

AN ABSTRACT OF THE THESIS OF

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(Name) (Degree)
in SOILS presented on May 6, 1971
(Major) (Date)

Title: LEAF STRESS IN CORN, BEANS, AND TOMATOES UNDER

OPTIMUM SOIL MOISTURE CONDITIONS

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Abstract approved:

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Under adverse soil moisture conditions a critical water stress or water potential develops in the plant and productivity is reduced, or in extreme cases, terminated. Research to determine the soil moisture status for maximum production of specific crops has been conducted for decades. The results have done much to increase the productivity of the irrigable acreage. Yet, even with irrigation water available, under adverse atmospheric conditions water stress will still develop in the agronomic crops. The degree of stress that develops and the duration, however, is generally unknown. Limited research in controlled environments has been conducted, but actual plant water stress levels under field conditions have not been studied.

The purpose of this research was to determine the levels of leaf water potential (water stress) that develop in specific horticultural crops under conditions of optimum soil moisture. Further

studies were made to relate the leaf water potential to atmospheric parameters and leaf temperature.

Three horticultural crops, sweet corn (Zea mays), tomatoes (Lycopersicon esculentum), and bush beans (Phaseolus vulgaris) were grown on a Cloquato silt loam soil under high soil moisture conditions and exposed to the natural atmospheric conditions common to the Willamette Valley of Oregon. A pressure chamber was used to monitor, in the field, the leaf water potential that developed during each of five days throughout the summer months. An infrared radiometer was utilized to monitor the temperatures of the leaves during the same periods.

Sweet corn consistently developed the highest leaf water potential, reaching as high as 13.0 atmospheres. The tomatoes and beans developed leaf water potentials above 10.0 atmospheres. On all five days the corn plants developed leaf water potentials above the critical 8.0 to 9.0 atmospheres suction levels reported in the literature by other investigators. On four of the five days, the ψ_l of the tomato and bean plants equalled or exceeded these critical levels although not to the same degree as the corn plants. The length of time that the leaf water potential remained above 8.0 atmospheres suction varied, but lasted up to 9 1/4 hours in the corn and up to 7 hours in the beans and tomatoes. During these periods photosynthesis formation, soluble nitrogenous and phosphorous compounds formation, RNA accumulation, carbohydrate synthesis, and cell growth are reportedly impaired, limiting productivity.

Leaf temperature under these stress conditions followed closely the same general trends as ambient air temperature. High levels

of leaf water potential did not necessarily cause the temperature of the leaf to rise significantly. Leaf temperatures exceeded ambient air temperature by a maximum of 3.8 °C, but were generally in close agreement with or below ambient air temperature.

The results of this study indicated that many horticulture crops may be limited in productivity by fairly frequent periods of critical leaf water potential even though soil moisture levels are adequate. On none of the five days studies were made did the atmospheric conditions exceed those normally experienced in the Willamette Valley. The maximum air temperature was 32.5 °C and the maximum solar radiation level was 1.16 cal/cm²/min.

Further investigation is required to determine the effects on yield, quantity and quality, of detrimental plant water potentials and to develop means of alleviating ψ_l before it reaches detrimental levels. Further investigation could also lead to a new outlook in plant breeding.

Leaf Stress in Corn, Beans, and Tomatoes
Under Optimum Soil Moisture Conditions

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1971

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May 6, 1971

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ACKNOWLEDGEMENTS

Sincere appreciation and thanks are expressed to my wife, LaRee, and to the other members of my family for their tolerance and sacrifices which made the realization of these goals possible.

Grateful appreciation is expressed to Dr. James A. Vomocil for his helpful guidance and suggestions during the course of this research and in the preparation of this thesis.

Appreciation is expressed to Messrs. Robert Bennett and Richard Tipton and to Mrs. Leta Worth for their assistance in the course of data collection and compilation.

Appreciation is also expressed to Drs. L. L. Boersma and J. W. Wolfe for their interest and encouragement through this investigation.

Lastly, appreciation is extended to Vitro Corporation of America for permission to rearrange my work load during the course of this research and for financial assistance through their Educational Assistance Program.

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LEAF STRESS IN CORN, BEANS, AND TOMATOES UNDER OPTIMUM SOIL MOISTURE CONDITIONS

INTRODUCTION

The role of water in plant and cell development claims the honor of being both one of the oldest and one of the most current subjects of physiological research. As early as 1675, scientists were intrigued by the essential role of water in plant life (Crafts, Currier, and Stocking, 1949).

Today, as populations increase and increased food production becomes more and more important, methods of obtaining higher yields on the acreage now in production gains impetus. The literature available on this subject is voluminous. Dominating an impressive portion of this literature is the potential positive effect of water in achieving this aim.

The source of most of the water for food production is the soil in which the plant grows. Research, then, is essential to determine the soil moisture status at which maximum production can be obtained. Soil moisture status is evaluated in terms of suction; a negative pressure measured in bars and created by reducing air pressure. In general, water held in the soil at suctions of less than 15 bars, is regarded as available to the plant. Nevertheless, research has shown that many plant species exhibit a decrease in yield at some point within the "available water" range. That the same point does not apply to all plants is known. Hagan, et al (1957) in experiments with Ladino Clover determined that when more than 75% of the available

moisture had been depleted, forage yield and seed production were substantially reduced. Similar results were obtained by Hobbs, Krogman, and Sonmor (1963) for sweet clover, barley, and sugar beets. However, with alfalfa, wheat, and corn, 50% soil moisture depletion was the point at which production began decreasing. Haynes (1948), also working with corn, obtained highest yields at soil moisture tensions of less than 1.0 atmosphere. A maximum of 25% available soil moisture depletion resulted in higher potato yields than 50% depletion (Hobbs, et al, 1963; Haddock, 1961).

Frequently experiments are performed using a limited number of soil moisture depletion points. Vittum, Tapley, and Peck (1958) reported that irrigating when the available soil moisture in the upper 24 inches of soil dropped to 50%, resulted in marketable tomato yield increases of as much as 6.65 tons/A over non-irrigated plots. Increases differed markedly between varieties as did total tonnage. Further emphasis of this is exhibited in the case where depletion limits of 5% produced higher tomato yields and grades than depletion limits of 35% for a specific variety (Salter, 1954).

Mack, et al, (1966) and Burman and Bohmont (1961) found, in working with beans, that the lower the soil moisture tensions, the higher the yields and the better the quality. Tensions of 0.5 atmospheres produced the highest yields.

It has also been determined that certain stages of growth are often more sensitive to soil moisture stress than other stages. High soil moisture suction at the tasselling stage in corn appears to be

more harmful than at any other single growth stage (Denmead and Shaw, 1960; Robins and Domingo, 1953). Beans exhibit this same pattern being most sensitive to soil moisture stress at the pre-flowering to flowering stage (Dubetz and Mahalle, 1969; Kattan and Fleming, 1956; Mackay and Evans, 1962).

In spite of the general adverse effects of soil moisture stress on plant development, there are exceptions. Coffee plants, for instance, require this stress before the buds will break dormancy (Alvim, 1960). If stress is not induced, flowering will not occur.

It has also been proposed (Owen, 1958a, b) that the duration a plant suffers from soil water stress is as important as the degree of the stress imposed. Studies with tomato plants have shown that the longer the period of wilting, the longer the recovery period. Leaves wilted for four days were transpiring at only 80% the normal rate three days after watering (Kramer, 1950). Further, extreme caution is recommended in generalizing about plant responses to soil moisture conditions in the field from experiments in pots and artificially regulated environments since the conditions are so vastly different (Hagan, Vaadia, and Russel, 1959). A summary by Stanhill (1957), of the results of approximately 80 published experiments supports this word of caution.

That conditions will vary widely, not only between the greenhouse and the field, but also from day to day in the same field is generally understood. Less well understood is the concept that the temporary wilting point of plants can be expected to vary widely even

at the same soil moisture content. Wilting point is influenced by meteorological conditions, root characteristics, degree of water potential developed in the plant, as well as the hydraulic conductivity and moisture content of the soil (Philip, 1957; Slatyer and Denmead, 1963). Transpiration rate of a plant is not only controlled by leaf structure, but also by the aerial environment of the leaf (Kozlowski, 1968). If the rate of water supplied by the roots decreases under high transpiration conditions, plant water potential will increase and the crop yield can be adversely affected (Stanhill and Vaadia, 1967). The lower the plant water potentials, the greater will be the green and dry weight production.

The rhizosphere is the region of highest resistance to water movement (Kramer, 1969). Root growth is affected by availability of soil water. The amount of root growth, direction, lateral extension, abundance and activity of root hairs, and depth of penetration all depend on the soil water characteristics (Peters and Runkles, 1967). Water absorption and root hair development occurs in the young epidermal cells. As the cells mature, cutinization occurs and both the epidermis and endodermis become relatively impervious (Danielson, 1967; Zholkevitch and Koretskaya, 1959; Slatyer, 1967). During periods of high soil water suction, root growth slows, maturation of the cells continues, and the water absorptive capacity decreases. This high soil water suction at the root soil interface can develop under relatively high soil moisture content if the environmental conditions are conducive to high transpiration rates.

An important factor in water uptake by root systems is the suction gradient between the soil water and the plant root water. As suction of a few atmospheres develop, water uptake by the roots results from passive forces (Crafts, et al, 1949; Gardner, 1960). High gradients can develop. Water can be expected to move only a few centimeters in the time available since the distance water will move in the soil is proportional to the square root of time (Slatyer, 1967). Furthermore, as the water content of the soil decreases near the roots, the hydraulic conductivity of the soil also decreases, resulting in still steeper potential gradients in the root-soil system. In order to create high suction in the root system, the suction of the leaves must increase. The suction in the leaves increases as the water absorptive capacity in the roots decreases. The necessary gradient between soil and root water suction must be maintained to continue water uptake (Denmead and Shaw, 1962). As a result, the whole plant develops a high suction in times of high water demand periods. That this is due to factors of the soil rather than roots has been indicated by Weatherley (1965) when he failed to induce stress in plants grown in a water culture, but could induce a stress in plants grown in soil.

Numerous methods of determining the degree of suction, or water stress in plants have been devised over the years.

As early as 1727, Hales (1727) attempted to determine the pressure gradients in trees with respect to height using mercury

manometers. With the advance of science since then, numerous methods using varying approaches have been proposed. Excellent reviews of the methods generally in use today have been prepared (Barrs, 1968; Kozlowski, 1968; Slatyer, 1967) and include valuable summaries of the components measured and the potential sources of error.

An increasing awareness of the need for a universal terminology is also being evidenced. As various disciplines have studied forces occurring in either plants or soils, each has devised or utilized terminology common to that discipline. It is now advocated (Kozlowski, 1968; Slatyer, 1967) that perhaps total water potential (ψ) is the most useful term to be used universally. ψ represents the free energy of the water system under study, compared with the free energy of pure water and is expressed as energy per unit volume. This provides a term with units dimensionally equivalent to pressures ($\text{ergs cm}^{-3} = \text{dyne cm}^{-2}$; $1 \text{ bar} = 10^6 \text{ dyne cm}^{-2} = 0.987 \text{ atm.}$) and thus ψ can be expressed in traditional pressure units if desired. ψ is also equal, but opposite in sign, to Diffusion Pressure Deficit (DPD), a term widely used in plant physiology (Corey, Slatyer, and Kemper, 1967).

Regardless of the terminology used to express the water stress developed in plant tissues - it is generally accepted that such stress has adverse effects. Excellent discussions (Craft, 1968; Gates, 1964; Kramer, 1963; Stocker, 1960; and Vaadia, Roney, and Hagan, 1961) which reference as many as 435 papers have been published on the subject. It is generally agreed that plant growth

and physiological processes are controlled directly by the plant water stress and only indirectly by the soil moisture stress. A condition of water deficit in the plant, whether brought about by low soil moisture, high solute concentration in the soil solution, or desiccating atmospheric conditions, modifies the transpirational, photosynthetic, assimilatory, respirational and reproductive activities of the plant (Crafts, et al, 1949). Furthermore, the effects of moisture stress differ only in degree in the various parts of plants - not in nature (Gates, 1968).

It is clear that plant water deficits reduce growth by reducing turgor and cell wall development (Vaadia, and Waisel, 1967). In working with the vegetative portion of the potato plant, Werner (1954) determined that even when soil moisture is abundant, when evaporation exceeds the rate of water supply from the soil, relative turgidity will decrease. The rate of decrease is constant in the morning with a decreasing rate taking place in the afternoon. Recovery is very slow, beginning in early evening and often failing to reach 100% by the next morning.

While young sunflower plants contain the least water in the leaves at 1200 - 1600 hours, the minimum water content in the stem occurs at approximately 1700 hours (Wilson, Boggess, and Kramer, 1953). Growth in the sunflower occurs almost entirely at night with a growth rate of five to six times that during the day. Boyer (1968) found that at ψ_l (water potential of leaf) of 2.0 bars, the

growth rate begins to decrease markedly. At Ψ_l of 3.5 bars growth has ceased. Kramer (1969) determined that as Ψ_l increased in beans from 8 bars to 14 bars, the rate of leaf growth decreased from 11.5 mm/day to 0.25 mm/day. The greatest rate decrease occurred between 10 and 13 bars Ψ_l . Similarly, Kemper, Robinson, and Golus (1961), found that a Ψ_s (water potential in soil) increase of from 1.0 to 2.0 atmospheres resulted in a 50% decrease in growth rate. Unfortunately Ψ_l was not measured. Gardner and Nieman (1964) subjected radish leaves to various Ψ_l . At 8 bars cell enlargement was almost completely prevented and total growth was virtually stopped. Gates (1955a, b), working with young tomato plants determined that with "moderate wilting", leaf water content decreased approximately 25%. The youngest leaves were the first to show a growth rate reduction and the first to begin recovery. In a similar study, Slatyer (1967) found that as Ψ_l increased to 10 bars, the water content of the leaf decreased 15%. At Ψ_l 15 bars, the decrease in leaf water content was 27%. Permanent wilting occurred at Ψ_l of 19 bars with a decrease in leaf water content of 36%. Working with wheat, Prusakova (1960) concluded that subjecting leaves to a high Ψ_l results in a rapid termination of growth and a faster rate of maturity. This results in smaller plants. Further, during periods of high plant water stress, less water is lost from the fruit than the vegetative parts (Konovalov, 1958). However, this stimulates movement of nitrogenous materials into the grain. Intensified proteolysis in the vegetative organs releases mobile

nitrogen compounds.

As early as 1938, Petrie (1938a, b) found that decreasing the water content of plants decreased the rate of protein synthesis and led to protein hydrolysis. Wadleigh and Ayer (1945) found a rapid decrease in starches and non-reducing sugars under increasing plant water deficits and a marked increase in nitrate nitrogen. Woodham and Kozlowski (1954) found that even after a brief period of water stress a significant decrease in carbohydrates occurred in tomatoes and beans.

Gates (1957), also working with tomatoes, found a failure of soluble nitrogenous and phosphorous compounds to form into more highly organized compounds under plant water stress. Also noted was a decrease in nitrogen and phosphorus uptake and a translocation of these materials from the leaves to the stem. In a more recent study Gates and Bonner (1959) determined that under the influence of water stress net accumulation of RNA ceases in young tomato plant leaves. This does not necessarily indicate an inability to synthesize RNA, but rather an accelerated destruction of RNA. Shah and Loomis (1965) support this with work performed using sugar beets. Kessler (1961) determined that a plant water deficit resulted in increased RNase activity. The water stress destroys RNase-binding fraction I setting free RNase which in turn, results in hydrolysis of RNA and impaired protein synthesis.

An additional detrimental effect of moisture suction, or stress is that of decreased transpiration rate. In reality, the increased

ψ_p is created by the inability of the plant to meet evaporative demands with increasing ψ_s (Pallas, Michel, and Harris, 1967).

Thus, while it is true that growth during daylight hours may necessarily be slow under moisture stress conditions, night growth rates will also be slow if biochemical and biophysical responses to stress prevent the accumulation of energy in a chemical form in the plant during daylight hours.

Using young sunflower plants Frei (1954) determined that the highest transpiration rate occurs at the lowest soil moisture suction. At a soil moisture suction of 0.48 atmospheres transpiration had decreased 50% in the test plants. Kramer (1969) estimated that with a potential transpiration rate of 2.5 mm/day, the actual transpiration rate would fall below the potential rate at ψ_s of approximately 5 bars. At a potential transpiration rate of 7.5 mm/day, the actual transpiration rate would differ from the potential rate at a ψ_s of only 2 bars. Slatyer and Denmead (1963) found, in working with tomato plants, that actual transpiration dropped below the potential rate at ψ_s of 1 bar. However, the potential transpiration rate was not recorded. Denmead and Shaw (1962) determined that corn, at a potential transpiration rate of 6.4 mm/day, will experience a 50% decrease in actual transpiration rate as the soil moisture suction increases from 0.2 bars to 0.5 bars. However, if the potential transpiration rate is only 4.1 mm/day, as the soil moisture suction increases from 0.2 bars to 0.5 bars, the decrease in actual transpiration will be only 1%. Baker and Musgrave (1964), also using corn as a test plant, deter-

mined that the transpiration rate at a soil moisture suction of 1.0 atmospheres was only 71% of the transpiration rate with a soil moisture suction of only 0.2 atmosphere. Similarly Slatyer (1957) found that increasing the soil moisture suction from 3.5 atmospheres to 5.5 atmospheres decreased the transpiration rate of corn 67%. Hagan et al, (1957) found no decrease in transpiration rate in mature stands of Ladino Clover as soil moisture stress increased, but attributed this to the deep root systems which were invariably in contact with sufficient soil moisture at greater depths than those monitored. Closs (1958) found a definite decrease in the transpiration rate of mustard plants as ψ_s increased. Schneider and Childers (1941) indicated a 65% reduction in transpiration rate of apple tree leaves before wilting became apparent. It is unfortunate that in the literature reviewed there is a lack of measured ψ_p to compare with decreasing transpiration rates.

As the transpiration rate and relative turgidity of leaves decrease, the temperature of the leaf will increase. Wiegand and Namken (1966) observed a leaf temperature (T_l) increase of 3.6 °C as the relative turgidity of a cotton plant leaf decreased to 60%. T_l was always above ambient air temperature (T_a) with $T_l - T_a$ ranging from 0.4 to 8.7 °C as illumination and temperature increased. Pallas, et al, (1967) further verified this with relative humidities of 60% or higher. At relative humidities of 30%, however, T_a exceeded T_l . Palmer (1967), recorded similar results on non-irrigated cotton plants. With irrigated cotton plants, however, leaf temp-

eratures exceeded air temperature only on very hot days. Baker and Musgrave (1964) recorded average leaf temperatures of 3 °F above average air temperatures at high light intensities and soil moisture suctions of less than 1.0 atmosphere. Gates (1963) recorded tree leaf temperatures as high as 20 °C above air temperature, but made no mention of soil moisture conditions. Shaded leaves on the same trees averaged 1.5 °C below air temperature. Quite different results were recorded by van Bavel and Ehrler (1968) using well watered sorghum plants. During the periods of the day when solar radiation was maximum, leaf temperatures were 3 °C less than the 38 °C air temperature. By early evening leaf temperatures were 8 °C lower than air temperature.

That leaf temperature depends on transpiration rate, radiation levels, air temperature, and vapor pressure deficit is well understood (Linacre, 1964). D. Gates, (1964) presents an excellent discussion on the relationship of transpiration rate and leaf temperature modifications.

Still another physiological process affected by the water potential of the plant is photosynthesis. While less than 1% of the water absorbed by a plant is utilized directly in the photosynthetic process, the internal water deficit of the leaves is a critical factor affecting photosynthetic rate (Ashton, 1956). Water deficit can limit photosynthesis in two ways. As the ψ_d increases, the stomatal openings begin to close. Inherent with the closing stomata is a lowering of the CO_2 availability to the photo-

synthetic process which is necessarily inhibited (Vaadia and Waisel, 1967). Secondly, as ψ_d increases, dehydration of the photosynthesizing tissue limits the rate of CO_2 assimilation regardless of the status of the stomata (Slavik, 1965).

Most of the work involving moisture stress and the photosynthetic process has been conducted by increasing soil moisture suction. Hagan, et al, (1957) determined that as the soil moisture suction approached 6 atmospheres the photosynthetic rate of Ladino Clover began decreasing. Similarly, Upchurch, Peterson, and Hagan, (1955), found that when clover showed the first signs of wilting, photosynthesis had decreased 30%. In work performed with apple trees (Kramer, 1959; Loustalot, 1945; Schneider and Childer, 1941) photosynthesis was determined to have decreased 50% prior to visible signs of wilting. At 20% available soil moisture depletion the photosynthetic rate was adversely affected. Baker and Musgrave (1964) experimented with corn and determined that as soil moisture suction increased from field capacity to 1.0 atmosphere, the rate of photosynthesis decreased 18%. Moss, Musgrave, and Lemon, (1961) had similar results. That these results are similar among many plant species is demonstrated by the results of El-Sharkawy and Hesketh (1964) and Pallas et al, (1967). Sorghum, sunflower, and cotton were tested and in all cases as the ψ_s increased, creating a plant water deficiency, net photosynthesis declined.

Brix (1962) reported an especially significant experiment with tomatoes and loblolly pine. Instead of monitoring soil moisture suc-

tion and photosynthetic rate, DPD and rate of photosynthesis were utilized as variables. With a DPD of 4 atmospheres in loblolly pine, photosynthesis had ceased. Similarly, with tomato plants, a DPD of 7 atmospheres caused a decline in photosynthetic rate and had completely arrested it at a DPD of 14 atmospheres. Light and temperature levels were within those normally experienced in the field.

While recognizing the need for continued research into the effects of ψ_p on all of the physiological processes, it is nevertheless understood that such adverse effects do occur. Furthermore, it is apparent that such effects are initiated at relatively low ψ_p . However, that some arid zone plant species can survive at high ψ_p has been demonstrated. Scholander, et al, (1965) measured ψ_x as high as 80 atmospheres when sampling a wide range of hardy shrubs and trees. Carr and Gaff (1961) provide an excellent discussion as to the reason certain plants can do well under such conditions. Apparently the effects of dehydration on the physiological process depend on the water status of the protoplasm rather than the water status of the whole leaf. Arid zone plants "harden off." A greater amount than normal of cell wall material is formed, resulting in a higher buffering effect before water stress in the protoplasm occurs. Agronomic crops do not possess this characteristic and are very sensitive to water stress.

To date little is known of the extent of the diurnal variations of ψ_p . The classic schematic depicting the ψ_p and ψ_s limits

over the entire soil-plant-atmosphere range was developed by Philip (1957). Similar schematics of the diurnal changes in ψ_p and ψ_s have since been developed by Slatyer and Denmead (1963) and by Slatyer (1967). In all cases the maximum ψ_p under low ψ_s is depicted as being less than 10 atmospheres. Gardner and Nieman (1964) in an experiment with pepper plants present an actual diurnal ψ_p and ψ_s fluctuation curve very similar to the hypothetical cases with a maximum ψ_p of 8 bars under low ψ_s . However, transpiration rate, temperature, and humidity were held constant. As a result, interpolation of these results to plants under actual field conditions would be extremely hazardous.

Yet, since it is known that plant stress is detrimental to physiological processes and to growth, it is important to know the extent to which such stress occurs under normal farming practices. To merely understand that severe adverse effects are possible, and that they do occur under conditions of high ψ_s is insufficient. Knowledge that these conditions can also occur temporarily during periods of ample soil moisture is also insufficient. It is too general. Since the water status in plants is only partially controlled by the soil moisture status, it is next to impossible to determine a specific and finite level of soil moisture under which a species of plant will consistently begin to show adverse effects. Atmospheric conditions are also factors involved in determining this point.

The economics and practicality of water application rates and techniques make it extremely difficult to maintain a field soil at maximum water holding capacity. As a result, for most agronomic crops grown under irrigated farming conditions, feasible and practical limits of available soil water depletion have been determined and recommended. An excellent reference on this subject is edited by Hagan, Haise, and Edminster, (1967).

Nevertheless, even when soil moisture for a specific crop is maintained within the recommended range, little is known of the DPD or Ψ_p that develops under field conditions during the life of the crop.

It has been indicated that physiological processes are affected before visible wilting takes place. Therefore, while it is recognized that under certain extreme atmospheric conditions a plant will wilt and obviously suffer temporary decreased productivity, it may very well be that even under less extreme atmospheric conditions and with no visible signs of wilting, a plant is experiencing a Ψ_d sufficiently high to inhibit productivity. Very little can be found in the literature on this subject and many of the articles that are available do not involve studies conducted under actual field conditions.

While it is recognized that attempting to determine the actual diurnal fluctuations of soil and plant potentials under field conditions has many limitations, it is proposed that such studies would provide information not now generally available. It is further pro-

posed that studies of this nature, while valid only for the specific conditions experienced at the time of testing, could indicate more accurately the diurnal trends of Ψ_p . From an examination of the Ψ_p limits recorded, it is conceivable that a rough estimation could be made of the plant's potential productivity as compared to its actual productivity. This would then lead to a greater emphasis of utilizing or developing means of alleviating Ψ_p before it reached detrimental levels or to a new outlook in plant breeding.

This study was conducted to determine the water stress conditions developing in three important agronomic crops in the Willamette Valley under atmospheric conditions imposed naturally during the 1970 growing season. Since the primary purpose was to determine the range of Ψ_ℓ under actual conditions, yields were not recorded and potential productivity was not estimated.

While it is readily admitted that interpolating the results to other plant species and other climatic conditions would be risky, it is strongly advocated that atmospheric conditions are not exceptionally extreme in the area of this study and therefore, the Ψ_ℓ measured are not as high as might be expected in areas of higher temperatures and/or lower humidities. It is also advocated that under soil moisture conditions of less than optimum levels, the Ψ_ℓ would also be higher. Therefore the results of this study should be meaningful and in no way represent abnormal conditions.

METHODS AND MATERIALS

Field Plots

Description

The crops chosen for the study were Jubilee variety sweet corn (Zea mays), Willamette Variety tomato (Lycopersicon esculentum), and Oregon 58 variety bush bean (Phaseolus vulgaris). These represent not only three crops economically important to the Willamette Valley, but also three completely different plant species with respect to rooting habit, size and shape of leaf, growth pattern and rate of maturity.

Three plots were designed in an east-west orientation on a uniform Cloquato silt loam soil (Table 1) with a 60 foot minimum clean cultivated border surrounding each plot. Each plot (60' x 40') contained a single variety. The location was on a flood plain of the McKenzie River; on the property of Dale Bartholomew, immediately north of the Springfield city limits.

Table 1. Cloquato Series soil description

The Cloquato Series is a member of a coarse-silty, mixed mesic family of Cumulic Ultic Haploxerolls. These soils have uniform dark brown, friable, slightly acid silt loam weakly developed profiles.

- Ap - - 0 - 9" Dark brown (10YR 3/3)* silt loam, brown (10YR 5/3) dry; weak fine granular structure; slightly hard, friable; nonsticky and slightly plastic; many very fine and fine interstitial pores; slightly acid (pH 6.1); abrupt smooth boundary. (6 to 10 inches thick.)
- B2 - - 9 -36" Dark brown (10YR 3/3) silt loam, yellowish brown (10YR 5/4) dry; weak very fine subangular blocky structure; slightly hard, friable, nonsticky and slightly plastic; many very fine, many fine, and few medium tubular and interstitial pores; slightly acid (pH 6.5); clear wavy boundary. (15 to 30 inches thick.)
- C1 - - 36 -57" Dark brown (10YR 3/3) silt loam, pale brown (10YR 6/3) dry; weak very fine subangular blocky structure or massive; slightly hard, friable, slightly sticky, and slightly plastic; many very fine and fine and few medium tubular and interstitial pores; slightly acid (pH 6.5); gradual wavy boundary. (18 to 24 inches thick.)
- C2 - - 57 -65 $\frac{1}{2}$ " Dark brown (10YR 3/3) heavy silt loam, light yellowish brown (10YR 6/4) dry; massive; common medium distinct mottles of yellowish red (5YR 4/8) and light gray (10YR 5/2); hard, friable, sticky and plastic; common very fine, fine and medium interstitial pores; slightly acid (pH 6.4).

* Colors for moist conditions unless otherwise stated.

Drainage and Permeability: Well drained. Runoff is slow, and the permeability of the C horizon is moderate. The soil is subject to overflow.

Distribution and Extent: Cloquato soils occur in stream valleys of Western Washington and Oregon in the trough lying between the Cascade and Coast Ranges. It is moderately extensive.

Preparation

Soil samples were taken from the upper 24 inches of the soil to determine fertility level (Table 2). The plots were then fertilized in the following manner:

1) corn plot - 24 lbs of 33.5 - 0 - 0

16 lbs of 0 - 20 - 0

the fertilizer was broadcast and disked into the soil

2) bean plot - 24 lbs of 33.5 - 0 - 0

20 lbs of 0 - 20 - 0

the fertilizer was broadcast and disked in the soil

3) tomato plot - 0.2 lb of 16 - 20 - 0 /hill

the fertilizer was concentrated at each site marked for a young tomato transplant and rototilled into the soil

The potassium level in all three plots was adequate.

Table 2. Fertility level of plot area, December 9, 1969.

Depth (Inches)	pH	P (ppm)	K ^a (meq/100g)	Ca ^b (meq/100g)	Mg ^c (meq/100g)	Total Bases
0 - 12	5.9	129	0.95	11.4	4.7	17.05
12 - 24	6.3	28	0.51	9.2	5.7	15.41

^a 1 meq/100g K = 780 lbs/A Potassium

^b 1 meq/100g Ca = 400 lbs/A Calcium

^c 1 meq/100g Mg = 240 lbs/A Magnesium

Immediately prior to planting, all plots were treated with Dyfonate 10 granular (10% 0-ethyl S-phenyl ethylphosphonodithioate) at the rate of 20 lbs/A for wireworm (Limoniussp.) and symphylan (Scutigera immaculata) control. Also prior to planting the bean and corn seed, Eptam 10 granular (10% S-ethyl dipropylthio-carbonate) at the rate of 20 lbs/A was broadcast over the plots for pre-emergent control of annual broadleaves and grasses. One day prior to the emergence of the young bean and corn plants, Sinox P. E. (triethanolamine salt of 4, 6-dinitro - 0 - sec-butylphenol) at 2 qt/A was sprayed on the rows for annual and perennial broadleaf control. No herbicide treatments were used on the tomato plot.

