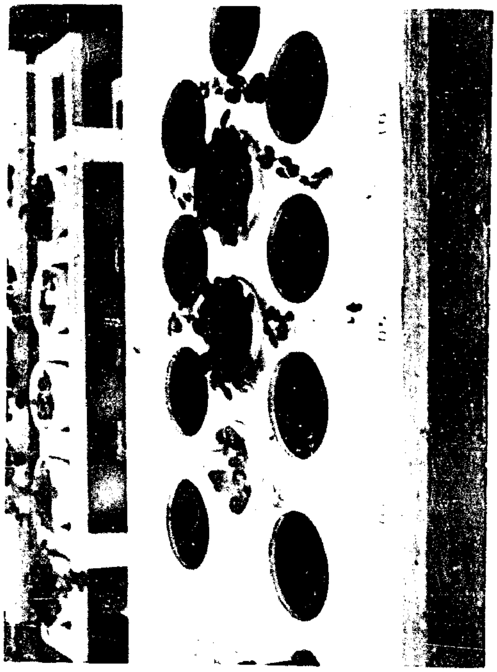


B

C

three-quarter-inch plywood removable top on each tank had twelve round holes, each nine inches in diameter. Through each hole a two-gallon glazed crock could be plunged into the temperature controlled water bath. The top of the crocks were at the level of the top of the tanks and supported by wooden frames resting on the bottom of each tank. An overflow pipe located near the bottom of the box-enclosed tank regulated the water level around the crocks in the tank.

Each tank contained both a thermostatically controlled lead heating cable and a refrigeration unit to control the water temperature within 2° F of the desired water temperature. Circulation of the water in the tank to assure even distribution of temperature effects was accomplished by a standard centrifugal pump of six-gallon-per-minute capacity.

The containers, two-gallon glazed crocks, were used to hold the sand in which the plants were grown. Such crocks were commonly used as coffee urn liners. These containers were well suited to the purpose for which they were used, since they had a tapered base and a one-inch round hole in the botton, which provided complete drainage. This drainage was provided for and at the same time the water kept out of the crocks by means of a No. 11 rubber stopper fitted with a glass tube, a small piece of rubber tubing and a pinch clamp. When in the tank, the pinch clamp on the drainage tube kept out the water. When solution was to be added and the excess drained off, the crock was removed and placed in racks made for this purpose. The pinch clamp was then removed, the solution added, and after drainage, the clamp replaced in the tank. In order to prevent the sand from clogging the glass tube inside the crock, a four-inch watch glass was inverted over the inside opening. This method of handling the crocks provided excellent drainage and aeration throughout the time of the experiment. Twelve such containers were available in each tank. The plants in each crock were equally exposed to light, air circulation and other temperature effects as shown by recording thermographs.

Plants

Strawberry plants of the Robinson variety, that had been stored through the winter, were used in these studies. These runner plants were washed free of soil and all but two leaves were removed from each. The roots were pruned uniformly to two inches in length. The plants were graded into two weight classes - 6 $\pm$ 1 gm and 4 $\pm$ 1 gm. One plant from each group was planted in each crock. These plants were typical of those used in commercial planting during the spring, after storage. All blossom clusters were removed as soon as they appeared in the crown to assure additional uniformity. The fruiting phase was not considered in this study.

Atmospheric Conditions

Atmospheric temperatures were maintained by manual operation of the ventilators. Night temperatures were maintained between 50-60° F during the first month (March 22 to April 22) and at 60-65° F during the final month (April 22 to May 26). The average night temperature varied less than 5° during the period of a week. Day temperatures varied more because of the constantly changing solar radiation during the two-months period. Day temperatures increased slowly from the night temperatures mentioned to a maximum of 80° F during the day (first month) and to a 100° F maximum (slightly higher on a few days) during the last 30 days of the experiment. However, the daily average approximated 70° F during the first month and 80° F during the second month.

Solar radiation was variable during the fore part of the 60-day period, but was uniformly high during the last 30 days of the experiment. However, light could not be considered a limiting factor in the growth of the strawberry plants.

Nutrient Solutions

The nutrient solutions used in these studies consisted of three concentrations of Hoagland's standard nutrient solution No. 1. The concentration of these solutions were full-Hoagland's (1.0); half-Hoagland's (0.5); and one-tenth-Hoagland's (0.1). The dilute solutions were prepared by adding the necessary amount of molar stock solutions to distilled water. Chemically pure chemicals were used throughout. The following gives the amounts of the various elements present in such solutions:

Element	1.0 Hoagland	0.5 Hoagland	0.1 Hoagland
N	210.10 ppm	105.05 ppm	21.01 ppm
P	30.98	15.49	3.10
K	234.60	117.30	23.46
Ca	200.40	100.20	20.04
Mg	48.64	24.32	4.86
B	0.50	0.25	0.05
Mn	0.50	0.25	0.05
Cu	0.02	0.01	0.002
Mo	0.01	0.005	0.001
Fe	1.37	0.685	0.137

Reaction of solution: The pH of the Hoagland's solutions as prepared for these experiments were 5.0, 5.0 and 5.4 for the 1.0, 0.5 and 0.1 solutions respectively.

At various times during the course of the experiment the pH was determined after the solution had been left standing for two days time (the maximum time that the dilute solution was ever left standing). The average of these determinations were 5.0, 5.4 and 5.6 for the 1.0, 0.5 and 0.1 Hoagland's solutions respectively.

Since the difference between the pH of the fresh and two-day old solution and between the various concentrations was never greater than 0.6 it was not considered necessary to adjust the pH of the solutions.

Renewal of solutions: In order to assure a minimum amount of change in the relative concentration of the various ions present in the solution as a result of differential absorption of these ions by the plants, the solutions were renewed often and more or less regularly depending on weather conditions. During the first month of growth when light intensity, air temperatures and transpiration were not excessively high, the solutions were renewed every second day. When increasing atmospheric temperature and solar radiation during the second month increased transpiration and metabolic activity, particularly when associated with the two higher (65° and 75° F) root temperatures, the solutions were renewed each day. Renewal of the solution was accomplished by the addition of 500 ml of the nutrient solution to each crock. This amount was approximately two to three times the volume which could be held by the sand. At regular intervals (10-14 days) the sand was leached with distilled water to avoid the possible accumulation of salts on the surface of the sand particles. Fresh solution was then added immediately.

In order to determine the efficiency of the above practices in maintaining uniform salt concentration about the plant roots, samples of leachate were taken periodically and tested with a Solu-bridge for total salts present.

Fresh Hoagland's solutions of 1.0, 0.5 and 0.1 concentration gave Solu-bridge readings of 200, 110 and 24 mhos x 10^{-5} respectively. Leachate displaced from the sand by additions of fresh solution after two days gave Solu-bridge readings of 200, 100 and 20 mhos x 10^{-5} respectively from the 1.0, 0.5 and 0.1 solutions in which the plants were growing. When the leachate was obtained by displacement with distilled water the readings dropped to 170, 85 and 20 mhos x 10^{-5} for the same solution concentrations. These data indicate that there was not appreciable change in the salt concentration of the solutions before they were renewed.

A medium fine quartz sand used in well footings was used as the medium in which to grow the plants. This sand was washed repeatedly with tap water and then treated for four days with a 10 percent solution of commercial hydrochloric acid. This was followed by repeated leachings with tap water and finally with distilled water. The pH of the final wash water averaged approximately 6.5.

Summary of Treatments

The strawberry plants which had been prepared as described were planted in the crocks on March 1 and placed on a greenhouse bench to become established before starting the treatments. Each crock of two plants was assigned permanent treatment numbers which designated the root temperature treatment and concentration of solution they were to receive. From that time on, they received the respective nutrient solutions as designated at intervals until they were well established. On April 4, they were placed in the various temperature control tanks.

One each of the four temperature tanks was maintained at 45°, 55°, 65°, and 75° F. Twelve crocks were placed in each of these tanks. Each group of four crocks in each tank received Hoagland's nutrient solution at concentrations of 1.0, 0.5 or 0.1. This provided four replications of each nutrient concentration at any given root remperature. Since each crock contained two strawberry plants, there were eight plants for each combination of nutrient level and root temperature. The plants were maintained as described in the foregoing sections from April 4 to May 28, a period of 54 days, after which time the treatments were terminated.

Growth Measurements

Upon completion of the period of treatment, the entire plant including the roots was removed from the crocks by carefully washing away the sand. After removal, both the roots and tops were washed in tap water and rinsed twice in distilled water. The number of leaves and runners produced by each set of two plants were recorded. The plants were then divided into roots, crowns, leaves, petioles, and runners for dry weight determinations. The petioles were measured for length prior to drying. Dry weight determinations were made by rapidly bringing the plant parts to constant weight in a dehydrator provided with air circulation and maintained at a temperature of 70° C. The plant parts were weighed separately for each replication on a torsion balance.

Composition Analyses

In view of the small amount of total dry matter of the various plant parts, the four replications were combined into one sample for organic and ash analysis. Since quantitative analyses of several organic and ash fractions seemed desirable, the analyses were limited to the roots and leaves. These parts, representing the aerial and non-aerial portions of the plants, were considered as an index of the organic and ash composition of the variously treated plants as a whole.

All samples in these tests were prepared by grinding the previously dried plant material in a Wiley mill (20 mesh screen). The ground samples were stored in glass sample bottles. Prior to a series of determinations, the samples were oven-dried for 24 to 48 hours at 100° C to constant weight.

Organic analyses: The primary interest in these studies was in measuring the relative efficiency in dry weight production of the photosynthetic-respiratory balance resulting from exposure to the various root temperature and solution concentration combinations. Analyses for organic constituents were therefore confined to broad groupings rather than to a number of fractions of individual substances. The total amount of any one of these substances might vary greatly depending upon the stage of growth when the sample was taken. For this reason the analyses for organic composition consisted of a series of quantitative evaluations used by the Department of Agricultural Chemistry at Michigan State College in assaying the nutritional qualities of feeds for livestock. Such an analysis provides the composition of the dry matter in terms of protein (from Kjeldahl nitrogen), crude fiber, ether extract, total ash and then by difference, nitrogen-free extract - considered as that portion not accounted for as protein, crude fiber, ether extract and total ash.

The quantitative methods for each of these tests are modifications of those found in the Official Methods of Analysis of the Association of Official Agricultural Chemists as used by the analytical laboratory of the Department of Agricultural Chemistry at Michigan State College.

Ash analyses: In addition to a total ash determination of the roots and leaves from each treatment in the series, analyses were also made for several of the constituents contained in the ash of the plant material. Potassium determinations were made on the Perkins-Elmer Flame Photometer and content of phosphorus, magnesium, calcium, manganese, iron, copper and boron was determined by means of spectrographic procedures.

Statistical Analysis

The data for growth measurements, dry weight produced and composition (organic and ash), were subjected to analysis of variance. Since replicates were composited for composition analysis, a statistical evaluation of the interaction between root temperature and nutrient solution concentration was not possible. The compositing of samples also would tend to increase the requirements for statistical differences between main effects (root temperature and nutrient solution concentration). In some instances trends in the data were indicated graphically that were not supported by statistical analysis.

Correlations between several organic and ash components were tested for significance. These included those between total ash and nitrogen-free extract; potassium and nitrogen-free extract and between protein and nitrogen-free extract.

EXPERIMENTAL RESULTS

Growth Measurements

Total Growth

The photographs in Figure 2 show the total growth of aerial parts by representative plants from each combination of root temperature and nutrient solution.

The total dry weight of plant material, including all aerial and root portions, produced by each combination of root temperature-nutrient concentration conditions are shown in Table I and Figure 3. The total dry matter was significantly greater when the plants were grown in the 0.5 than in the 0.1 Hoagland's solution. However, 1.0 Hoagland's solution did not increase above that obtained with a nutrient solution concentration of 0.5. The 0.5 concentration of Hoagland's solution was sufficient to result in a maximum amount of growth as measured in terms of dry weight production.

In general, root temperature had the same effect on total dry weight accumulation regardless of the concentration of the nutrient solution employed. The trend was toward increasing dry weight as root temperatures increased from 45° F to 65° F. There was no significant increase between 65° F and 75° F. Significantly greater growth was

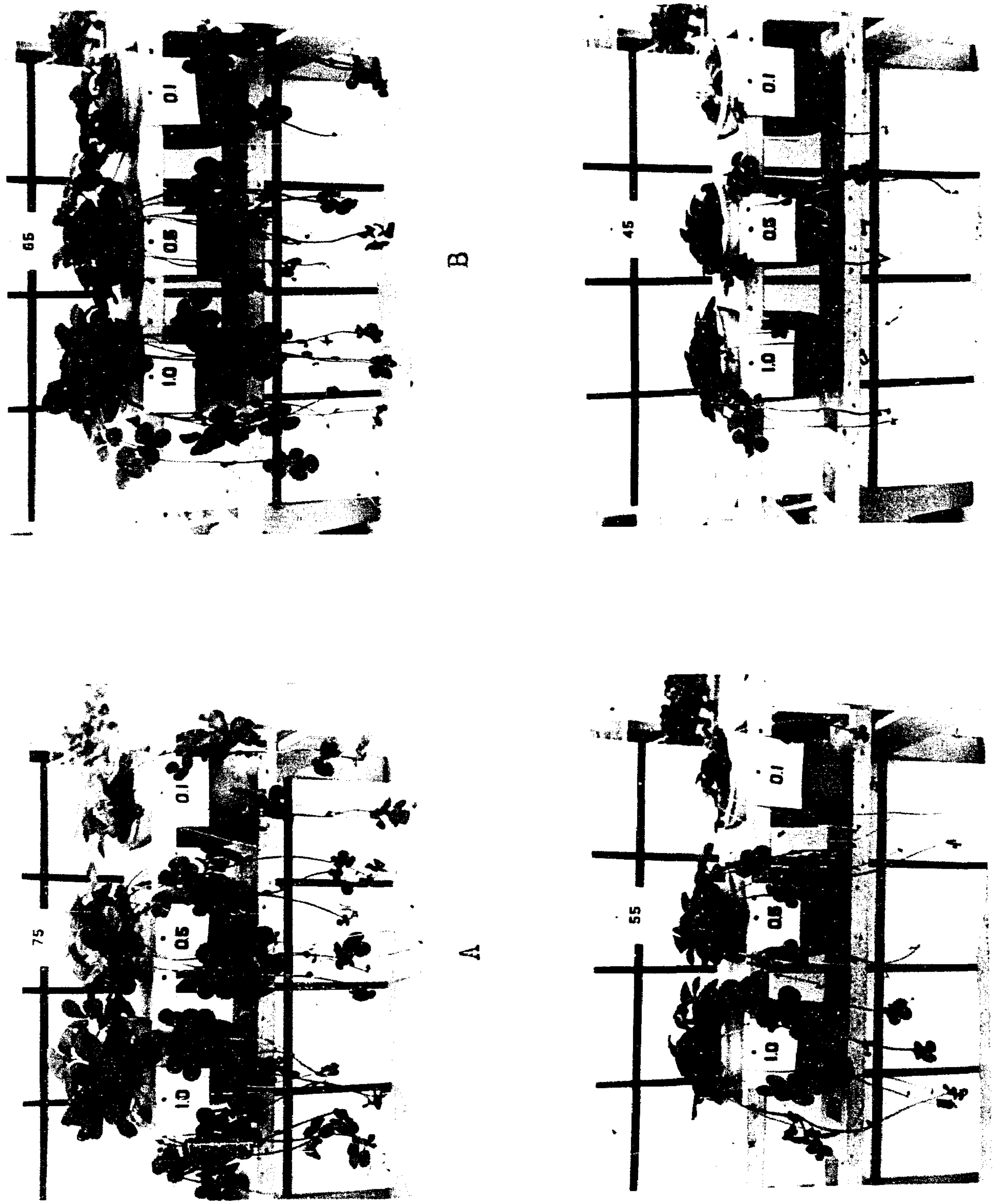
Figure 2. Effects of root temperature and concentration of nutrient solution on growth of Robinson strawberry plants

