The effect of temperature on the development of the taproot and lateral roots of soybeans

James Allen Stone
Iowa State University

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THE EFFECT OF TEMPERATURE ON THE DEVELOPMENT OF THE TAPROOT AND LATERAL ROOTS OF SOYBEANS

Iowa State University

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The effect of temperature on the development of the taproot and lateral roots of soybeans

by

James Allen Stone

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of DOCTOR OF PHILOSOPHY

Department: Agronomy
Major: Soil Physics

Approved:

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In Charge of Major Work

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For the Major Department

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For the Graduate College

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Ames, Iowa
1982
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GENERAL INTRODUCTION

In 1973, Dr. Howard M. Taylor began a research program at Iowa State University to test the hypothesis that the onset of severe water stress for soybean (Glycine max (L.) Merr.) plants grown in Iowa could be postponed by rooting modifications. Experiments directed by Dr. Taylor have provided the following conclusions.

1) Deep percolation provides extra water for soybeans. In eastern Iowa this represents a dependable source of extra water, but in western Iowa extra water might be available only in about one year in two.

2) Increasing the rooting depth is more likely to successfully postpone water stress than increasing the rooting density or the water uptake rate per unit root length.

3) There are substantial differences among genotypes in the rate that rooting depth increases during the growing season.

4) Some soybean cultivars currently grown in Iowa have a rooting depth of more than 200 cm.

5) Rooting depths continue to increase during reproductive stages of development in the indeterminate soybeans usually grown in Iowa.

6) Adding fertilizer to a deficient soil will increase the depth of water extraction.

7) Pruning of soybean roots by temporary high water tables sometimes may have relatively minor consequences in soybeans.

8) Soil temperature probably plays a major role in the rate of root extension. Soil temperature is investigated in this dissertation.

A viable method of evaluating the effects of soil temperature on
rooting depth is by computer simulation of root growth. Several dif-
ferent approaches have been used to develop root growth models.
Lungley (1973) and Hackett and Rose (1972) developed models from experi-
mentally derived root initiation and extension data. Others have
estimated root growth as a function of physical processes (Dexter, 1978;
Page and Gerwitz, 1974; Römkens and Miller, 1971) or by simulating
physiological processes (Narda and Curry, 1981; Bar-Yosef and Lambert,
1977). However, the usefulness of root growth models is limited by the
lack of root growth data and by uncertainties about incorporating the
effects of soil physical conditions such as temperature.

Procuring data about the effects of soil temperature on root ex-
tension requires controlling root temperature while allowing serial
observation of root development. This can be achieved by adapting glass-
wall container methods (Bühl, 1979) to some method of temperature control.
The value of acrylic tubes and boxes for root growth observation has
been repeatedly demonstrated (Taylor et al., 1978; Voorhees, 1976;
Nilsson, 1965, 1969, 1973; Kemp, 1972; Reicosky et al., 1972; Flocker
water baths have been designed for root development studies (Nilsson, 1973;
Kemp, 1972; Grobbelaar, 1963; Martin et al., 1962; Cooper et al., 1960).
Only Kemp (1972) and Nilsson (1973) have designed water bath systems
that allow simultaneous root observation and accurate temperature
control.

The purpose of this dissertation is to evaluate the role of soil
temperature in the rate of soybean root extension. Three experiments
were performed. The objective of the first experiment was to develop a
system for controlling root-zone temperatures while allowing serial observations of taproot and lateral root development to a depth of 120 cm. The objectives of the second experiment were 1) to evaluate the effect of root-zone temperature on the development of the taproot and lateral roots of soybeans grown to an appreciable depth, 2) to evaluate the cultivar-temperature interactions for taproot and lateral root development, and 3) to describe the results in a manner adaptable to a root growth simulation model. The objectives of the third experiment were to illustrate the importance of soil temperature in modeling soybean root development and in extrapolating greenhouse root extension data to a field situation.

Explanation of Dissertation Format

This dissertation has been prepared using the alternate format option available at Iowa State University. The dissertation contains a general introduction, a general literature review, three major sections, a general summary and discussion, a general list of literature cited, and appendices.

The three major sections are presented as complete typescripts of papers submitted to either the Soil Science Society of America Journal or the Agronomy Journal.
LITERATURE REVIEW

Methods of Studying Root Systems in Controlled Environments

Extensive reviews of the methods of studying root systems have been published by Böhm (1979) and Schuurman and Goedewaagen (1964). No attempt will be made to duplicate these works but root observation techniques applicable to controlled environment studies will be briefly reviewed. Field methods for observing root growth and distribution such as soil water depletion, monolith, core sampling, trench profile and tracer techniques will not be considered applicable to controlled environment studies because they either require destruction of the plant for observation or impose obvious physical constraints. The root observation methods most useful in observing root growth in controlled environments are the glass wall techniques.