Nine rows each of beans and corn were planted on 54 inch spacings. Ninety-six young tomato plants approximately 12 inches high were transplanted on 5' x 5' square spacings to facilitate cultivation in two directions.

All plots were irrigated with 1.0 inch of water immediately following the transplanting of the tomatoes. The irrigation system was comprised of an aluminum lateral along the north and south boundary of each plot. The sprinkler pattern was designed as a 40' x 40' triangular spacing. The pressure at each nozzle was set at 50 psi using pressure-flow regulators. Rainbird 14V - TNT sprinklers and 3/32" nozzles were used. The application rate was 0.12 inches per hour. On June 22, the nozzles were changed to 1/8" to increase the application rate to 0.21 in/hr.

Soil Moisture Determinations

Undisturbed soil core samples 5.1 cm in diameter and 3.5 cm in height were taken from all plots and the area immediately surrounding the plots at 6, 12, and 24 inch depths. Moisture content at 0.1, 0.2, 0.4, and 0.8 atmospheres was determined for each sample on a porous plate apparatus (Richards, 1948) following complete saturation of each sample. Bulk density determinations (Table 3) were made on all core samples by determining the total volume and mass of each core and dividing the mass by the volume.

Table 3. Bulk densities at specific depths.

Depth (Inches)	Sample				\bar{X}
	1	2	3 (g/cc)	4	
6	1.28	1.16	1.24	1.20	1.22
12	1.23	1.26	1.11	1.32	1.23
24	1.25	1.07	1.13	1.15	1.15

By multiplying the percent moisture (by weight) by the bulk density, percent moisture by volume was obtained for the specific suction levels utilized in the soil moisture curves. At this point it is possible to determine the actual amount of available water between the designated suctions (Table 4).

Table 4. Available soil moisture between designated suctions.

Soil Block (inches depth)	Suction (atmospheres)							
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
	(inches water in designated layer)							
3 - 9	.102	.060	.048	.018	.012	.012	.012	.012
Accumulative	.102	.162	.210	.228	.240	.252	.264	
9 - 15	.126	.054	.048	.018	.012	.018	.016	
Accumulative	.126	.180	.228	.246	.258	.276	.282	
15 - 33	.567	.342	.234	.108	.090	.072	.036	
Accumulative	.567	.909	1.143	1.251	1.341	1.413	1.449	

Thus the exact amount of water that was to be replaced by each irrigation could be calculated when the suction at the time of irrigation was known. Figures 1, 2, and 3 represent the soil moisture curves for the three sampled depths.

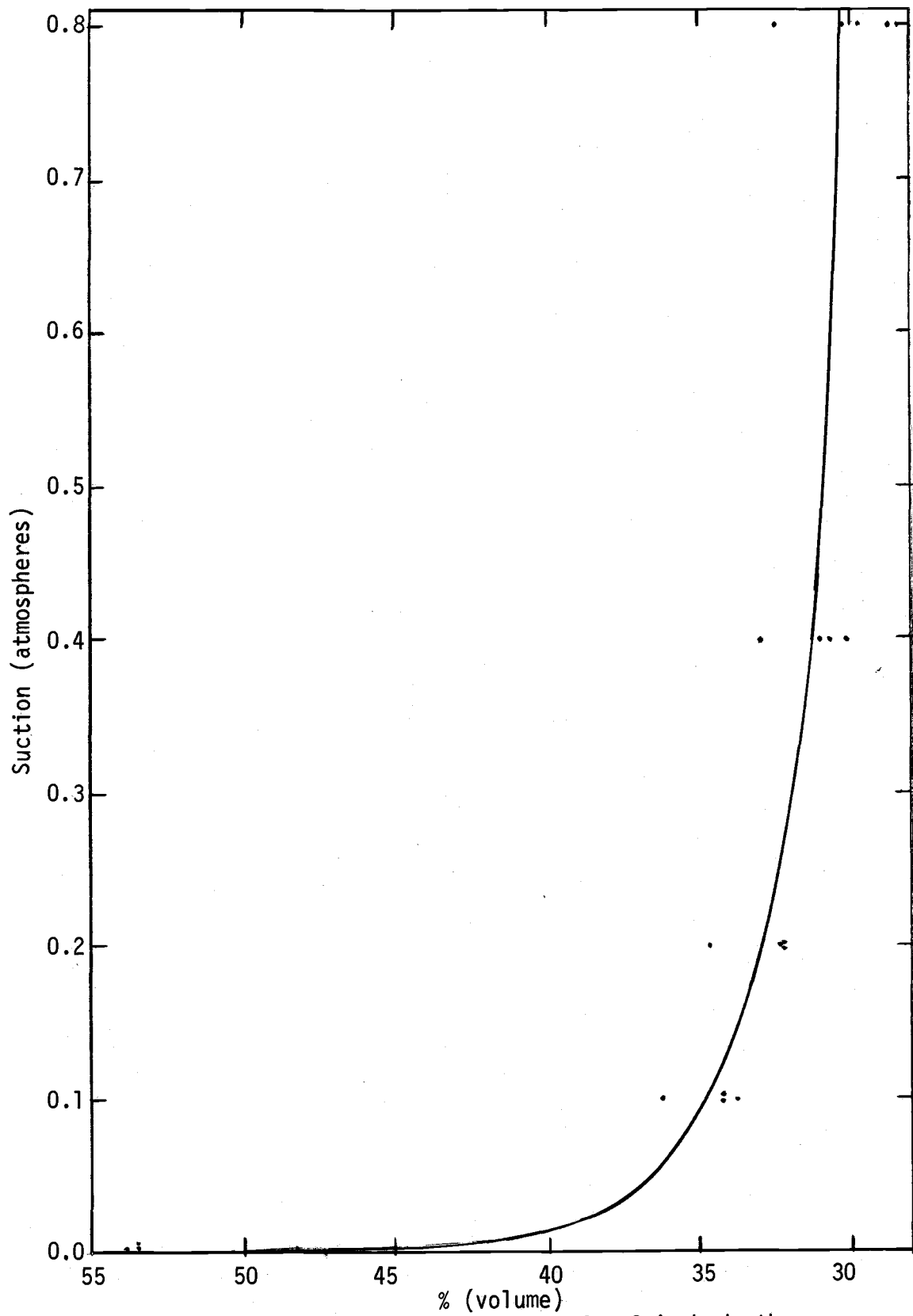


Figure 1. Soil moisture suction curve for 6 inch depth.

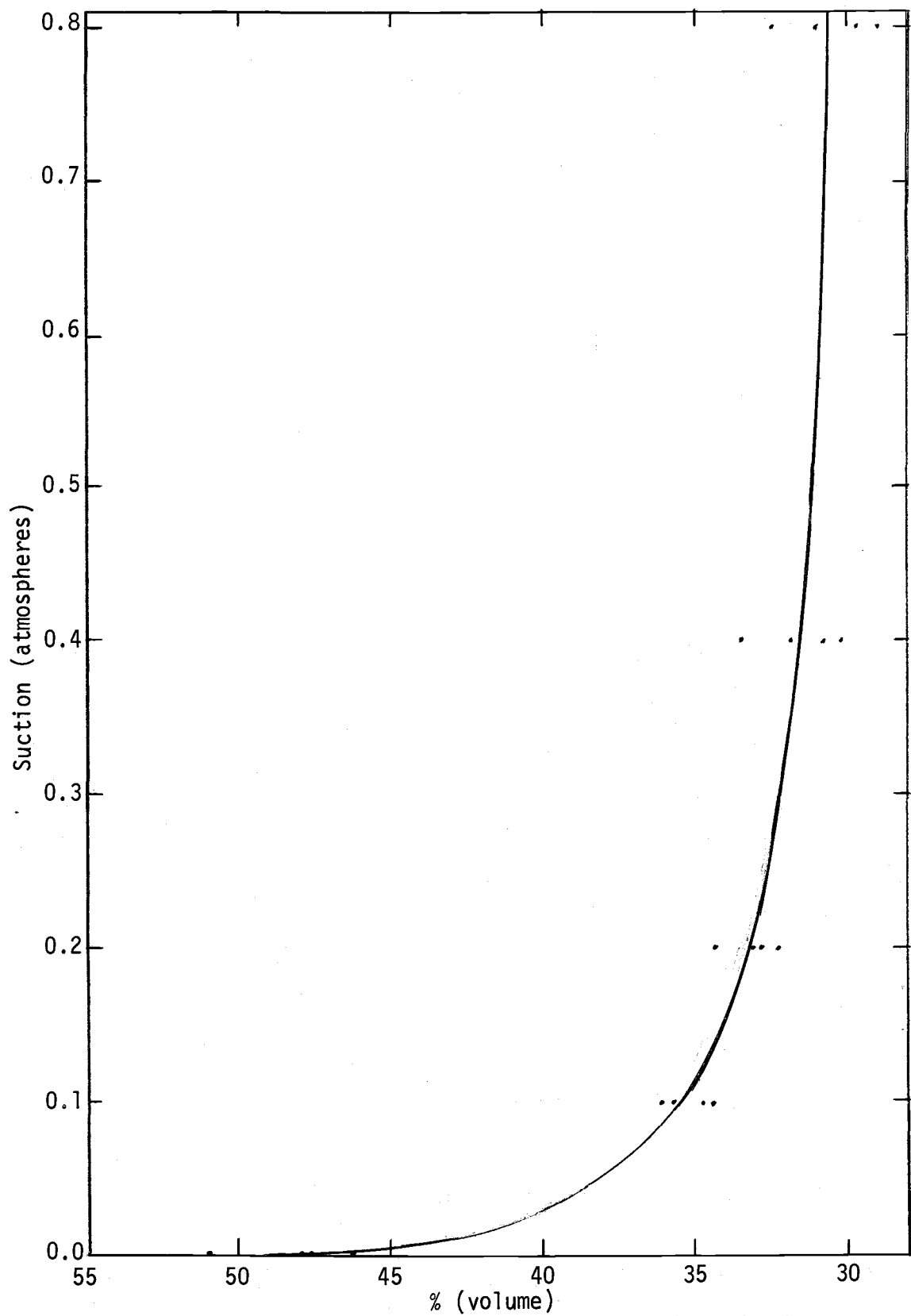


Figure 2. Soil moisture suction curve for 12 inch depth.

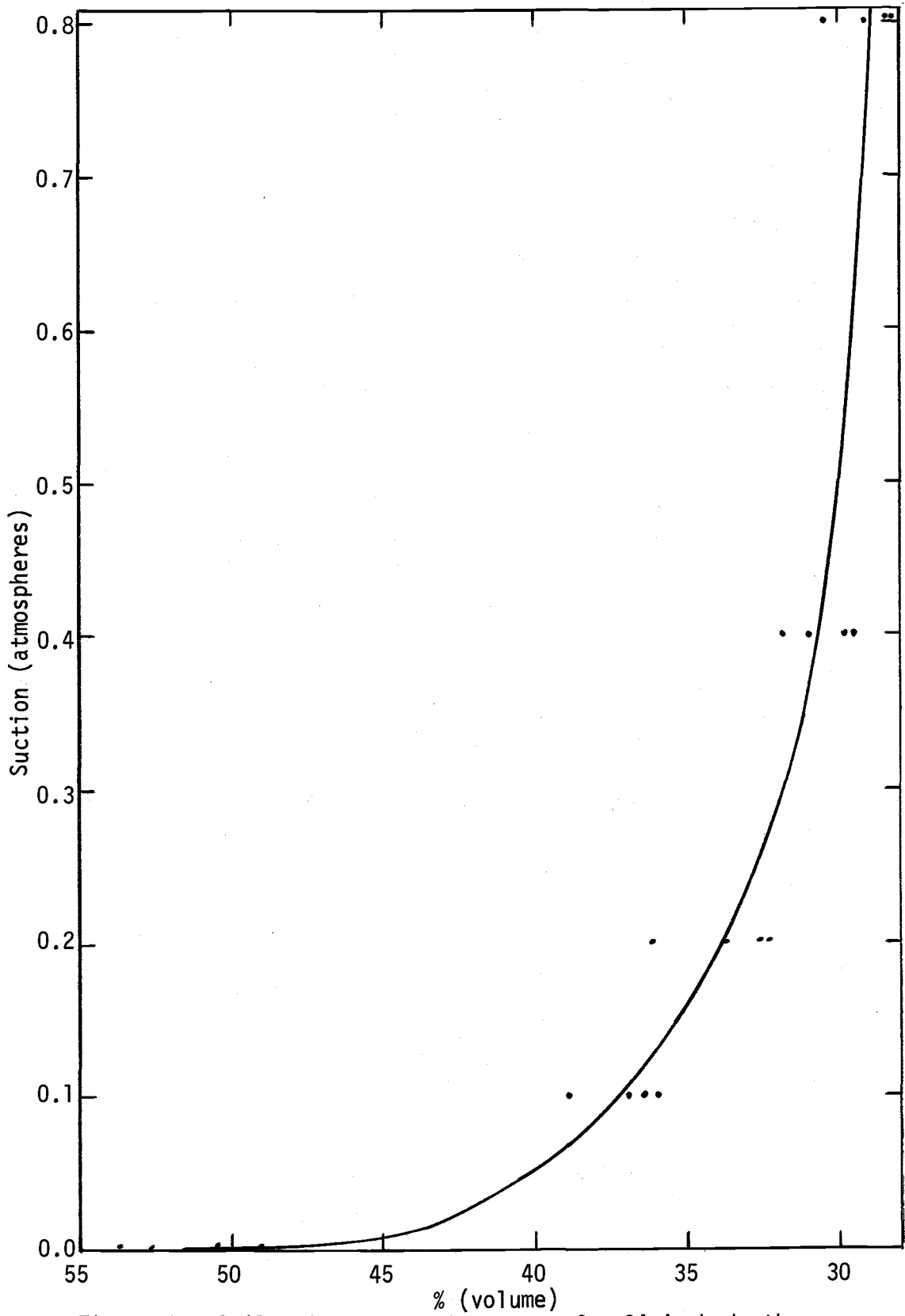


Figure 3. Soil moisture suction curve for 24 inch depth.

Instrumentation

Tensiometers

The most sensitive and reliable instrument for the range of suction or ψ_s to be employed in this study is the tensiometer. While it is recognized that the only real means of measuring ψ_s is through the use of psychrometers, the tensiometer is the only instrument that will directly measure matric potential (ψ_m). ψ_s is composed of $\psi_m + \psi_o$ (where ψ_o represents osmotic potential). But ψ_o can only be measured after the soil solutions are extracted from the soil and will vary with water content, or ionic strength of the solution. At the ψ_s of interest in this study, the soil water content is relatively high, thus minimizing ψ_o . Furthermore, ψ_s is most frequently based on ψ_m and is sufficiently close at high soil water contents (Slatyer, 1967).

While it is also recognized that tensiometers are temperature sensitive (Haise and Kelly, 1950) and that diurnal fluctuations occur when a temperature gradient exists between the porous cup and the soil, it is also possible to minimize the temperature effects to the point that they become insignificant. Tensiometers with molded-in diaphragms that compensate for variations in temperature and barometric pressure were utilized to eliminate these effects on the exposed portion of the instruments. In addition the instruments

were protected from direct solar radiation by shading. To minimize the temperature gradient between the porous cup and the surrounding soil, plastic materials with a low heat conductivity were used for the body of the tensiometers. As a further precaution, readings commenced in early morning as recommended by Haise and Kelly (1950).

In the bean plot, five tensiometers were installed in the root zone, or future root zone at each of three depths - 6", 12", and 18". The soil moisture conditions of 15 separate randomly selected plants was thus monitored. The same procedure was followed in the corn plot - with an additional depth of 24" being installed. Thus 20 separate plants were involved in the soil moisture monitoring in the corn plot.

Since tomato plants characteristically root deeper than either beans or corn, five depths were chosen for tensiometer installation. These depths were 6", 12", 18", 24", and 36". A total of 25 tomato plants were utilized.

Each of the 60 tensiometers used in the study was recalibrated in the laboratory.

Soil Thermometers

Soil temperature measurements were recorded in all plots. Three manually read dial-type thermometers were installed at three depths in each plot. Soil temperatures at the 6", 9", and 12" depths

were recorded with a precision of $\pm 1/2$ °F. Soil temperatures not only affect the viscosity of the soil water, but excessively high soil temperatures inhibit root growth.

Wind Recording System

A sensitive wind recording system was installed 40 feet east of the corn plot with the sensor at a height of 12 feet. A three-cup aluminum anemometer assembly with a starting speed of approximately 0.75 mph drove an A.C. generator. The wind direction potentiometer provided complete tracking at wind speeds even below three mph. The recording console was of a continually recording nature with a chart speed of 1 in/hr.

Microbarograph

A continuously recording microbarograph with a resolution of 0.005 in. of Hg. (0.25 millibars) and a lag-time of less than 0.1 sec. was installed in a Standard U. S. Weather Bureau instrument shelter. Location was 30 feet east of the corn plot and 20 feet south of the wind recording system.

Hygrothermograph

Also installed in the instrument shelter was a continuously recording hygrothermograph. The human hair bundle humidity sensor was specified to be accurate to within $\pm 1\%$ with a sensitivity of 1%. The aged bimetallic strip utilized for ambient air temperature monitoring was specified to within $\pm 1\%$.

Pyranograph and Evaporimeter

A mechanical pyranograph and an evaporimeter were installed 120 feet due east of the wind sensor. The instruments were located two feet above ground level 30 feet from either the tomato or bean plots. The continuously recording pyranograph, calibrated in $\text{gm cal/cm}^2/\text{min}$, sensed 90% of the wavelengths of electromagnetic energy between 0.36 and 3.0 microns. In a study by Tanner, Peterson, and Love (1960), it was determined that approximately 80% of the energy at the soil level in mature corn was solar radiation that had penetrated the foliage. Less than 20% was longwave re-radiation.

The evaporimeter was continuously recording and calibrated in millimeters.

Infrared Radiometer

Since a major objective of the study was to determine the

effects of adverse meteorological conditions on plant growth - even under optimum soil moisture conditions - it was imperative to employ precise, yet versatile, instruments to measure plant leaf temperatures and leaf potential.

An infrared radiometer with a temperature sensitivity of ± 0.2 °C and a response time of two seconds was employed. All physical objects are continually emitting electromagnetic radiation in proportion to their temperature (Weaver, 1969). At temperatures in the range of interest here, the radiation falls within the infrared portion of the spectrum. In the infrared radiometer, thermistors form a compensating element in a Wheatstone bridge. Calibration of the instrument is accomplished by pointing it towards a black body. The energy radiated by any body is $\epsilon\sigma T^4$ where:

ϵ - emissivity of body surface

σ - Stephan-Boltzmann constant, and

T - temperature of body (absolute scale).

Since ϵ of a black body is 1.0 and σ is a constant, T can be readily determined. At this point, a calibration curve transformed to give the temperature of the radiating surface in °C can be readily constructed (Gates, 1963).

Pressure Bomb

In order to obtain numerous measurements of ψ_l in the field, the Pressure Bomb was used. The concept, although first mentioned

by Dixon (1914), was not utilized until 1965. At that time Scholander, et al (1965) developed a pressure chamber whereby the potential of plant tissue could be determined. The instrument operates on the theory that the tension at which water is held in a leaf is equal to the pressure required to force it out. The commercial model was only recently developed by Waring and Cleary (1967).

Basically, freshly cut leaf tissue is threaded through a rubber stopper (Figure 4) and a metal disk seated with an "O" ring. The disk seats into a stainless steel cap which makes a rotating breech-block seal with a pressure chamber. The cut edge of the leaf is exposed while the remainder of the leaf is inside the chamber. Nitrogen flows through a rate control valve and a shut-off valve to the chamber. A pressure gauge indicates the pressure in the chamber (Figure 5). The equilibrium pressure is reached at the point when water droplets first form at the cut surface.

Boyer (1967) conducted a series of tests with the pressure chamber utilizing three plants with a vastly differing leaf and stem anatomy. The results were checked against those obtained with a thermocouple psychrometer. The final conclusion was that the pressure chamber measures the nonosmotic component of Ψ_{ℓ} ($\Psi_{\ell} = \Psi_x + \Psi_o$ where Ψ_x is the xylem potential and Ψ_o is the osmotic potential).

The two methods generally agreed to within ± 2 bars. Barrs (1968) also contends that the pressure bomb, in reality, measures Ψ_x . Since Ψ_x is measured, Ψ_{ℓ} would be slightly higher. However, this does not pose as a serious detriment in this study since a

still higher ψ_0 than that recorded would lend further significance to the data obtained.

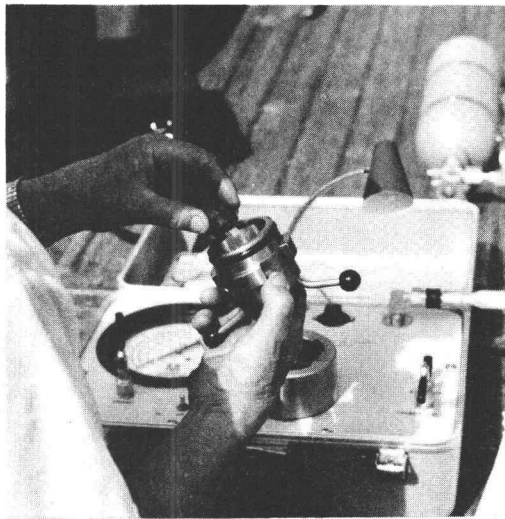
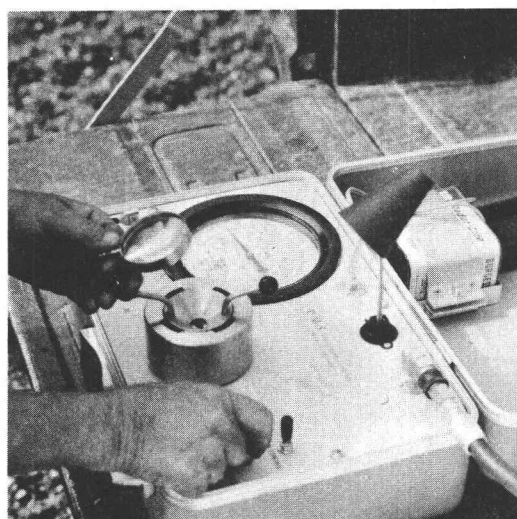


Figure 4. Freshly cut corn leaf prepared for sampling.

Figure 5. Leaf sample under pressure.



Sampling Methods

Soil Moisture

Tensiometer readings were necessary daily to maintain the soil moisture content above the designated minimum levels. Readings were taken in the early morning period and the necessary irrigations were carried out during the calm period 10 P.M. and 6 A.M. whenever possible to facilitate a uniform water distribution pattern.

During the first month following planting or transplanting, soil moisture was monitored at the 6" depth. After the root systems had become more deeply established, the critical depth was changed to 12". The maximum ψ_m allowed at the critical depth in the corn was 0.50 atmospheres while in the beans and tomatoes the suction was allowed to approach 0.7 atmospheres. These parameters are well within the recommended range for optimum plant growth (Taylor, 1965; Hagan, et al, 1967).

On the days designated for ψ_ℓ and T_ℓ measurements, soil moisture suctions were recorded during the day as well as early morning.

Soil Temperature

Monitored and recorded throughout the testing periods were the soil temperatures at the designated depths. Soil temperatures were then tabulated for the significant periods.

Meteorological Parameters

Wind characteristics, barometric pressure, air temperature, humidity, solar radiation, and evaporative potential were continuously recorded and all short period fluctuations automatically integrated. Therefore, sampling was continuous and automatic.

Leaf Temperature

Immediately following completion of the pressure bomb readings at a given plot, the infrared radiometer was utilized to record the temperature of the upper surface of six exposed leaves still attached to the plants (Figure 6). The radiometer was recalibrated prior to each set of readings, checked every 30 seconds during the readings, and rechecked upon completion of the readings. Readings of six leaves seldom required more than 2 or 3 minutes. Readings on each leaf were taken from a distance of exactly 2 inches from the leaf surface (Figure 7). A special wire guard projecting exactly 2 inches from the sensor window was attached to the radiometer for this purpose. At this distance a circle 0.5 inches in diameter was monitored on each leaf. The radiometer was held in such a position that the leaf was shaded only for the few seconds necessary to obtain a reading. In this way reflection was minimized, yet the leaf surface did not cool appreciably.



Figure 6. Monitoring leaf temperature with infrared radiometer.

Figure 7. Infrared radiometer.



Figure 8. Leaf selection for determining leaf water potential.

Leaf Water Potential

At each designated reading period, randomly selected leaves from each plot were systematically inserted in the pressure chamber and the pressure required to reach equilibrium with the ψ_l recorded. The time lapse between the detachment of the leaf with a razor blade and the insertion into the pressure bomb was kept to 30 seconds or less.

The time required to increase the gas pressure to equilibrium with ψ_l of the sample leaf varied directly with the amount of pressure required. Care was exercised to regulate the flow rate in such a manner as to minimize the possibility of approaching the equilibrium point too quickly, and yet still maintain a rapid enough rate increase to clearly indicate the equilibrium point. The rate of increase was slightly varied with each of the six samples. By so doing, the human error in the detection of the equilibrium point was minimized. The length of leaf material allowed to protrude above the metal disk and rubber stopper was kept to one centimeter or less.

Only fully exposed, mature leaves were sampled (Figure 8). Each tomato and bean leaf was detached as close to the plant stem as possible, thus keeping the petiole intact for insertion through the rubber stopper.

The shape of a corn leaf necessitated modification of the sample

leaves immediately prior to inserting them into the stopper and disk. An artificial "stem" was created by cutting a 1/2 inch strip centered at the midrib and approximately 1 1/2 inches long with a razor blade. From the base of the "stem," the cut on each side was curved out to the outer edge of the leaf, thus giving the leaf sample an arrowhead appearance. A flat insertion tool was used to insert the leaf through the rubber stopper without damaging the leaf. Readings were taken immediately and recorded. The leaf sample was then discarded.

Data Analysis

Soil Moisture

The depth of the major portion of the root system was determined by closely observing the moisture extraction pattern at the three depths monitored by the tensiometers.

The average soil moisture suction was calculated for the specific soil block containing the major portion of the root system by averaging the readings of all tensiometers in the designated block. It is recognized that the computed average does not necessarily represent the suction at the soil-root interface. The suction at that point will be higher as discussed previously. Nevertheless, this average soil moisture suction does represent the nominal state of the soil water in the soil mass a few centimeters from the soil-root interface. This is also the region normally utilized for irrigation scheduling.

Leaf Temperature

The six observations per crop from each time period of each day were averaged to obtain the mean. Comparisons were then made among crops. Since the variation among readings for each crop at each time period was very small it was unnecessary to compute an

analysis of variance. A variation of 1 °C among crops would be significant since the error term of the analysis of variance would be essentially zero. Comparisons were also made in each instance with ambient air and wet bulb temperatures.

A comparison was made between the temperature trend of an excised leaf and an intact leaf. The differences in temperature were due to the lack of water available to the excised leaf and hence, a lack of ability to transpire, resulting in a lack of evaporative cooling.

Leaf Water Potential

The six observations per crop from each time period were statistically analysed to determine significant variations among crops. The daily trends of each crop were also compared with the solar radiation levels and the ambient air and wet bulb temperatures. The ψ_2 levels reached on the sampling days were compared to the critical limits of ψ_2 as cited in the Literature Review.

RESULTS AND DISCUSSION

Soil Moisture

The critical soil moisture monitoring depth was set at 12 inches for irrigation purposes although several other depths were also monitored. Defining the maximum Ψ_s at this depth in the corn, tomatoes, and beans as 0.50, 0.70, and 0.70 atmospheres, respectively, resulted in a moist rhizosphere throughout the growing season. The mean soil moisture suction in the root zones of all plots was 0.5 atmospheres or less on all days Ψ_s measurements were made (Table 5). In several instances the mean soil moisture suction was at or very near field capacity (approximately 0.08 atmospheres suction) at the time leaf water potential measurements were taken.

Table 5. Mean soil moisture suction on measurement days

Date	Plot		
	Corn	Tomato	Bean
	(atmospheres)		
7-15-70	0.12	0.40	0.53
7-23-70	0.06	0.07	0.06
8-04-70	0.28	0.24	0.24
8-11-70	0.13	0.17	0.14
8-19-70	0.25	0.30	0.33

Of the depths monitored, the 9 - 18 inch depth layer dried down fastest for all three varieties with a maximum diurnal ψ_s increase of .13 atmospheres suction occurring in the tomato plot on July 15. In all other instances the diurnal ψ_s increase was less than .13 atmospheres.

The corn plot required more water applied through the irrigation system than did the tomato or bean plots. A total of 13.8 inches of water was applied to the corn plot in June, July, and August while the tomato and bean plots each received 12.6 inches of irrigation water in this period. This is based on the amount of water delivered through the sprinkler nozzles. The corn plot, however, was not allowed to develop stresses in excess of 0.50 atmospheres suction at the critical depth, while the tomato and bean plots were allowed to develop 0.70 atmospheres suction before irrigating. Consequently evaporative losses were slightly higher in the corn plot and the one inch more water applied was not significant.

Soil Temperature

Soil temperatures were never extremely high. Daily temperature fluctuations at the 6 inch depth ranged from 1.1 to 6.7 °C (Table 6). At the 9 inch depth the daily temperature fluctuations ranged from 0 to 1.1 °C. At the 12 inch depth, diurnal fluctuations were not common - occurring on only one day ψ_d was measured.