A -- Root temperature 75°; concentration of Hoagland's solution 1.0, 0.5 and 0.1 (left to right)

B -- Root temperature 65°; concentration of Hoagland's solution 1.0, 0.5 and 0.1 (left to right)

C -- Root temperature 55°; concentration of Hoagland's solution 1.0, 0.5 and 0.1 (left to right)

D -- Root temperature 45°; concentration of Hoagland's solution 1.0, 0.5 and 0.1 (left to right)



A B C D

TABLE I

EFFECTS OF ROOT TEMPERATURE AND CONCENTRATION OF NUTRIENT SOLUTION ON DRY WEIGHT ACCUMULATION IN ROBINSON STRAWBERRY

Plant part	Root temperature (° F)	Concentration of Hoagland's solution 1.0	0.5	0.1
		Gms	Gms	Gms
Total plant	75	45.48	48.04	23.17
	65	39.66	43.14	21.94
	55	30.89	30.67	13.53
	45	19.26	20.71	8.70
		L.S.D. - 5% = 7.98; 1% = 10.69		
Roots	75	6.00	6.64	4.09
	65	6.01	6.50	4.53
	55	6.40	6.96	4.79
	45	6.65	7.40	4.11
		L.S.D. - 5% = 1.35; 1% = 1.81		
Leaves	75	11.67	13.34	7.14
	65	10.71	12.67	6.41
	55	8.46	8.69	4.02
	45	6.34	5.59	2.34
		L.S.D. - 5% = 1.77; 1% = 2.38		
Petioles	75	3.50	3.50	1.85
	65	2.64	3.11	1.48
	55	2.04	2.01	0.90
	45	1.46	1.18	0.54
		L.S.D. - 5% = 0.52; 1% = 0.70		
Runners	75	21.80	21.50	8.30
	65	17.78	18.20	7.64
	55	11.55	10.67	2.06
	45	2.64	4.70	0.35
		L.S.D. - 5% = 5.14; 1% = 6.88		
Crowns	75	2.53	3.07	1.80
	65	2.53	2.66	1.88
	55	2.44	2.34	1.77
	45	2.18	1.85	1.36
		L.S.D. - 5% = 0.58; 1% = 0.78		

Weights based on 4 replications of 2 plants each (total of 8 plants). Averages given are for 2 plants.

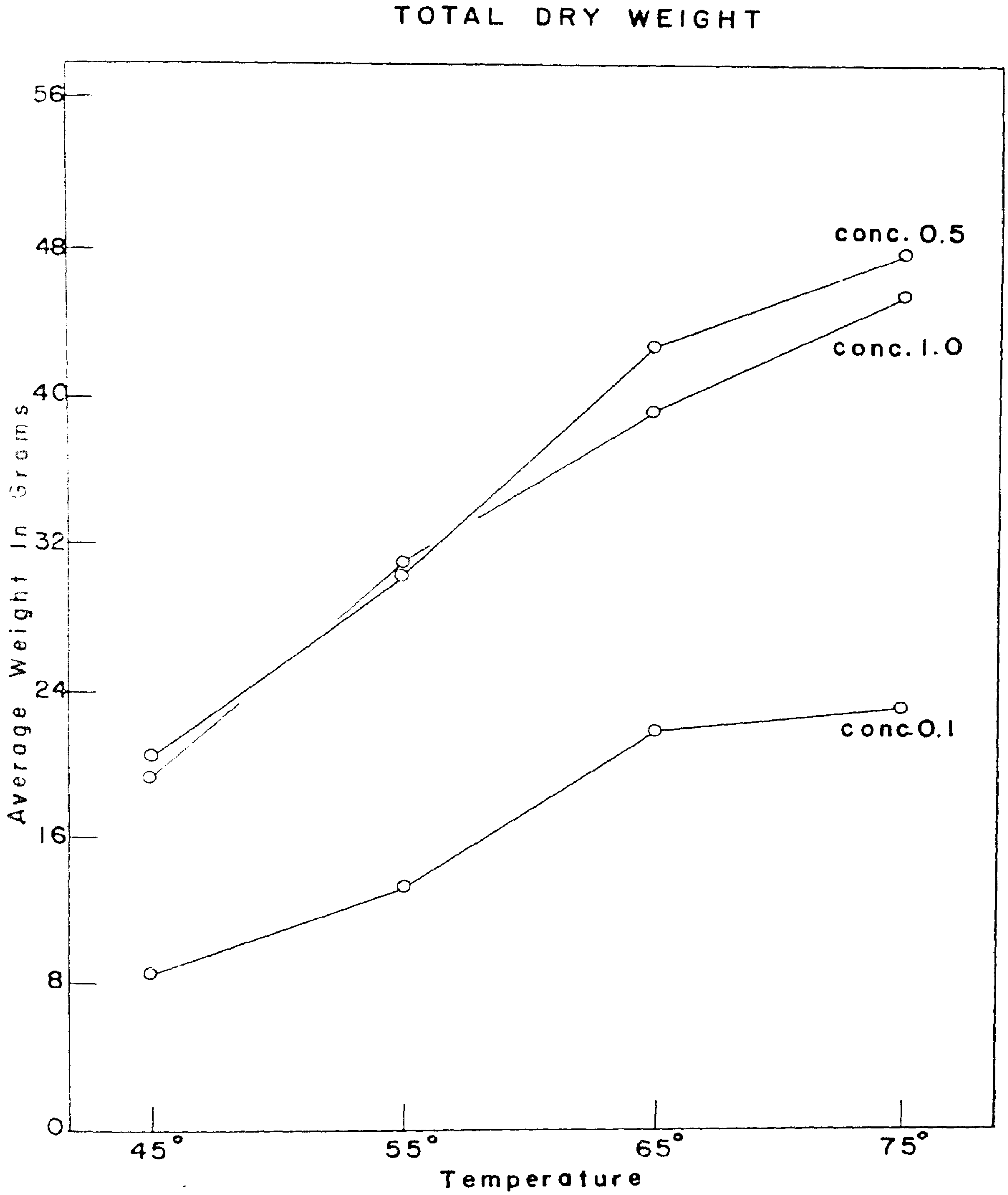


Figure 3. Effects of root remperature and concentration of the nutrient solution on total dry weight accumulation in plants of Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

obtained with the 0.5 solution than the 0.1 solution. However, somewhat less growth was obtained with the 1.0 solution than the 0.5 solution.

The only exception to this pattern was with plants grown in the weak (0.1 Hoagland's) solution, where as much plant material was produced at 45° F as at 55° F, although dry weight was significantly greater at 65° F than at 55° F. While not statistically significant, the trend in all three solutions was for increased total dry weight accumulation with each ten-degree increase in root temperature from 45° F to 75° F. Increases of root temperature above 65° F did not result in significantly more dry matter regardless of the nutrient solution concentration.

<u>Root Development of the Plant</u>

The effects of root temperature on the accumulation of dry weight of root, as shown in Table I and Figure 4, were noticeably different from those on the aerial portions of the plant. There were no significant differences in the dry weight of roots of plants growing at root temperatures from 45° F to 75° F. However, there was a definite trend at all solution concentrations to indicate that root weight increased as root temperature decreased. This was exactly the opposite of that found for the aerial portions of the plant.

Dry weight of roots was greatest in the 0.5 Hoagland's solution, as were the aerial portions. Weight of roots was not increased when the solution concentration was raised to

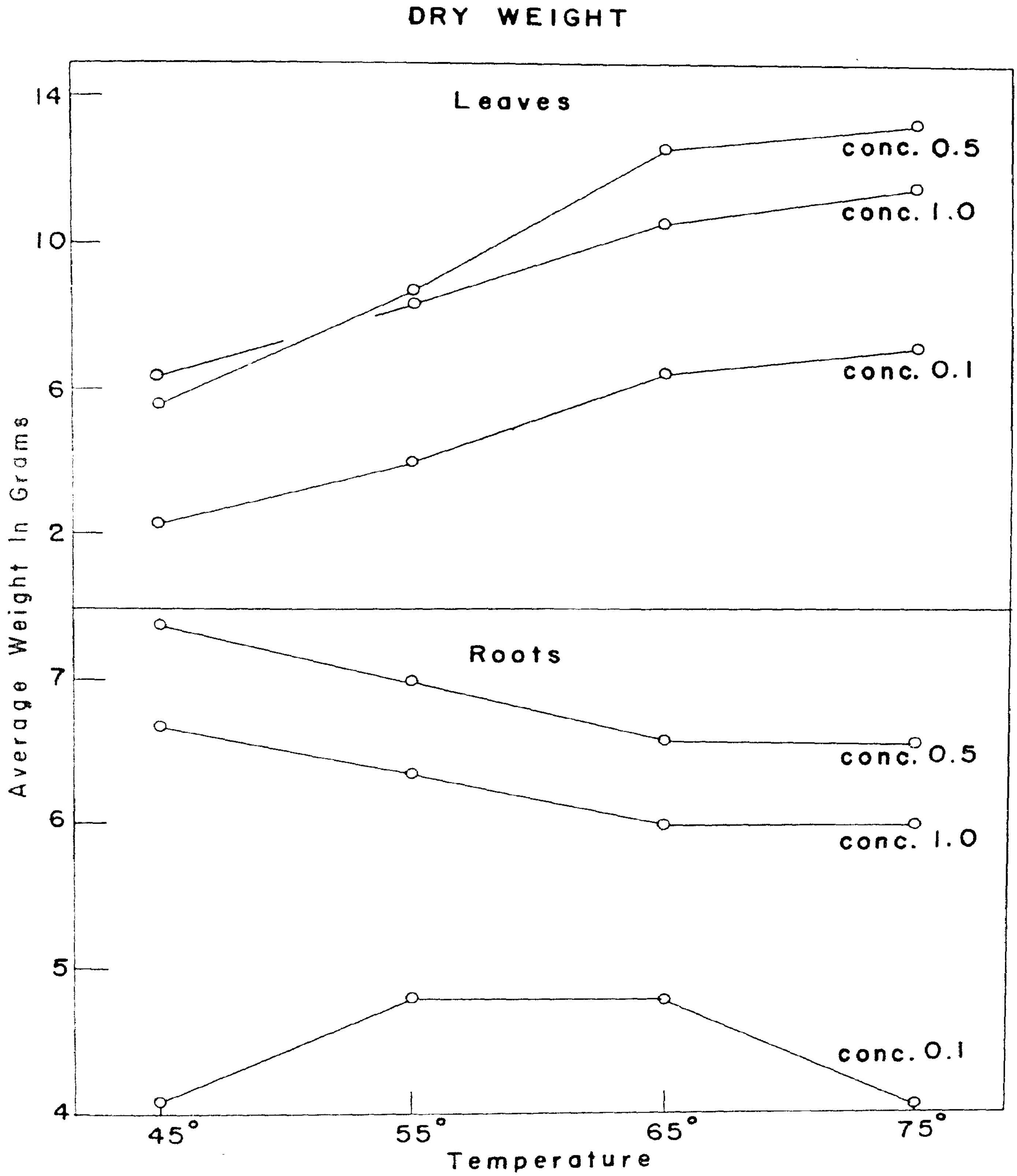


Figure 4. Effects of root temperature and concentration of the nutrient solution on dry weight accumulation in leaves and roots of Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

1.0 Hoagland's.

Aerial Portions of the Plant

The dry weight of the aerial portions of the plant, which include the petioles, leaves and runners, are also given in Table I. The growth of these plant parts associated with increased root temperature and greater nutrient concentration followed, in general, the same trend as that observed in total dry weight. Since the response was the same for leaves, petioles and runners, only the dry weights of leaves are shown in Figure 4.

Leaves: Increasing the concentration of the nutrient solution from 0.1 to 0.5 increased slightly the number of leaves but further increase in concentration had no effect on leaf numbers (Table II). Root temperature had even less effect upon the number of leaves. Raising the root temperature from 45° F to 55° F slightly increased the number of leaves in the two lower concentrations of nutrient solutions.

While root temperature and concentration of the nutrient solution had little effect on number of leaves, there was considerable effect on leaf size as expressed in the dry weight of the leaves. There was no significant difference in the dry weight of leaves produced by the 1.0 and 0.5 Hoagland's solutions, but these were considerably above those produced in the 0.1 Hoagland's solution. As found for total dry weight, leaf weight increased with root temperature from 45° F to a maximum at 65° F with no further significant increase at 75° F.

TABLE II

EFFECTS OF ROOT TEMPERATURE AND CONCENTRATION OF NUTRIENT SOLUTION ON THE NUMBER OF LEAVES AND RUNNERS PRODUCED BY ROBINSON STRAWBERRY PLANTS

Root temperature (° F)	Concentration of Hoagland's solution		
	1.0	0.5	0.1
	Leaves		
75	24.50	27.25	24.00
65	25.00	27.25	20.75
55	24.00	25.50	17.00
45	20.75	19.00	14.00
L.S.D. - 5% = 4.69; 1% = 6.28			
	Runners		
75	17.80	20.30	13.30
65	17.30	16.30	10.50
55	12.50	12.80	5.00
45	3.00	5.80	0.50
L.S.D. - 5% = 2.90; 1% = 3.89			

Averages based on 4 replications of 2 plant each (total of 8 plants). Averages given are for 2 plants.

Petioles: The observations made in regard to dry weights of the leaves were also manifest in the dry weight of the petioles (Table I). The responses to root temperature and concentration of the nutrient solution were similar.

The effect of the treatments on petiole elongation are shown in Table III. Root temperature had a pronounced effect on petiole length. There was a general trend toward increased petiole length with higher root temperatures, although petiole length at 75° F was not significantly greater than at 65° F. Petiole length was one of the more obvious visible expressions of the influence of root temperatures upon the growth and development of the aerial portions of the strawberry plant. This increased petiole length resulted in a marked increase in plant height.

Runners: Table II shows that the number of runners (an indication of the vegetative condition in the strawberry) was significantly greater with temperatures ranging from 45° F to 75° F in both the 0.1 and 0.5 Hoagland's solutions but only to 65° F in the 1.0 solution. The production of runners appeared to reach a maximum in the 0.5 solution. The 1.0 concentration failed to increase production of runners.

Crowns: Root temperatures had greater effect upon the dry weight accumulated by the crowns when 0.5 Hoagland's solution was used. There was a significant increase in crown weight in 0.5 over that produced in 0.1 Hoagland's, but raising the nutrient concentration to 1.0 failed to

TABLE III

EFFECT OF ROOT TEMPERATURE AND CONCENTRATION OF NUTRIENT SOLUTION ON PETIOLE LENGTH OF ROBINSON STRAWBERRY LEAVES

Root temperature (° F)	Concentration of Hoagland's solution		
	1.0	0.5	0.1
	mm	mm	mm
75	123.61	128.67	107.08
65	111.22	118.23	92.02
55	89.69	88.52	69.14
45	72.12	68.09	58.68
	L.S.D. - 5% = 13.17; 1% = 17.65		

Averages based on 4 replications of 2 plants each (total of 8 plants). Averages given are for 2 plants.

increase dry weight of crown. Root temperatures and solution concentrations were less effective on crown development than on any other part of the plant.