In the field, the glass wall technique is utilized in underground root laboratories which are commonly called rhizotrons. Böhm (1979) describes many of the rhizotrons currently used in root growth research. Generally rhizotrons consist of observation windows with natural or undisturbed soil profiles behind. The size is dependent on the aim of the research. Roots are observed through the windows and root sampling can be accomplished by removal of the window. Mini-rhizotrons are a modification of the glass wall technique in which transparent tubes are inserted into the soil for root observation (Böhm, 1974). Roots are observed from the inside of the tube with the aid of a light source.
Methods of root observation

Observing root growth at a glass or acrylic plastic-soil interface is a widely used technique in controlled environment studies because it allows direct observation of the root without destruction, reducing replication and labor. For use in controlled environments, the glass wall technique consists of viewing roots through windows in rectangular boxes or through acrylic plastic or glass tubes filled with soil.

Böhm (1979) states that root studies have been performed in rectangular boxes and observed through windows for forty years. Some examples of recent research utilizing rectangular containers are Flocker and Timm (1969) who constructed 5 x 11 x 100 cm high boxes and Nilsson (1969) who constructed 70 x 8 x 100 cm high boxes of acrylic plastic.

Transparent tubes have also been used for years by several researchers, notably Schuurman and Goedewaagen (1964), Reicosky et al. (1972), Murdock et al. (1974), Nilsson (1965, 1969, 1973), Voorhees (1976) and Taylor et al. (1978). Tube size varies with the purpose of the research but generally falls within the range tested by Nilsson (1969). He tested lengths ranging from 30 to 150 cm and internal diameters ranging from 2.5 to 8.5 cm.

Nilsson (1969) also experimented with some innovative variations of the tube technique. Thin plastic bags were inserted in tubes and filled with perlite. Drainage was facilitated by making perforations in the bag, removal and cleaning by lifting the plastic bag out of the tube, and root access and sampling by slitting the bags open. A checker pattern of longitudinal and transverse lines one cm apart printed on
the bags served as a system of coordinates to monitor movement of different roots.

Böhme (1979) tried using flexible polyethylene tubes 100 cm long by 15 cm in diameter. The major advantage of this technique was the time saved in freeing the roots from the growth media resulting in decreased labor costs. Disadvantages were the development of folds or wrinkles in the tube which serve as root pathways and the tendency of the tube and soil to settle together. Nilsson (1969) tried a similar technique with free hanging tubular plastic bags.

In rhizotrons, observation windows are usually placed vertical to minimize the difference in rooting density observed behind the glass and that present in the bulk soil. When development of individual roots is studied, sloping windows are used. As a result of geotropism, the roots will grow along the inside face of the window. Boxes and tubes are generally inclined from 3° to 30° from the vertical. The angle is dependent on the type of root studied and its tendency to grow along the window. Work by the author and Taylor (1981) has shown that several varieties of soybeans will grow along the acrylic plastic surface at angles 12° to 15° from the vertical.

The growth medium used will have a substantial impact on how a root system develops. MacKey (1973) performed a study of various rooting mediums to demonstrate the differences in root and shoot development under optimum nutrient and moisture conditions. He grew wheat in soil (texture was not given), sand, perlite, vermiculite and

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polytherm (hydrophobic, spherical, low density plastic). The roots developed in soil were few, fine and deeply penetrating with few crown roots contrasting the proliferous, stout and little-branched roots developed in nutrient solution. The roots developed in sand and perlite were similar to the water culture. Root development similar to soil was attained with vermiculite and root development intermediate between the soil and nutrient solution for the polytherm.

The procedure used to fill a container with growth media may also affect the development of root systems. Care must be taken to avoid differences in bulk density which may result from layering or separation of soil particles according to size during the process of filling. Containers should be tamped in a consistent manner to settle and firm the media or be wetted and drained until no more settling occurs (Taylor et al., 1978).

Various techniques have been developed to take measurements when glass wall root study methods are used (Böhm, 1979). The technique used will vary with the type of research. Generally the quickest way to measure root growth behind an observation window is to count root intersections at a given depth or record the depth of individual roots.

Several techniques have been used to aid in taking measurements. As stated by Böhm (1979), photographs can be taken of observation windows in rhizotrons and data recorded by an image analyzing computer. Hilton and Khatamian (1973) were able to collect data on root elongation rates of woody plants by measuring root growth from time lapse films of rhizotron windows marked with grids. Sanders and Brown (1978) and Waddington (1971) have used a duodenoscope inserted in mini-rhizotrons.
Sanders and Brown recorded these data with a camera. Bhar et al. (1969) designed a microscope trolley system also adaptable to a camera for use in a rhizotron.

Root studies using glass wall methods are often criticized because of the unnatural rooting conditions imposed on the root system. Two unnatural conditions inherent with this technique are the exposure of the root system to light during sampling and the effect of the growth medium-observation window interface.

Much research has been performed concerning the exposure of roots to light. Interpretation of the results is complex. However, the following statement by Bohm (1979) provides a concise summary. "The short time when the roots are exposed to light during recording in most cases has no strong influence on the results. As glass wall methods yield only relative data, so weak light effects during recording can be neglected in the solution of most ecological research questions. Keeping the windows dark at all other times is necessary to prevent production of algae."