The maximum soil temperature recorded was 27.2 °C. This was recorded at the 6 inch depth. The temperature at the 12 inch depth was 5 °C lower. At no time was the soil temperature sufficiently high to be detrimental to root activity or to soil water movement.

Table 6. Soil temperatures at three depths on measurement days.

Date	Corn Plot			Tomato Plot			Bean Plot		
	6"	9"	12"	6"	9"	12"	6"	9"	12"
7-15-70 AM	20.5	21.7	21.7	20.5	21.7	21.7	21.1	22.2	22.2
7-15-70 PM	23.9	22.2	21.7	27.2	22.2	21.7	27.2	23.3	22.2
7-23-70 AM	16.1	16.7	17.2	16.1	16.7	17.2	16.1	16.7	17.2
7-23-70 PM	17.2	17.2	17.2	17.2	17.2	17.2	17.2	17.2	17.2
8-04-70 AM	17.8	18.9	18.9	17.8	18.9	18.9	17.8	18.9	18.9
8-04-70 PM	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9	18.9
8-11-70 AM	17.8	18.9	18.9	17.8	18.9	18.9	17.8	18.9	18.9
8-11-70 PM	22.2	20.0	19.5	22.2	20.0	19.5	21.1	19.5	18.9
8-19-70 AM	15.6	17.2	17.8	16.7	18.4	18.4	16.1	18.4	18.4
8-19-70 PM	20.0	17.8	17.8	20.5	18.9	18.4	19.5	18.9	18.4

Leaf Water Potential

Comparison of Three Varieties

On five days during the summer months of 1970, Ψ_{ℓ} measurements were made throughout the day to establish the nature and extent of the daylight portion of the Ψ_{ℓ} diurnal fluctuations. The means of these measurements for each time period are reported in Figures 9 through 14 and Table 7. Since periodic measurements were used to establish the changes in Ψ_{ℓ} , the mean measured values were linearly connected in the figures. No assumptions were made as to the nature of the curve between the time periods of the actual readings.

With the exception of the curves for August 19, the Ψ_{ℓ} of the corn was consistently higher than the Ψ_{ℓ} of the tomatoes and beans. A statistical analysis using a completely randomized design indicated that 78% of the mean Ψ_{ℓ} values of the corn were significantly higher ($P = .05$) than the mean values of the tomatoes and beans. The greatest variation occurred on August 11, at 1430 hours when the recorded difference was 3.75 atmospheres. Only infrequently did the Ψ_{ℓ} of the tomatoes and beans differ significantly.

The Ψ_{ℓ} of the corn and beans increased to above 8.0 atmospheres suction on all measurement days. On all but one occasion, August 4, the Ψ_{ℓ} of the tomatoes exceeded 8.0 atmospheres. The leaf water

potential of the corn consistently developed above 10.0 atmospheres, reaching 13.0 atmospheres on July 15 (Table 7). The maximum Ψ_L of the tomatoes was recorded as 11.0 atmospheres, while the beans developed a maximum Ψ_L of 10.8 atmospheres, both also occurring on July 15 (Table 7).

On July 23, Ψ_L of the corn remained above 8.0 atmospheres for 9 1/4 hours and above 9.0 atmospheres suction for 8 1/4 hours. On all occasions 8.0 atmospheres suction was exceeded for 3 3/4 hours or greater in the corn plant.

In the beans and tomatoes, leaf water potential rose above 8.0 atmospheres suction for a maximum of 7 hours. On July 15 the maximum bean and tomato leaf water potential was above 9.0 atmospheres for 6 hours. On August 4 the Ψ_L of the tomatoes and beans did not develop above 8.0 atmospheres suction.

The values recorded become much more meaningful when reviewing the reportings of Brix (1962), Gates (1957), Gates and Bonner (1959), Kramer (1969), Slatyer (1967), Woodham and Kozlowski (1954), and others regarding the effects of high Ψ_L on photosynthesis, formation of soluble nitrogenous and phosphorous compounds, RNA destruction, carbohydrate synthesis, and plant growth.

The curve characteristics determined by this study are also generally in contrast with the levels of leaf water potential under low Ψ_S in the hypothetical generalities of Philip (1957), Slatyer and Denmead (1963), and Slatyer (1967).

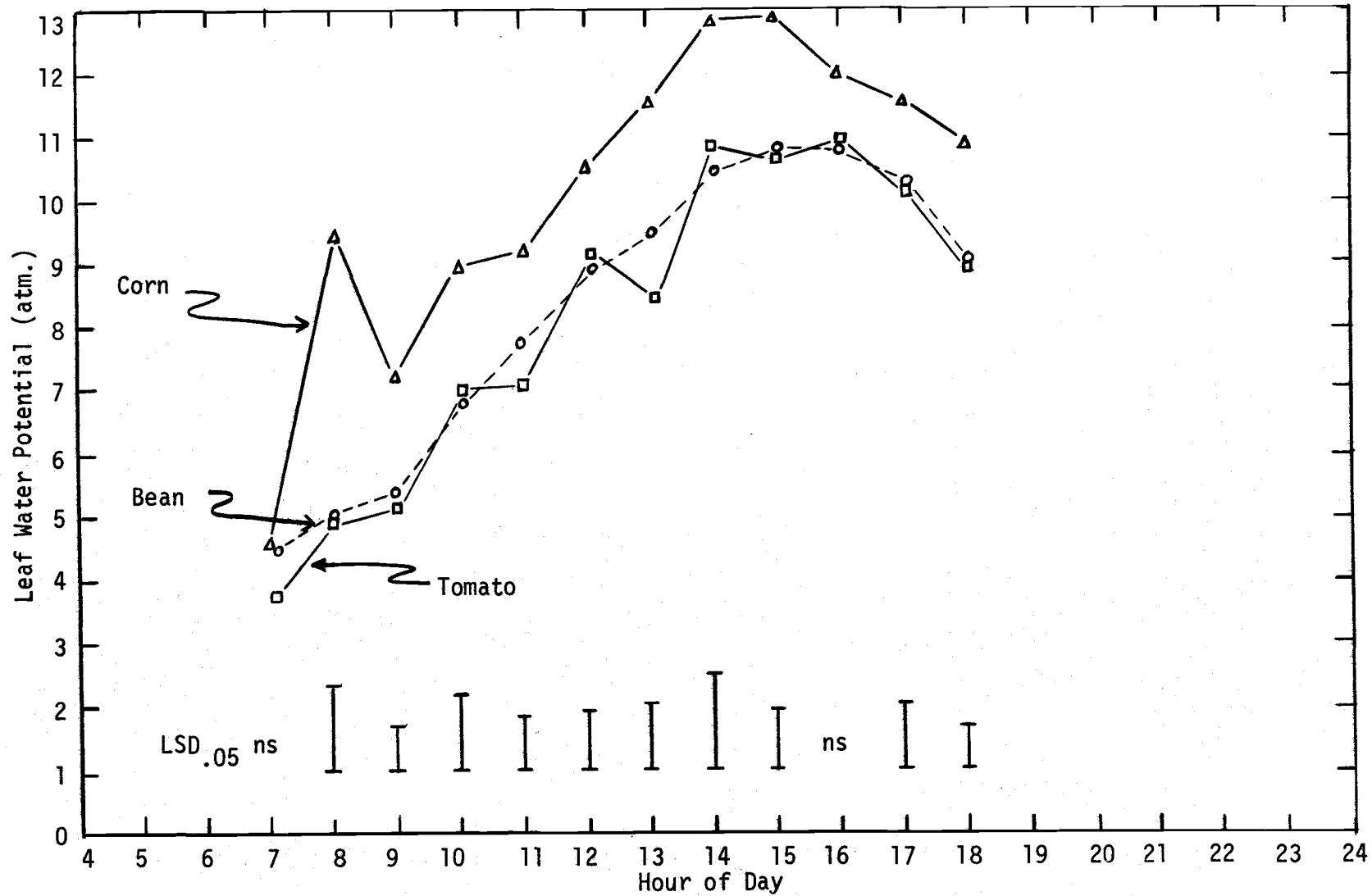


Figure 9. Leaf water potential of three crops, 7/15/70.

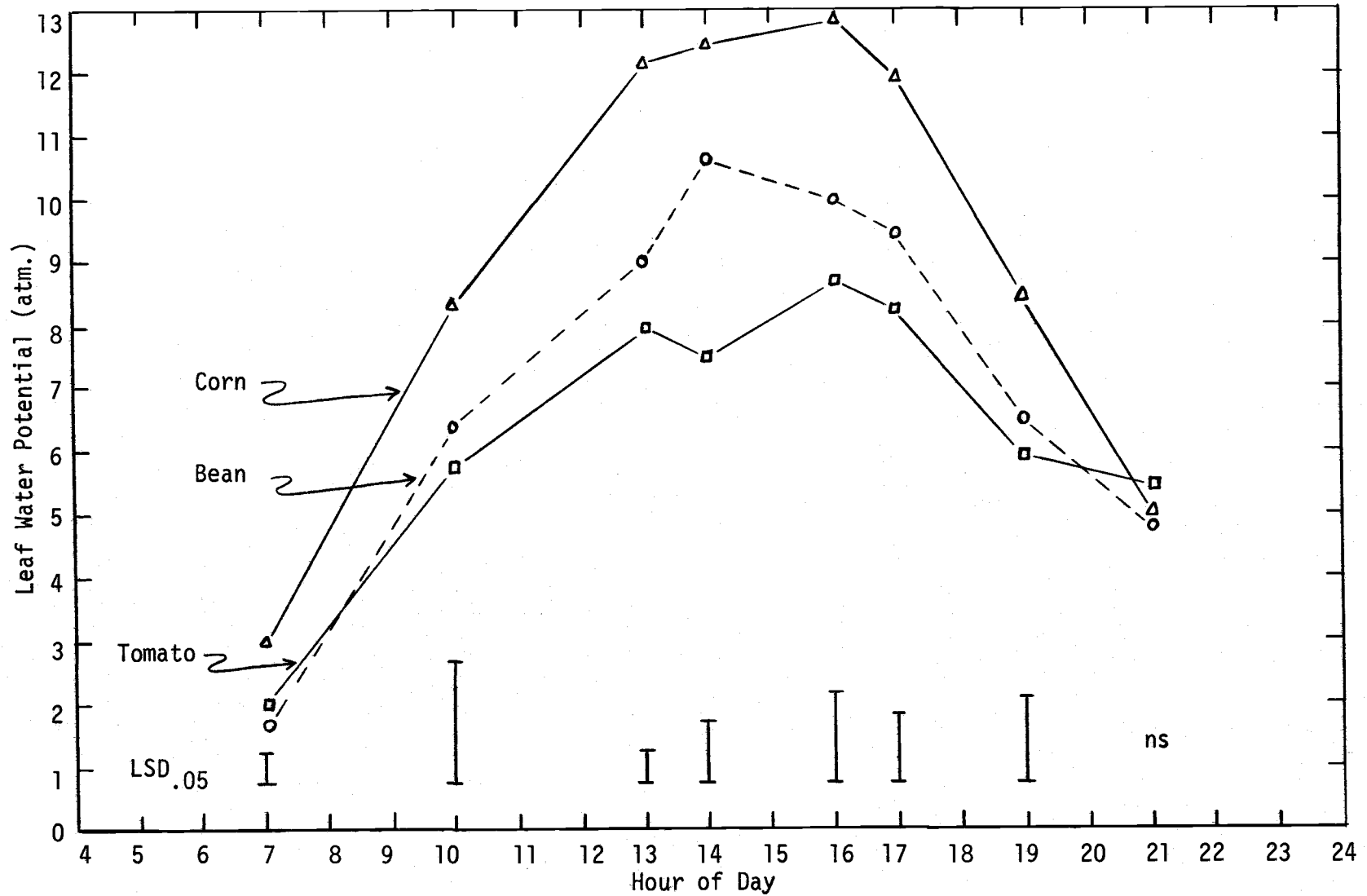


Figure 10. Leaf water potential of three crops, 7/23/70.

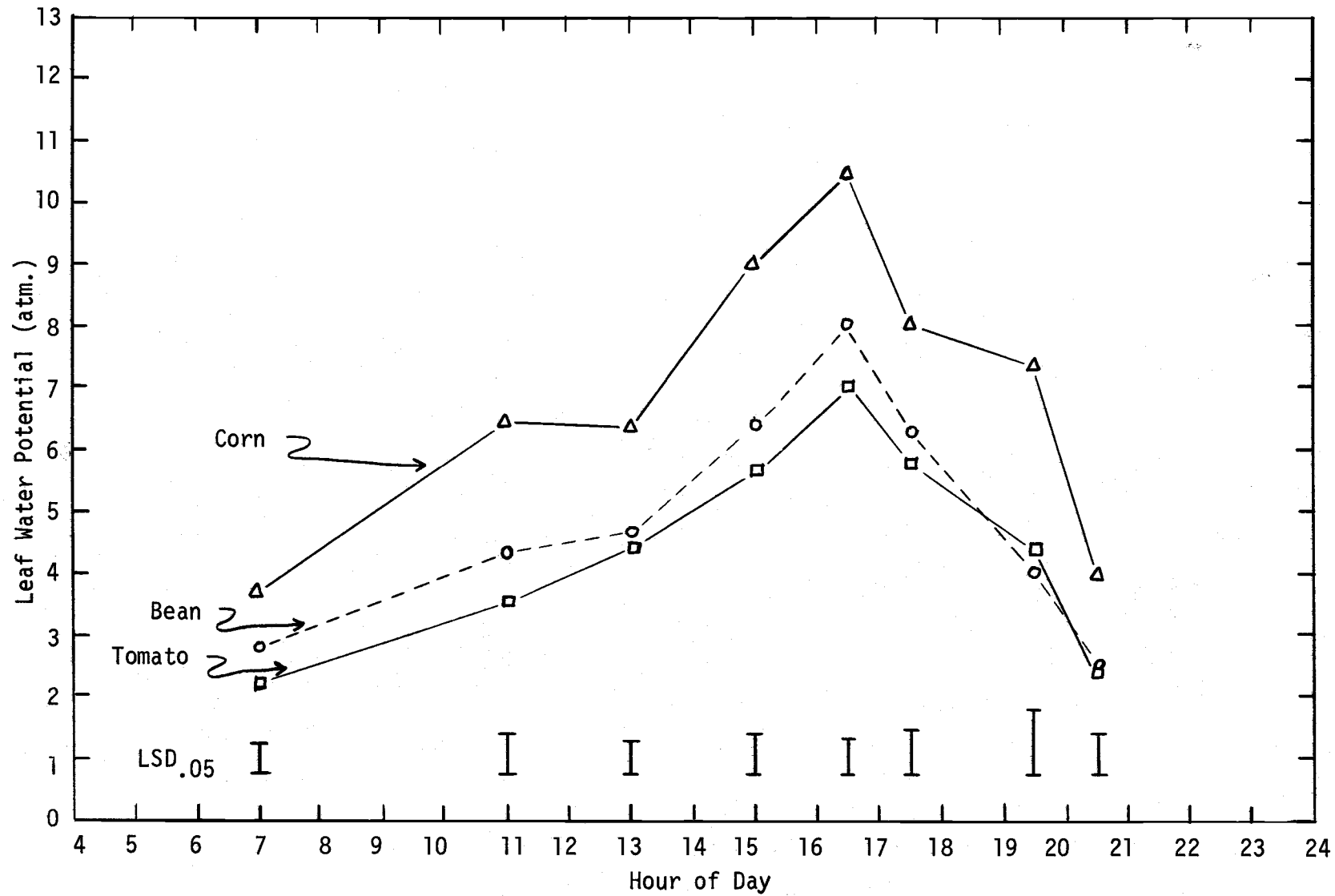


Figure 11. Leaf water potential of three crops, 8/4/70.

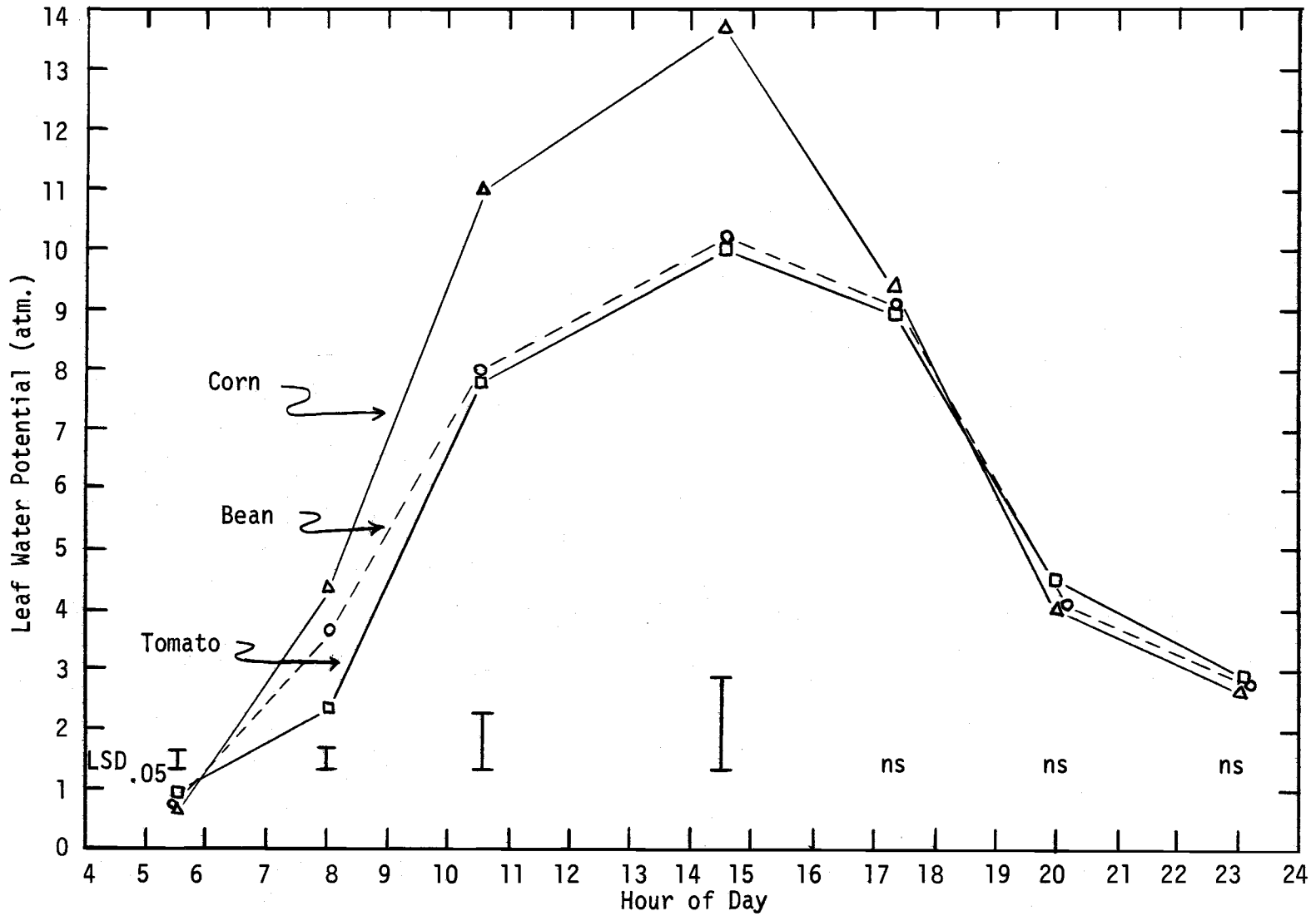


Figure 12. Leaf water potential of three crops, 8/11/70.

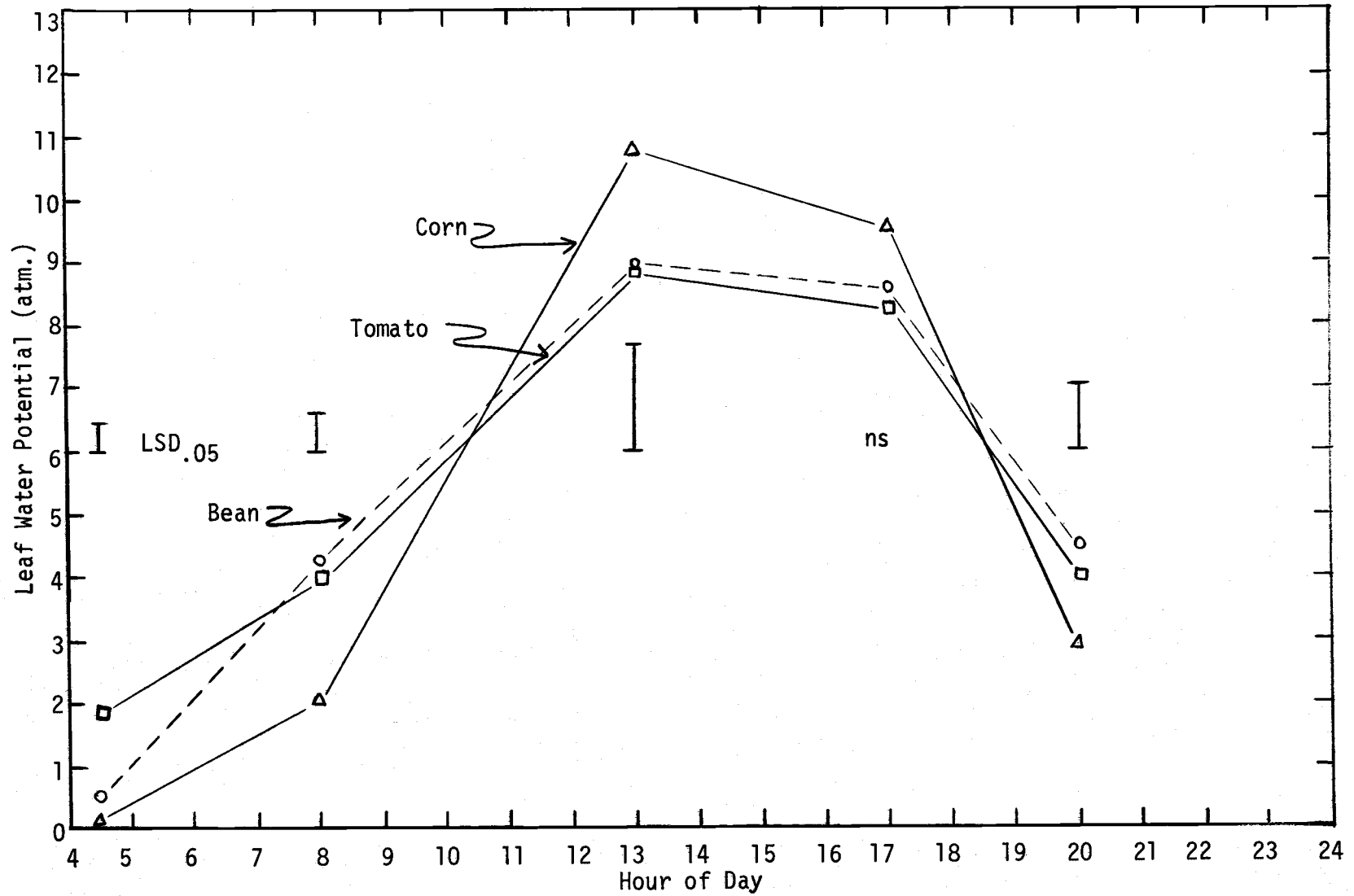


Figure 13. Leaf water potential of three crops, 8/19/70.

Table 7. Mean leaf water potential of three crops at selected time periods.

Time of Day	Crop			LSD _{.05}
	Corn	Tomato	Bean	
<u>July 15, 1970</u>				
0700-0730	4.46	3.75	4.38	ns
0800-0830	9.58	5.08	5.04	1.34
0900-0930	7.29	5.21	5.38	0.73
1000-1030	9.00	7.04	6.88	1.17
1100-1130	9.21	7.13	7.79	0.79
1200-1230	10.63	9.21	9.00	0.94
1300-1330	11.63	8.29	9.54	1.10
1400-1430	12.83	10.88	10.54	1.49
1500-1530	12.92	10.71	10.79	0.91
1600-1630	12.04	11.00	10.79	ns
1700-1730	11.63	10.21	10.29	1.08
1800-1830	10.88	8.96	9.08	0.67
<u>July 23, 1970</u>				
0700-0730	3.08	2.04	1.75	0.38
1000-1030	8.42	5.54	6.46	1.94
1300-1330	12.25	8.00	9.08	0.46
1400-1430	12.50	7.50	10.71	0.95
1600-1630	12.85	8.75	10.05	1.39
1700-1730	12.00	8.31	9.50	1.09
1900-1930	8.56	5.94	6.50	1.29
2100-2130	5.06	5.50	4.88	ns
<u>August 4, 1970</u>				
0700-0730	3.75	2.25	2.79	0.54
1100-1130	6.50	3.58	4.33	0.72
1300-1330	6.42	4.42	4.71	0.57
1500-1530	9.10	5.70	6.45	0.67
1630-1700	10.56	7.06	8.13	0.57
1730-1800	8.13	5.81	6.31	0.74
1930-2000	7.44	4.38	4.06	1.13
2030-2100	4.00	2.38	2.44	0.68

(Table 7. - continued)

Time of Day	Crop			LSD .05
	Corn	Tomato (atmospheres)	Bean	
<u>August 11, 1970</u>				
0530-0600	0.65	0.98	0.70	0.26
1800-1830	4.35	2.35	3.65	0.31
1030-1100	11.00	7.75	7.90	0.96
1430-1500	13.75	10.00	10.20	1.47
1700-1730	9.45	8.95	9.15	ns
2000-2030	4.00	4.45	4.05	ns
2300-2330	2.56	2.81	2.63	ns
<u>August 19, 1970</u>				
0430-0500	0.08	1.85	0.49	0.38
0800-0830	2.10	3.95	4.25	0.64
1300-1330	10.80	8.80	8.90	1.70
1700-1730	9.65	8.25	8.65	ns
2000-2030	2.85	3.94	4.46	1.10

Leaf Water Potential and Solar Radiation

Leaf water potential was directly influenced by solar radiation as reported in Figures 14 through 22. The morning of August 4 was extremely cloudy (Figures 20 through 22) with the sun breaking through at approximately 1400 hours. The Ψ_{ℓ} of all three varieties very closely reflected this condition; the increase in Ψ_{ℓ} was comparatively minor during the morning and early afternoon. However, the Ψ_{ℓ} recorded at 1500 hours showed a marked increase in all three crops.

A definite time lag in response between peak solar radiation and maximum Ψ_{ℓ} was found in all cases (Figures 15 through 23). The time differential was consistently 2 to 3 hours, with the Ψ_{ℓ} being the latter to respond. Since the measured Ψ_{ℓ} levels were linearly connected without attempting to smooth the curve, the relationship between solar radiation and Ψ_{ℓ} between measured points is only an approximation. Thus, the apparent lack of a time lag between peak solar radiation and maximum Ψ_{ℓ} of the corn in Figure 20 is likely not valid.

Solar radiation curves for August 11 and 19 are not included. Inclusion of the data for these days, however, would not change the observed trends.

The failure of the Ψ_{ℓ} of the tomatoes to reach the same maximum on July 23 (Figure 18) as on July 15 (Figure 15) cannot be attri-

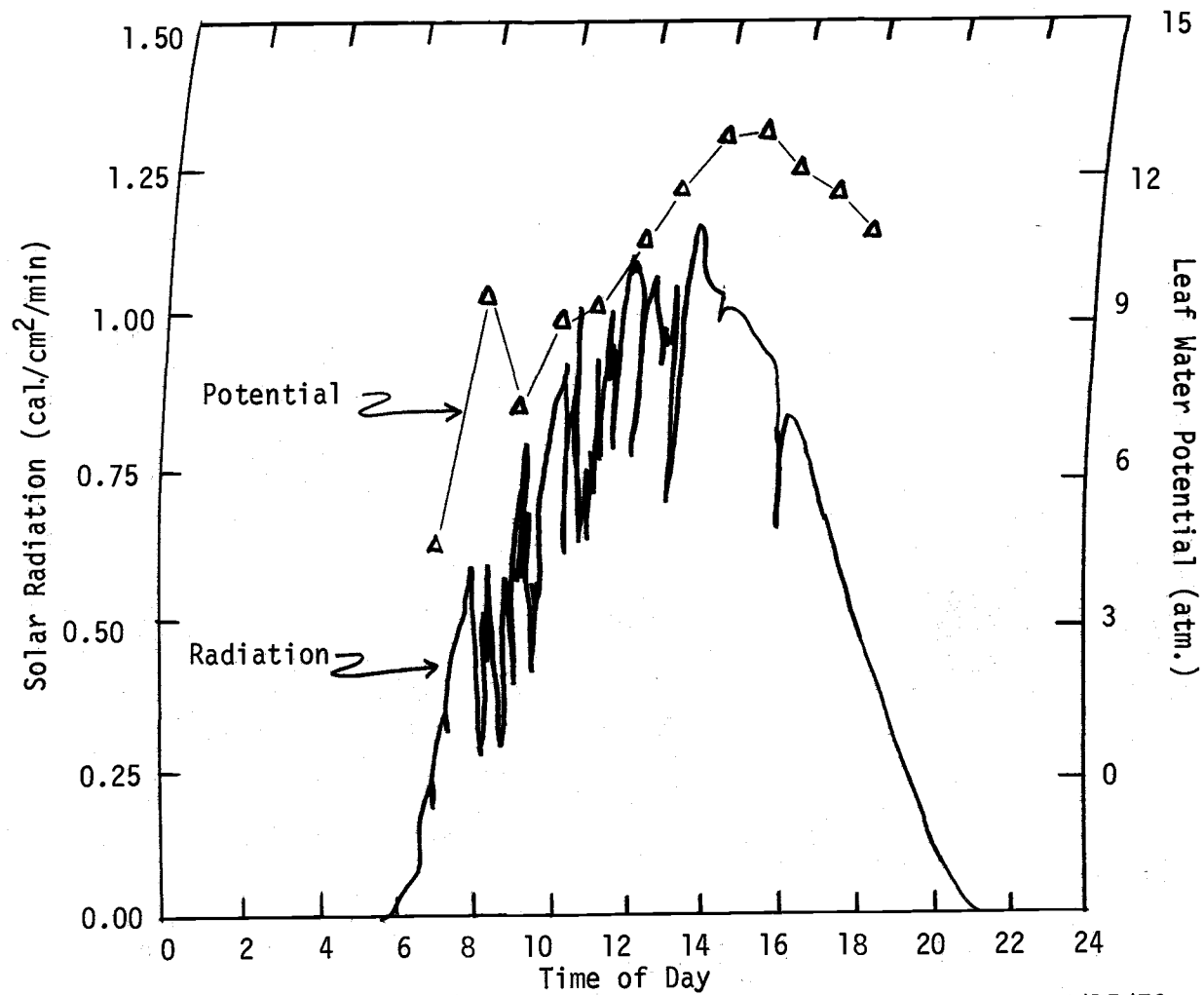


Figure 14. Solar radiation and leaf water potential of corn, 7/15/70.