Top-Root Ratio

Both root temperature and concentration of nutrient solution had a pronounced effect on the ratio of top growth to that of the roots. These ratios are given in Table IV. Each increase in root temperature of ten degrees was accompanied by a significant increase in the top-root ratio regardless of the concentration of the nutrient solution. This would indicate that increases in root temperature favor growth of the aerial portions to a greater extent than growth of the root system. The dilute, 0.1 Hoagland's solution, favored a relatively lower top-root ratio than the 0.5 solution. Raising the concentration of the solution to 1.0 did not significantly increase the ratio of tops to roots over that of the 0.5 solution. The top-root ratio was at a maximum in the 0.5 solution.

Plant Composition

Effect of Root Temperature on Organic Composition

The amounts of certain organic fractions contained in the leaves and roots as influenced by the series of root temperatures are presented in Table V and Figures 5-8. Protein, crude fiber, ether extractable materials, and nitrogen-free extract content of the leaves were not significantly influenced by root temperature variations.

TABLE IV

EFFECT OF ROOT TEMPERATURE AND CONCENTRATION OF NUTRIENT SOLUTION ON THE TOP-ROOT RATIO OF ROBINSON STRAWBERRY

Root temperature (° F)	Concentration of Hoagland's solution		
	1.0	0.5	0.1
75	6.66	6.25	4.75
65	5.56	5.61	3.87
55	3.80	3.39	1.81
45	1.87	1.79	1.12

L.S.D. - 5% = 0.64; 1% = 0.86

Averages based on 4 replications of 2 plants each (total of 8 plants). Averages given are for 2 plants.

TABLE V

EFFECT OF ROOT TEMPERATURE ON THE ORGANIC COMPOSITION OF THE ROOTS AND LEAVES OF ROBINSON STRAWBERRY PLANTS

(Percentage Dry Weight)

Root temperature (° F)		Organic components			
		Protein	Crude fiber	Ether extract	N-free extract
		Leaves			
75		15.48	10.44	4.84	60.73
65		16.21	10.40	4.85	59.28
55		16.15	10.13	5.16	59.70
45		17.08	10.06	5.25	59.37
L.S.D. -	5% =	N.S.	N.S.	N.S.	N.S.
	1% =				
		Roots			
75		16.13	19.96	2.75	49.24
65		17.46	18.03	2.17	51.27
55		16.92	15.24	2.03	55.83
45		17.60	13.26	1.89	56.00
L.S.D. -	5% =	N.S.	1.21	0.47	2.67
	1% =		1.83	0.72	4.04

N.S. -- F value not significant

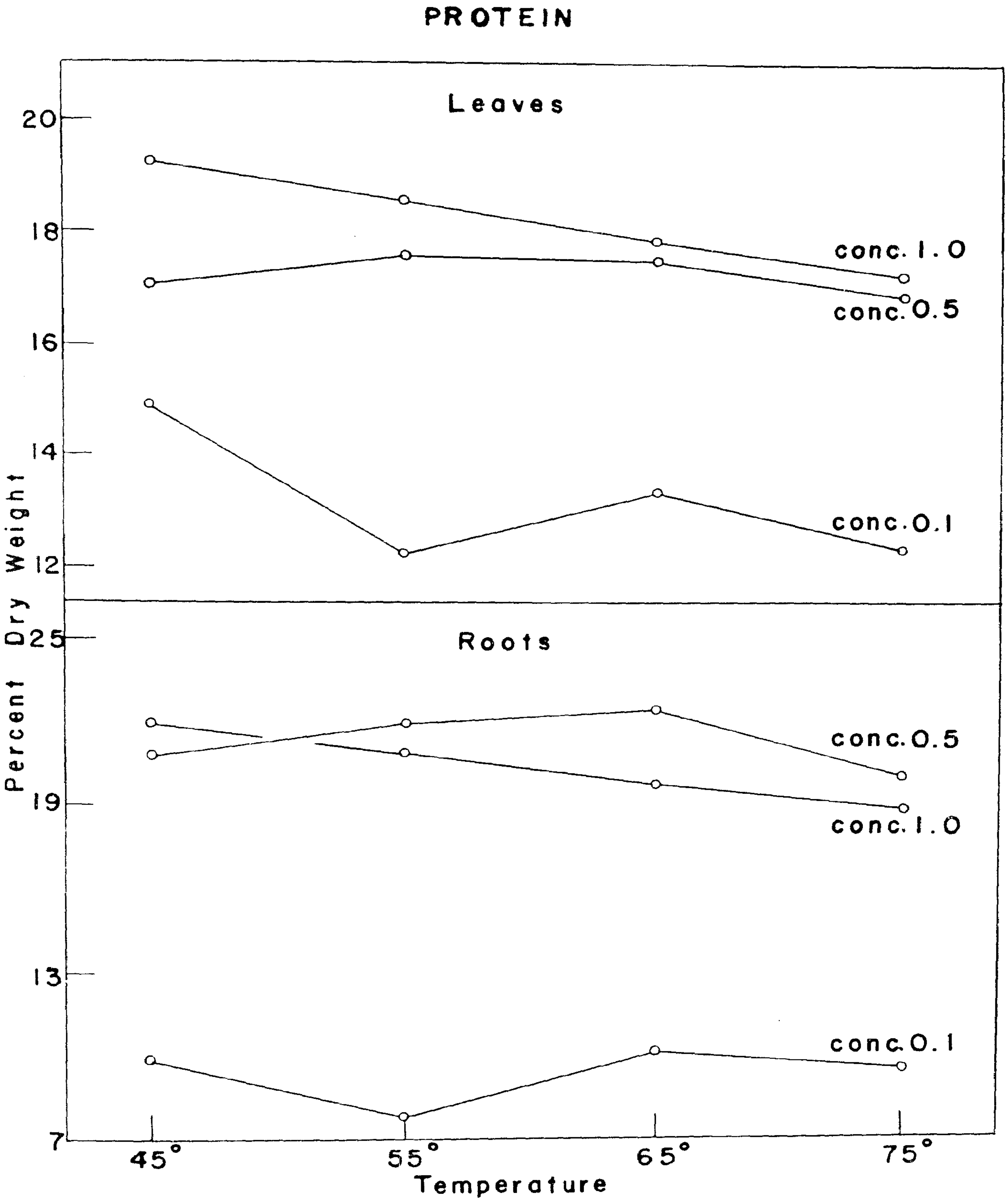


Figure 5. Effects of root temperature and concentration of the nutrient solution on the protein content of the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

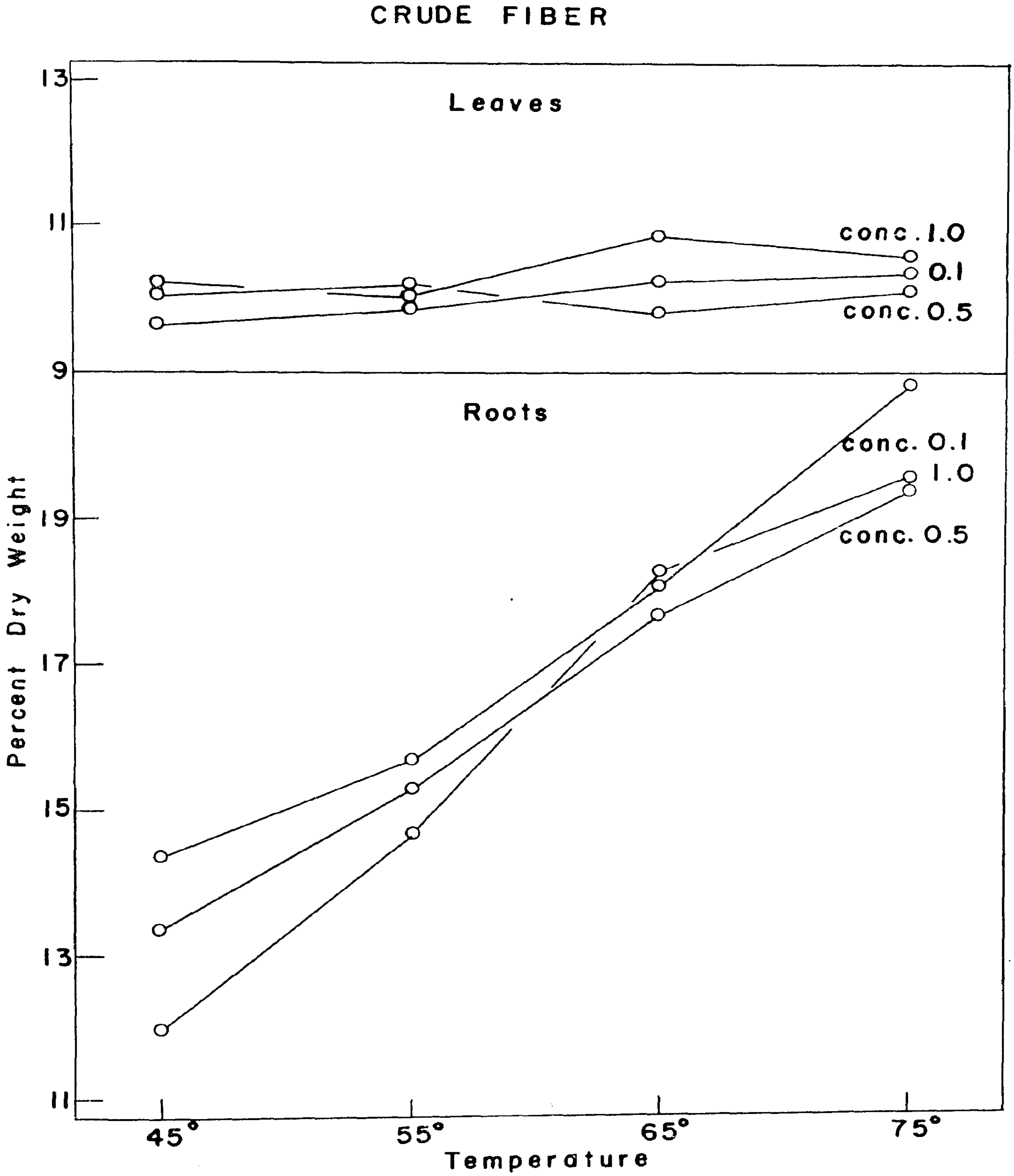


Figure 6. Effects of root temperature and concentration of the nutrient solution on the crude fiber content of the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

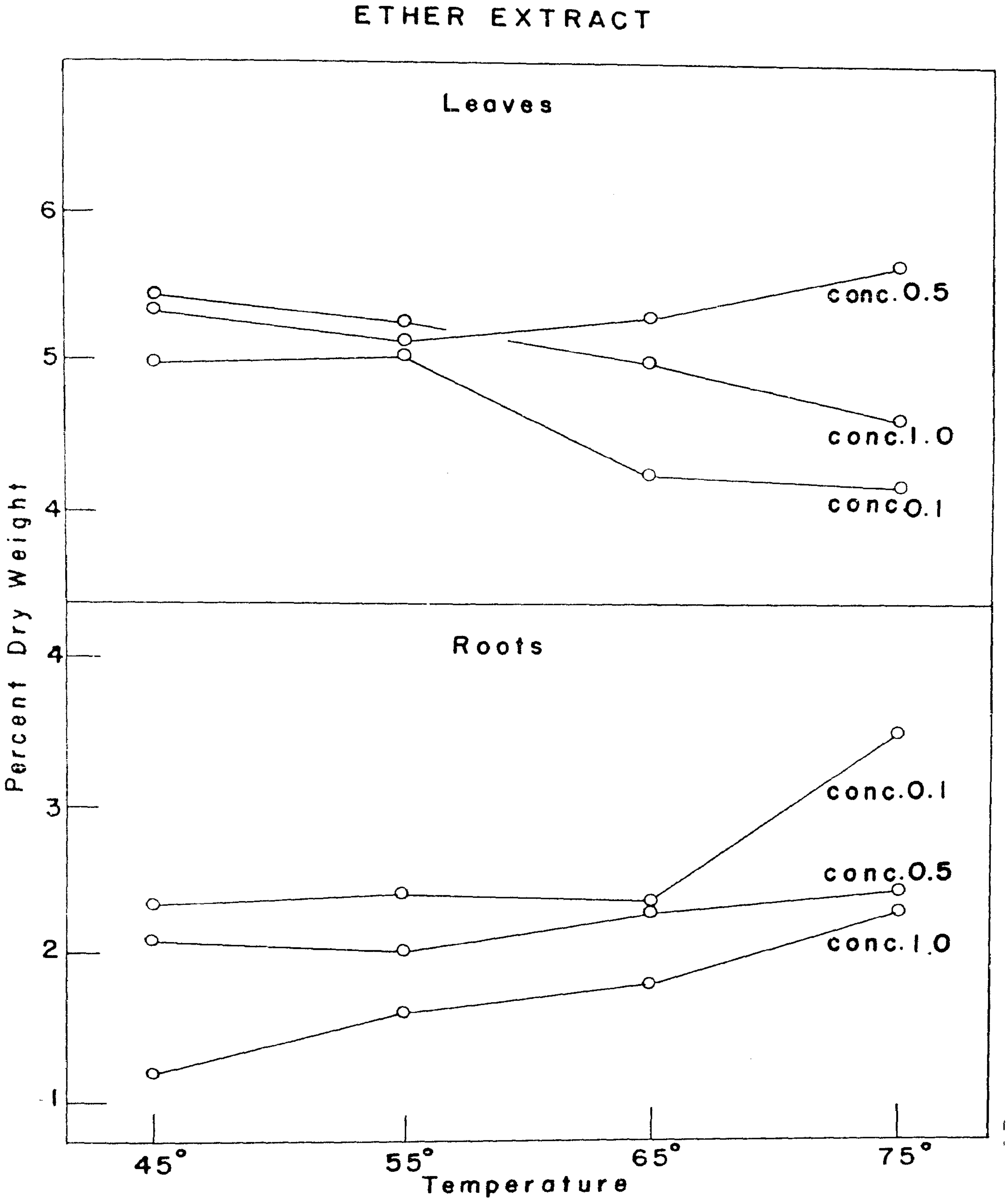


Figure 7. Effects of root temperature and concentration of the nutrient solution on the content of ether extractable materials in the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

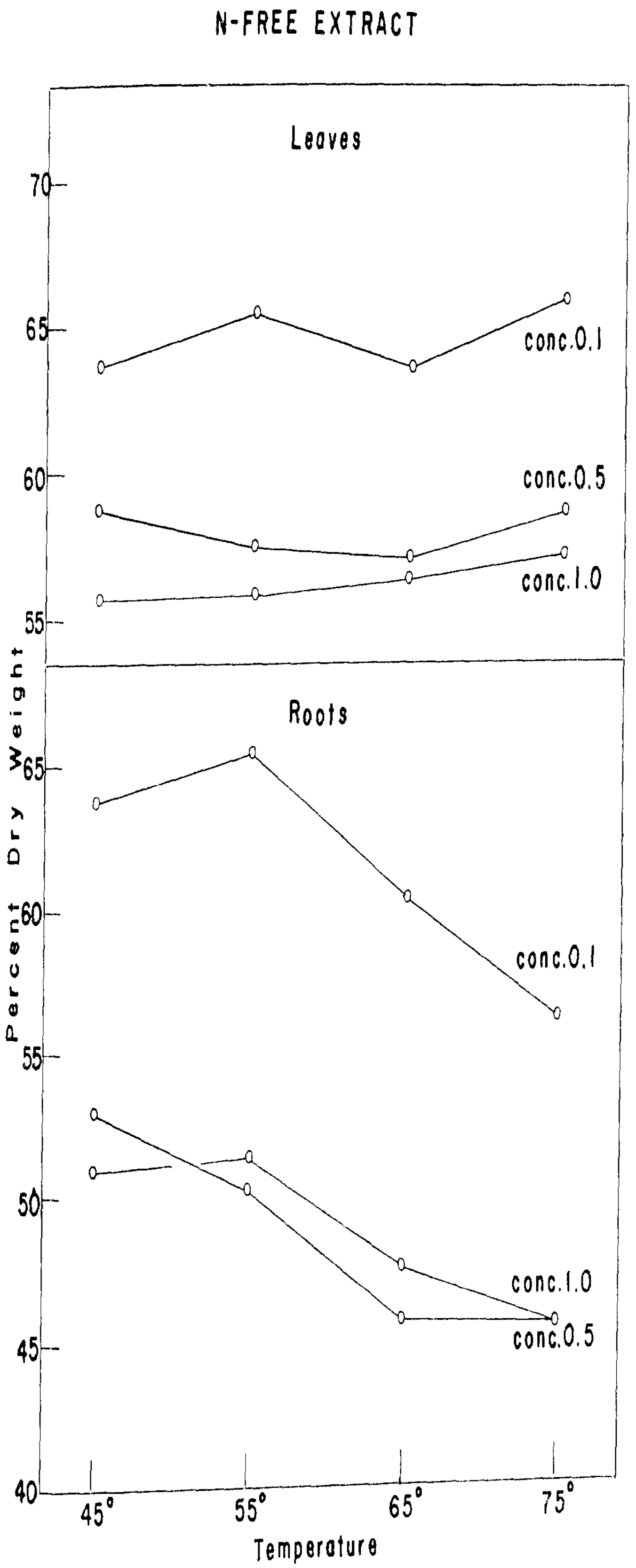


Figure 8. Effects of root temperature and concentration of the nutrient solution on content of nitrogen-free extract in the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

Root temperature did influence the amount of certain organic constituents contained in the roots of these plants. As was found for leaves, the protein content was not changed in the roots by root temperatures ranging from 45° F to 75° F. The amount of crude fiber accumulated by the roots increased steadily from 45° F to 75° F. The amount of ether-extractable materials was not significantly different at root temperatures of 45°, 55°, and 65° F. At 75° F there was a significant increase in ether-extractable materials.