The effect of the soil-window interface on observed root growth has received considerable attention (Taylor et al., 1970; Voorhees, 1976). Taylor found that root concentration can be increased considerably at the soil-acrylic plastic window interface with rhizotron compartments filled with clay soil. Side walls and glass windows showed no concentrating effect on root growth. The concentrating of roots at the window surface is probably due to poor contact between the window and the soil as a result of filling the compartment or of soil drying, creating cracks and gaps. Any existing free space can alter the environmental
conditions of the root by allowing water to condense and roots to pro-
liferate in a simulated water culture. This is aggravated by the fact that the adhesion between soil and acrylic plastic is less than between soil and glass windows. Voorhees showed that root elongation rates along an inclined (25°) soil-acrylic plastic container interface were significantly lower than those measured within the bulk soil mass. He hypothesized that this was a result of either higher soil strength at the interface or an attracting electrical charge at the acrylic plastic surface.

Acrylic plastic windows apparently are satisfactory for comparative or phenological purposes but glass windows should be used for rooting density studies (Taylor and Böhm, 1976). As a result of the concentrating effect, Taylor et al. (1970) termed the cm of root length visible per square cm of viewing surface as rooting intensity.

**Methods of controlling soil temperature**

In root growth studies, soil temperature control is often desirable. Various techniques have been used to achieve general temperature control. The easiest technique is wrapping the soil containers in some type of insulation. Nilsson (1965) controlled the temperature of 50 x 6 cm inside diameter tubes by using a jacket of temperature controlled water tanks made of brass. Rykbost et al. (1975) achieved the temperature control required for his experiment by placing heating cables in the soil. Hanson and Juska (1961) and Schuurman and Goedewaagen (1964) have controlled soil temperature by inserting containers in the ground. However, to obtain accurate soil temperature control, it is necessary
to place the soil containers in a constant temperature room or bath.

To control soil temperature, growth chambers are commonly used but highly sophisticated units such as the soil plant atmosphere research (SPAR) units used by Lambert et al. (1975) and the phytotron designed by Zscheile et al. (1965) add flexibility and impressive temperature control. These units are often equipped to control soil and air temperature independently. For example, Aldous et al. (1977) utilized a modified chest type freezer placed in a growth chamber. The more conventional approach is to place a constant temperature bath inside a constant temperature room or temperature controlled greenhouse.

Most constant temperature baths are variations of the "Wisconsin tank" designed by Jones et al. (1926). This bath had a volume of approximately 765 l and was designed to be used in the greenhouse. Water temperature could be controlled within 1°C. Cooper et al. (1960), Martin et al. (1962) and Grobbelaar (1963) used systems similar to the "Wisconsin tank" in their studies. They were able to control the water temperature within ± 0.3°C, ± 0.6°C and ± 1.0°C, respectively.

Kleinendorst and Brouwer (1965) and Cooper et al. (1972) built systems which controlled root temperature by growing the plant directly in a temperature controlled nutrient solution. Cooper's system which was very elaborate was enclosed in a large controlled environment cabinet. By continually recirculating the nutrient solution by pumping, the root temperature could be changed quickly. At root temperatures ranging from 5°C to 30°C in an ambient temperature of 20°C, plant containers remained within ± 0.15°C of the control setting during any one day. Over six weeks the mean temperature deviated less than ± 0.8°C.
In most cases, accurate temperature control is accomplished by systems having cooling and heating capacity. A typical example is the method of temperature control used by Cooper et al. (1960). Refrigeration coils were located at the bottom of the tank and were connected to a refrigeration unit of sufficient capacity to handle the heat load. Immersion-type heaters were also located in the tanks. Separate thermostats were used to regulate the heating and cooling units. Circulation was provided by convection.

Controlling root temperature while allowing serial observation requires adapting glass wall container methods for immersion in a constant temperature bath as well as designing a system which allows removing the containers from the bath for data collection. Kemp (1972) and Nilsson (1969, 1973) have worked with such systems.

Kemp (1972) placed 2.5 x 28 x 28 cm acrylic plastic containers inclined at 30° in an approximately 210 l water bath. Root growth observations were made by lifting the boxes out of the bath by hand. Water temperature could be controlled with ± 0.5°C over a range from 4.5°C to 24.0°C with an ambient temperature of about 23°C.

Nilsson (1973) designed a sophisticated system which controlled root temperature and permitted root observation. His system consisted of four independent thermostatically regulated water baths, 195 cm long, 90 cm wide and 125 cm deep. Acrylic plastic tubes, 100 x 6.4 cm internal diameter, were mounted on scaffolds inclined at 30° and suspended in the bath. The tubes were closed at the bottom to allow immersion and were equipped with an internal nutrient solution recirculating system. The temperature control system kept the water
temperature within ± 0.3°C at the applied range of temperatures of 8°C to 24°C. To facilitate data collection and observation, the tube scaffolds could be hoisted out of the water bath. This system was very versatile, also allowing adaptation to rectangular root boxes and lowering and raising of the lighting system.

Soil temperature gradients in the root growth containers at the soil-air interface are difficult to minimize in experiments with separate soil and air temperatures. Often the temperature gradient is not reported making experimental results hard to interpret. However, some researchers have experimented with various insulators and measured the temperature gradients.

Walker (1967) published a thorough study of temperature gradients in immersed containers which showed that the temperature of the soil deviates from that of the water bath both radially and vertically. It became obvious that to achieve isothermal soil temperature control, transfer of heat by evaporation and direct contact between soil and air must be eliminated by use of an insulator.