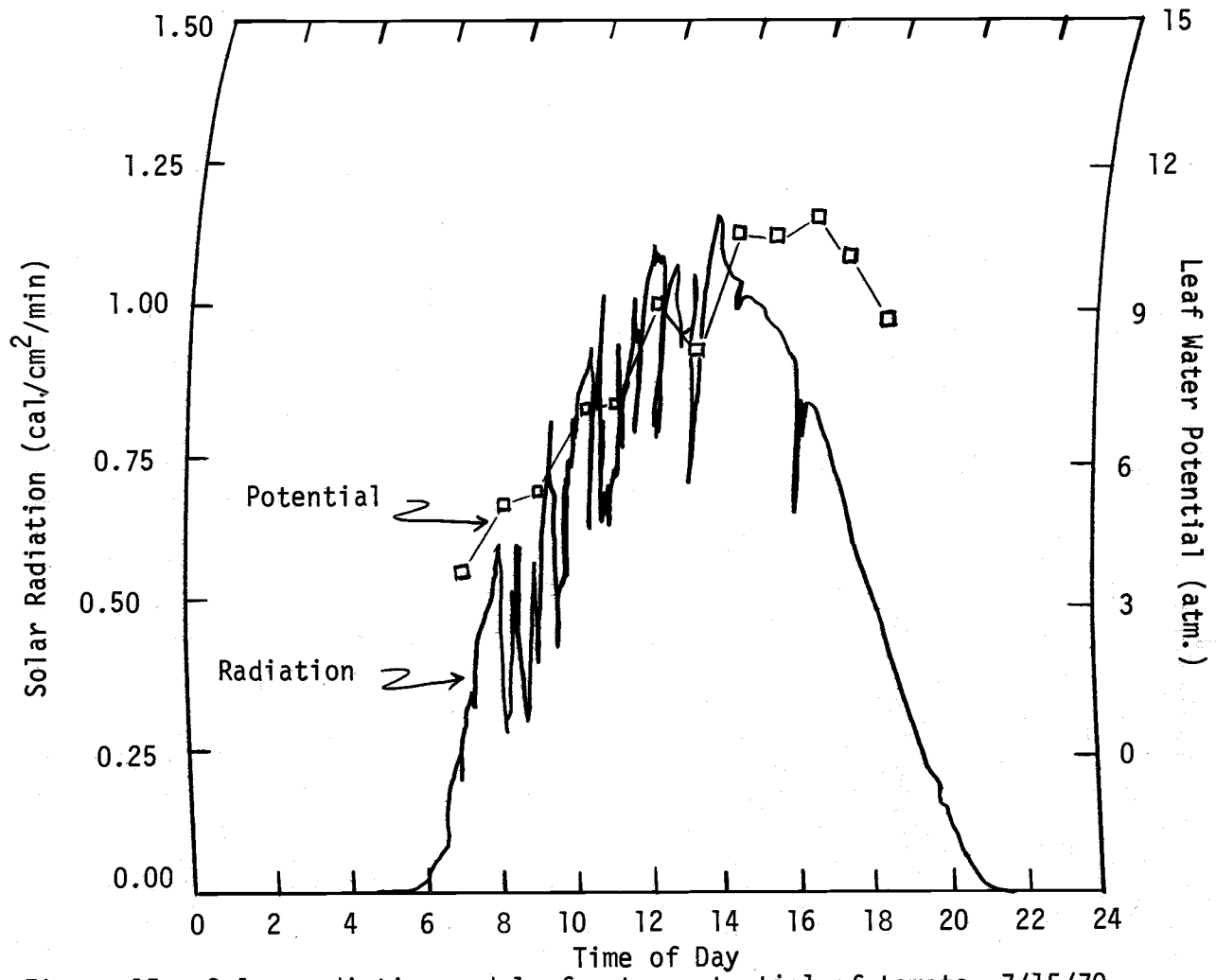


Figure 15. Solar radiation and leaf water potential of tomato, 7/15/70.

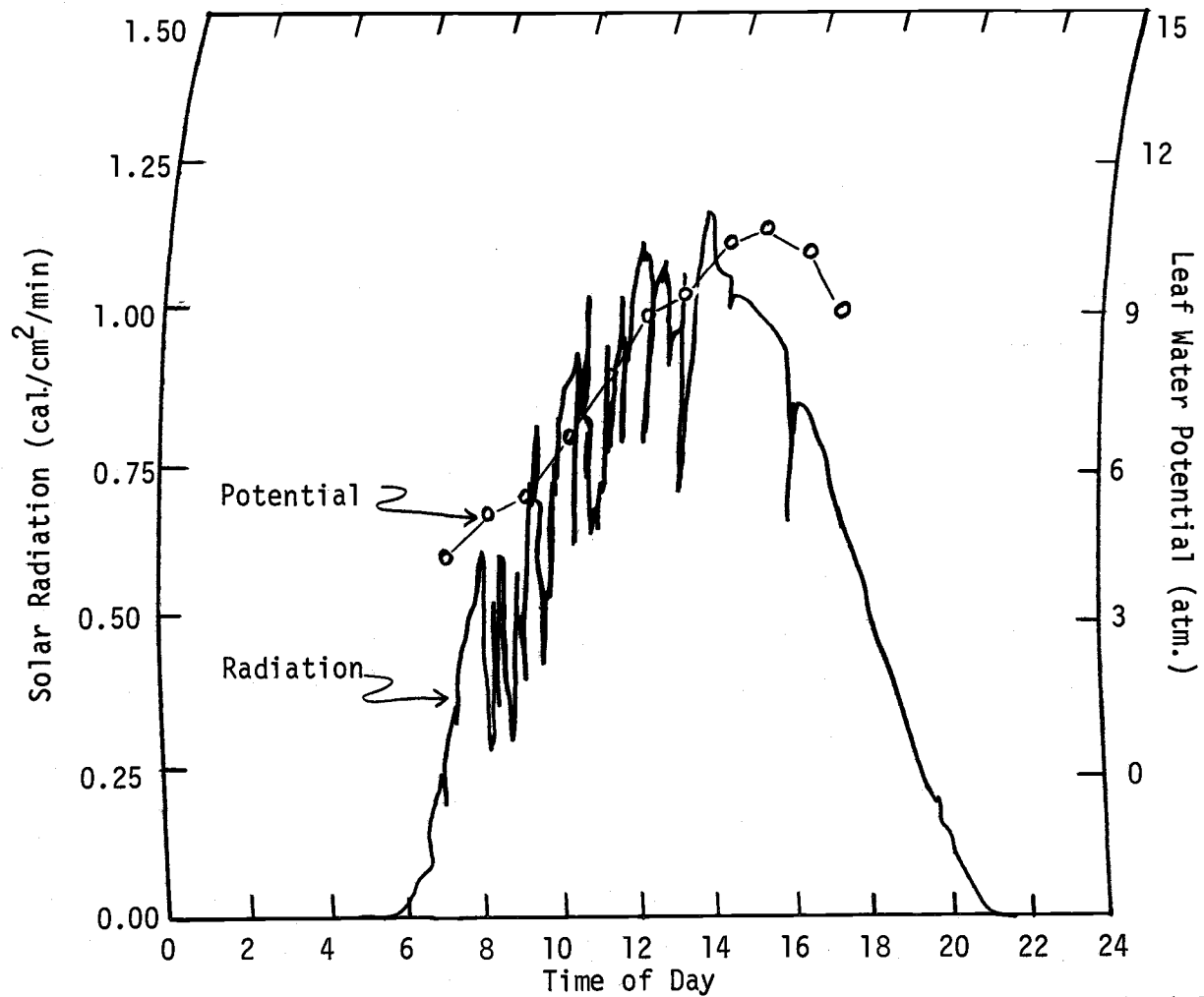


Figure 16. Solar radiation and leaf water potential of beans, 7/15/70.

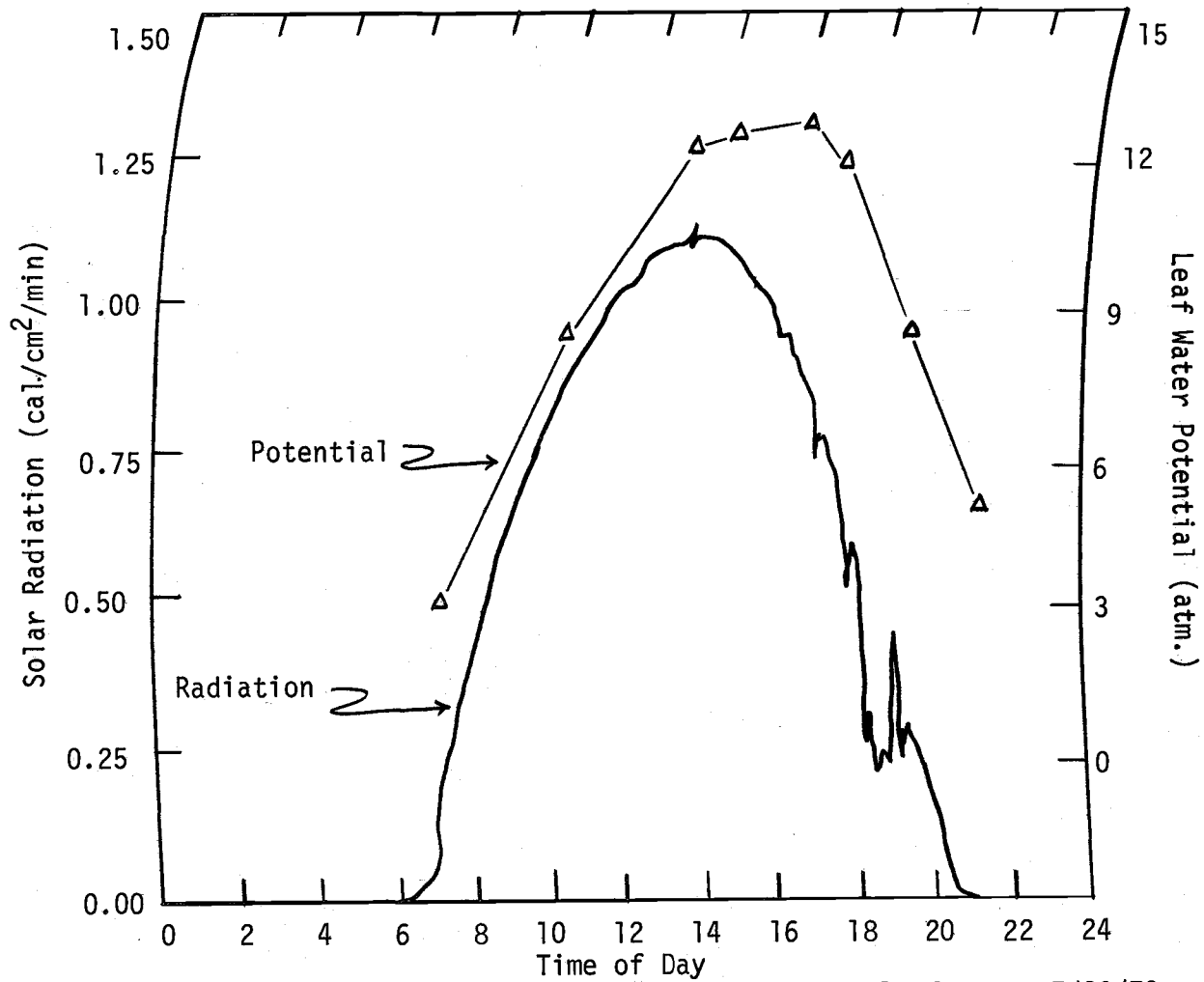


Figure 17. Solar radiation and leaf water potential of corn, 7/23/70.

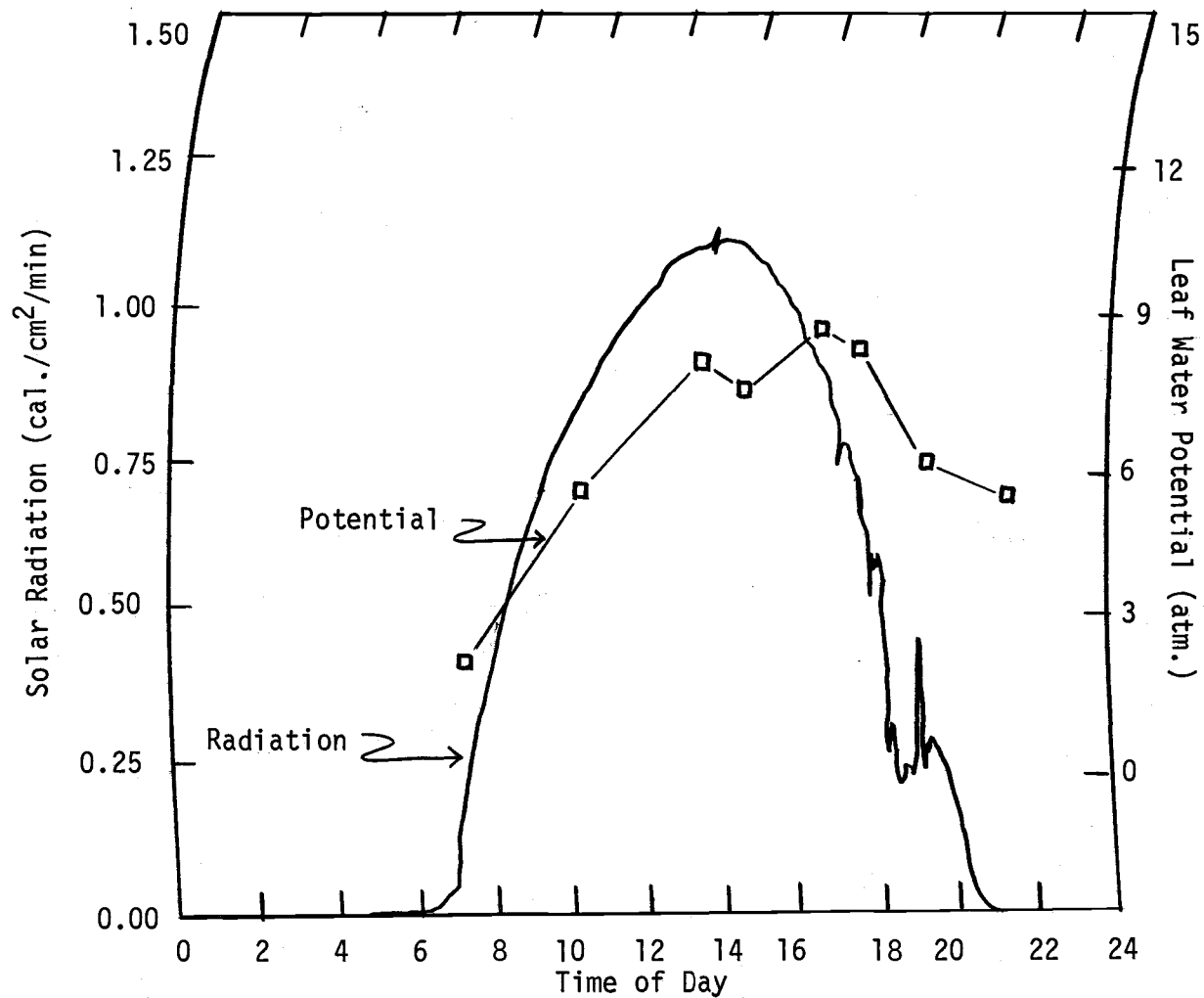


Figure 18. Solar radiation and leaf water potential of tomato, 7/23/70.

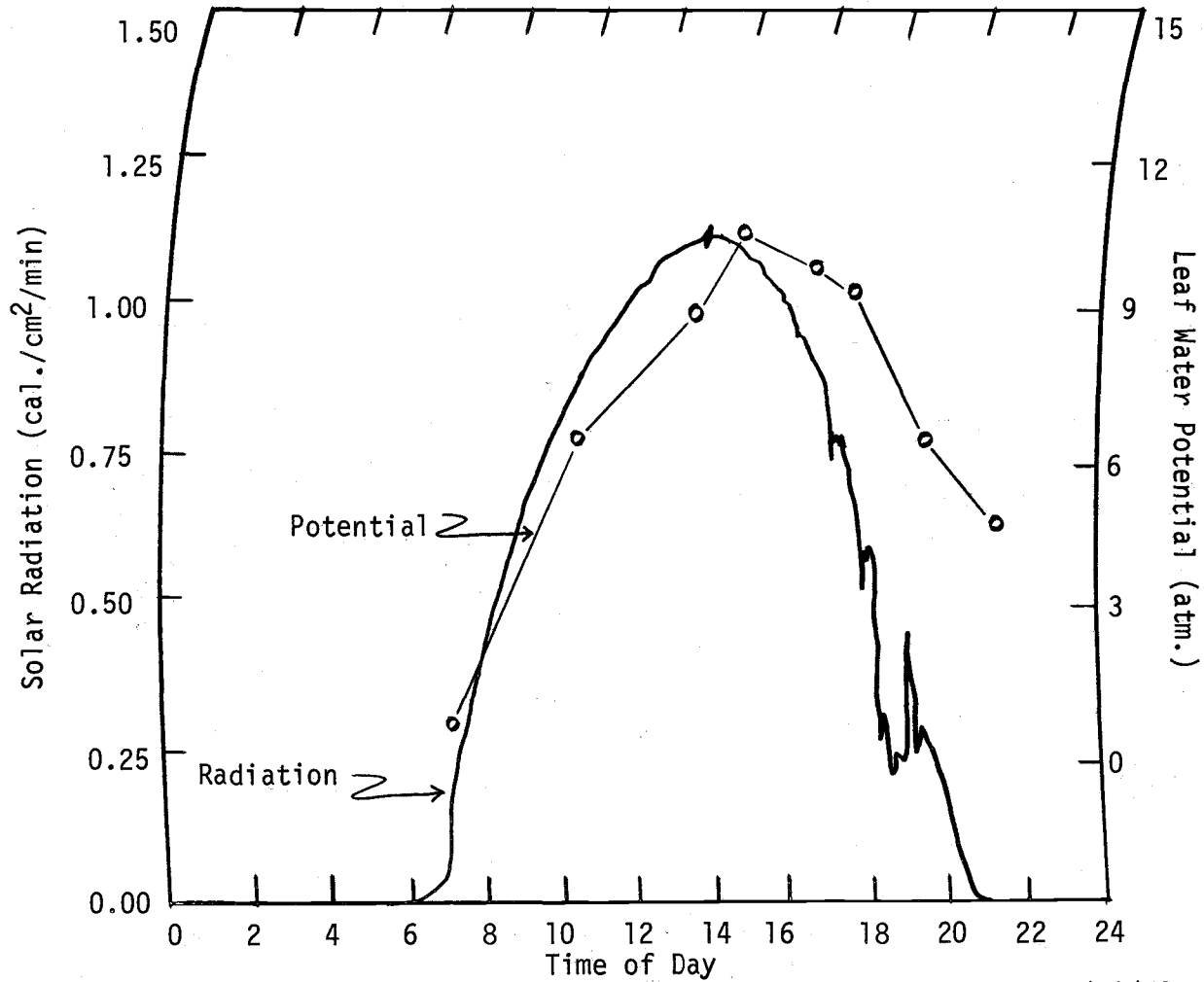


Figure 19. Solar radiation and leaf water potential of beans, 7/23/70.

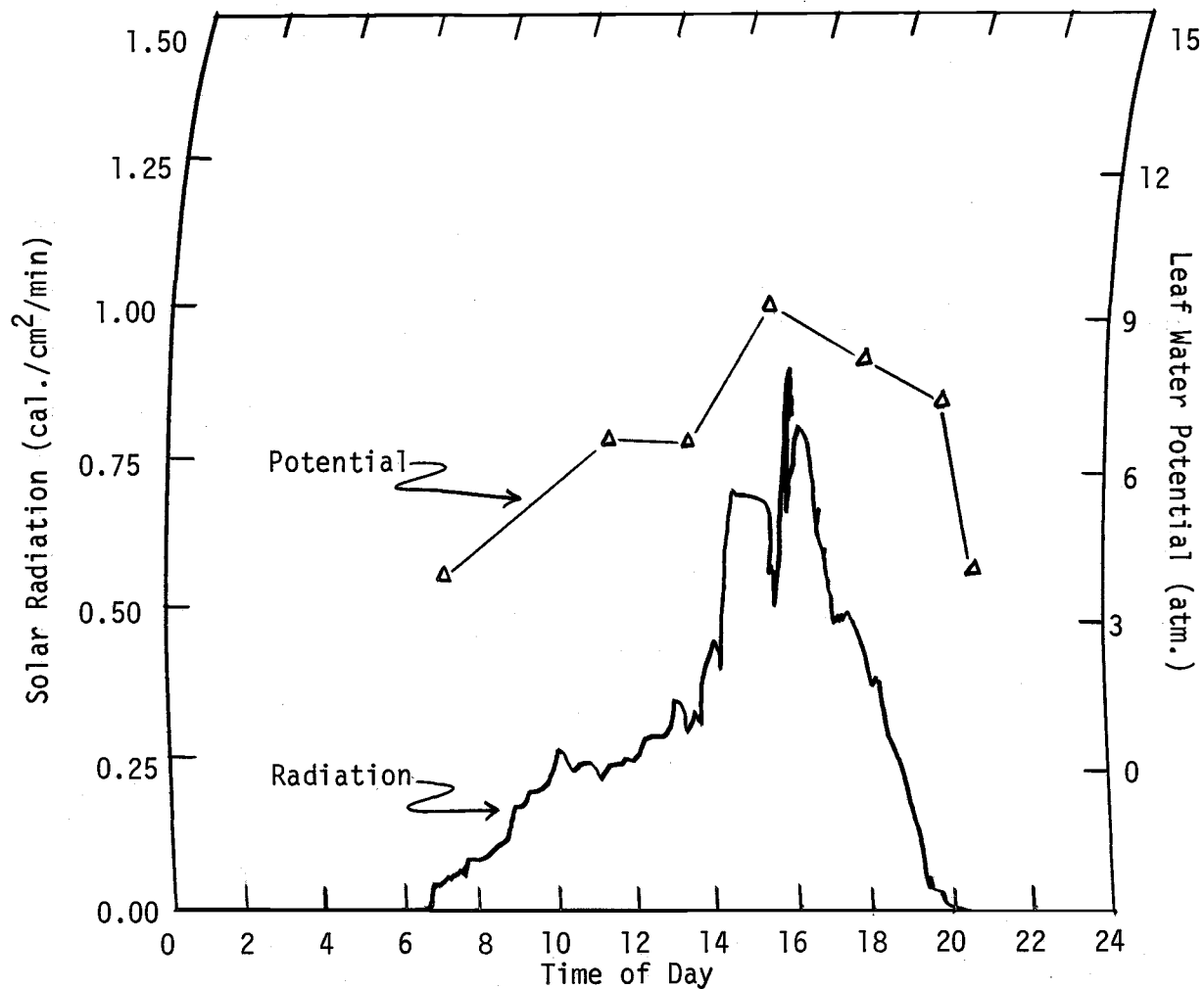


Figure 20. Solar radiation and leaf water potential of corn, 8/4/70.

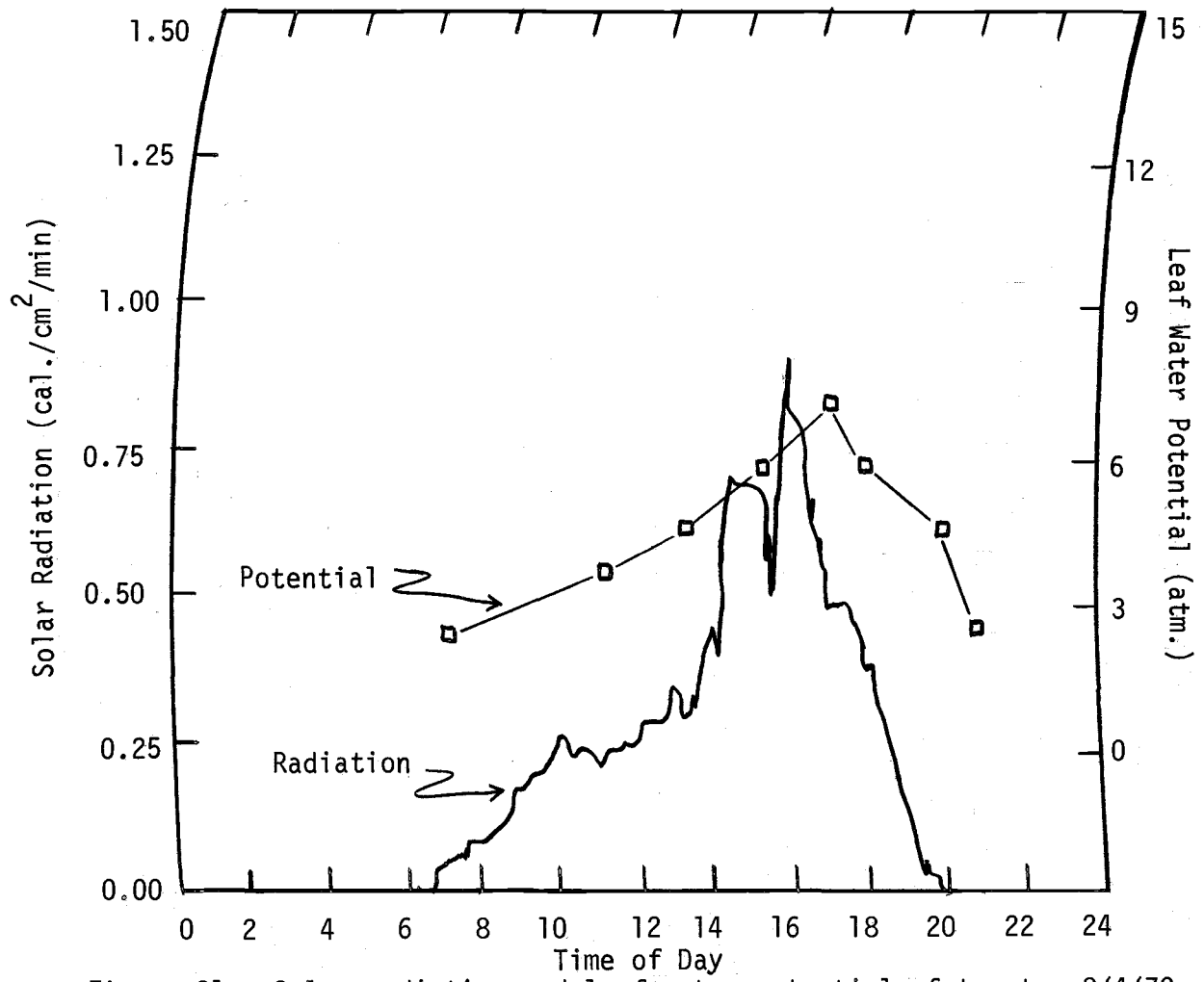


Figure 21. Solar radiation and leaf water potential of tomato, 8/4/70.

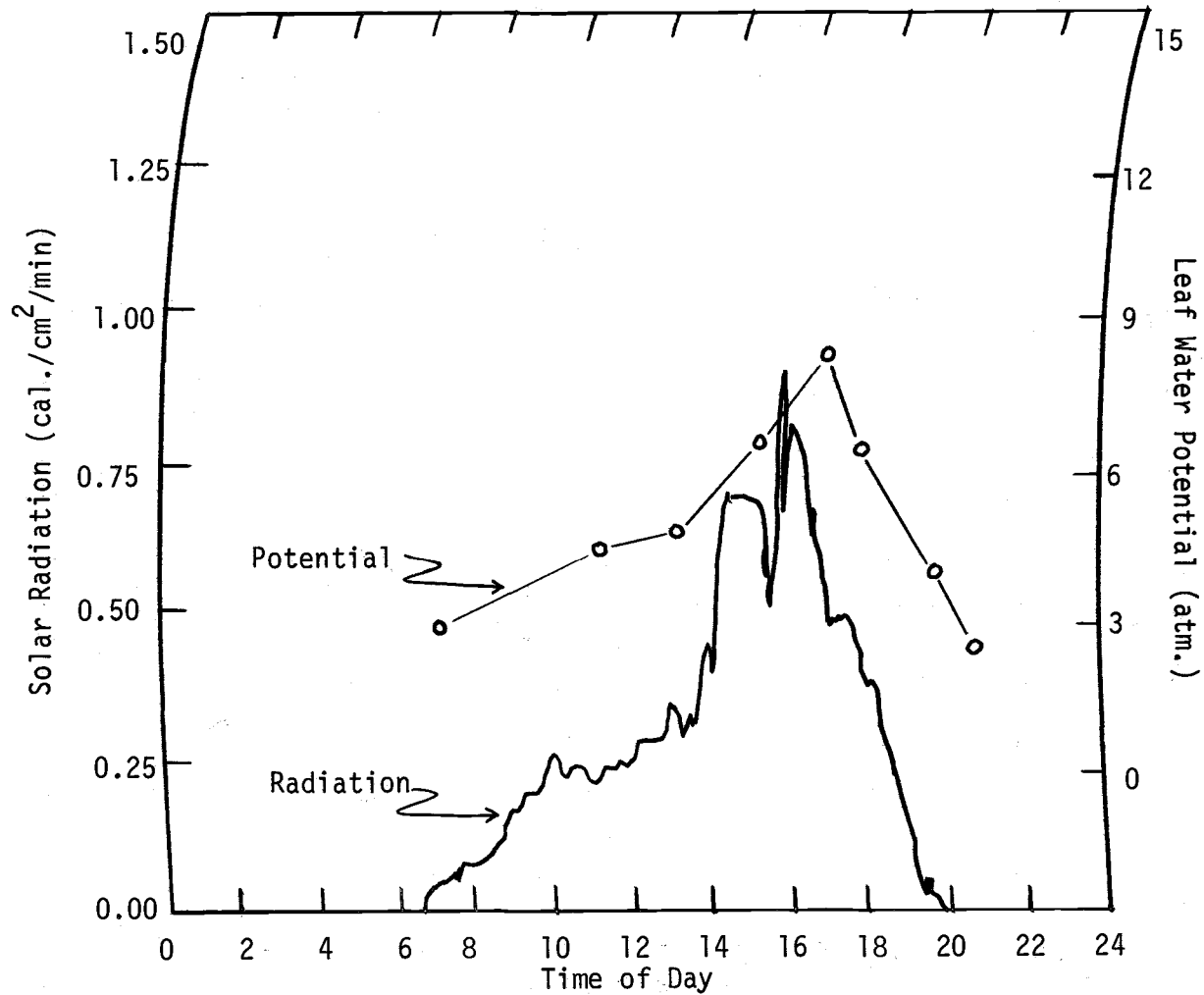


Figure 22. Solar radiation and leaf water potential of beans, 8/4/70.

buted to a decrease in solar radiation or higher ψ_s (Table 5). The maximum ψ_ℓ of the corn and beans was very similar on the two days (Figures 14, 16, 17, and 19).