Probably the most important and significant influence of root temperature on the organic composition of these strawberry plants was in the amount of nitrogen-free extract. Accumulation of the nitrogen-free extract fraction was definitely favored by the lower root temperatures. The greatest increase in the accumulation of nitrogen-free extract occurred between 55° F and 65° F.

Effect of Concentration of Nutrient Solution on Organic Composition

The data for the average percentage composition of organic materials in relation to concentration of the nutrient solution are given in Table VI and are presented in Figures 5-8.

The concentration of the nutrient solution had no significant effect on the percentage composition of crude fiber and ether-extractable materials in the leaves but did influence the amount of protein and nitrogen-free extract. The more concentrated solutions reduced the

TABLE VI

EFFECT OF CONCENTRATION OF NUTRIENT SOLUTION ON THE ORGANIC COMPOSITION OF THE ROOTS AND LEAVES OF ROBINSON STRAWBERRY

(Percentage Dry Weight)

Concentration of nutrient solution (Hoagland's)		Organic components			
		Protein	Crude fiber	Ether extract	N-free extract
		Leaves			
1.0		18.27	10.51	5.09	56.49
0.5		17.24	10.13	5.36	58.12
0.1		13.19	10.13	4.64	64.70
L.S.D. -	5% =	1.37	N.S.	N.S.	1.46
	1% =	2.07			2.21
		Roots			
1.0		20.42	16.14	1.74	48.87
0.5		21.32	16.48	2.22	48.81
0.1		9.35	17.26	2.68	61.58
L.S.D. -	5% =	2.04	N.S.	0.41	2.31
	1% =	3.09		0.62	3.50

N.S. -- F value not significant

nitrogen-free extract content of the leaves. There was a significantly greater amount of proteinaceous materials present in the leaves of the plants grown in the 0.5 and 1.0 Hoagland's solution than in those grown in the 0.1 solution. However, the 1.0 solution concentration did not significantly increase the protein content of the plants over that of the 0.5 Hoagland's solution.

In the roots, as in the leaves, the concentration of the solution did not significantly change the percentage of crude fiber, but did affect the content of protein, ether-extract and nitrogen-free extract. The roots had the same protein content when grown in a 0.5 as in a 1.0 Hoagland's solution. At a concentration of 0.1, there was a very marked reduction in protein content. There was more ether-extractable material present with lower concentrations of the nutrient solution. The percentage dry weight of nitrogen-free extract was essentially the same when grown in a 1.0 as in the 0.5 Hoagland's solution. On a percentage basis, there was a large increase in these materials when the concentration of the solution was reduced to 0.1 Hoagland's.

Effect of Root Temperature on Ash Composition

The average percentage composition of total ash and of eight of its constituents found in the leaves and roots of the plants grown at various root temperatures are evaluated statistically in Tables VII and VIII. A summary of some of these results are to be found in Figures 9-13.

TABLE VII

EFFECTS OF ROOT TEMPERATURE ON THE NUTRIENT-ELEMENT COMPOSITION OF THE ROOTS AND LEAVES OF ROBINSON STRAWBERRY PLANTS

(Percentage Dry Weight)

Root temperature (° F)	Nutrient elements								Total ash
	K	P	Ca	Mg	B	Fe	Mn	Cu	
Leaves									
75	2.37	.740	2.28	.554	.0125	.024	.612	.0005	8.51
65	2.29	.923	2.04	.502	.0107	.025	.740	.0010	9.27
55	2.23	.842	1.69	.638	.0119	.025	1.306	.0008	8.87
45	2.15	.996	2.06	.699	.0110	.030	.901	.0008	8.23
L.S.D. - 5% =	0.15	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
1% =	0.22								
Roots									
75	1.98	.819	.228	.490	.0019	.633	.025	.0001	11.92
65	1.20	.506	.240	.502	.0020	.800	.030	.0001	11.06
55	1.57	.403	.227	.559	.0024	.533	.033	.0001	9.98
45	2.07	.407	.133	.602	.0021	.767	.020	.0001	11.25
L.S.D. - 5% =	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	1.32
1% =									1.90

N.S. -- F value not significant

TABLE VIII

EFFECTS OF THE CONCENTRATION OF THE NUTRIENT SOLUTION ON THE NUTRIENT-ELEMENT COMPOSITION OF THE ROOTS AND LEAVES OF ROBINSON STRAWBERRY PLANTS

(Percentage Dry Weight)

Solution concentration (Hoagland's)	Nutrient elements								Total ash
	K	P	Ca	Mg	B	Fe	Mn	Cu	
				Leaves					
1.0	2.47	1.288	1.59	.638	.0170	.019	.796	.0012	9.65
0.5	2.23	.861	1.58	.544	.0108	.025	.078	.0007	9.16
0.1	2.08	.477	2.88	.613	.0068	.035	1.800	.0005	7.35
L.S.D. - 5% =	0.13	.393	.85	N.S.	.0025	.007	N.S.	N.S.	0.81
1% =	0.19	.617	1.34		.0040	.011			1.22
				Roots					
1.0	2.13	1.008	.353	.536	.0027	.700	.066	.0002	12.83
0.5	2.16	.313	.135	.623	.0020	.700	.013	.0001	11.19
0.1	1.43	.281	.134	.455	.0017	.650	.002	.0001	9.14
L.S.D. - 5% =	0.55	.302	.169	N.S.	.0004	N.S.	.015	N.S.	1.09
1% =	0.87	.474	.265		.0006		.024		1.64

N.S. -- F value not significant

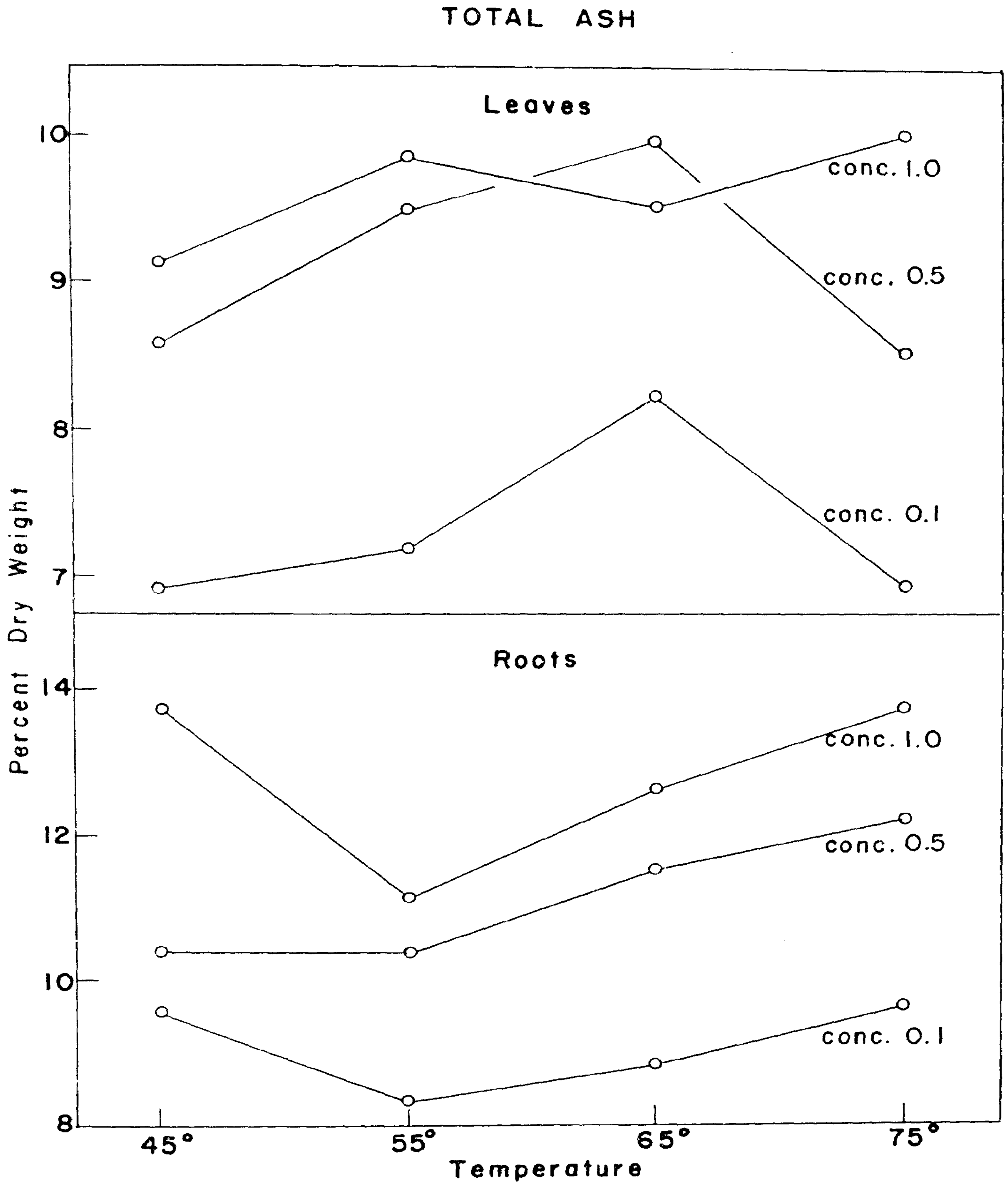


Figure 9. Effects of root temperature and concentration of the nutrient solution on the ash content of the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

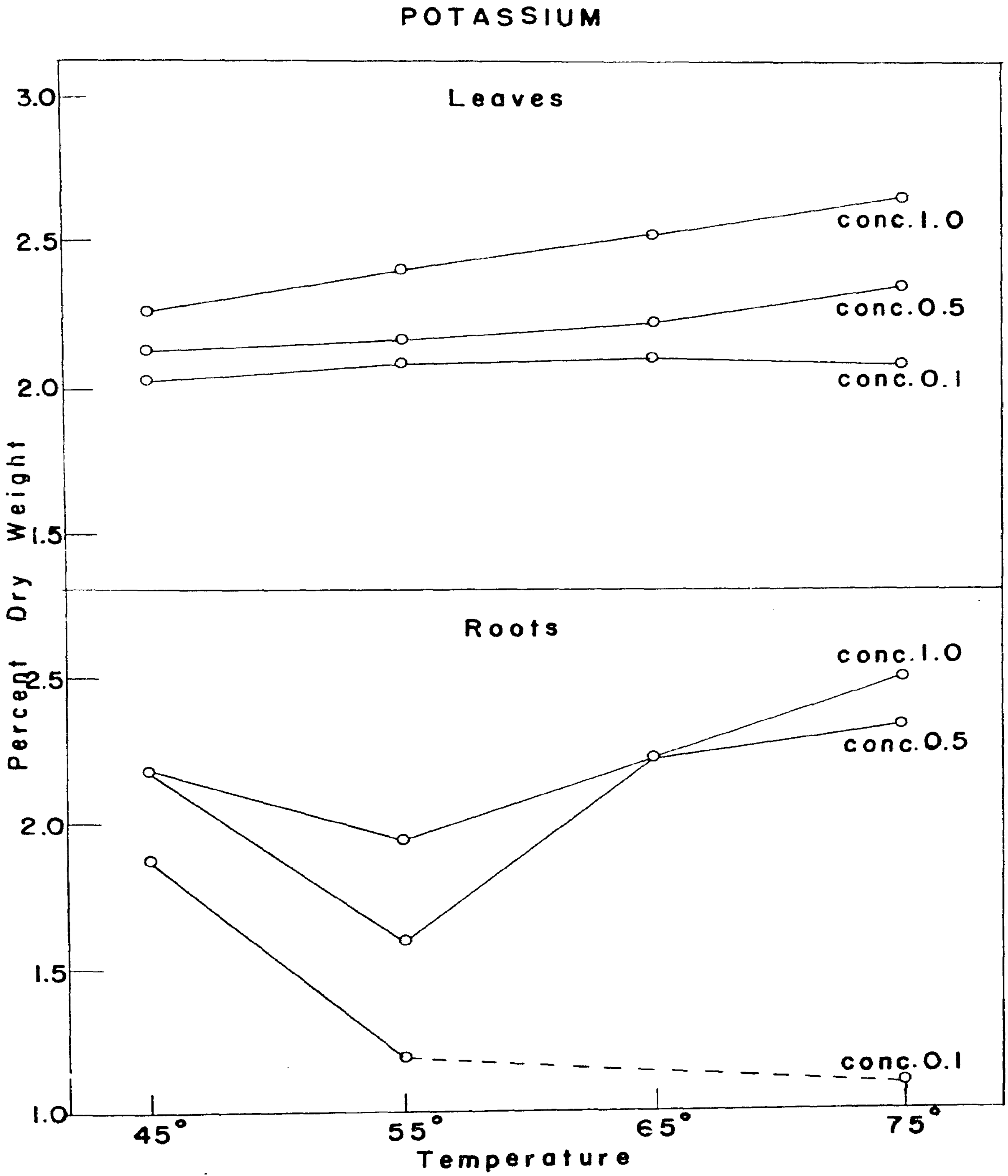


Figure 10. Effects of root temperature and concentration of the nutrient solution on the potassium content of the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