Jones et al. (1926) mentions insulating soil surfaces with a dry mulch, coarse sand, or mineral wool. In cases where transpiration was a problem, they suggested sealing over the surface of the container with wax.

Cooper et al. (1960) tested separately 1.91 cm layers of sand, vermiculite, and beaded expanded polystyrene. Sand was found to be the poorest and polystyrene the best insulator.

Walker (1967) evaluated the temperature gradients at the soil surface of a 16 cm diameter container using layers of the following:
1) 0.5 cm perlite, 2) 3.5 cm perlite, 3) 3.5 cm perlite surface 5.5 cm below the water level, 4) 3.5 cm polystyrene beads, and 5) 3.5 cm perlite covered with loose fitting aluminized polyethylene sheet. The following table presents an example of the performance of the various insulators.

Table 1. Temperature deviation from the surface to a depth of 12 cm with ambient temperature of 27°C (Walker, 1967)

<table>
<thead>
<tr>
<th>Bath temperature °C</th>
<th>Insulator 1</th>
<th>Insulator 2, 4, 5</th>
<th>Insulator 3</th>
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<tr>
<td>15</td>
<td>7.0</td>
<td>4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>25</td>
<td>2.0</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>35</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Kemp (1972) measured the temperature gradient at the surface of 2.5 x 28 x 28 cm acrylic plastic boxes. He measured approximately 1°C variation at a 2.5 cm depth over a range of water temperatures from 4.5°C to 24.0°C with an ambient temperature of 23°C.

Walker (1969) developed a system which provided nearly isothermal control of soil temperature even when soil and air temperatures differed by as much as 15°C. Soil temperatures were maintained by submerging the soil containers in constant temperature water baths. The containers were placed in the baths so that the water covered their lids to a depth of 2 cm. Tubes were installed in the cover to allow growth of the stem. Containers were aerated with temperature controlled
The greatest variation in the soil temperature was less than 5% of the difference between the soil and air temperature.

The Effect of Temperature on the Morphological Development of Root Systems

The effects of soil temperature on the morphological development of roots have been studied for a wide range of plant species and temperatures. General conclusions can be drawn from the reviews of Kaspar (1979), Cooper (1973) and Nielsen and Humphries (1966).

The response curve of most morphological root growth parameters is sigmoidal. There is a positive response with increasing temperature until an optimum is achieved. Above the optimum there is a negative response. The optimum varies with species and with cultivars within a species. The response to a unit change in root temperature is greater above the optimum than below indicating different mechanisms may be involved. The response to changes in soil temperature probably results from changes in root metabolic activity. However, the direct and indirect soil temperature effects on the viscosity of water, the hydraulic conductivity of the soil root system, and cell wall physics are also involved.

The general effects of root temperature on the development of root systems over a range of approximately 5°C to 40°C are presented in the following list.

a) Root dry weight, root length (rate of extension) and root branching follow the general temperature response curve.
b) The mean diameter of roots decreases as temperature increases.
c) At low temperatures young roots tend to be white and succulent. At higher temperatures young roots tend to be light brown and nonsucculent.
d) The number of root hairs decreases with increasing temperature.
e) Temperature can influence the inclination or direction of root growth.

Mosher and Miller (1972) found that the radicles of maize plants grew more vertical as temperature was increased. Kaspar et al. (1981) found that the temperature effect on the inclination of lateral roots of young soybeans was more complex. Generally the roots grew more vertical with increasing temperature following the general temperature response curve and varied between soybean cultivars.

The preceding list is compiled from many experiments involving different species so it cannot be concluded that it applies to all. Specific data are lacking. The following are approximate optimum root temperatures for some common agronomic crops as indicated by the reviews of Cooper (1973) and Kaspar (1979); soybeans, 25°C; maize, 30°C; cotton, 32°C; and potatoes and oats, 5°C.

Few researchers have examined how the aforementioned conclusions change with time (are they constant over the life of the plant?), light intensity and air temperature. These effects will be reviewed in the following sections.
Changes in root temperature effects with time

Researchers have shown that the optimum root temperature for plant growth changes with time. Brouwer and van Vliet (1960) and Army and Miller (1957) found that the optimum root temperature decreased as the plants aged for peas and turnips, respectively. Nielsen et al. (1960) and Ehler and Bernstein (1958) more finely defined this effect by showing that optimal root temperatures differ with the stage of development. Changes in the root temperature effects on morphological development with time are not as well-known.

The rate of root extension decreases with time. The magnitude of the decrease appears to increase with temperature. Taylor et al. (1972) present data which show that the rate of extension of cotton roots decreases with time at 24°C, 28°C, 32°C and 36°C, the greatest decrease in rate occurring at 36°C. Barney (1950) found that the rate of pine seedling root extension was initially higher at 35°C as compared to lower temperatures but decreased to a constant rate after 5 days. Arndt (1945) found that the optimum temperature for extension of the primary roots of cotton seedlings shifted downward from 33°C to 36°C at the start, to about 27°C after 3 to 4 days of growth. Perhaps the most detailed work has been performed by May et al. (1967) who grew barley plants for 19 days in a controlled environment at 20°C. They found that the root extension rates were very high at first but decreased during the first 4 days of growth. Thereafter, the rates were effectively constant with time, although demonstrating some cyclic changes associated with the initiation of the various orders of branches. This observation was most evident for the primary roots, although each
successive order of roots showed the same pattern.