Neither can the significant, but brief, deviation of ψ_ℓ of the corn at 0800 hours on July 15 (Figure 14 and Table 7) be explained by abrupt changes in solar radiation levels.

Leaf Water Potential and Air Temperature

The effect of ambient air temperature alone on the nature of the ψ_ℓ curves was not consistent (Figures 23 through 28) and wet bulb temperature had no apparent effect on the nature of the ψ_ℓ curves.

On July 15, the time period of the peak ambient air temperature and the maximum ψ_ℓ was basically the same (Figures 23 through 25) for all three crops. On July 23, however, the maximum ψ_ℓ of the corn and tomatoes occurred 2 hours prior to the maximum ambient air temperature (Figures 26 and 27). The lag period of maximum air temperature to maximum ψ_ℓ of the beans was about 3 hours (Figure 28). Figures were not included for the two days in August. Inclusion of these figures would not alter the lack of consistency between ambient air temperature and ψ_ℓ . The summary data for these dates are included in Tables 7 and 10.

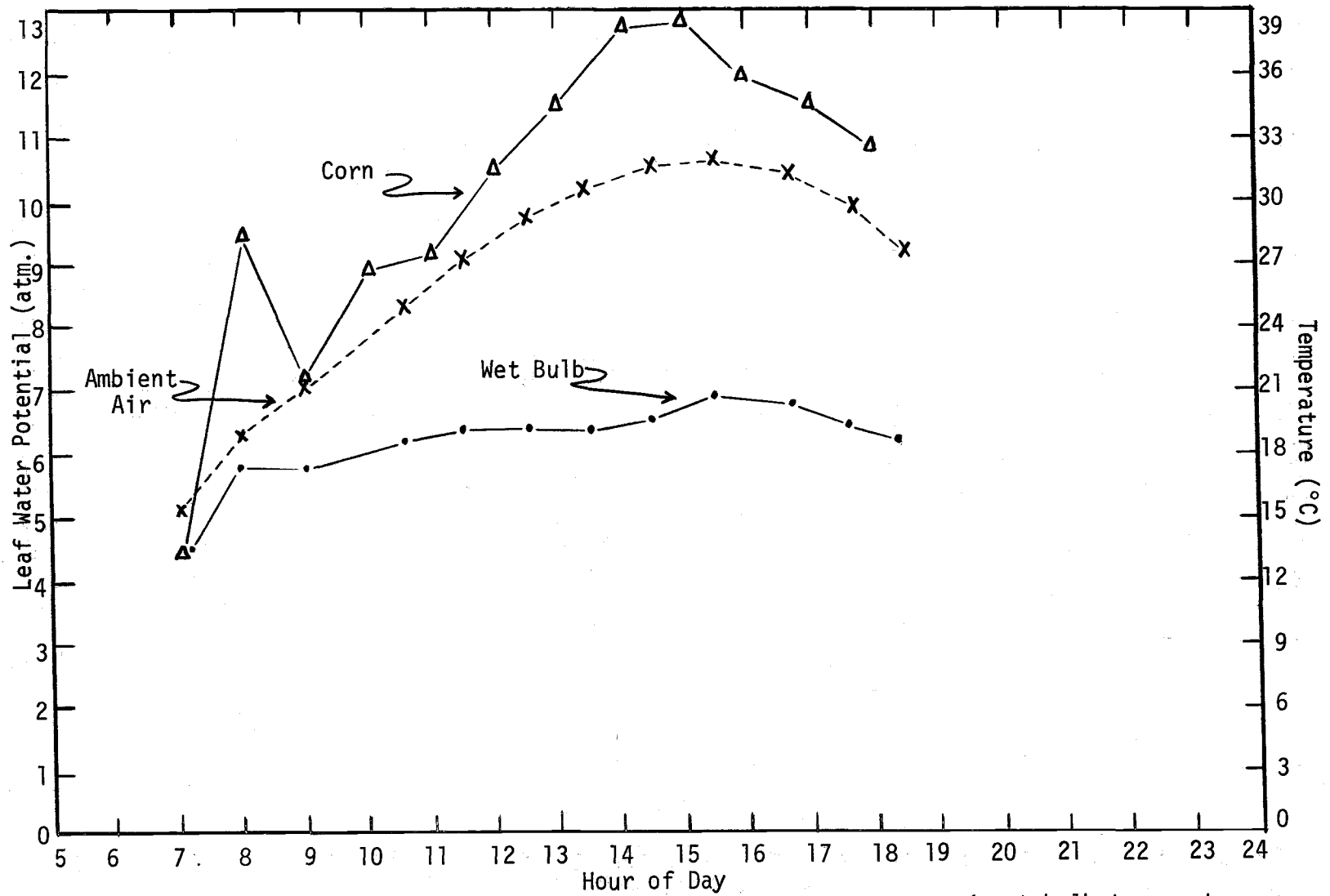


Figure 23. Leaf water potential of corn, ambient air temperature, and wet bulb temperature, 7/15/70.

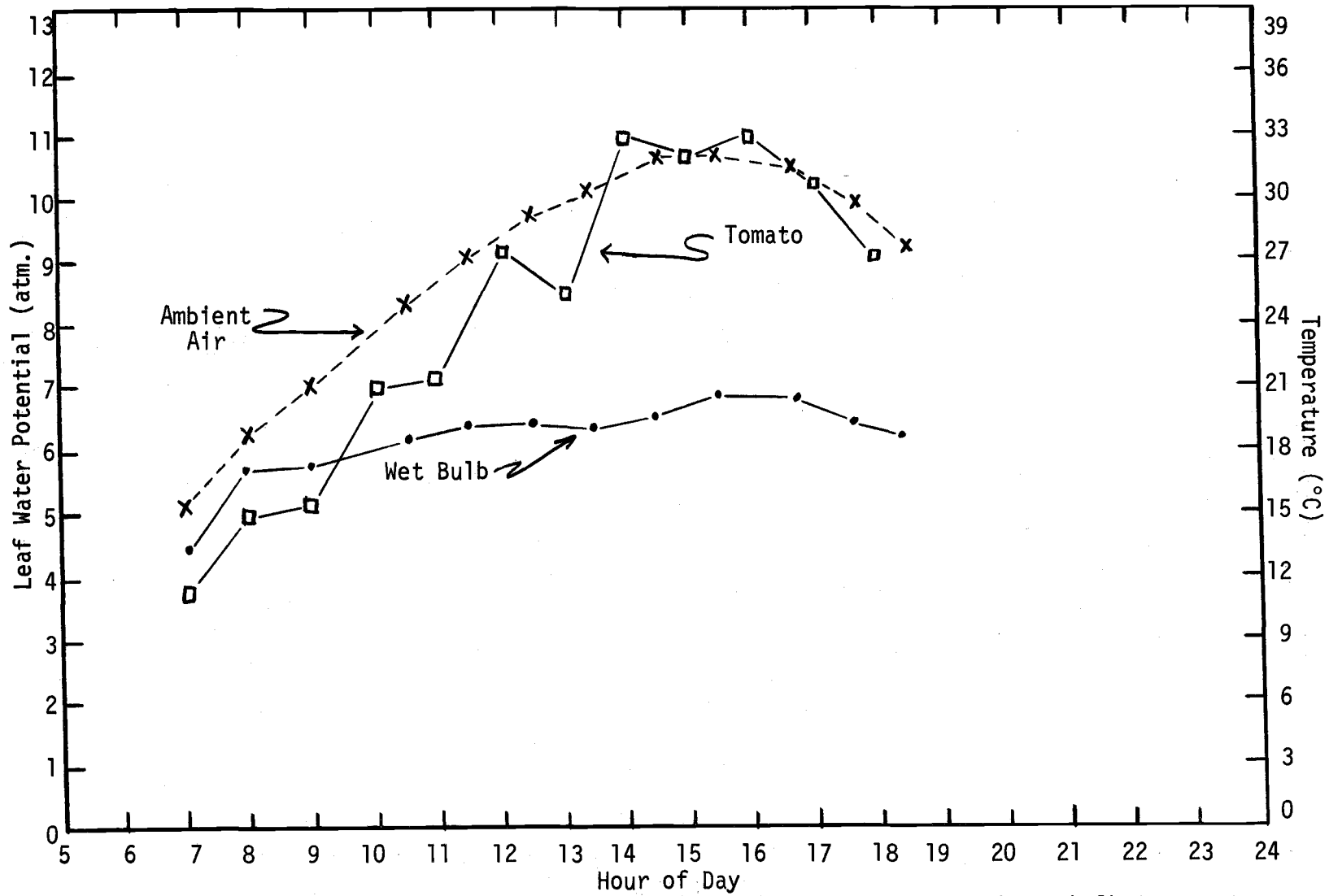


Figure 24. Leaf water potential of tomato, ambient air temperature, and wet bulb temperature, 7/15/70.

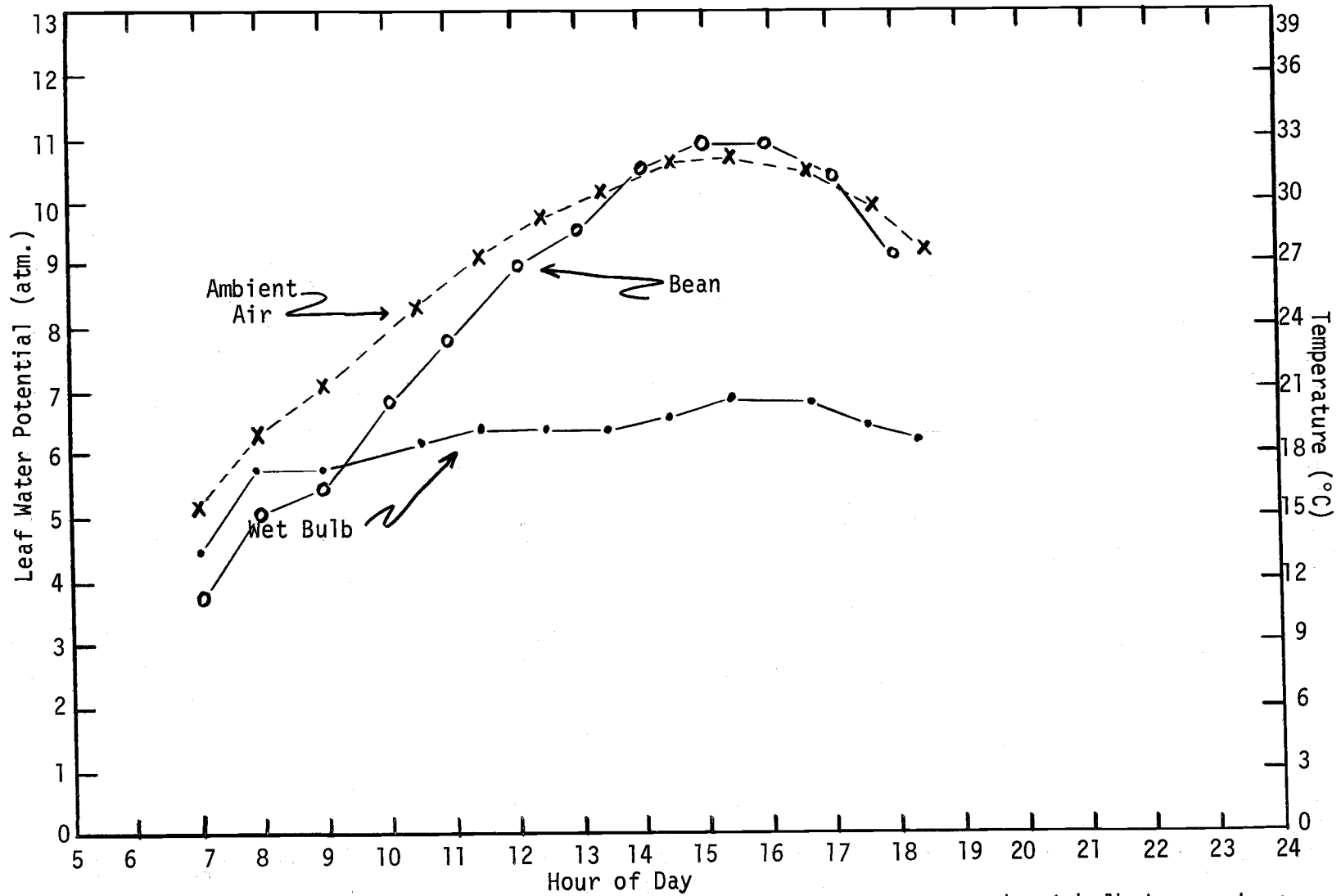


Figure 25. Leaf water potential of beans, ambient air temperature, and wet bulb temperature, 7/15/70.

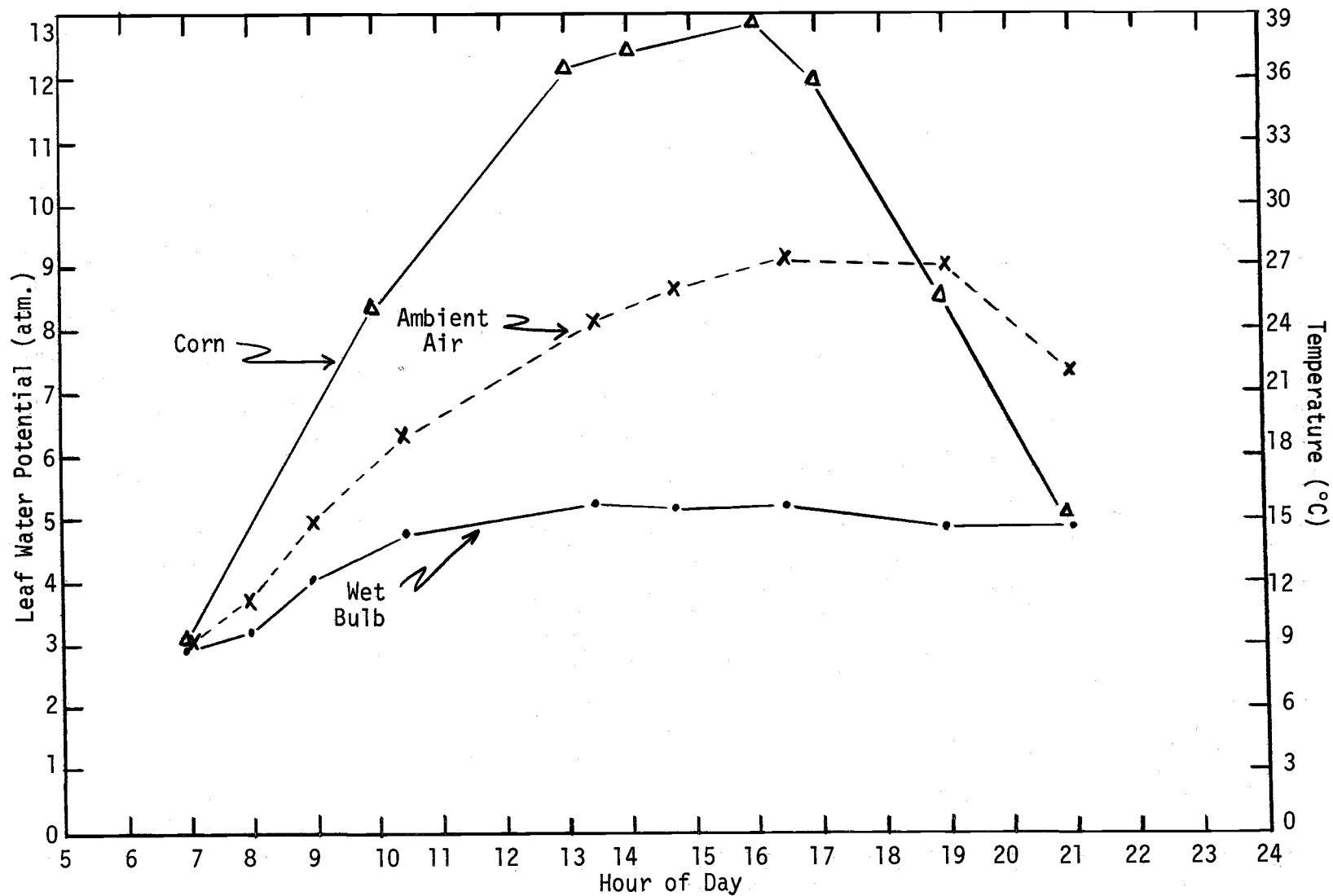


Figure 26. Leaf water potential of corn, ambient air temperature, and wet bulb temperature, 7/23/70.

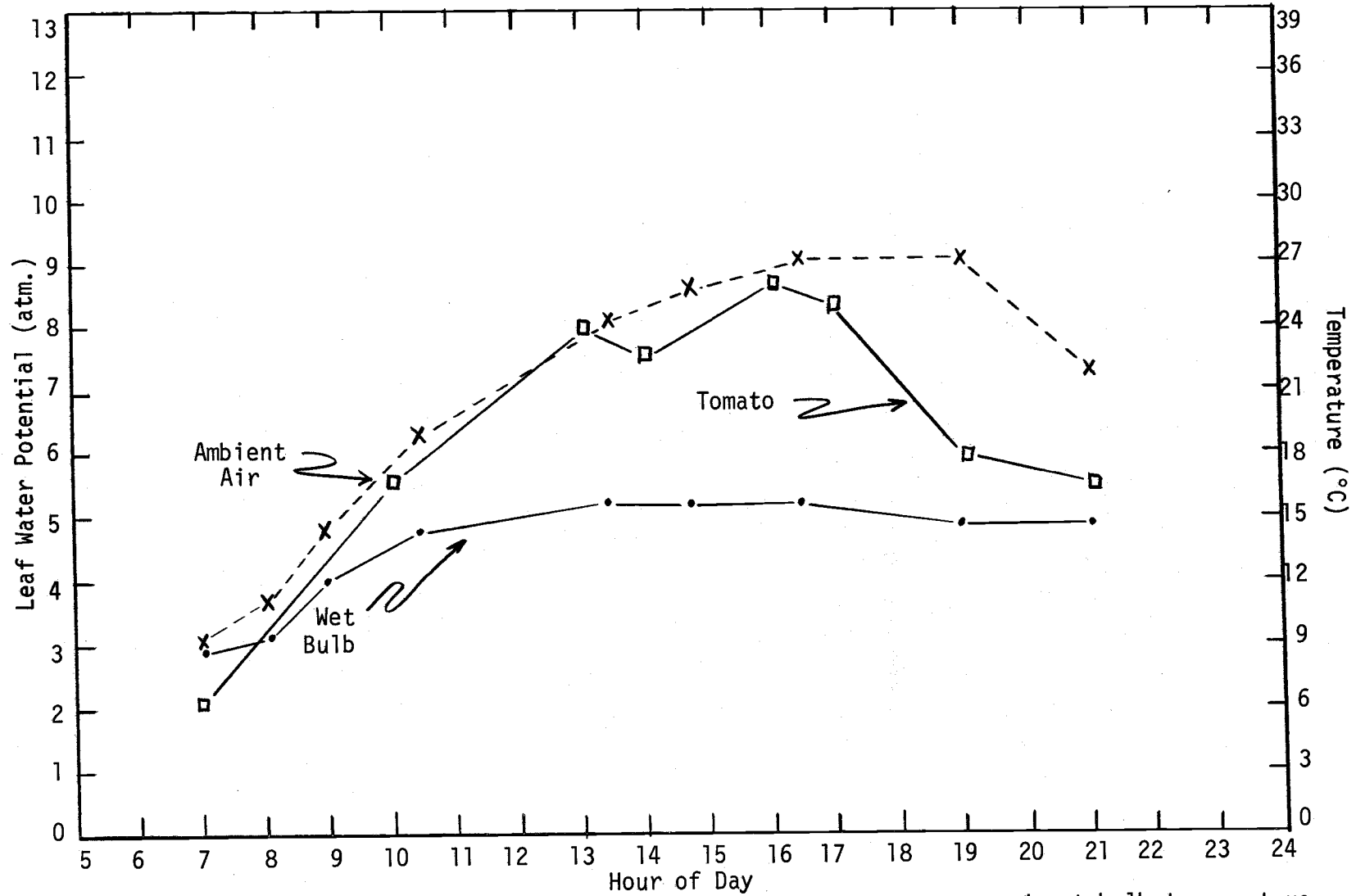


Figure 27. Leaf water potential of tomato, ambient air temperature, and wet bulb temperature, 7/23/70.

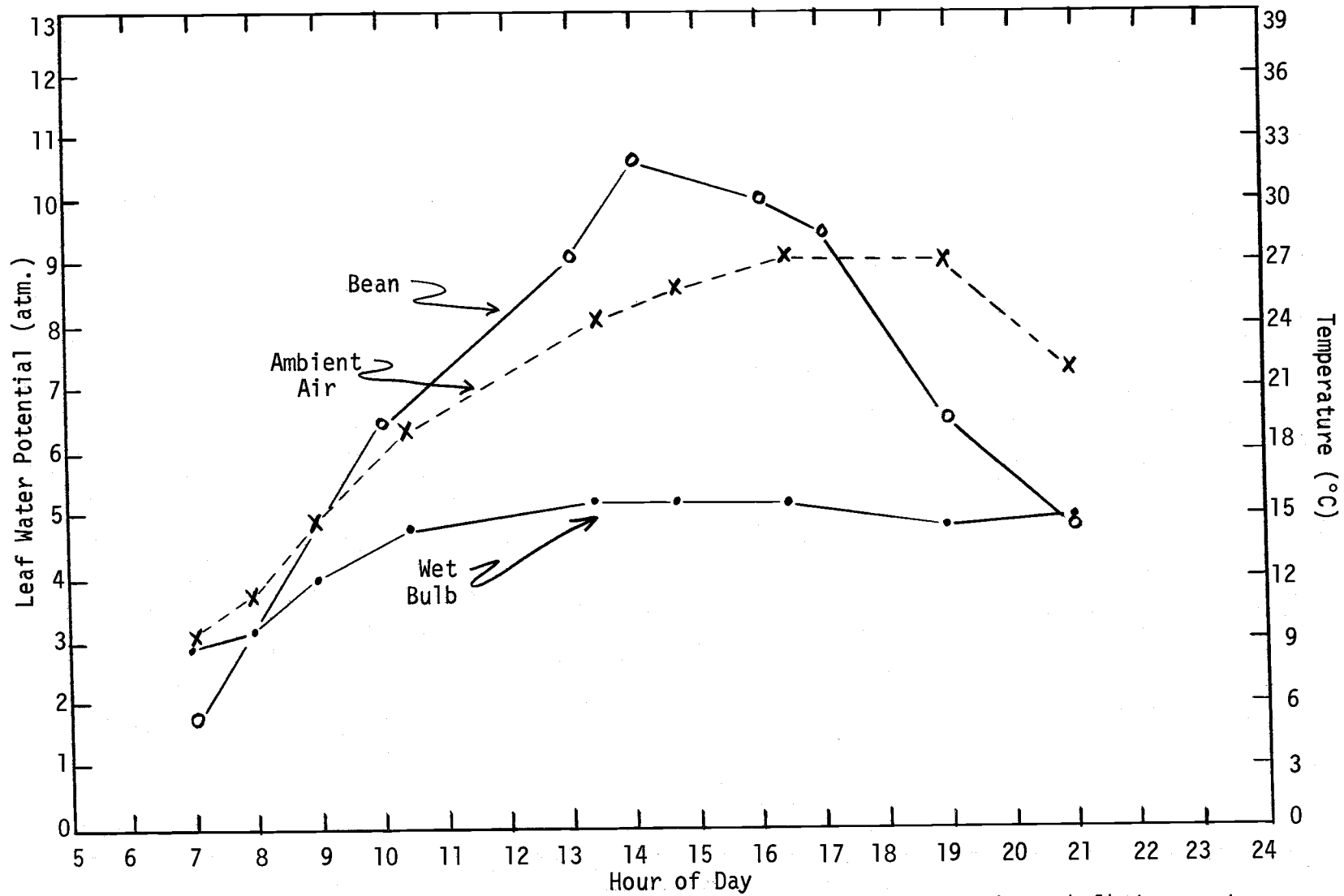


Figure 28. Leaf water potential of beans, ambient air temperature, and wet bulb temperature, 7/23/70.

Leaf Water Potential and Other Meteorological Parameters

The air movement was generally at a minimum from near mid-night to approximately 1000 hours at the site of this study. Near 1000 hours the air currents began moving in an easterly direction (Table 8), reaching a peak in mid-afternoon. By early evening the wind velocity had begun to subside. Only the air movement data of three days are included in Table 8. Inclusion of the data of the other two days would not alter the trends or general velocities depicted in Table 8. Changes in the leaf water potential curves did not coincide with changes in the air movement characteristics.

A summary of the major meteorological parameters of the crop environment was reported in Table 9. Peak solar radiation varied from $0.90 \text{ cal/cm}^2/\text{min}$ to $1.16 \text{ cal/cm}^2/\text{min}$. Maximum air temperature varied $11.9 \text{ }^\circ\text{C}$ among days; from $20.6 \text{ }^\circ\text{C}$ to $32.5 \text{ }^\circ\text{C}$. Total evaporation varied from 6.20 mm/day to 9.50 mm/day . Barometric pressure varied little; maximum fluctuations were 3.60 mm Hg/day . All days were fair, and varied from overcast to a cloudless sky.

Table 8. Air movement characteristics on three specific days.

Time of Day	August 4, 1970		August 11, 1970		August 19, 1970	
	Direction	Speed (mph)	Direction	Speed (mph)	Direction	Speed (mph)
0800	---	2	---	0	---	0
0900	---	0	E	2	---	0
1000	WNW	2	---	0	WSW	2
1100	WNW	4	W	6	W	6
1200	WNW	1	WSW	7	W	6
1300	WNW	4	W	8	W	10
1400	WNW	1	WNW	9	W	9
1500	NW	1	WNW	8	WNW	8
1600	NW	3	NW	10	WNW	10
1700	WNW	5	NW	8	NW	9
1800	WNW	3	ENE	4	NW	8
1900	W	2	NNW	3	NW	8
2000	---	0	WNW	6	WNW	5
2100	---	0	ESE	2	WSW	6
2200	---	0	WNW	1	WSW	4

Table 9. Effects of meteorological conditions on leaf water potential

Date	Peak Solar Radiation (cal/cm ² /min)	Maximum Air Temperature (°C)	Total Evaporation (mm)	Barometric Pressure		Maximum Leaf Water Potential			Maximum Leaf Temperature		
				Minimum (mm Hg)	Maximum (mm Hg)	Corn	Tomato	Bean	Corn	Tomato	Bean
7-15-70	1.16	32.1	9.50	746.31	749.31	12.92	11.00	10.79	31.0	31.2	32.3
7-23-70	1.12	27.5	9.00	749.31	752.91	12.85	8.75	10.71	27.8	26.6	27.8
8-04-70	0.90	20.6	6.25	748.93	751.56	10.56	7.06	8.13	23.2	19.4	20.6
8-11-70	1.04	32.5	9.40	750.06	752.69	13.75	10.00	10.20	29.2	28.4	28.8
8-19-70	1.03	27.5	6.50	750.81	752.91	10.80	8.80	8.90	25.8	25.8	27.4

Leaf Temperature

Comparison of Three Crops

While the actual mean leaf temperatures of all crops fluctuated to varying degrees, the general trends of all three crops were similar (Figures 29, 30, and Table 10). Figures depicting the temperature trends of July 23 and August 11 and 19 were not included. Inclusion would not have altered the general trends as depicted in Figures 29 and 30.