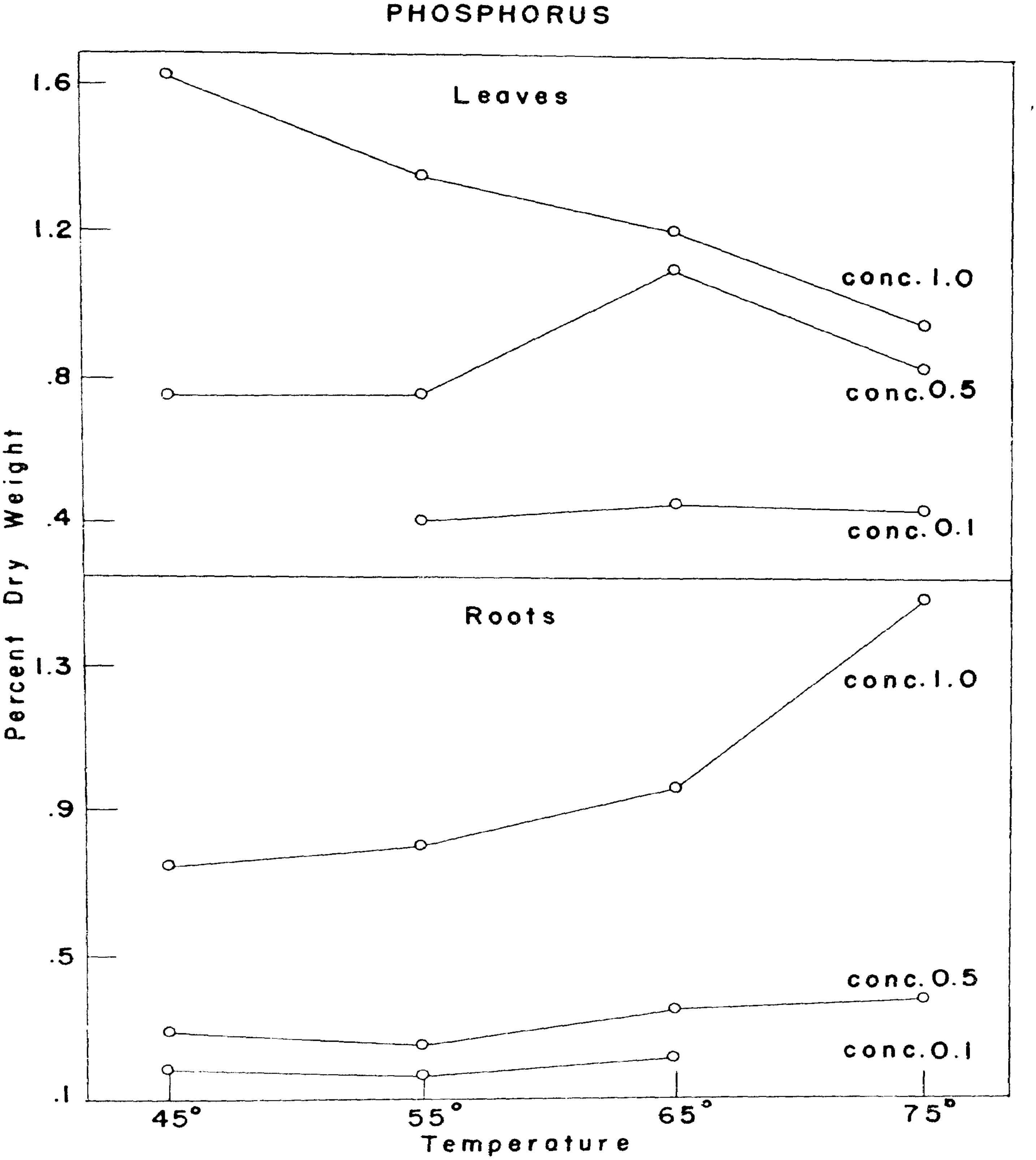


Figure 11. Effects of root temperature and concentration of the nutrient solution on the phosphorus content of the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

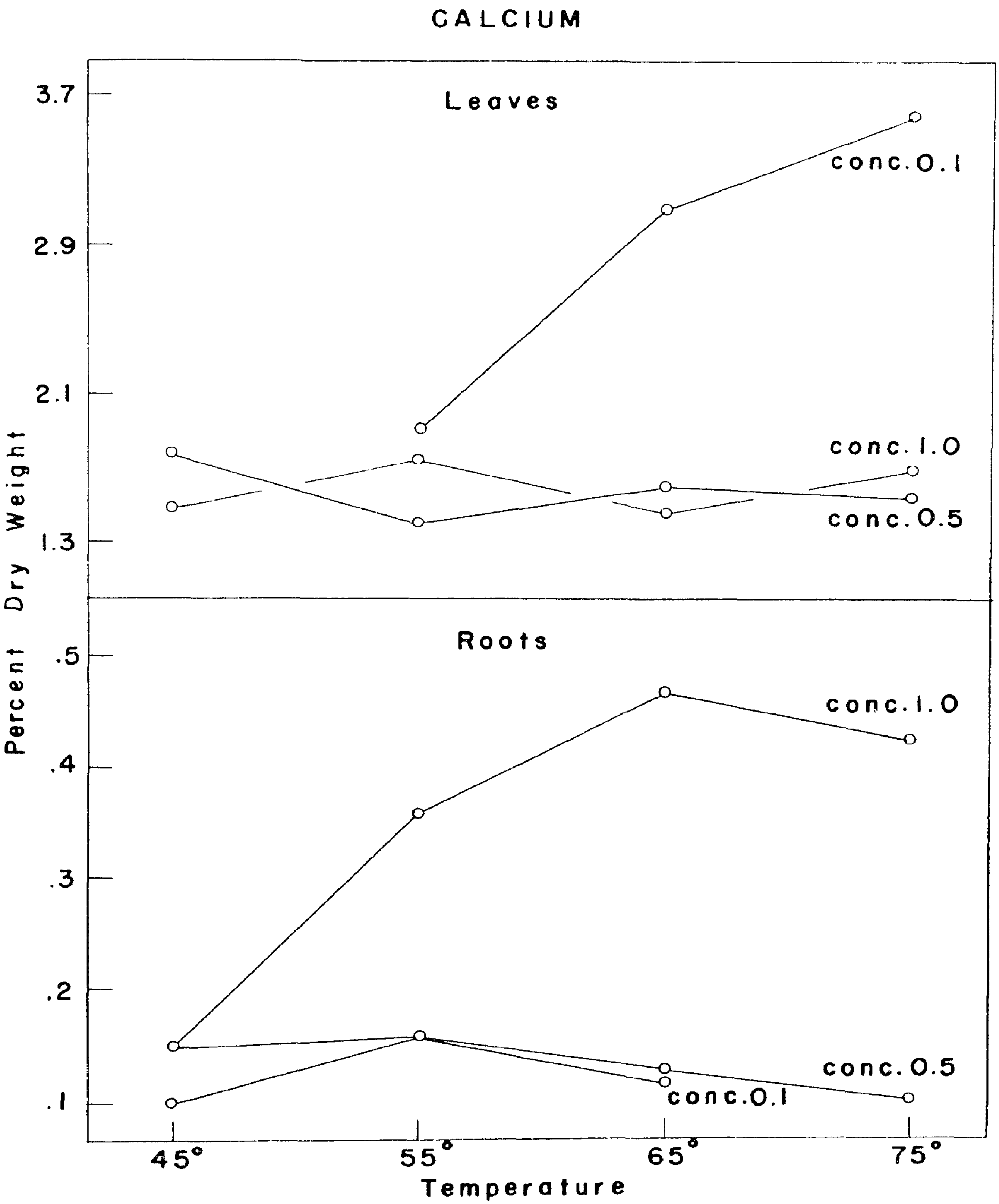


Figure 12. Effects of root temperature and concentration of the nutrient solution on the calcium content of the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

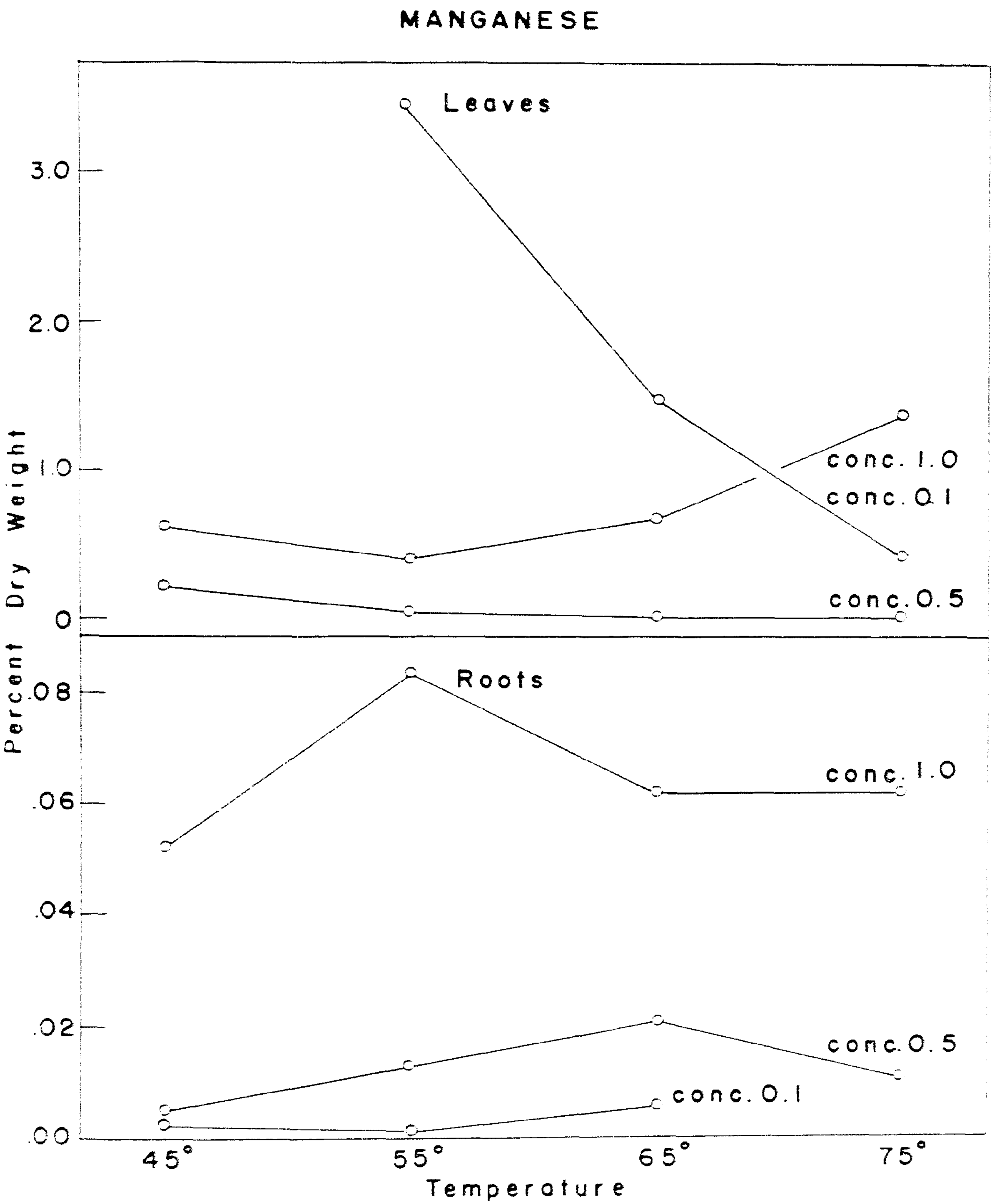


Figure 13. Effects of root temperature and concentration of the nutrient solution on the manganese content of the roots and leaves of the Robinson strawberry (Using 1.0, 0.5 and 0.1 Hoagland's solution).

With but one exception, neither the percentage of total ash nor any of its components (P, K, Ca, Mg, B, Fe, Mn, Cu) in the leaves were significantly influenced by root temperatures from 45° F to 75° F. The one exception was in potassium content. There was a trend of increasing content of potassium with increasing temperature from 45° F to 75° F.

The fact that differences in mineral content of the leaves and roots was obtained with changes in concentration of the nutrient solution lends support to the assumption that the above findings were not a result of inability of the analytical methods used to accurately measure the differences. Since, all of the plant material of the plant part in question produced by eight plants in four replications was composited to obtain the sample used, it would seem that lack of differences cannot be attributed to sampling methods.

While there were significant differences in the total ash content of the roots that could be linked to differences in root temperature, these could not be attributed statistically to any of the eight nutrient elements for which determinations were made. The percentage of total ash in the roots, appeared to be affected by the concentration of the solution used at low temperatures (45° F). There was less effect at 55° F. However, with temperatures of 55° F and above, there was a further increase in total content of minerals.

Effect of Nutrient Concentration on Ash Composition

Table VIII and Figures 9-13 show that the concentration of the nutrient solution had a more pronounced effect on the mineral content of the strawberry than did root temperature.

The total ash content of the leaves increased with greater concentrations of the nutrient solution. However, total ash of the leaves of plants grown in the 1.0 solution was not statistically greater than that of plants grown in the 0.5 solution. The percentage content of potassium, phosphorus and boron in the leaves increased with higher concentrations of the nutrient solution, whereas that of calcium and iron was less with higher concentrations of the nutrient solution. There was no significant change in the percentage content of magnesium, manganese and copper in the leaves.

The total ash content of the roots increased with each concentration increment of the Hoagland's solution. There was no significant change in the composition of the roots with respect to magnesium, iron, and copper associated with concentration of the nutrient solution. Phosphorus, calcium and manganese increased with concentration increments of the Hoagland's solution. There was an increase in the potassium and boron content of the roots associated with increasing solution concentration. The potassium content of the roots was not significantly increased when the concentration of the nutrient solution was changed from 0.5 to 1.0 Hoagland's.

Correlations

Using the results of the analyses, correlations were determined for various constituents. Correlations or relationships between the organic fractions and nutrient elements of the plant aid in the interpretation of the effects of root temperatures and nutrient intensity on the growth behavior of these strawberry plants. Since nitrogen-free extract and protein were the two organic constituents that are directly related to the photosynthetic-respiratory balance and may be in a form that is utilized either in growth or respiration, the trends in percentage composition of these two constituents were correlated with each other and also with that of total ash and certain nutrient elements.

N-Free Extract and Protein

A significant correlation was found in both leaf and root tissue between the percentage of nitrogen-free extract and protein content (Figures 14 and 15). The coefficient of correlation was -0.864 for root tissue and -0.984 for leaf tissue. These negative correlations indicated that increases in the percentage of proteinaceous material in the leaves and roots was accompanied with decreases in the percentage of carbohydrate fractions.