The time dependent fall in the extension rate of the total root system is probably the result of the depletion of endosperm reserves and competition for carbohydrates between the primary and secondary root tips after initiation of branching.

There is also evidence that both secondary root development and geotropism show a temperature response which changes with time. Arndt (1945) found that the earliest emergence of secondary roots of cotton seedlings occurred at 33°C and 36°C but after 7 days their total length was greatest at 30°C and they were most numerous at 27°C. However, May et al. (1967) found that at a constant temperature the distance between secondary roots was relatively unaffected by time. The principal factor governing the rate of production of new branch roots was the rate of growth of the parent root. The work of Sheppard and Miller (1977) indicates that the geotropic response of maize radicles may be regulated by the length of the temperature treatment. They suggest that the geotropic response to soil temperature involves several components of plant metabolism, each with a different temperature response time.

Changes in root temperature effects with changes in light intensity

As light intensity decreases so does root growth (Rufty et al., 1981; Brouwer and De Wit, 1968; and Barney, 1950). The general explanation is that the leaves and roots are competing for carbohydrates and that the organ which will be most successful in obtaining its requirement is that which is nearest the source. Since the roots are furthest from
the source, they benefit the most during periods of bright light.

The effect of light intensity on root growth becomes more complex when the soil temperature is changed. Army and Miller (1957) found that the optimum root temperature of turnips depended on the amount of radiation received, the lower the radiation the lower the optimum root temperature. Rufty et al. (1981) found that the optimum soil temperature for growth of soybeans increased with greater incident radiation. However, when ambient CO₂ concentration was enriched, root growth appeared less sensitive to root temperature changes demonstrating the involvement of photosynthate supply. Earley and Cartter (1945) found that root growth (measured by dry weight) of soybeans increased from about 2°C to 27°C decreasing as the temperature increased to 37°C. The magnitude of the response increased with light intensity. However, at temperatures less than 12°C, temperature rather than light intensity appeared to be limiting.

As a result of its involvement in root growth, light intensity also affects other root growth parameters, for example, the top/root ratio (Brouwer and De Wit, 1968; and Earley and Cartter, 1945). As light intensity decreases, root growth decreases more than leaf growth, resulting in higher top/root ratios. This relationship becomes more complex when the root temperature-light intensity combination is altered. Working with maize, Kleinendorst and Brouwer (1972) found that at 5°C water stress increased with increases in light intensity. When root temperature is lowered, the resistance to water flow in the root tissue increases and water absorption is inhibited. At the same time, transpiration continues and a temporary decrease in the amount of water in the
plant body results (Locher and Brouwer, 1965). The end result will be an alteration in the distribution of carbohydrates between the shoot and root, i.e., a change in the top/root ratio.

**Changes in root temperature effects with changes in air temperature**

It is generally accepted that the optimal temperature for root growth is less than for tops and that roots experience less temperature variation. As a result, roots tolerate a narrower range of temperatures than tops (Richards et al., 1952). The value of many experiments on the effects of temperature on intact plants is limited because both roots and shoots were exposed to the same temperature. However, unless root temperature is properly adjusted to the aerial environment, it may limit or cancel the response of plants to other factors under investigation. The importance of the shoot temperature must be evaluated separately for each experiment.

Anderson and Kemper (1964) grew maize at soil temperatures of 17°C, 23°C, and 30°C with ambient temperatures of approximately 23 ± 6°C. They found that yield, top/root ratio, and root length followed the general temperature response curve. Working with ryegrass over a range of root temperatures from 5°C to 40°C, Kleinendorst and Brouwer (1965) found that shoot growth was the same when the ambient was 15°C or 25°C. If the preceding ranges in ambient temperature did not affect shoot growth, the photosynthate available for root growth should not have changed.

The effect of different root and shoot temperatures is dependent on the location of the apical meristem (Watts, 1972; Grobbelaar,
1963). For example, top growth of maize is very dependent on soil temperature rather than air temperature because of the dominating effect of soil temperature on the apical meristem.

Hall (1950) studied the effects of independent root and shoot temperature combinations on the growth and development of buckwheat. He presents the following conclusion. If a distinction is made between growth and development, defining growth as increase in size and development as the rapidity of progression through the life cycle, the shoot temperature appears to regulate development and the root temperature to influence the general growth processes.