Leaf Temperature and Leaf Water Potential

Increases in T_{ℓ} and ψ_{ℓ} followed the same general trends (Figures 10, 11, 29, and 30). Time of maximum T_{ℓ} and ψ_{ℓ} , however, did not necessarily coincide. On July 15, (Figures 10 and 29) close agreement in time was recorded, but on July 23 the maximum T_{ℓ} of the beans lagged approximately 3 1/2 hours behind maximum ψ_{ℓ} . Maximum T_{ℓ} occurred near 1800 hours while ψ_{ℓ} had reached the maximum near 1430 hours. On August 4 the T_{ℓ} of both the tomatoes and beans lagged maximum ψ_{ℓ} by approximately 1 1/2 hours (Figure 12 and Table 10). A constant lag of 2 to 3 hours was recorded on all crops on August 11. On August 19, the same lag was evident on the corn and tomatoes. The maximum T_{ℓ} of the beans on August 19, however,

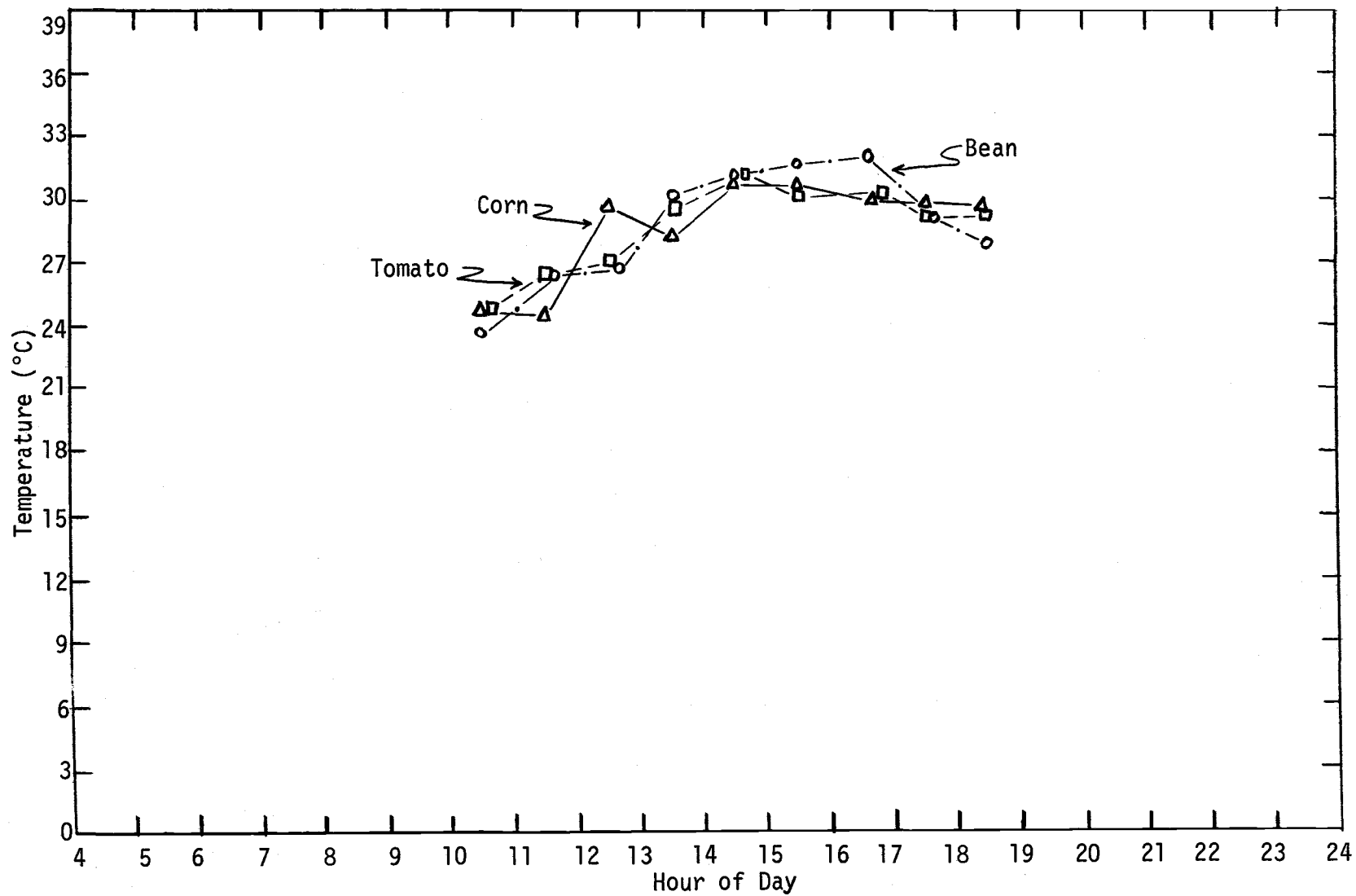


Figure 29. Leaf temperature of three crops, 7/15/70.

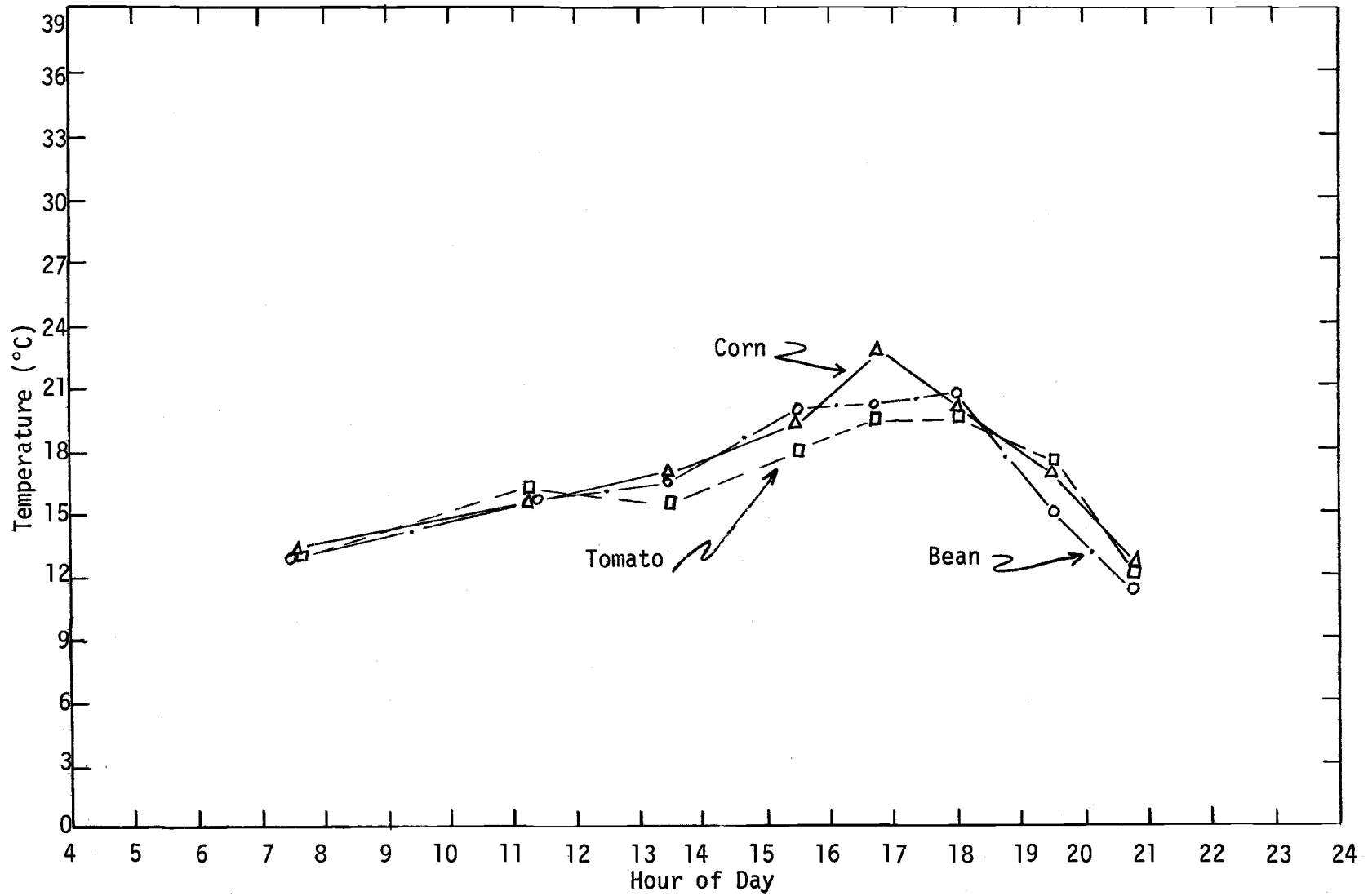


Figure 30. Leaf temperature of three crops, 8/4/70.

Table 10. Mean T_{ℓ} , T_D , and T_w at selected time periods.

Time of Day	Crop			Ambient Air	Wet Bulb
	Corn	Tomato	Bean (°C)		
<u>July 15, 1970</u>					
1025	25.0	25.0	23.8	25.0	18.5
1125	24.7	26.5	26.5	27.2	19.0
1220	29.7	27.3	27.0	29.5	19.0
1330	28.5	29.7	30.3	30.6	18.8
1430	31.0	31.2	31.2	31.7	19.6
1530	30.7	30.2	31.7	32.1	20.8
1640	30.0	30.2	32.3	31.7	20.6
1730	29.8	28.5	28.5	29.9	19.0
1820	29.7	29.3	27.8	27.8	18.6
<u>July 23, 1970</u>					
1020	21.7	22.2	22.7	18.9	14.5
1330	25.5	24.7	26.7	24.5	15.8
1445	25.8	26.4	26.6	26.1	15.5
1620	27.8	26.6	27.8	27.5	15.5
<u>August 4, 1970</u>					
0730	13.0	13.0	13.0	13.3	13.3
1115	15.8	16.0	15.8	15.0	13.1
1330	17.0	15.8	16.8	16.1	13.3
1530	19.6	18.4	20.0	18.4	14.2
1645	23.2	19.2	19.8	20.6	15.0
1800	19.8	19.4	20.6	20.6	15.0
1935	17.0	17.4	15.0	19.2	15.8
2045	12.8	12.2	11.4	15.5	15.0

(Table 10 - continued)

Time of Day	Crop			Ambient Air	Wet Bulb
	Corn	Tomato	Bean (°C)		
<u>August 11, 1970</u>					
0600	11.0	11.0	11.0	15.3	13.9
0830	18.0	19.0	19.2	16.1	14.1
1115	24.4	25.4	27.8	25.0	18.1
1445	29.2	27.6	28.8	31.1	17.8
1730	28.8	28.4	28.6	32.5	17.0
2015	26.0	24.2	22.8	28.9	16.4
2320	15.0	15.0	15.0	17.8	15.0
<u>August 19, 1970</u>					
0530	04.0	05.0	05.0	08.1	08.1
0845	12.2	13.0	16.0	13.9	12.0
1345	25.2	24.6	27.4	25.0	14.0
1720	25.8	25.8	24.8	27.5	16.3
2010	18.6	19.2	17.6	23.4	15.5

coincided closely with the maximum Ψ_{ℓ} ; both occurring near 1530 hours (Figure 13 and Tables 7 and 10).

Leaf Temperature and Solar Radiation

Leaf temperature continued to rise after solar radiation was beginning to decline (Figures 31 and 39). The lag before T_{ℓ} began declining ranged from 1 hour (Figure 31) to over 2 hours (Figure 36). A definite response of T_{ℓ} to a change in solar radiation was not evident. However, in the leaf temperature curves, the recorded temperatures were linearly connected to depict the general T_{ℓ} trend. Therefore, the T_{ℓ} between recorded temperatures was only an approximation. Figures for the dates August 11 and 19 were not included. However, the trends on those dates did not deviate from those included.

Leaf Temperature and Air Temperature

The temperature of the leaves of all three crops corresponded closely with the ambient air temperature (Figures 40 through 48, and Table 10) and not at all with wet bulb temperature. The leaf temperature of the beans exceeded ambient air temperature by the greatest amount on July 23 at 1020 hours. The temperature of the bean leaves reached 22.7 °C while the air temperature was 18.9 °C.

(Table 10). The general observation was for the temperature of the leaves of all crops to be near or below ambient air temperature. Temperature figures for July 23 and August 19 were not included. Inclusion would not have altered the general trend as exhibited by figures 40 through 48.

The temperature of a detached tomato leaf was consistently higher than the temperature of the leaf receiving the same exposure but remaining intact on the plant (Figure 49 and Table 11). The temperature curve of the intact leaf followed very closely that of the ambient air temperature, differing less than 1.5 °C in all instances.

The temperature of the detached leaf deviated further from ambient air temperature with each successive reading. While both leaves were 8.0 °C at 1000 hours (the time of detachment), by 1500 hours the detached leaf temperature was 4 °C higher than the temperature of the intact leaf.

Table 11. Comparison of temperature of intact leaf with detached leaf.

Time of Day	Attached Leaf	Detached Leaf (°C)	Ambient Air	Wet Bulb
<u>September 26, 1970</u>				
0945*	08.0	08.0	08.3	06.1
1130	18.0	20.0	16.7	09.2
1250	22.5	25.0	21.1	10.8
1445	25.0	29.0	25.6	12.0

*time of detachment.

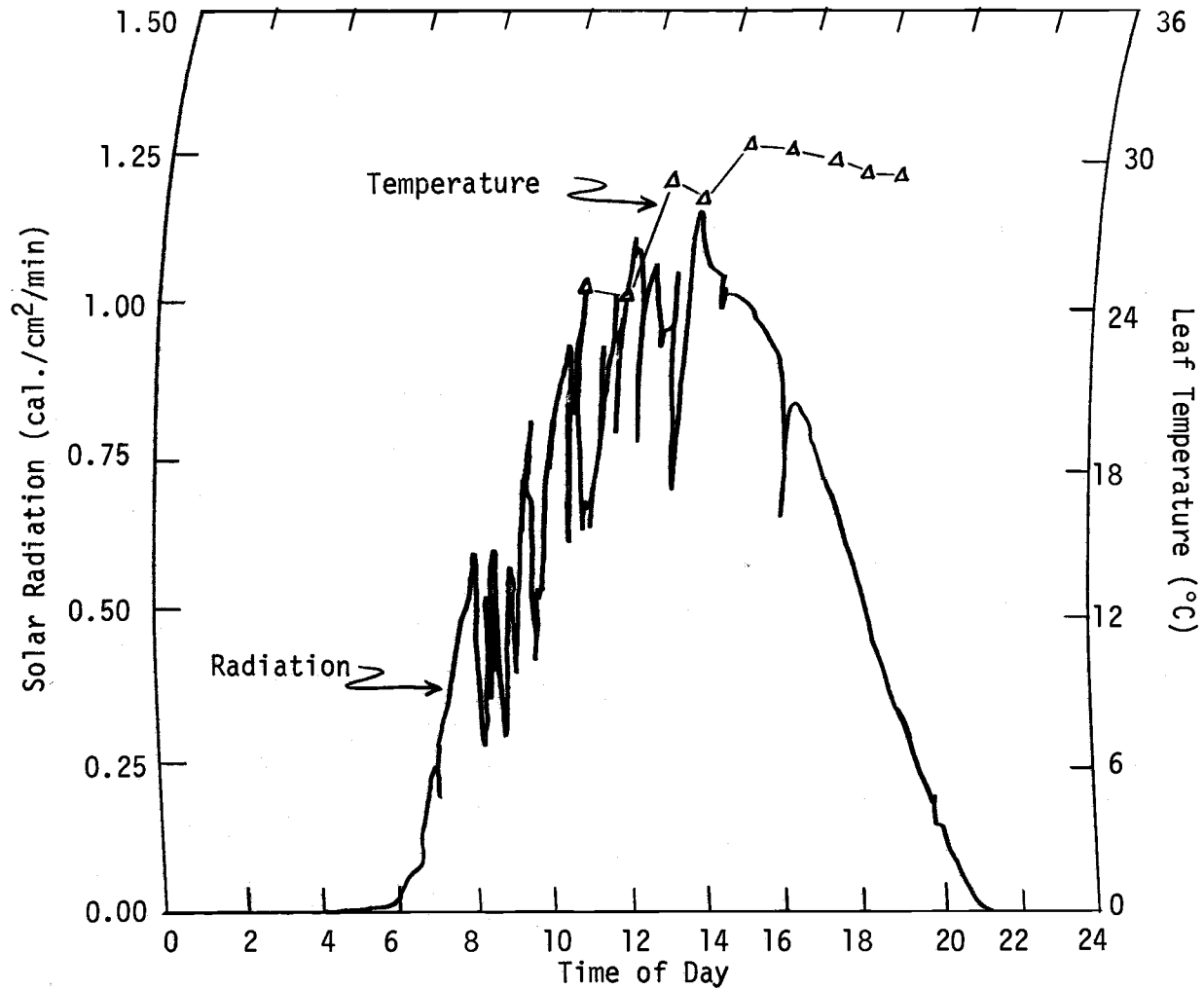


Figure 31. Solar radiation and leaf temperature of corn, 7/15/70.

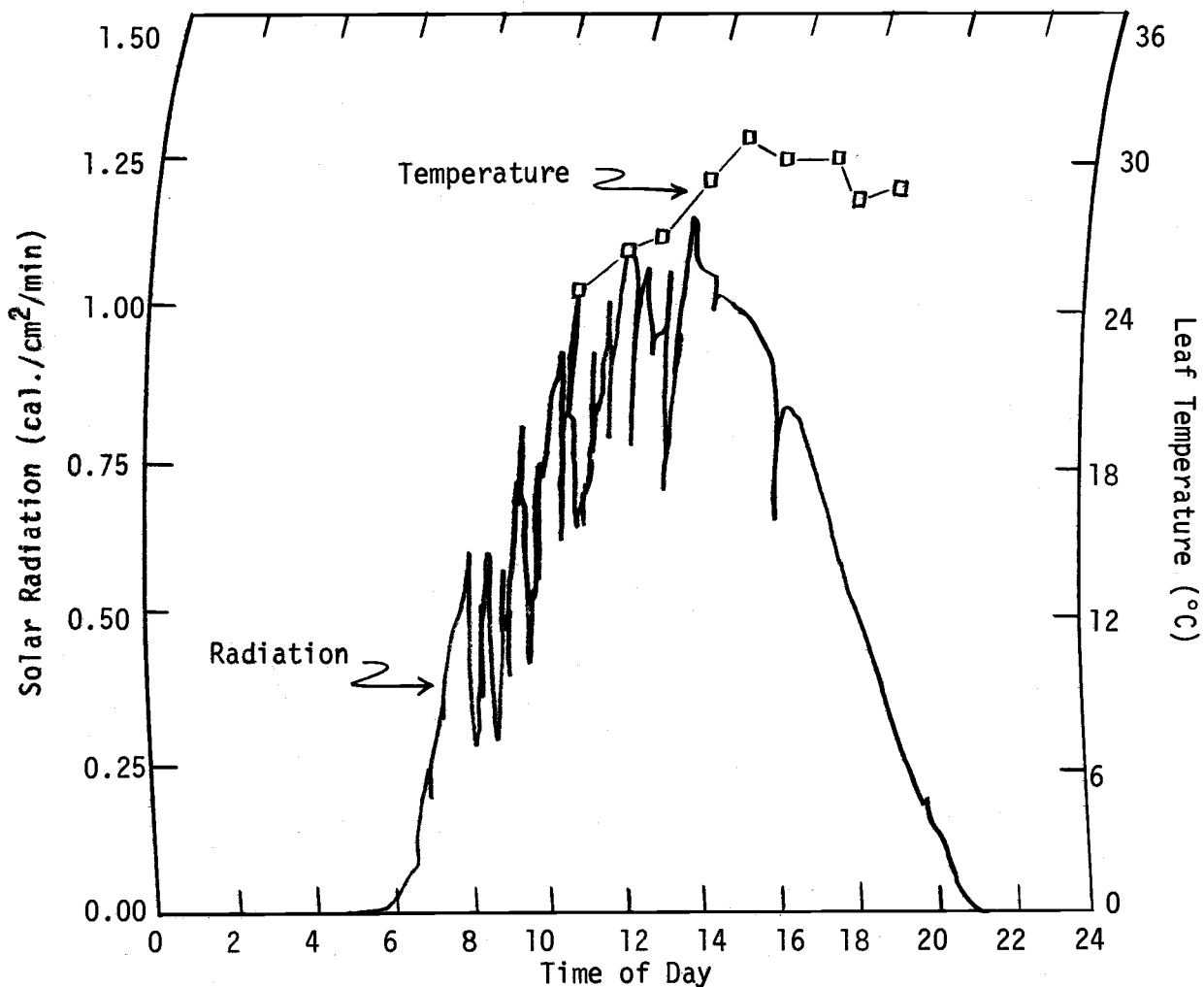


Figure 32. Solar radiation and leaf temperature of tomatoes, 7/15/70.

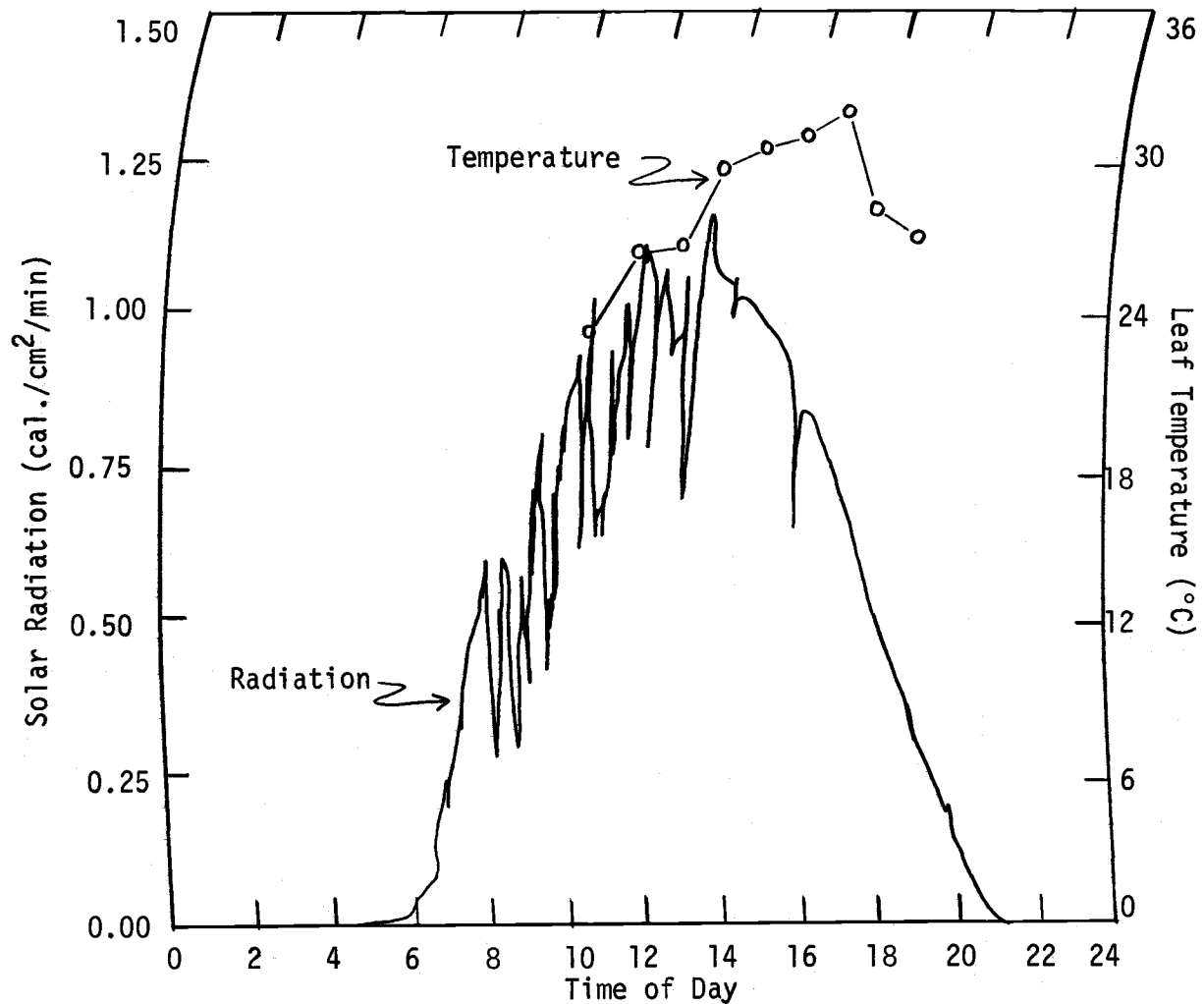


Figure 33. Solar radiation and leaf temperature of beans, 7/15/70.

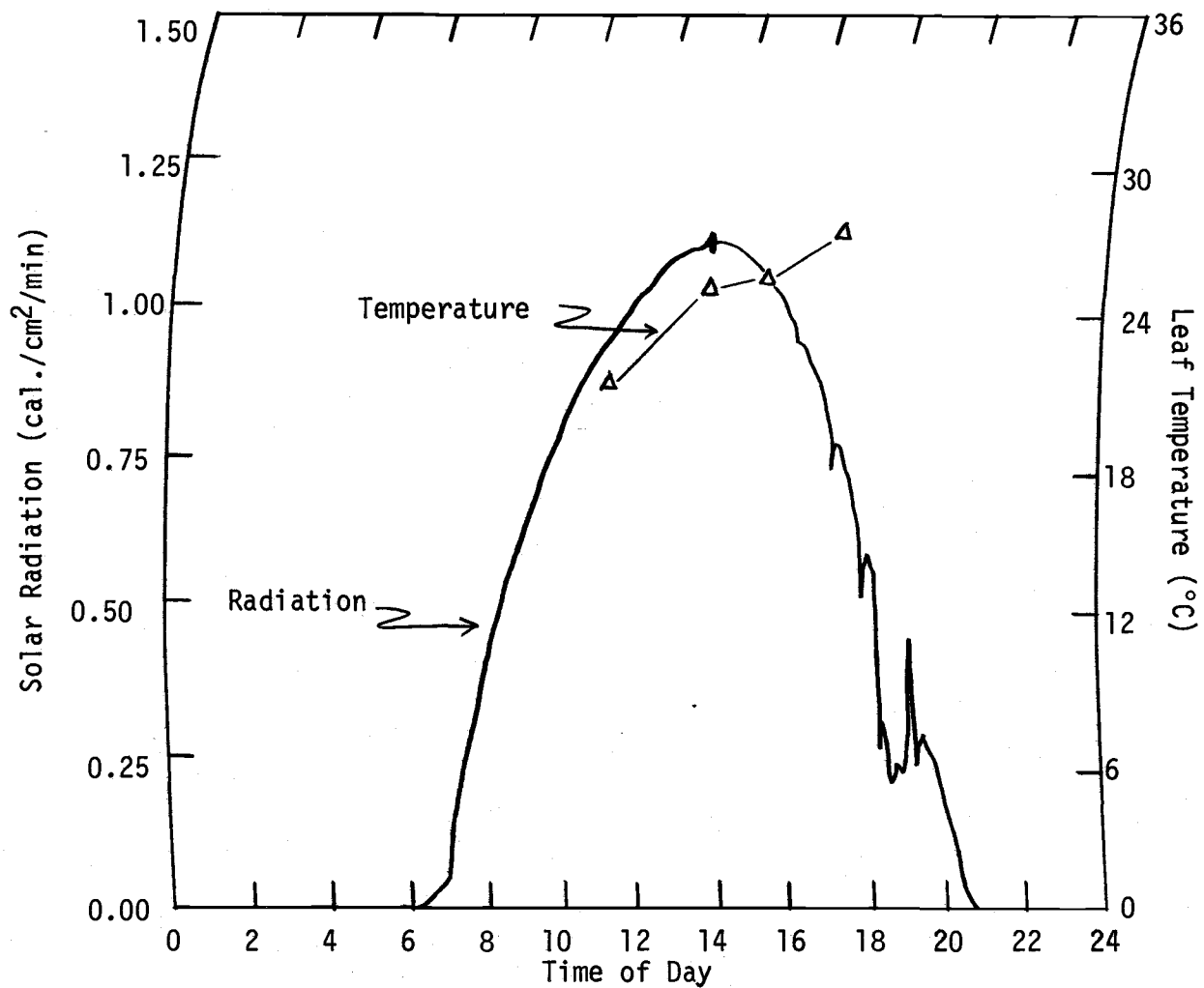


Figure 34. Solar radiation and leaf temperature of corn, 7/23/70.

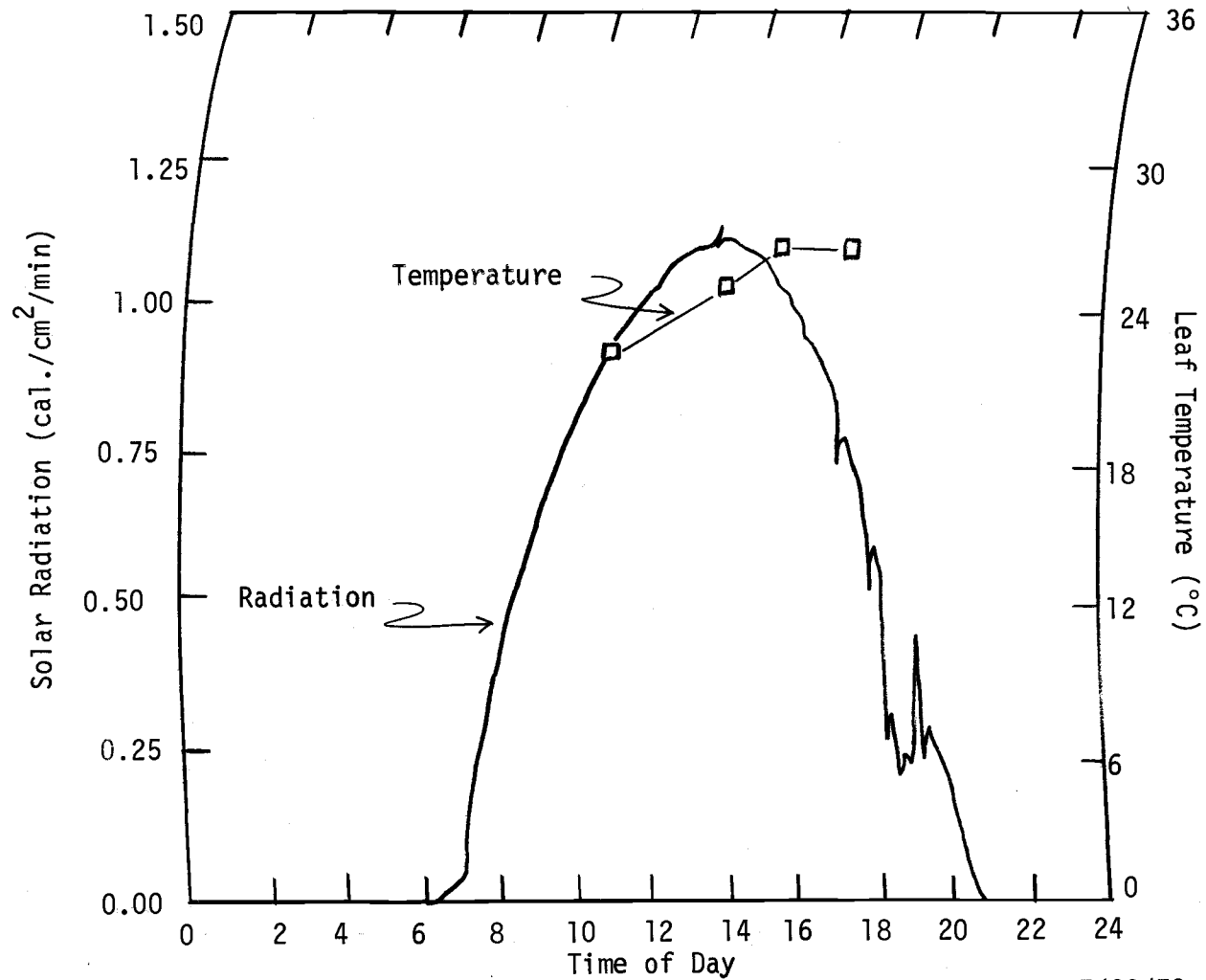


Figure 35. Solar radiation and leaf temperature of tomatoes, 7/23/70.