N-Free Extract and Total Ash

The relationships between the percentage nitrogen-free extract and total ash, on a dry weight basis, in the roots and leaves are illustrated in Figures 16 and 17. A coeffi-

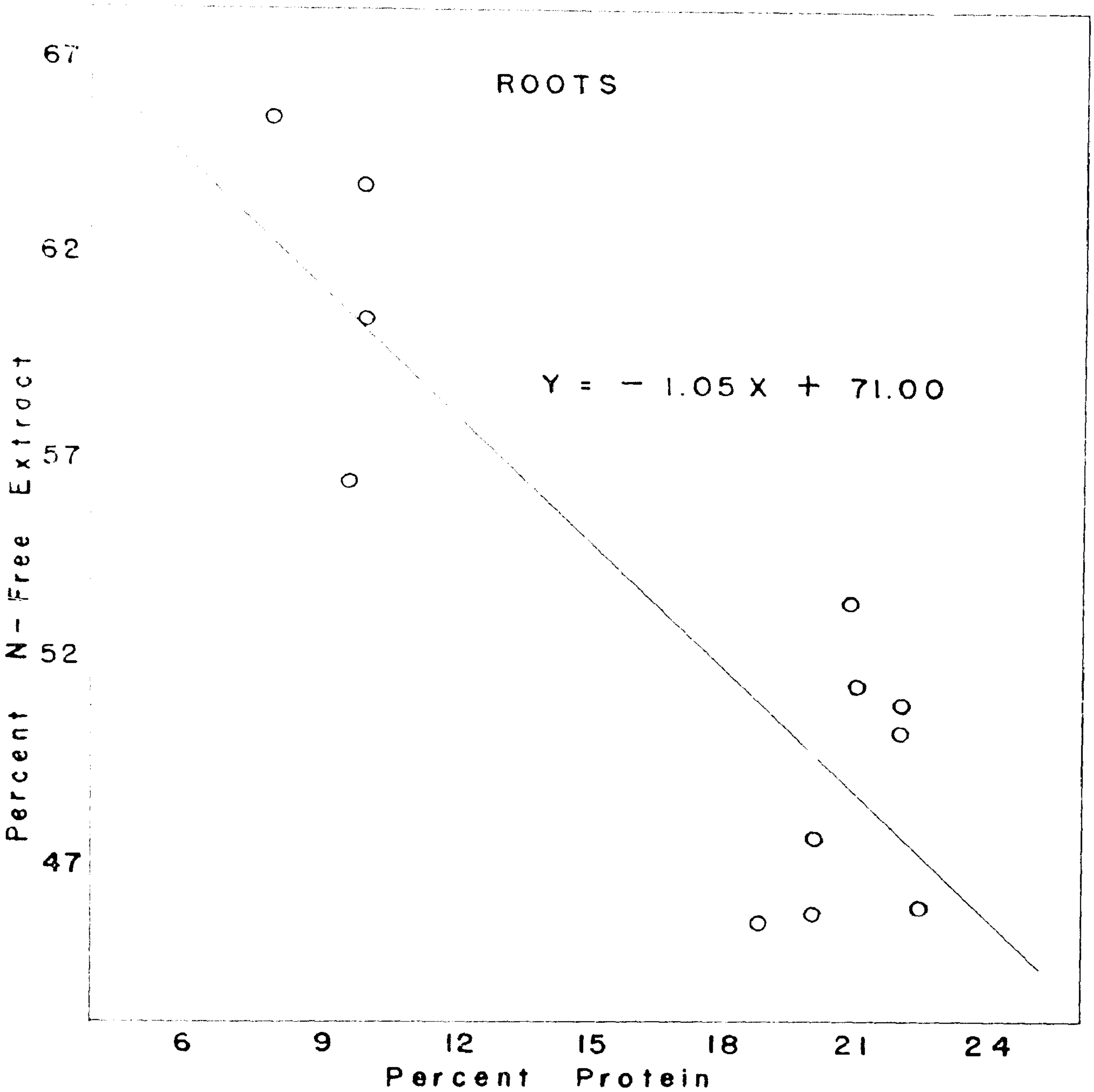


Figure 14. Relationship between percentage of nitrogen-free extract and percentage of protein on a dry weight basis in the roots of Robinson strawberry plants subjected to various root temperatures and nutrient concentrations.

Coefficient of Correlation = -0.864

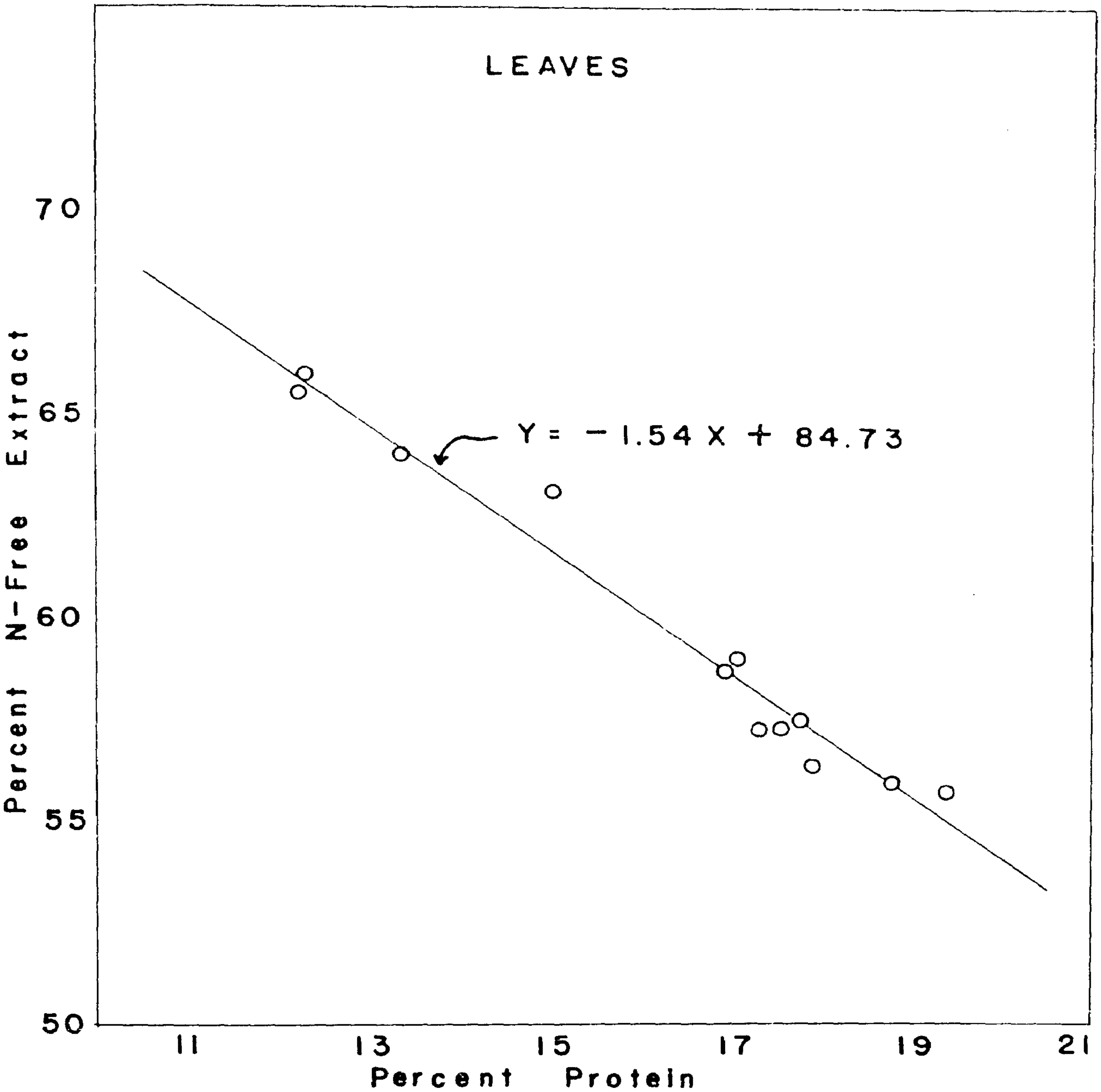


Figure 15. Relationship between percentage of nitrogen-free extract and percentage of protein on a dry weight basis in the leaves of Robinson strawberry plants subjected to various root temperatures and nutrient concentrations.

Coefficient of Correlation = -0.984

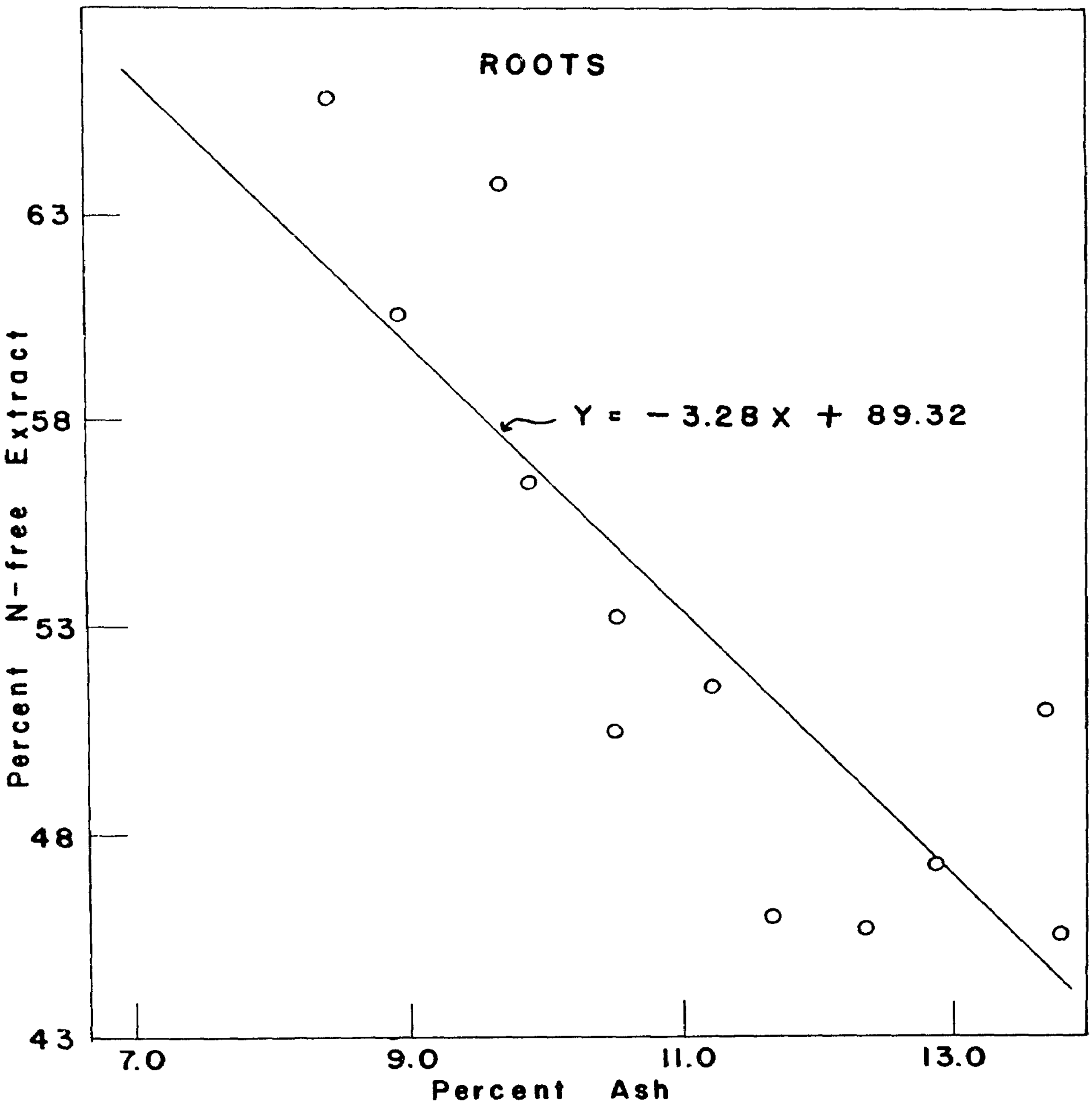


Figure 16. Relationship between percentage of nitrogen-free extract and percentage of total ash on a dry weight basis in the roots of Robinson strawberry plants subjected to various root temperatures and nutrient concentrations.

Coefficient of Correlation = -0.837

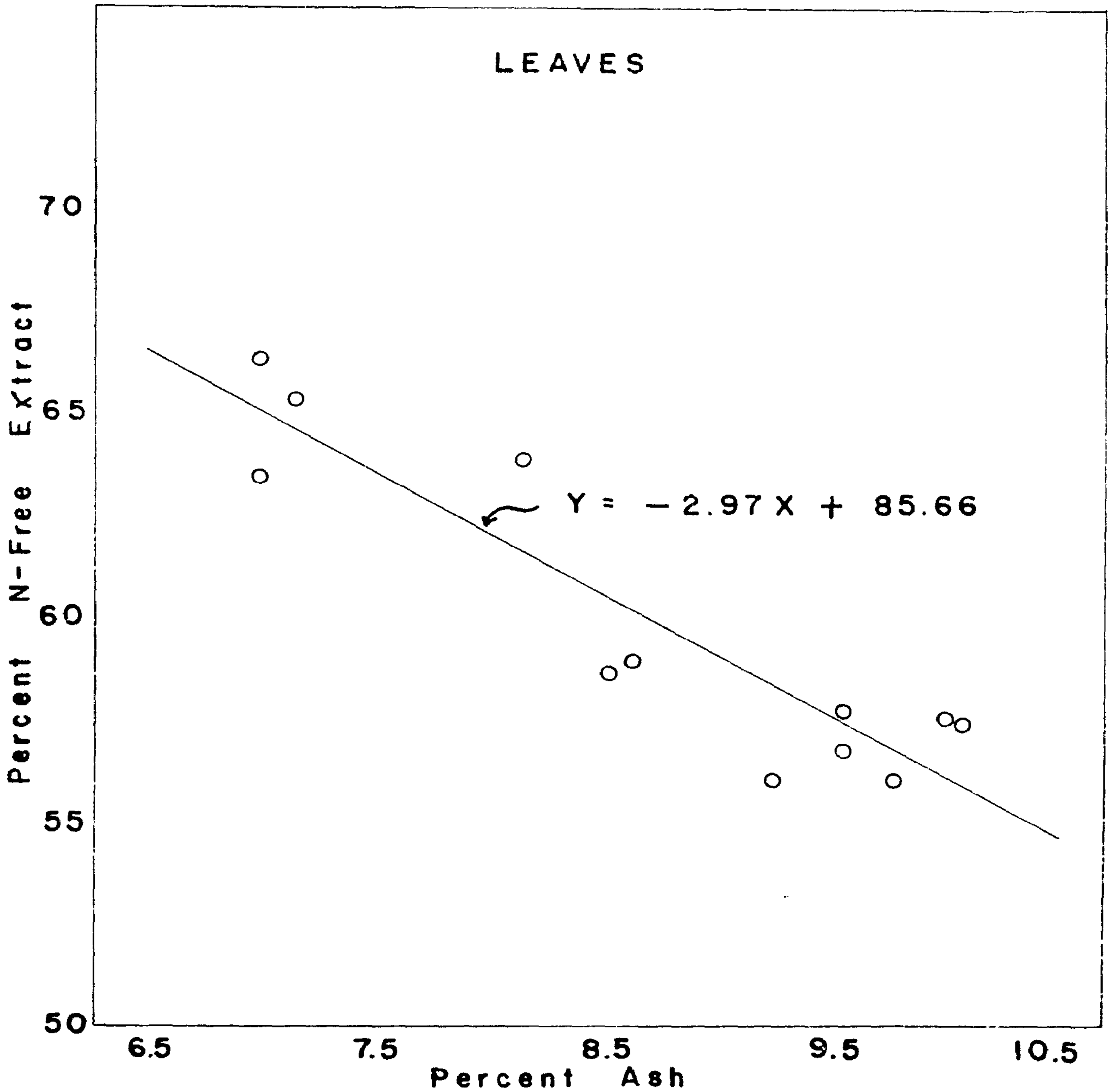


Figure 17. Relationship between percentage of nitrogen-free extract and percentage of total ash on a dry weight basis in the leaves of Robinson strawberry plants subjected to various root temperatures and nutrient concentrations.

Coefficient of Correlation = -0.906

cient of correlation of -0.906 was obtained for these fractions in the leaves and -0.837 in the roots. These negative correlations showed that increases in total ash content of the leaf and root tissues were accompanied by decreases in the utilizable carbohydrates (nitrogen-free extract).