Computer Simulation of Root Growth

Computer modeling or simulation can be defined as the development of mathematical equations which reproduce the behavior of a real system and solving these equations with the aid of a computer. Because a model that deals with all the details of a system would be as complicated as the system itself, a simulation model deals with a complex process by limiting its objectives and discriminating between essential and less essential aspects. Some uses of a plant growth model are: 1) extrapolating laboratory data to the field, 2) studying the influence of physical parameters, 3) analyzing the effects of differences in varieties or species, 4) evaluating the importance of plant growth characteristics, and 5) planning research (Brouwer and De Wit, 1968). This section will review approaches to computer simulation of root growth. Root growth models fall into two categories, those based solely on experimental data
Root growth models based on experimental data (empirical models)

Lungley (1973) and Hackett and Rose (1972) have developed root growth models from root initiation and extension data. Lungley's model calculated the total length and number of roots as a function of time from selected root parameters of small grain cereals. The parameters are the extension rate of the axis, 1st order and 2nd order laterals; and the lengths of the apical nonbranching zones of the axis and of the 1st order laterals. With these data in the form of equations, roots could be "grown" for a specified time increment, coordinates stored in the computer and a network of roots printed out on paper.

Hackett and Rose (1972) modeled the growth of seminal roots of barley. The root parameters required were the extension rate of the axis and laterals, rate of extension of the branched region along a root member, and density of branching. They assumed that the rates of extension and branching of each class of root member (axis, lateral) were uniform throughout the root system and constant with time. The end result of this model was the sum of number and length of each type of root member.

Gerwitz and Page (1974) developed an empirical model from root
density-depth relationships. They described the concentration of roots (% of the total) with depth with the following logarithmic equation:

\[
\frac{dp}{dx} = e^{-fx+c}
\]

where \( p \) represents the concentration of roots, \( x \) the depth, \( f \) the slope of the line relating root concentration to depth and \( c \) the intercept.

The percentage of the variances accounted for by the model in 71 out of the 107 sets of data was 80%.

Another approach to empirical plant growth models has been to estimate root growth as a function of physical processes that can be measured or estimated.

Page and Gerwitz (1974) developed a model which describes the density of plant roots in the soil by using equations which describe diffusion. The basic assumption is that roots spread from zones of high concentration to zones of lower concentration, and individual roots may be regarded growing in random directions as a result of repeated branching. The rate of penetration into a zone of lower concentration will, therefore, be proportional to the concentration of roots in the zone of higher concentration. It should, therefore, be possible to regard the roots of plants as growing into the soil in a manner analogous to the movement of a solute by diffusion in a liquid medium. There was reasonable agreement between the model and actual root distribution of lettuce and onions determined by placement of a radioactive source radially around individual plants.

Römken and Miller (1971) developed a mathematical model which relates root size and frequency to soil mechanical parameters obtained
from one-dimensional consolidation tests. This procedure is reasonable if it is assumed that soil strength is the factor limiting root development. The model is based on the following assumptions. A root can increase in size only if pressure exerted by the root on the soil results in consolidation of the surrounding soil. The soil must transmit a force equal and opposite of the root pressure. In the absence of tensile strength in the soil, reaction to the radial force developed by the root is as the reaction to one-dimensional compression. Therefore, the larger the root, the greater the compression or the radial stress in the soil increases with root diameter.

Dexter (1978) showed that the performance of single root axes in tilled soils can be predicted using measurements of soil macrostructure and of the deflection behavior of plant roots. This root growth model is stochastic. The occurrence of certain phenomena depends on the comparison of the appropriate probabilities with random numbers. Random numbers generated by a computer are used to create a simulated soil macrostructure, to choose angles of incidence between roots and aggregate surfaces, and to determine whether a root penetrates or is deflected by an aggregate surface. An equation which described the relative rate of elongation in structured soil was a function of the proportions of root length in aggregates, on aggregate surface or in voids, and a relative rate of elongation in a uniform soil of finite strength. In a later paper, Hewitt and Dexter (1979) used Dexter's (1978) model to show the affects of aggregate size and strength on root growth by modeling the growth of maize, sorghum and soybeans through beds of closely packed, equal, spherical aggregates.
Root growth models based on experimental data and physiological processes

Narda and Curry (1981) developed Soyroot, a model which simulates soybean root growth, root distribution and water uptake. The model consists of a root growth submodel and a macroscopic model of water uptake. The root growth submodel is developed from observations and measurements of potted plant field studies and predictions from Soymod (Curry et al., 1975) of carbohydrate available for root growth.

The root generation scheme of Narda and Curry (1981) was based on the following assumptions. 1) The axial root simultaneously initiates a set of four 1st order laterals from the same cross-sectional plane. The four laterals are equally spaced around the root. The interbranch distance between the 1st order laterals on the axial root is fixed. 2) A 1st order lateral initiates a set of two 2nd order laterals from the same cross-sectional plane. The interbranch distance between 2nd order laterals on the 1st order lateral is fixed. 3) No subsequent 1st or 2nd order laterals are initiated until the previously initiated 1st and 2nd order laterals have attained a given maximum length. 4) The length of a 1st order lateral decreases linearly with depth and do not exceed half the inter-row distance. 5) The length of a 2nd order lateral does not exceed 15 times the interbranch distance between the 1st order laterals on the axial root. 6) The roots contain 95% water and the elongation rates are calculated using the average radius of each kind of root. This model did not account for changes in physiological processes with time and effects of changes in soil physical processes (water content, mechanical impedance, temperature, etc.).