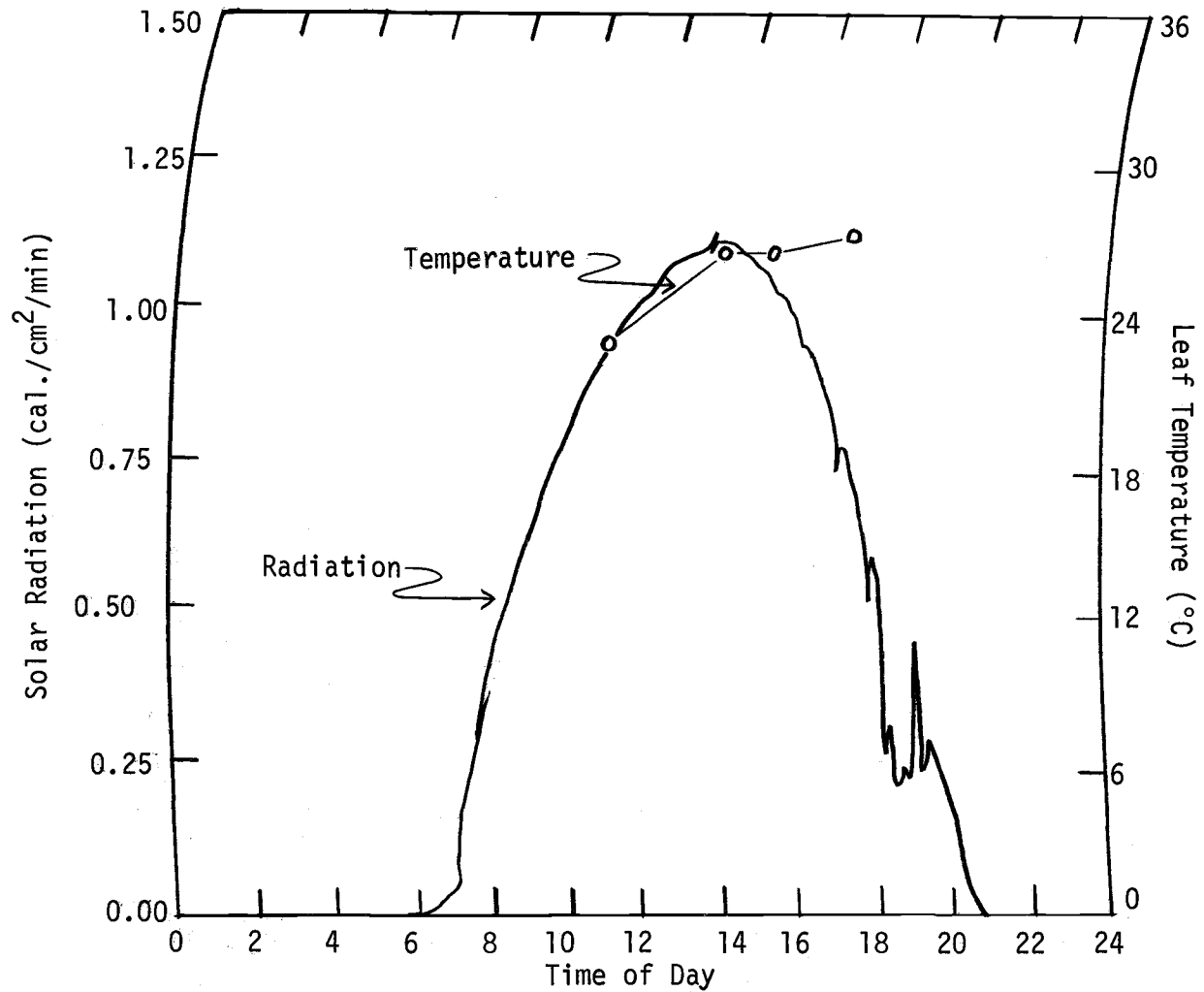


Figure 36. Solar radiation and leaf temperature of beans, 7/23/70.

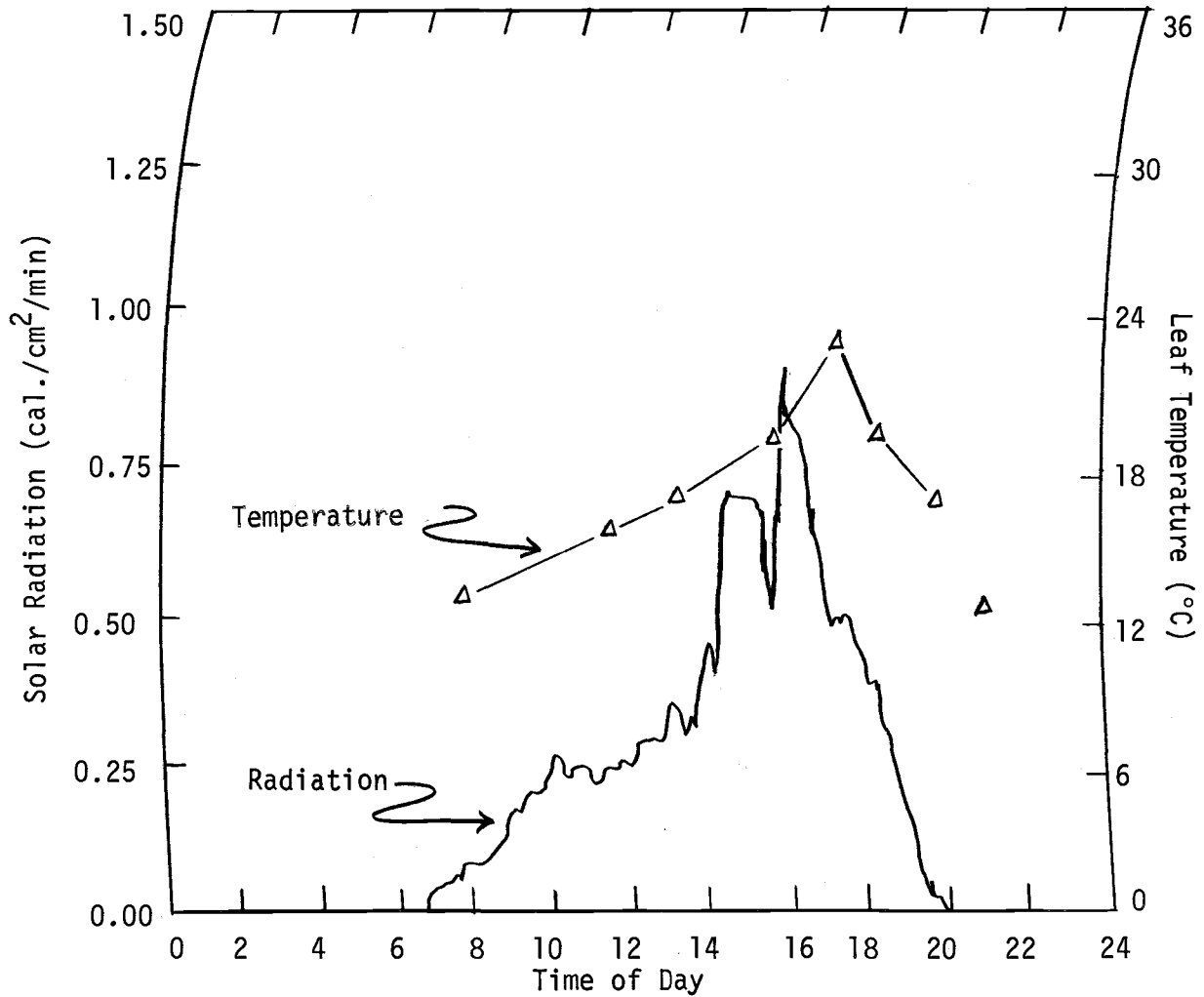


Figure 37. Solar radiation and leaf temperature of corn, 8/4/70.

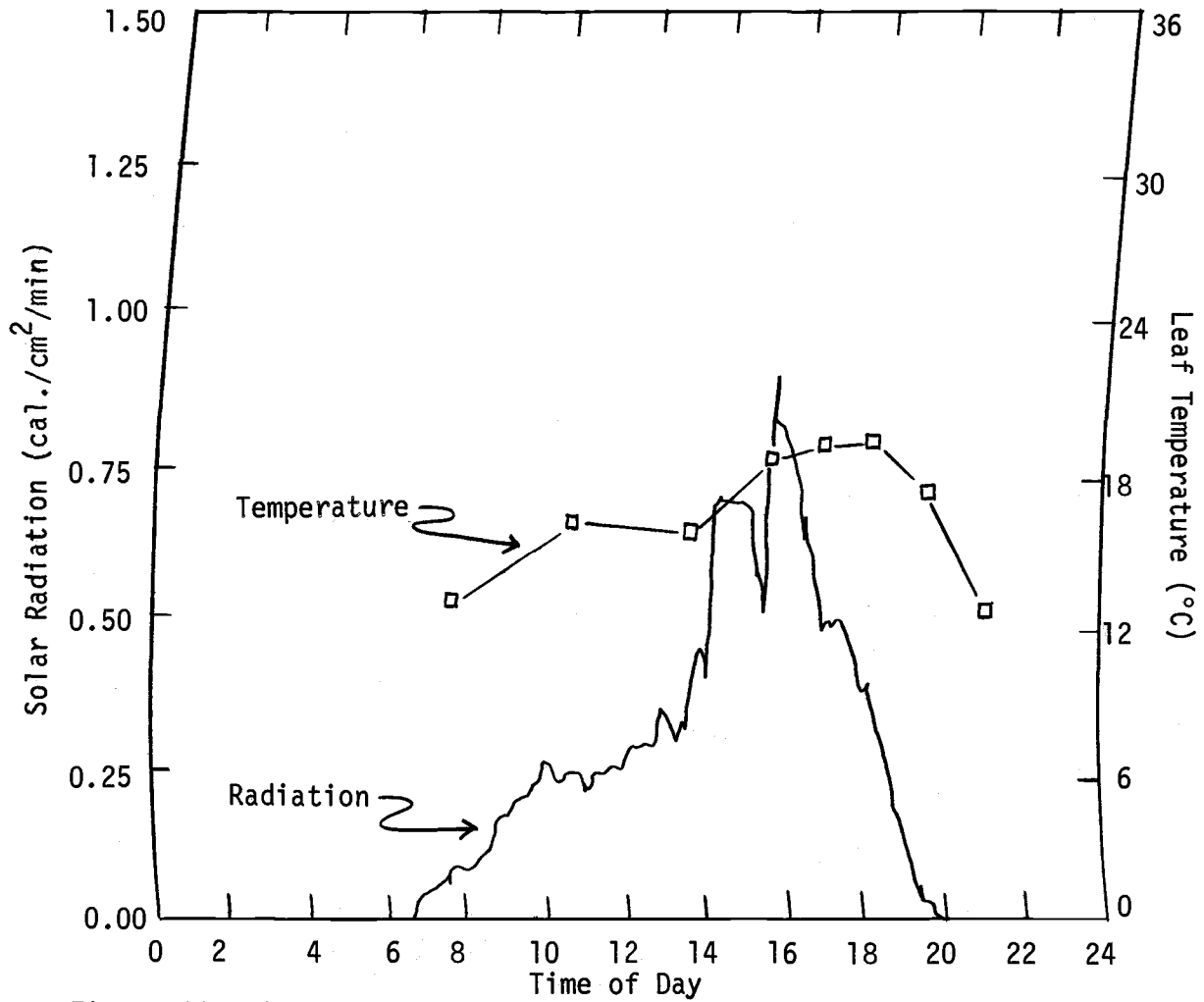


Figure 38. Solar radiation and leaf temperature of tomatoes, 8/4/70.

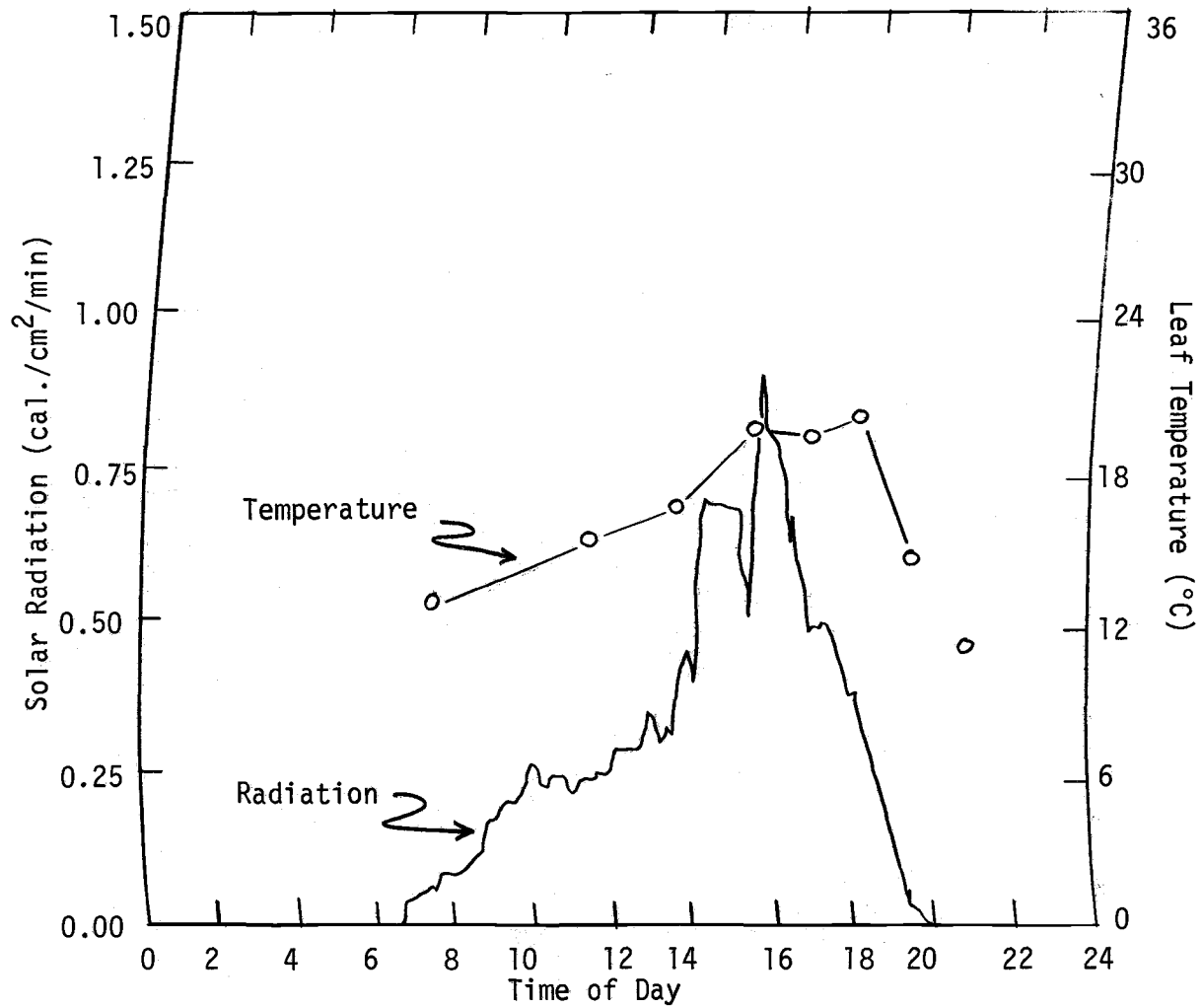


Figure 39. Solar radiation and leaf temperature of beans, 8/4/70.

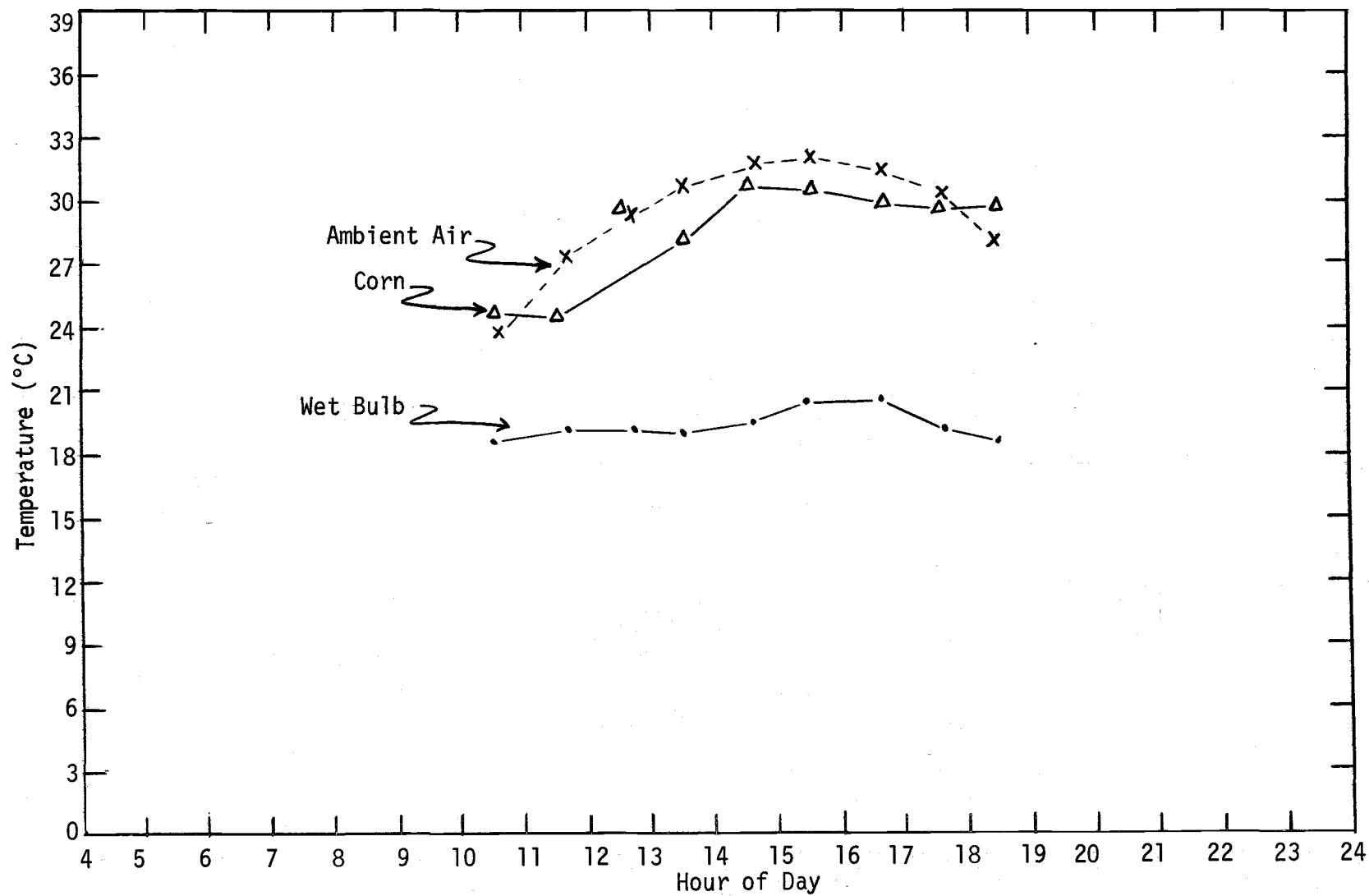


Figure 40. Leaf temperature of corn, 7/15/70.

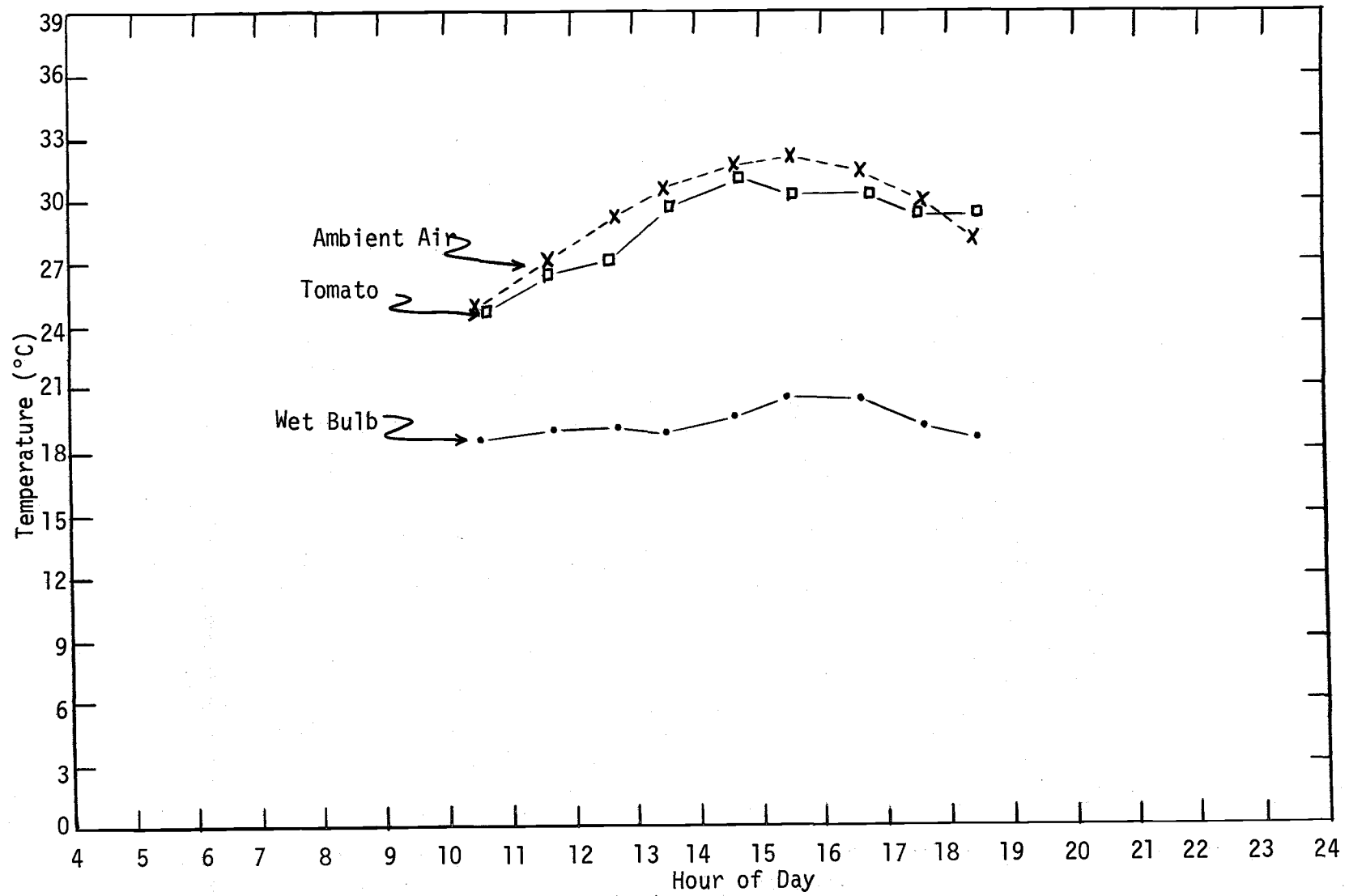


Figure 41. Leaf temperature of tomato, 7/15/70.

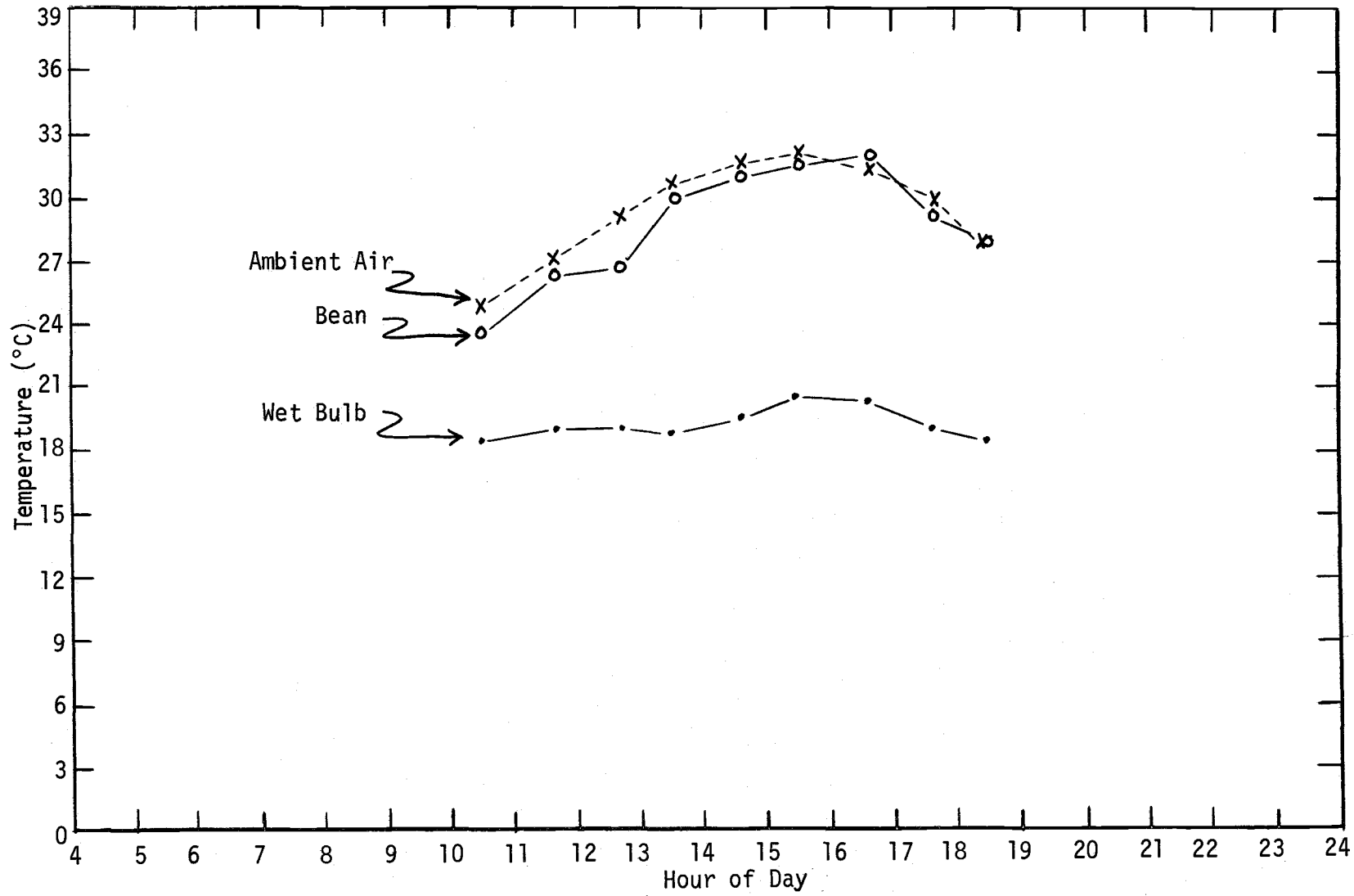


Figure 42. Leaf temperature of beans, 7/15/70.