N-Free Extract and Potassium

Since potassium was the only constituent of the total ash that showed significant differences in percentage composition as a result of changes in root temperature, a comparison was made between the percentage content of this element and that of the organic component measured as nitrogen-free extract. Significant correlations were obtained (Figures 18 and 19). In the leaf tissue the coefficient of correlation between content of nitrogen-free extract and potassium was -0.687, while in the roots it was -0.731.

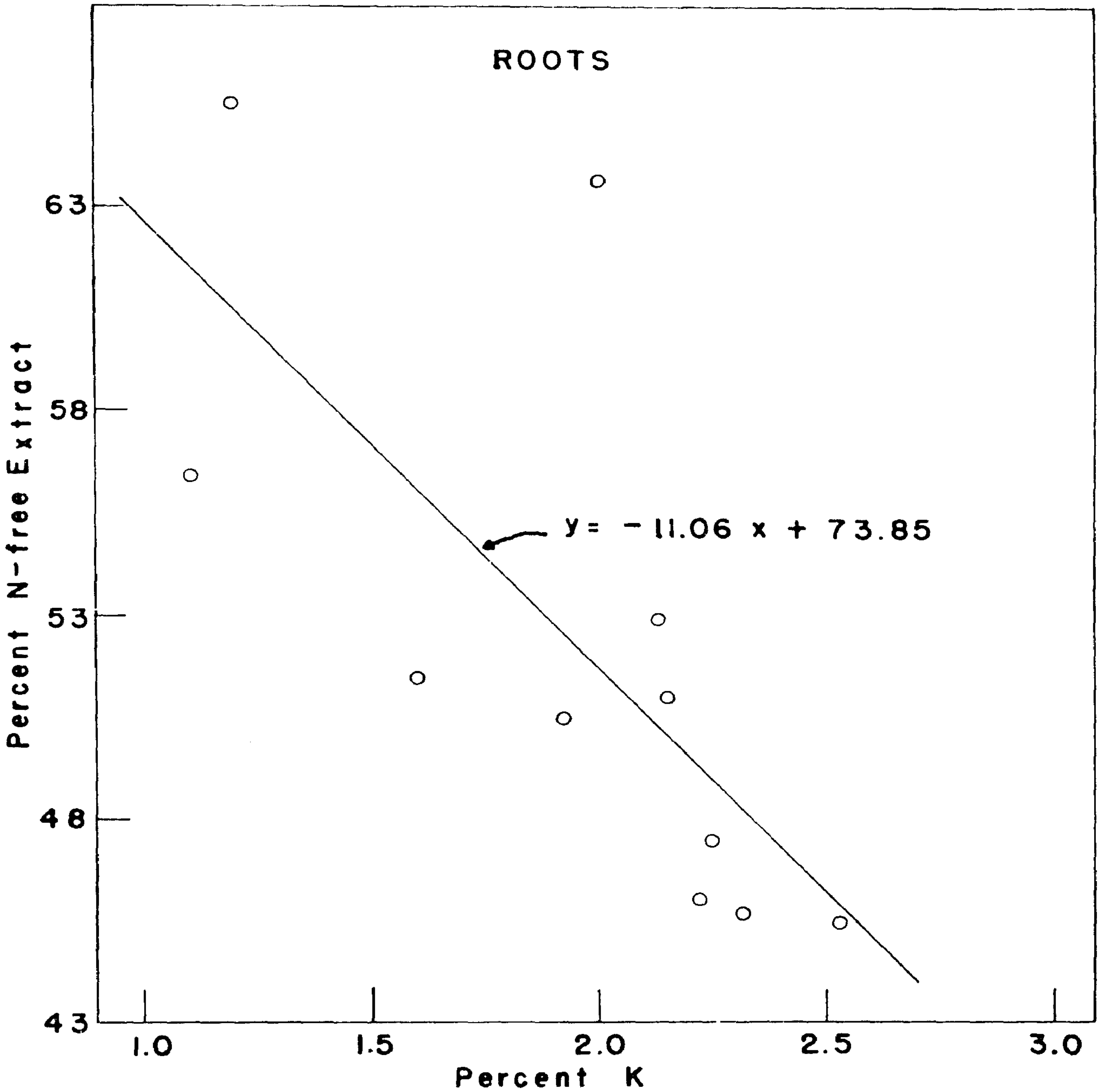


Figure 18. Relationship between percentage of nitrogen-free extract and percentage of potassium on a dry weight basis in the roots of Robinson strawberry plants subjected to various root temperatures and nutrient concentrations.

Coefficient of Correlation = -0.731

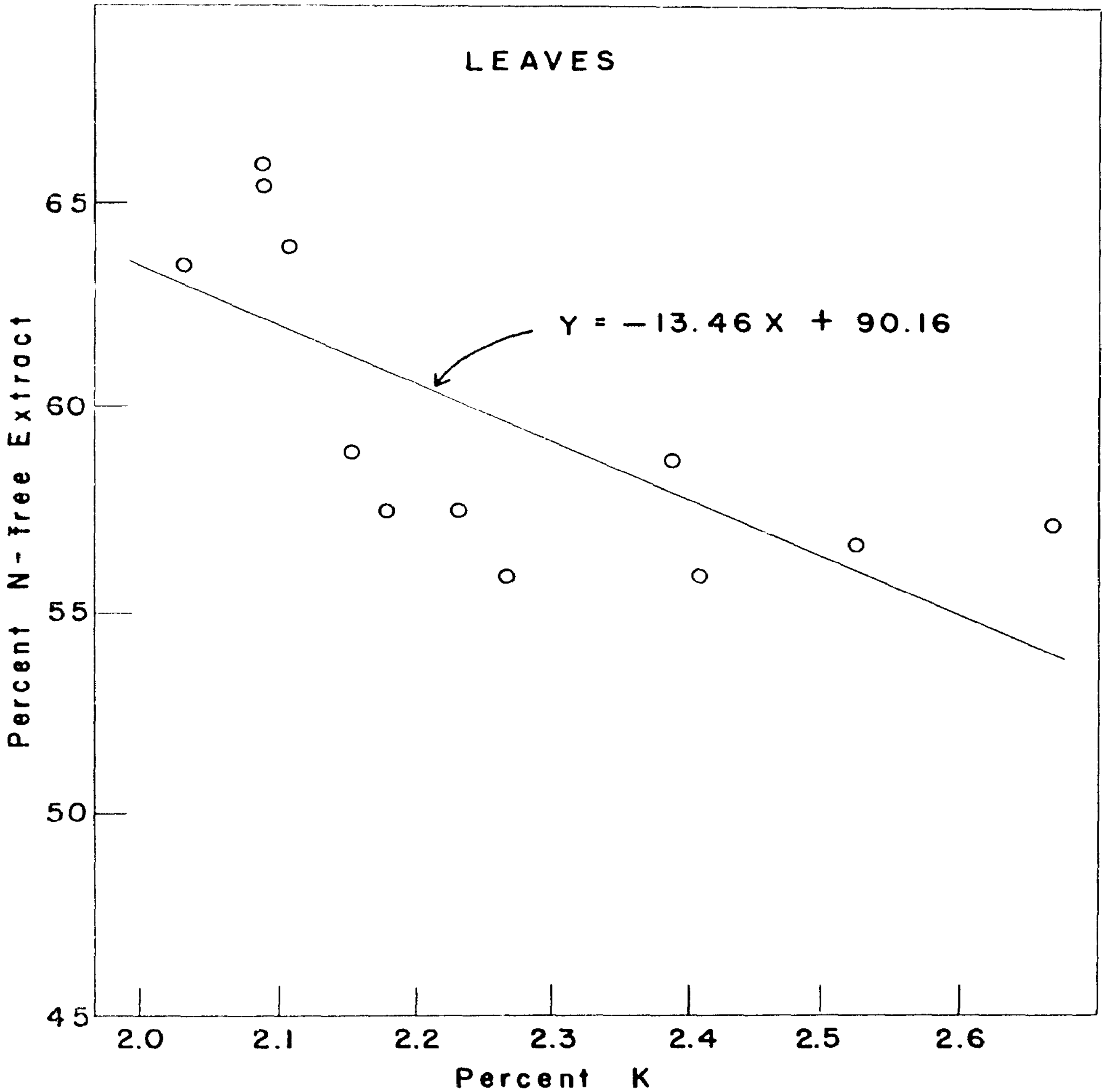


Figure 19. Relationship between percentage of nitrogen-free extract and percentage of potassium on a dry weight basis in the leaves of Robinson strawberry plants subjected to various root temperatures and nutrient concentrations.

Coefficient of Correlation = -0.687

DISCUSSION

In interpreting the results of these studies it should be kept in mind that the plants were in a stage of development where vegetative extension of both the tops and roots was taking place. The aerial environment of the plants during this period of development would be comparable both in temperature and light intensity to those found under normal Michigan field conditions. The period of time in which the vegetative growth was made in this experiment may be considered comparable to that found in the field during the spring and summer when newly planted strawberry plants are making their vegetative growth.

Root Temperature in Relation to Growth and Development

The data obtained in these studies indicated that, during the vegetative period of development, the production of aerial portions of the plant (leaves, petioles, crowns and runners) was closely correlated with root temperatures. As temperatures were varied from 45° F to 65° F there was a progressive increase in the dry weight of these plant parts and also in the height and spread of the plants as a result of increased petiole length. This increase in vegetative extension was also expressed in increased numbers of leaves and runners. Since there was no significant increase in the weight of these vegetative portions of the plant with an additional increase in root temperature to 75° F, it would appear that root temperatures between 65° F and 75° F were approximately "optimum" for growth and development of this variety of strawberry under normal or average conditions of light and air temperature. The close correlation observed between root temperature and shoot growth within certain temperature limits was in agreement with that found for apples (Nightingale, 1935; Batjer, 1939), peaches (Proebsting, 1943) and roses (Shanks and Laurie, 1949). If conditions for growth were wholly adequate in these studies, the results were not in agreement with those of Went, who was of the opinion that, if growing conditions are favorable, root temperature had very little if any effect on total plant growth.

As observed by Shanks and Laurie (1949) with roses and by others working with field crops, there was also a striking increase in top-root ratio with each increment in root temperature from 45° to 75° F. This indicated that high root temperatures favored growth of the top more than that of the roots.

Although there was no significant difference in the weight of roots produced at root temperature increments from 45° to 75° F, there was a steady, if but slight, decrease in root weight with each increase in root temperature, especially in the two higher nutrient concentrations. This was in agreement with the results obtained by Stuckey (1942), Brown (1939), and Darrow, R. A. (1939) for forage grasses and by Dickson (1923) and Wort (1940) for grains. These workers observed less root weight as soil temperature increased within the range of soil temperatures occurring during the growing season. Earley and Cartter (1945) called attention to the fact that light intensity may be a factor in determining the amount of root growth resulting from increases in root temperature. Light intensity was not considered as a limiting factor, however, during the period of this experiment.

The type of root system produced under the several root temperatures compared in a general way with those described by Nightingale (1935) and by Batjer (1939) for apple and peach, Stuckey (1942) for grasses and Shanks and Laurie (1949) for roses. At relatively low temperatures the roots were white, translucent and relatively unbranched. At higher temperatures the roots tended to be more slender and profusely branched. At the highest temperature (75° F) the roots were finer, more fibrous and less extensive than at the lower temperatures. Sections prepared from these various root materials, showed, in general, the same morphological differences described by Nightingale (1935) in his studies with the apple and peach.

When the total growth of both aerial and root portions were considered, it was apparent that a root temperature between 65° and 75° F was most favorable for maximum dry weight accumulation during the period of vegetative extension.

Concentration of Nutrient Solution in Relation to Growth and Development

The concentration of the nutrient solution was apparently near optimum at 0.5 Hoagland's. The 0.1 solution was too dilute even though renewed at frequent intervals. Increasing the concentration of the nutrient solution above the "optimum" (0.5 Hoagland's) had no significant effect on top growth when root temperatures were below 55° F. There was no difference in dry weight production of the tops. However, increasing the concentration of the solution to 1.0 Hoagland's when the root temperature was 65° F proved detrimental to growth of the tops. This detrimental effect of added concentration of nutrient salts was reduced by further increase of root temperature to 75° F.

The above results appeared to support the hypothesis that, under certain conditions, salt concentration may increase respiration to the extent of depleting organic reserves at higher root temperatures. Under the conditions of the growth period during this experiment, maximum growth of the tops was obtained at nutrient concentrations far below those that were used without visible injury to the root system. Total growth of the top was less at higher nutrient concentrations, if root temperatures were high.

Very dilute solutions (0.1 Hoagland's) even though continually renewed resulted in less total growth of roots. As in the case of the aerial portions of the plant maximum growth was obtained at a nutrient concentration of 0.5, which was much below that of 1.0. While there was no significant difference in the dry weight of roots produced by increasing the concentration of the nutrient solution from 0.5 to 1.0, there was a tendency for root production to be slightly greater at all temperatures in the 0.5 than in the 1.0 Hoagland's solution. This gave further support to the conclusion that excessively high salt concentrations can result in less total growth even in the absence of visible signs of injury.

Both root temperature and the concentration of the nutrient solution had greater effects on dry weight production of aerial portions of the plant than on those of the roots. This indicated that, during the period of vegetative extension of the plant, the aerial portions were more subject to influence from changes in these environmental conditions.

Root Temperature in Relation to Plant Composition

Organic Composition

Although root temperature had a profound effect on the total growth of the aerial portions of the plant, the organic composition of the leaves remained unchanged for the different root temperatures. If there were any changes in assimilation, translocation or utilization of organic materials as a result of changes in root temperatures from 45° to 75° F, they were not detectable in the percentage composition of the various organic fractions of the foliage used in these tests.

The significant changes in the organic composition of the roots associated with root temperature indicated that the effect of temperature on organic constituents were more or less localized. The increases in crude fiber and ether-extractable materials which were accompanied by decreases in nitrogen-free fractions and associated with increasing root temperatures, indicated that respiration and maturation processes were increased with higher root temperatures.

Since, the above changes in organic composition were not accompanied with increased total dry weight of the plant, they were only an indication of a normal shift in composition related to increased growth and metabolism as a result of increased root temperature within the optimum range. The lowest root temperatures used in this series of treatments were sufficient to reduce either assimilation or translocation, or both, to the extent that total growth of the tops was reduced. However, the highest temperature was not sufficient to reduce growth through depletion of carbohydrate reserves of the roots as was found by Nightingale and Blake (1934), Hewitt and Curtis (1948), Benedict (1950), et al working with excessively high root temperatures on other crops.

Total Ash and Nutrient-Element Composition

On the basis of the data obtained in these studies, root temperatures appeared to have very little if any appreciable effect on the mineral composition of the aerial parts of the plant during the vegetative phase of development. There was no significant increase in the percentage of total ash in the leaves associated with the increased dry weight production that resulted from increased root temperature. Of the several nutrient elements determined in composition analyses, only potassium showed a significant change in relation to root temperature. The percentage of leaf potassium increased with higher root temperature.

The different root temperatures influenced the ash content of the roots more than they influenced the ash content of the leaves. At temperatures above 55° F, the total ash content of the roots was increased with higher temperature. However, at 45° F the ash content of the roots was not significantly different from that at the highest (75° F) temperature, which might indicate a concentration effect resulting from reduced growth.