Hillel and Talpaz (1976) developed a general root growth-water
extraction model which demonstrated the importance of root extension as a factor prolonging the period of time a plant can continue to extract water from an unreplenished soil profile. This model predicted the density of active roots in a given layer at a given time as a function of: 1) root density in the given layer at a previous time, 2) the number of new roots formed per unit time as a fraction of the number of roots present, 3) the death rate per unit time as a fraction of the number of roots present, and 4) the extension rate per unit time as a fraction of the number of roots present at the previous time step in the overlying layer. This model did not account for changes in the rate of root extension with time nor for changes in the root death rate as a function of changes in soil water content.

A root growth submodel is included in the version of Rhizos reported by Bar-Yosef and Lambert (1977). Rhizos is a computer simulation of a two-dimensional root, water and nitrate distribution in the soil, and uptake by cotton plants. This model takes environmental and biological factors into account and is designed to predict root distribution in the soil by considering basic plant physiological processes. Like most macroscopic water extraction models, this model is based on the solution of the general flow equation for water and nitrate in the soil coupled with a volumetric sink term. Root growth is incorporated into the sink term. Root growth is calculated by making a distinction between potential and actual rates of root growth. The potential growth rate is assumed to depend on the amount of roots present, photoperiod, and day and night temperatures, while actual growth rate may be limited
by carbohydrate supply from the canopy to the roots. The root growth model also accounts for root thickening, geotropism and decomposition.

Rhizos can predict root and water distribution in the soil under various conditions prevailing in the field reasonably well. However, it should be pointed out that the model makes no distinction between the types of roots present. Root growth is calculated in terms of weight rather than length of individual members.

**Limitations of root growth models**

Root growth models generally predict root growth no better than "reasonably well." One reason is error inherent in quantitative root data collected in field or laboratory experiments which has been discussed earlier in this literature review. In addition, much uncertainty remains concerning the growth processes of roots and effects of soil factors. Major limitations in root growth models result from uncertainties about extrapolation of laboratory data on soil physical conditions to field situations; lack of understanding of conditions at the soil-root interface; inability to incorporate known effects of root age, time, temperature and aeration; and inadequate descriptions of root morphology (especially branching patterns) and anatomy of roots under field conditions (Klepper and Taylor, 1979).

Due to unavailability of the aforementioned root data, it is not possible to check the validity of assumptions and parameters used in the model.

In consideration of the present level of computer simulation of
root growth, its major role is evaluating the importance of soil and plant parameters and indicating the direction of future research.
SECTION I. A WATER BATH SYSTEM TO OBSERVE
TEMPERATURE EFFECTS ON TAPROOT AND
LATERAL ROOT DEVELOPMENT OF PLANTS
A Water Bath System to Observe Temperature Effects on Taproot and Lateral Root Development of Plants

J. A. Stone
H. M. Taylor

ABSTRACT

This paper describes a water bath system designed to provide accurate root-zone temperature control and serial observation of taproot and lateral root development to a depth of 120 cm. The system consists of a 137.2 x 100.3 x 121.9 cm deep constant-temperature water bath, twelve 2.5 x 30.5 x 121.9 cm immersed acrylic plastic plant-growth containers, movable lighting, and a derrick for removing the growth containers. The acrylic containers are lifted from the bath in tiers of three, and data recorded with photographs.

Temperature distribution within the bath has been measured at water temperatures ranging from 5°C to 35°C. Extensive research on root growth in the acrylic containers has been performed at water temperatures ranging from 17°C to 29°C. Temperatures remained with ± 0.3°C of the setting throughout the water bath for 25 days with no detectable spatial variability. Temperature gradients within the acrylic growth containers are presented.
INTRODUCTION

Controlling root temperature while allowing serial observation of root development requires adapting glass-wall container methods (Böhm, 1979) to some method of temperature control. The value of acrylic tubes and boxes for root growth observation has been repeatedly demonstrated (Taylor et al., 1978; Voorhees, 1976; Nilsson, 1965, 1969, 1973; Kemp, 1972; Reicosky et al., 1972; Flocker and Timm, 1969; Schuurman and Goedewaagen, 1964). Constant-temperature water baths have been designed for root development studies (Nilsson, 1973; Kemp, 1972; Grobbelaar, 1963; Martin et al., 1962; Cooper et al., 1960). Only Kemp (1972) and Nilsson (1973) have designed water bath systems that allow simultaneous serial root observation and accurate temperature control.

The objective of this experiment was to develop a system for controlling root-zone temperatures while allowing serial observations of taproot and lateral root development to a depth of 120 cm.

Other design criteria were (a) the temperature range of the water bath must at least span from 5° to 35°C, (b) temperature fluctuation must not be more than ± 0.3°C from the control temperature, (c) the system must not require permanent installation so that it can be moved to other environments or modified for other experiments, (d) provisions must be made for adding water to replace transpirational losses and for adding nutrients absorbed from the rooting medium, and (e) the rooting medium must not become water-saturated at any depth.

None of the previously designated water bath systems satisfies all these criteria.
CONSTRUCTION AND OPERATION

Figure 1 illustrates the general design of the system, which will be described in two sections. The first section describes the constant-temperature water bath, and the second section describes the root-growth observation system.