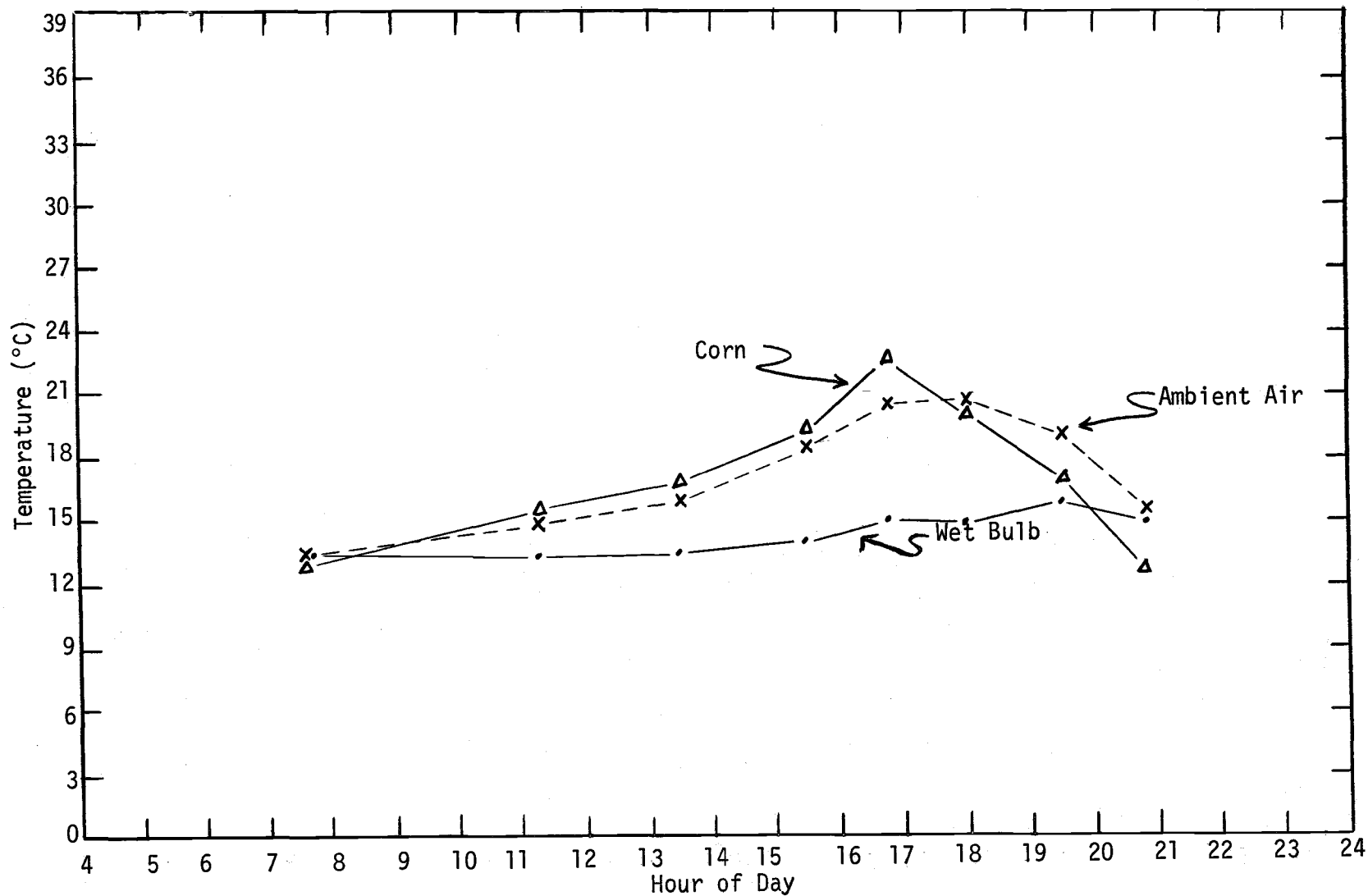


Figure 43. Leaf temperature of corn, 8/4/70.

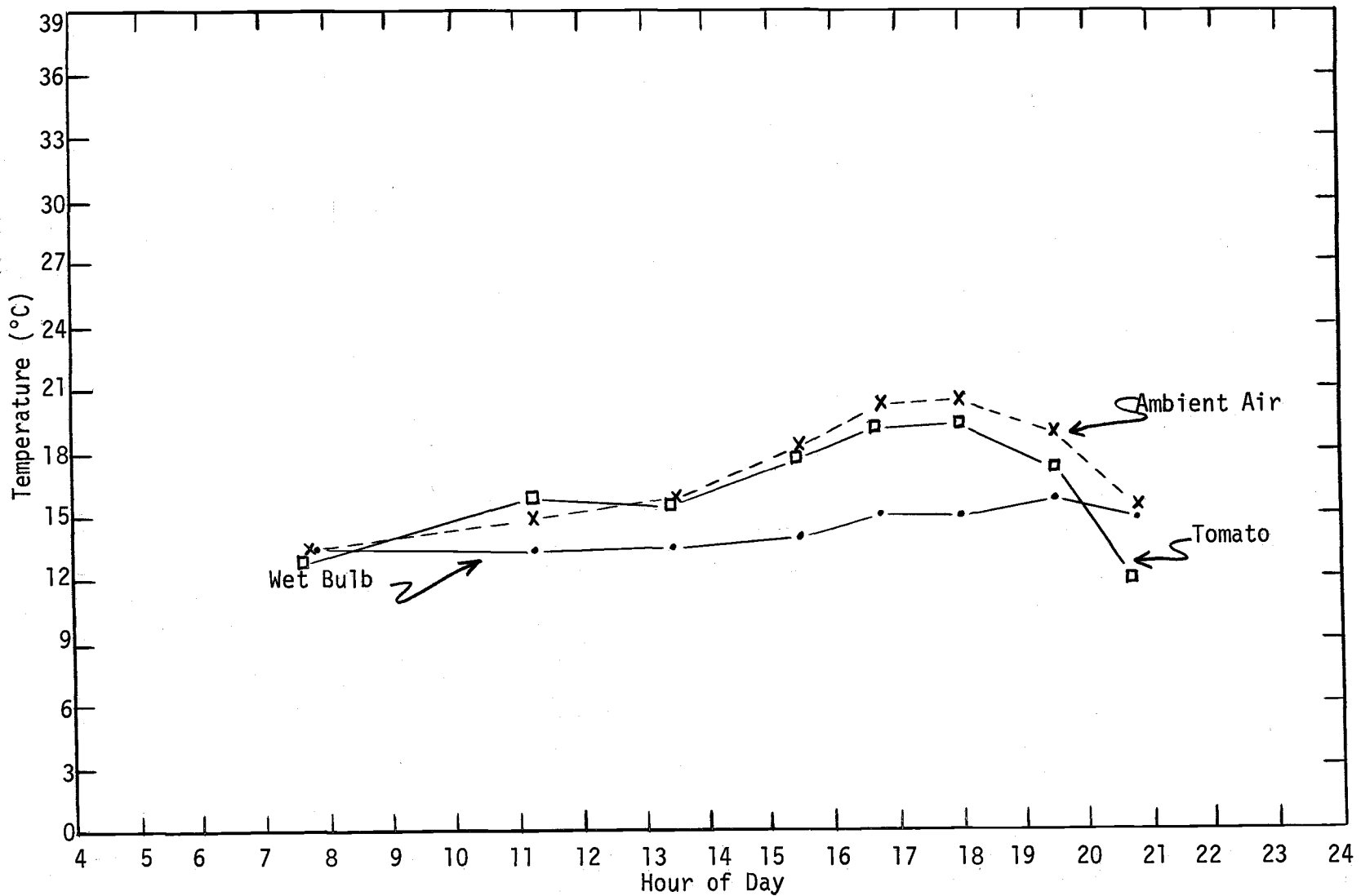


Figure 44. Leaf temperature of tomato, 8/4/70.

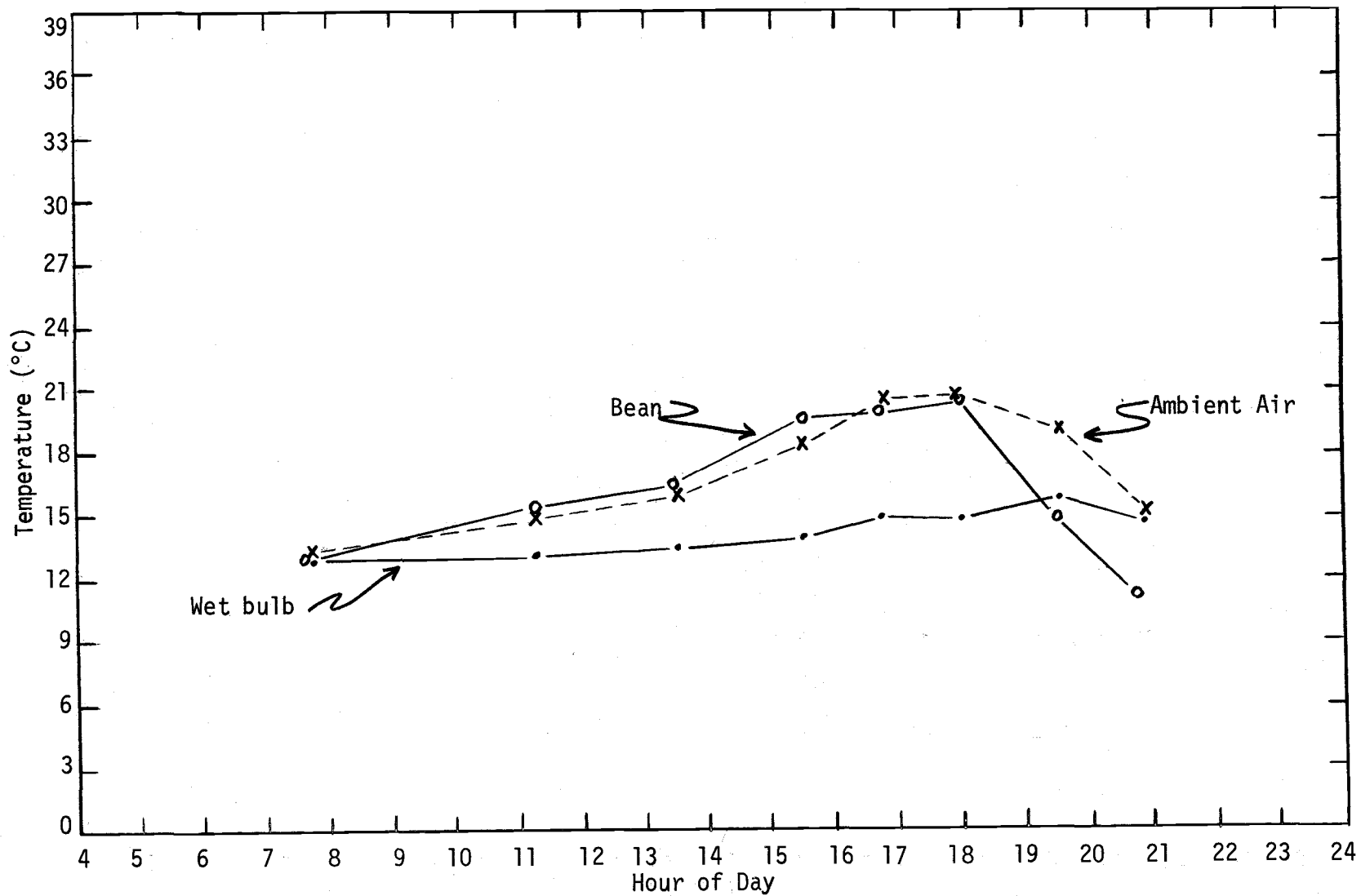


Figure 45. Leaf temperature of beans, 8/4/70.

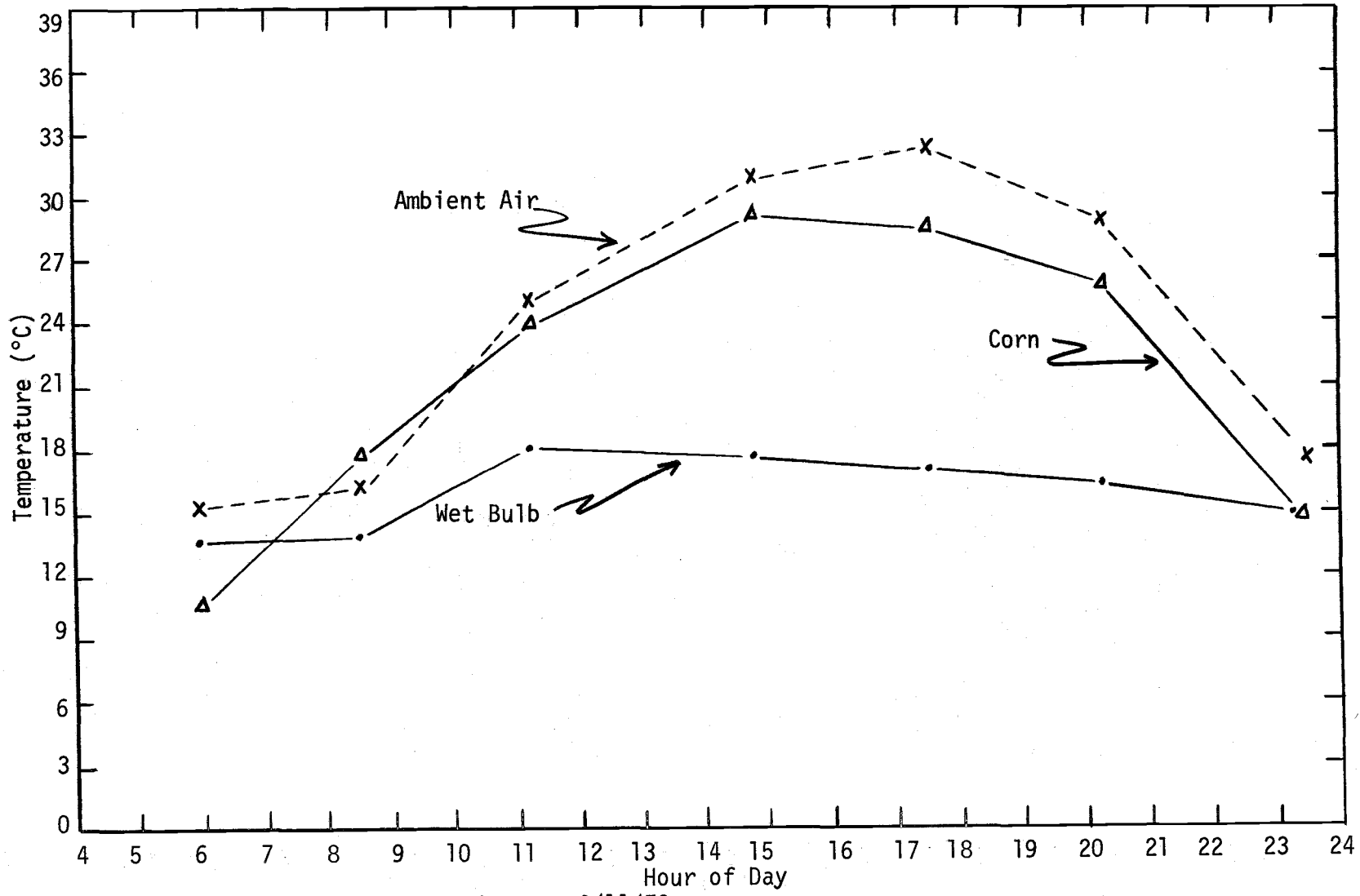


Figure 46. Leaf temperature of corn, 8/11/70.

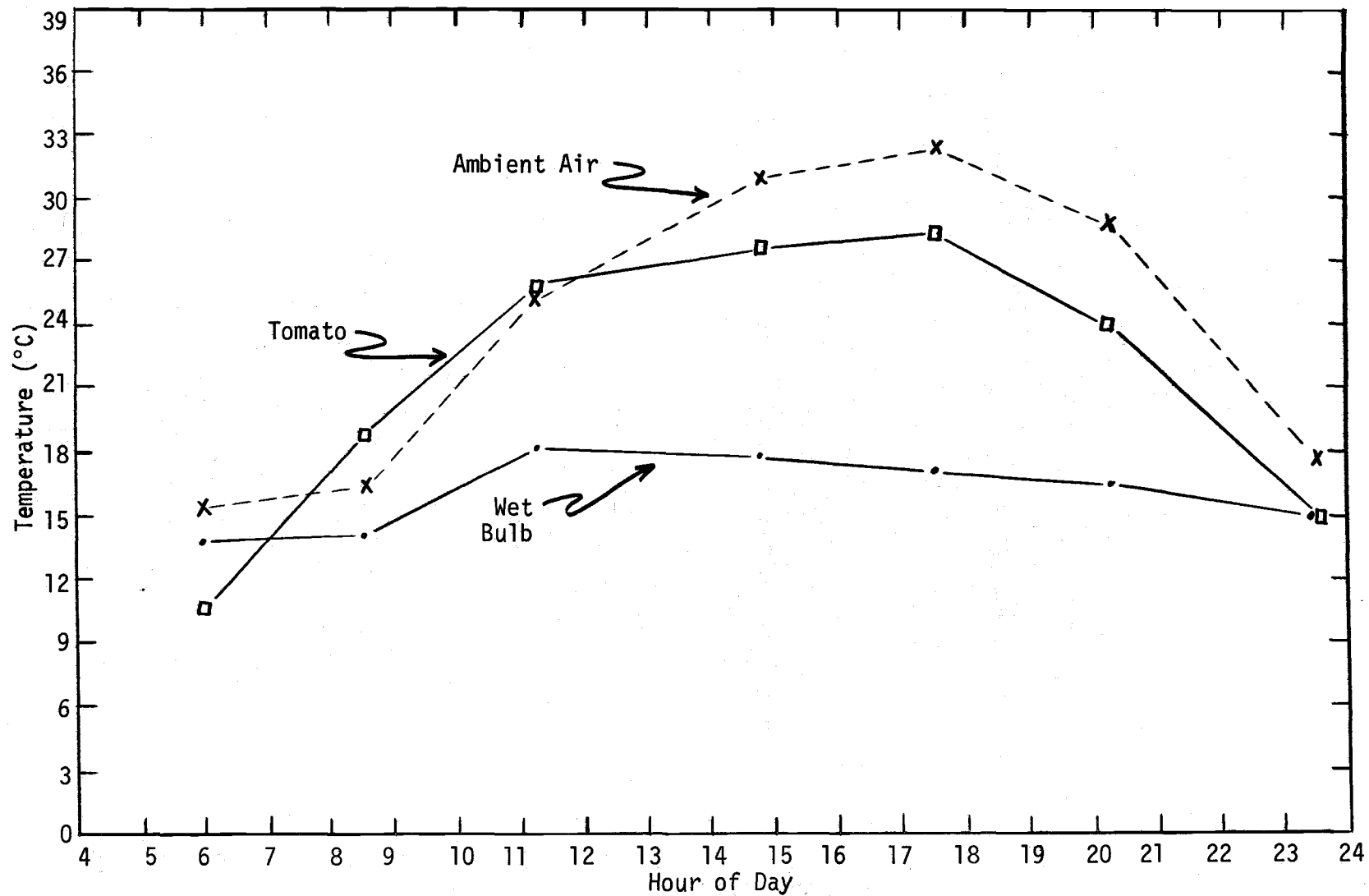


Figure 47. Leaf temperature of tomato, 8/11/70.

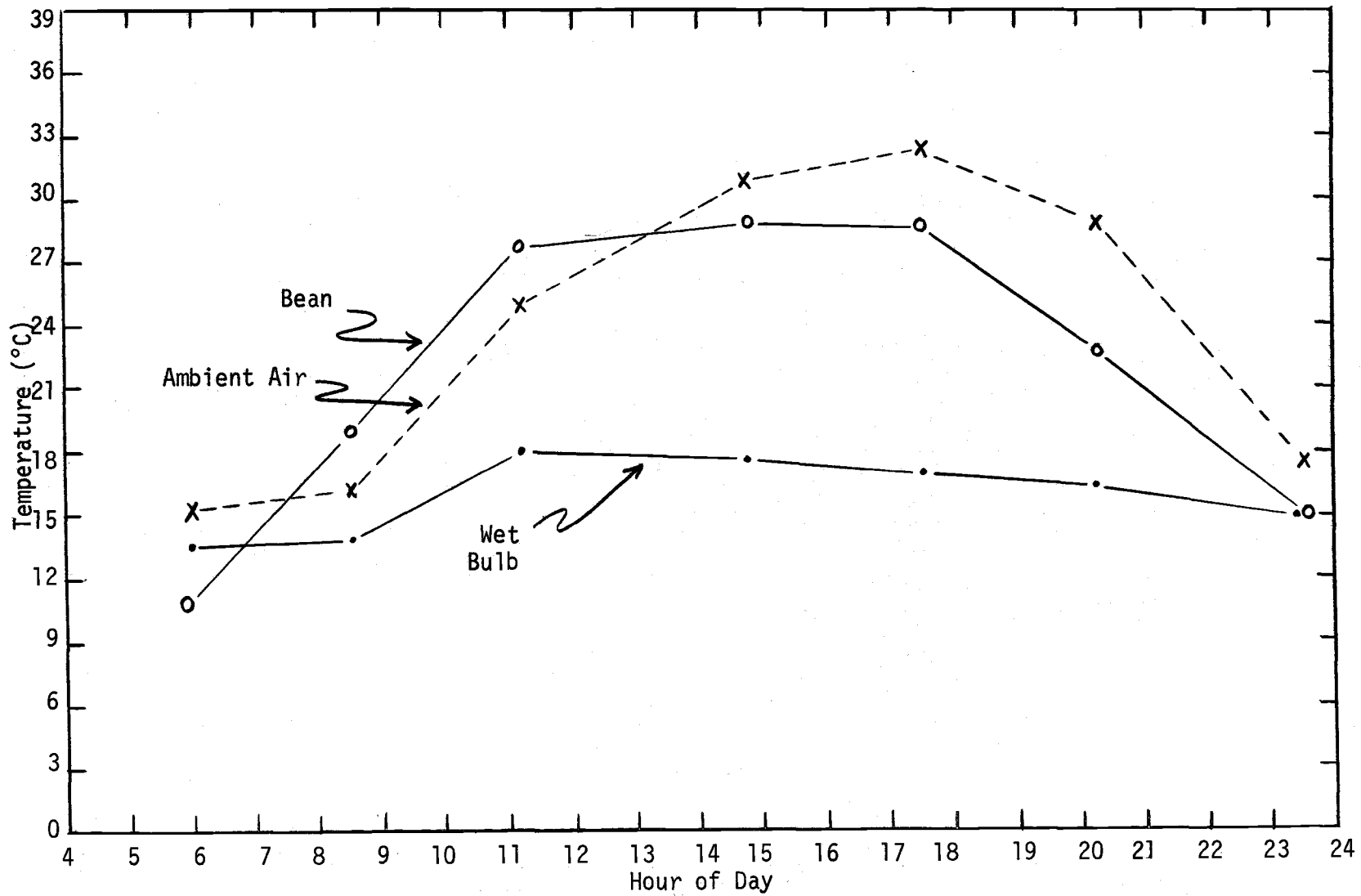


Figure 48. Leaf temperature of beans, 8/11/70.

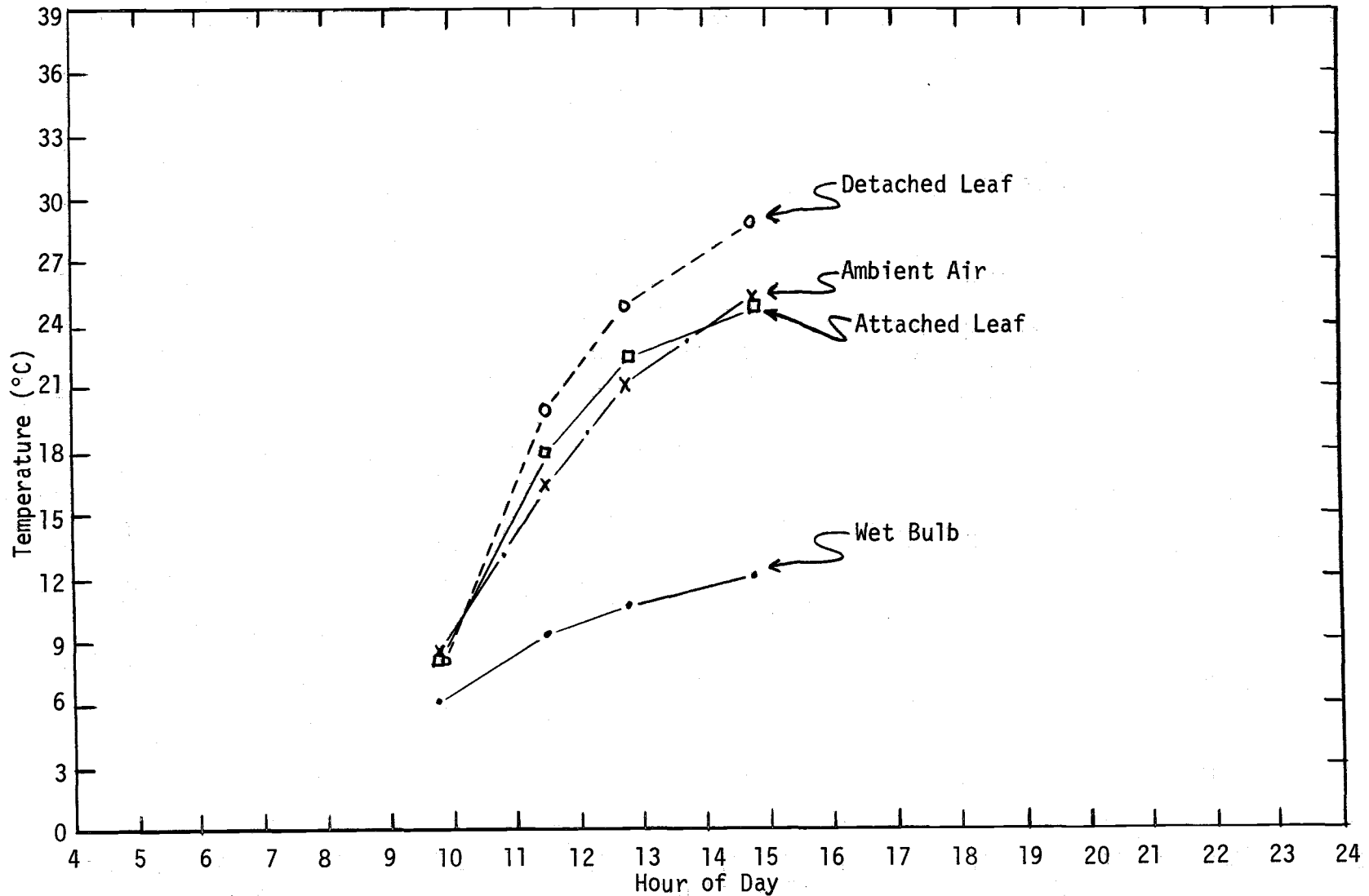


Figure 49. Temperature curve of attached and detached tomato leaf, 9/26/70.

SUMMARY AND CONCLUSIONS

Summary

Three crops important to the Willamette Valley, sweet corn (Zea mays), tomatoes (Lycopersicon esculentum), and bush beans (Phaseolus vulgaris), were studied to determine the water stress conditions (leaf water potential) that develop under naturally imposed atmospheric conditions and with soil moisture held at optimum levels.

Leaf temperature was also monitored to determine the effect of low leaf water potential on the temperature of the vegetative portion of the plant. The pressure chamber was utilized to obtain field measurements of leaf water potential and a portable infrared radiometer was used to monitor leaf temperature.

Under conditions of high solar radiation (in excess of 1.0 cal/cm²/min) and relatively high air temperatures (greater than 30 °C), the ψ_{ℓ} of corn reached, or exceeded, 13.0 atmospheres suction. Beans and tomatoes developed in excess of 10.0 atmospheres suction under these conditions. The corn consistently developed higher levels of ψ_{ℓ} than did the beans or tomatoes. Leaf water potentials of 8.0 atmospheres or greater were developed for up to 9 1/4 consecutive hours in corn and for up to 7 consecutive hours

in beans and tomatoes. Leaf water potential of 9.0 atmospheres or greater were held for up to 8 1/4 hours in the corn and for up to 6 hours in the tomatoes and beans. In research reported by Brix (1962), Gates (1957), Gates and Bonner (1959), Kramer (1969), Slatyer (1967), Woodham and Kozlowski (1954), and others, leaf water potentials of these magnitudes have definite adverse effects on photosynthesis, formation of soluble nitrogenous and phosphorous compounds, RNA accumulation, carbohydrate synthesis, and plant growth in general. These critical levels of ψ_L were held for significant portions of the daylight hours and in each case developed under optimum soil moisture conditions; soil moisture suction in the root zone, as monitored by tensiometers, ranged from 0.06 to 0.53 atmospheres suction.

Soil temperatures did not exceed 27.2 °C at the 6 inch depth or 22.2 °C at the 12 inch depth and did not inhibit root activity or soil moisture movement appreciably.

The meteorological factors which likely exhibited the greatest single effects on leaf water potential were solar radiation and ambient air temperature. However, the exact degree each affected ψ_L could not be determined under the conditions of the study. All meteorological conditions had an accumulative effect on leaf water potential. There was a lag of up to 3 hours following peak solar radiation before the maximum leaf water potential developed. A similar lag occurred frequently between leaf water potential and

ambient air temperature with maximum air temperature lagging maximum leaf water potential as much as 3 hours.

The time of maximum leaf water potential and maximum leaf temperature did not always coincide. Leaf temperature reached a maximum as much as 3 1/2 hours later than maximum leaf water potential developed. Yet on two occasions the time of maximum leaf water potential was the same as that of maximum leaf temperature.

The accumulative effect of leaf water potential, solar radiation, ambient air temperature, and the other meteorological factors masked the effects on leaf temperature, of each factor individually, making it difficult to assess the degree of influence of each. However, leaf temperature followed the same general trend as ambient air temperature. Most of the time leaf temperature was very near or below ambient air, exceeding ambient air to a small extent on several occasions. In one instance leaf temperature exceeded air temperature by 3.8 °C.

Conclusions

1. Even with optimum soil moisture conditions some crops will exceed 13 atmospheres suction under adverse atmospheric conditions.
2. The ψ_{ℓ} of many crops will exceed the "critical" level of 8.0 atmospheres for a significant portion of the day-

light hours frequently during a normal growing season in the Willamette Valley.

3. Not all sudden and extreme changes in Ψ_{ℓ} can be attributed to similar changes in solar radiation, ambient air temperature, or relative humidity.
4. Research on the effects of leaf water stresses of the magnitudes and durations reported in this study on actual plant productivity would be very meaningful.
5. Research into means of alleviating Ψ_{ℓ} or developing new plant strains which would not suffer adverse effects under the levels of Ψ_{ℓ} experienced in a normal growing season would also be very meaningful.

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