The tendency for the ash content of roots to increase with higher temperatures indicated that salt accumulation may occur at the expense of certain organic constituents, which supply energy release, because there was also a decrease in growth. Also, the effects of temperature on percentage mineral composition of plant tissues appeared to be more or less localized in the plant part subjected to the temperature differences. This further supported the hypothesis that movement of nutrient elements within the plant was dependent upon respirable organic materials and energy from them at greater rate with higher temperatures.

The evidence obtained in these studies, and those reviewed in the literature, was not sufficient to demonstrate that the reduced rate of growth at low temperatures was due to a reduction in absorption of nutrient elements. More growth was made by plants grown in the 0.5 than in the 1.0 Hoagland's solution even though the amount of nutrient elements absorbed by the plants in the 1.0 Hoagland's solution was greater at all root temperatures.

Concentration of the Nutrient Solution in Relation to Composition

Organic Composition

Although the total concentration of salts in the nutrient solution had no appreciable effect on the percentage of crude fiber and other-extractable materials, it did influence the percentage of nitrogenous and nitrogen-free extractable constituents in both the leaf and root tissue. Maximum growth of the plant was not associated with either the highest percentage of protein or of nitrogen-free extract. The small amount of growth of the plants in the dilute nutrient solution resulted in an excessively high carbohydrate-nitrogen relationship. In the most concentrated nutrient solution there was a lower carbohydrate-nitrogen relationship. An intermediate relationship appeared to exist for those plants grown in the 0.5 Hoagland's solution maximum growth was obtained. A shift in the carbohydrate-nitrogen balance was accomplished by changing the concentration of the nutrient solution even though the same relative proportion of salts in the solution was maintained.

These differences in organic composition were more obvious in leaves than in the roots of the plants grown with the higher salt concentrations but less so at lower concentrations. When low nutrition levels exist, the demands of materials manufactured in the leaves for nitrogen constituents appeared to be dominant over those of the roots.

When there was no difference in the dry weight of roots resulting from the 0.5 and 1.0 Hoagland's solutions, there was, likewise, no difference in the percentage of protein and carbohydrate components. Greater leaf production resulted in slightly lower content of protein and significantly higher carbohydrate components (N-free extract).

Total Ash and Nutrient Element Composition

The concentration of salts in the nutrient solution had a marked effect on both the total ash content and several ash constituents, especially potassium, phosphorus, calcium, boron and iron. This was in agreement with the findings of Hoagland and Broyer (1936), and Wanner (1948) cited earlier for other plants. The percentage of total ash increased significantly with each increase in the relative concentration of the solutions. This increase in total ash was found in both roots and leaves. However, not all nutrient elements increased in percentage composition with increases in solution concentration. Although, potassium, phosphorus and boron increased in the leaf tissue as the solution concentration increased, calcium and iron decreased in percentage of dry weight. However, in root tissue all of the above nutrient elements increased in percentage content with higher solution concentrations.

There was an increase in total ash in both the root and leaf tissue with increased solution concentration regardless of root temperature. Since maximum growth was obtained in the 0.5 Hoagland's solution, where ash content of the plants was considerably below that found in plants grown in the 1.0 solution, "luxury absorption" appeared to have occurred for several of these elements. This "luxury absorption" of nutrient elements appeared to be accomplished at the expense of organic reserves. Hoagland and Broyer (1936), believed that nutrient element absorption was affected through an energy exchange mechanism with the energy being supplied by respirable substrates. There seemed to be some support for this hypothesis, since there was actually reduction in total growth when root temperatures were 65° and 75° F and the concentration of the nutrient solution was increased from 0.5 to 1.0. This was accompanied by reduction in the percentage of respirable carbohydrate materials. Also, the highest percentage of total ash in the plant tissues was not associated with maximum growth of the roots or tops.

Wanner (1948) was of the opinion that less energy was required to remove salts from solutions of high concentration than solutions of low concentration. Perhaps the observed "luxury" accumulation from solutions of high concentration was not entirely at the expense of respirable reserve carbohydrates. However, the reduced dry weight production or efficiency of more concentrated solutions at higher root temperatures did not occur in solutions of similar concentrations at lower temperatures (45° - 55° F). The lower Q_{10} ratings found by Wanner (1948) for more concentrated solutions were not observed in these studies.

Relation of Composition to Growth

The significant negative correlation found between nitrogen-free extract and protein content was suggestive of the long accepted relationship between carbohydrate and nitrogen in the plant (Kraus and Kraybill, 1913). Greater amounts of nitrogenous materials in the plant were accompanied by lesser amounts of metabolizable carbohydrate fractions (nitrogen-free extract) necessary for assimilatory processes. Plants making the maximum amount of growth, on the basis of dry weight production, had an approximate ratio of nitrogen-free extract to protein or nitrogenous components of 59:17 (3.5) in leaf tissue and 52:20 (2.6) in root tissues.

The inverse relation established between nitrogen-free extract and total ash was especially significant in that maximum growth was not associated with the highest ash content of the roots and foliage. Since, content of nitrogen-free extract was lower with higher ash content, the increase in ash content above that necessary for maximum growth appeared to result from the utilization of carbohydrate materials. This appeared to be especially true with conditions of low photosynthetic efficiency, and agreed with evidence presented in previously cited literature.

The composition of the plants that produced the largest amount of total dry weight indicated that the ratio of nitrogen-free extract to total ash was approximately 59:9 (6.6) in leaf tissue and was approximately 50:11 (4.6) in root tissue.

A significant negative correlation, similar to that in relation to total ash, was found between the nitrogen-free extract and potassium in the tissue.

Plant tissue analysis was considered to be of value in interpreting the growth status of plants, during a given phase of their development, if these analyses were correlated with the growth and development of the plants. If the maximum production of dry matter indicated metabolic efficiency, the composition of the plants that produced the maximum amount of dry matter could provide some hint as to the most desirable set of nutritional conditions for bringing about maximum production of plant products.

Apparently certain of the organic and mineral constituents changed materially as a part of the percentage composition of the plant during growth in response to environmental conditions such as root temperature and concentration of the nutrient solution. Of the organic constituents, the nitrogen-free extract and protein varied most in relation to growth. There was also considerable variation in total ash and certain ash constituents in relation to total dry weight production. Certain constituents showed a positive correlation with growth while others showed a negative correlation. In general there was no case where maximum growth could be associated with the maximum content of any organic or mineral component. Apparently, greatest efficiency in dry weight production was associated with certain balances between organic and mineral fractions.

As already discussed, such correlations if consistent would be useful in determining nutritional needs of the plant. If the balance were strongly in favor of the organic side, applications of nutrient salts would be indicated. However, if nutrient element composition were above the minimum necessary for maximum dry weight production during a given physiological age, further additions of nutrient salts might result in expenditure of reserve carbohydrate materials. If the supply of nutrient salts or if nutrient element composition should be below the minimum required for maximum growth, further additions of nutrient salts might result in an accumulation of reserve carbohydrate materials.

An accumulation of reserve carbohydrate materials was found to be associated with depressions of growth resulting from root temperatures. This indicates that when low root temperatures restrict plant growth there may be an accumulation of reserve carbohydrates. Conversely, when high root temperatures restrict plant growth there may be a depletion of reserve carbohydrates.

The physiological age or stage of development of the plant may reverse such effects of nutrient salts or root temperatures upon the accumulation of reserve carbohydrate materials. If the plant was in the stage of vegetative development, the above relationship may exist. However, if the plant was in the reproductive stage of development, the above relationship may be reversed.

SUMMARY

The influence of root temperature and concentration of the nutrient solution on the growth and composition of the Robinson strawberry was studied. Root temperature control was obtained by growing the plants in crocks of sand plunged in temperature control tanks designed especially for this purpose. Concentration of the nutrient solution was maintained by frequent renewal of sand cultures with various concentrations of Hoagland's standard nutrient solution. Growth measurements were based on the total production of dry matter and the number of runner plants produced. Organic and nutrient-element composition of the plant material produced was obtained by standard analytical procedures.

During the vegetative period of development, the growth of aerial portions of the strawberry plant was closely correlated with root temperature. Such a relationship was not present for root growth. Therefore, the top-root ratio increased as root temperature increased.

Maximum dry weight accumulation in both root and aerial portions of the strawberry plant occurred in nutrient solutions of relatively low salt concentration (0.5 Hoagland's solution). However, normal growth occurred in more concentrated solutions.

On the basis of dry weight accumulation, maximum growth of all aerial parts of the plant during this vegetative phase of development occurred at root temperatures between 65° and 75° F, regardless of nutrient solution concentration. There was no significant difference in dry weight of roots produced within the range of root temperatures used in this study (45° to 75° F), regardless of nutrient solution concentration used.

Although root temperature had a pronounced effect on the total growth of the aerial portions of the plant, the organic composition of the foliage was not significantly altered by differences in root temperature. However, there were significant changes in the organic composition of the roots with changes in root temperature. The temperature effects upon organic components appeared to be more or less localized within a given plant part.

Root temperature appeared to have very little, if any, appreciable effect on the nutrient-element composition of the aerial portions of the plant during the vegetative period of development. Total ash of the roots was subject to greater influence from root temperature differences than was the foliage.

The total concentration of salts in the nutrient solution had no appreciable affect on the percentage of crude fiber and ether-extractable materials, but influenced the percentage of nitrogenous and metabolizable carbohydrate (N-free extract) components in both the leaf and root tissue.

The concentration of salts in the nutrient solution had a marked affect on both the total ash content and several of its components in both root and leaf tissues.

A significant negative correlation was found to exist between the metabolizable carbohydrate (N-free extract) and nitrogenous (protein) fractions in both the roots and foliage of the strawberry at this stage of development.

A significant negative correlation was also found to exist between the content of ash and these metabolizable carbohydrate fractions in both the roots and foliage. The same was true for these carbohydrate materials and the ash component, potassium.

The possible influence of root temperature and of "luxury" absorption of nutrient elements on the efficient utilization of organic fractions and efficiency in dry weight production was considered.

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APPENDIX

TABLE IX

EFFECTS OF ROOT TEMPERATURE AND CONCENTRATION OF THE NUTRIENT SOLUTION ON THE PERCENTAGE DRY WEIGHT OF CERTAIN ORGANIC COMPONENTS IN THE LEAVES AND ROOTS OF ROBINSON STRAWBERRY PLANTS

(A summary of the statistical analysis is given in Tables V and VI of the text)

Plant part	Root temperature (° F)	Concentration of Hoagland's solution		
		1.0	0.5	0.1
		Nitrogen-free Extract - %		
Leaves	75	57.43	58.73	66.03
	65	56.60	57.40	63.83
	55	56.07	57.48	65.54
	45	55.84	58.87	63.41
Roots	75	45.57	45.70	56.44
	65	47.39	45.93	60.50
	55	51.46	50.39	65.63
	45	51.05	53.21	63.75
		Protein - %		
Leaves	75	17.25	16.88	12.31
	65	17.88	17.44	13.31
	55	18.63	17.63	12.19
	45	19.31	17.00	14.94
Roots	75	18.81	20.13	9.44
	65	19.81	22.44	10.13
	55	21.00	21.88	7.88
	45	22.06	20.81	9.94
		Ether Extract - %		
Leaves	75	4.65	5.66	4.22
	65	5.00	5.29	4.26
	55	5.27	5.15	5.05
	45	5.43	5.32	5.01
Roots	75	2.31	2.45	3.50
	65	1.78	2.32	2.42
	55	1.65	2.01	2.44
	45	1.22	2.09	2.35

TABLE IX CONT.

Plant part	Root temperature (° F)	Concentration of Hoagland's solution 1.0	0.5	0.1
		Crude Fiber - %		
Leaves	75	10.64	10.19	10.49
	65	10.96	9.90	10.33
	55	10.17	10.22	9.99
	45	10.26	10.22	9.69
Roots	75	19.55	19.46	20.88
	65	18.30	17.70	18.09
	55	14.74	15.29	15.70
	45	11.97	13.45	14.35

TABLE X

EFFECTS OF ROOT TEMPERATURE AND CONCENTRATION OF THE NUTRIENT SOLUTION ON THE PERCENTAGE DRY WEIGHT OF TOTAL ASH AND CERTAIN ASH COMPONENTS IN THE LEAVES AND ROOTS OF ROBINSON STRAWBERRY PLANTS

(A summary of the statistical analysis is given in Tables VII and VIII of the text)

Plant part	Root temperature (° F)	Concentration of Hoagland's solution 1.0	0.5	0.1
		Total Ash - %		
Leaves	75	10.03	8.54	6.95
	65	9.56	9.97	8.27
	55	9.86	9.52	7.23
	45	9.16	8.59	6.95
Roots	75	13.76	12.26	9.74
	65	12.72	11.61	8.86
	55	11.15	10.43	8.35
	45	13.70	10.44	9.61
		Phosphorus - %		
Leaves	75	0.950	0.830	0.440
	65	1.210	1.100	0.460
	55	1.360	0.755	0.410
	45	1.630	0.760	---
Roots	75	1.510	0.380	---
	65	0.970	0.339	0.210
	55	0.800	0.244	0.165
	45	0.750	0.288	0.183
		Potassium - %		
Leaves	75	2.66	2.36	2.09
	65	2.52	2.23	2.11
	55	2.41	2.18	2.09
	45	2.27	2.14	2.03
Roots	75	2.51	2.32	1.10
	65	2.25	2.22	---
	55	1.60	1.93	1.19
	45	2.16	2.15	1.89

TABLE X CONT.

Plant part	Root temperature (° F)	Concentration of Hoagland's solution 1.0	0.5	0.1
		Calcium - %		
Leaves	75	1.70	1.55	3.60
	65	1.45	1.58	3.10
	55	1.74	1.42	1.91
	45	1.47	1.78	---
Roots	75	0.430	0.100	---
	65	0.470	0.130	0.120
	55	0.360	0.160	0.160
	45	0.150	0.150	0.100
		Magnesium - %		
Leaves	75	0.627	0.446	0.588
	65	0.527	0.318	0.660
	55	0.794	0.630	0.490
	45	0.603	0.780	---
Roots	75	0.484	0.580	---
	65	0.316	0.630	0.560
	55	0.645	0.663	0.368
	45	0.700	0.620	0.485
		Boron - %		
Leaves	75	0.0185	0.0122	0.0069
	65	0.0151	0.0094	0.0076
	55	0.0185	0.0107	0.0064
	45	0.0158	0.0110	---
Roots	75	0.0026	0.0017	---
	65	0.0026	0.0018	0.0019
	55	0.0029	0.0022	0.0020
	45	0.0027	0.0021	0.0014
		Iron - %		
Leaves	75	0.017	0.025	0.030
	65	0.018	0.023	0.035
	55	0.021	0.020	0.035
	45	0.019	0.033	---

TABLE X CONT.

Plant part	Root temperature (° F)	Concentration of Hoagland's solution 1.0	0.5	0.1
		Iron - %		
Roots	75	0.500	0.800	---
	65	0.800	0.800	0.800
	55	0.600	0.500	0.500
	45	0.900	0.700	0.700
		Manganese - %		
Leaves	75	1.430	0.012	0.395
	65	0.695	0.015	1.510
	55	0.391	0.057	3.470
	45	0.668	0.228	---
Roots	75	0.063	0.011	---
	65	0.064	0.021	0.005
	55	0.084	0.014	0.001
	45	0.053	0.004	0.002
		Copper - %		
Leaves	75	0.0004	0.0007	0.0004
	65	0.0021	0.0006	0.0004
	55	0.0010	0.0008	0.0005
	45	0.0012	0.0008	---
Roots	75	0.0002	0.0001	---
	65	0.0002	0.0001	0.0001
	55	0.0001	0.0001	0.0001
	45	0.0001	0.0001	0.0001