Constant Temperature Water Bath

The water bath is located in a temperature-controlled greenhouse. Inside dimensions of the bath are 137.2 cm x 100.3 cm x 121.9 cm deep. The box is constructed of 1.9-cm plywood and banded on the outside by 3.8 cm x 8.9 cm pine located at the top, center, and base. A 8.9-cm layer of fiberglass insulation surrounds the plywood. The insulation is covered with 0.6-cm plywood. The inside of the box is waterproofed with fiberglass resin and cloth, which has a double thickness in the corners. The box rests on 1.9 cm of polystyrene expanded-bead insulation, which lies directly on the concrete greenhouse floor. The outside of the box is painted with white latex to protect the wood and minimize heat absorption. Blueprints of the box are provided elsewhere.

The water temperature is controlled by a Neslab HX 100 refrigerated, recirculating heat exchanger equipped with a water-cooled condenser. Maximum cooling capacity is 2500 Kcal/hr. The unit is capable

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2Trade and company names are included for the benefit of the reader and do not imply endorsement by Iowa State University.
of controlling water temperature within ± 0.3° over a range of 5°C to 35°C, with an ambient temperature ranging from 5°C to 38°C. The general design of the heat-exchanger unit is illustrated in Figures 1 and 2.

The heat exchanger was modified for use with the water bath. The heat-exchanger recirculating pump, which was not adaptable to the system, was connected to a hose, forming a closed loop, and recirculated water only in its 30-l reservoir, which contained the heat-exchanging coils. The thermocouple, which regulated operation of the heat exchanger, was removed from the reservoir and placed in the water bath. The top of the reservoir was sealed with a plate of 1.3-cm acrylic plastic, allowing the reservoir to be pressurized. This permitted locating the heat-exchanger unit below the water level of the bath and installing an additional bronze 62.1 W (1/12 hp) Teel^1 (Model 1P903) brand water-circulating pump. Figure 1 illustrates how the heat-exchanger unit and external circulating pump are orientated relative to the entire system.

The plumbing used for water recirculation between the heat exchanger and water bath is shown in Figure 2. All pipe except the loop containing the filter is 3.8 cm schedule 40 PVC. The inflow and outflow manifolds are located on one end of the bath. The inflow manifold pulls water from the bottom of the bath directly into the heat-exchanger reservoir. The diameter of the inflow holes ranged from 0.6 cm to 1.3 cm to provide a constant inflow rate across the bottom of the bath. The external circulating pump is located on the outflow side of the reservoir. This

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created a negative pressure in the reservoir, which aided in sealing the acrylic plate to the top of the heat-exchanger reservoir. The pump, which runs continuously, circulates water at the rate of approximately 0.0018 m$^3$/s under the total head imposed by gravitational and frictional head loss of the system. A filter was installed on a loop connected to the main pipe between the pump and the outflow manifold.

The filter helped to inhibit algal and bacterial growth. Flow through the filter is controlled with a ball valve located on the main pipe. Water exits through 0.3-cm-diameter holes in the outflow manifold located at the top of the bath. The flow rate creates sufficient turbulent flow to provide excellent mixing within the water bath.

A vertical length of flexible hose was installed on the main pipes to allow position adjustment of the inflow and outflow manifolds. Tubes, which could be connected to vacuum lines, were installed in the heat-exchanger reservoir and main pipe so that entrapped air could be removed and the circulation pump primed to start water circulation.

Root Observation System

Plants are grown in twelve 30.5 cm x 2.5 cm x 121.9 cm acrylic plastic boxes immersed in the water bath. Figure 3 illustrates the box design. The sides and bottom are 1.3-cm acrylic plastic. The faces are 0.3-cm acrylic plastic. Each box has two 16-gauge aluminum flanges to permit removal and installation. The boxes are maintained at a 140° angle from the vertical by attaching a 2.721-kg lead weight to
the base of each box and by anchoring the aluminum flanges to the strips of aluminum channel spanning the top of the bath. Anchoring was necessary because of the turbulence in the bath. The boxes hang on 1.3-cm-diameter iron bars in tiers of three.

As illustrated in Figure 3, vacuum tubes with glass wool filters are installed at the bottom of each box for drainage. The tubes are connected to a manifold, which drains into a 20-l collection flask (Figure 4).

The boxes are filled with grade No. 3 horticultural vermiculite to within 2.5 cm of the top. Pieces of 1.9-cm insulation (Dow Styrofoam, TG1) were installed on top of the vermiculite to allow a 2.54-cm square opening for watering and growth of the stem. The water level in the bath is adjusted to the level of the vermiculite surface.

The plants are watered with a double-strength modified Hoaglands solution (Epstein, 1972). The double strength is necessary to overcome nutrient deficiencies presumably caused by ionic imbalances in the vermiculite. To minimize temperature changes resulting from watering, the nutrient solution is passed through a series of two 20-l carboys located in the bath by means of a gravitation head. By use of this method, the watering solution is always the same temperature as the water bath.

To protect the roots from light, 1.9 cm of insulation and black PVC sheeting were cut and fitted between the acrylic boxes. The insulation PVC combination floats on the water surface.

\footnote{Trade and company names are included for the benefit of the reader and do not imply endorsement by Iowa State University.}
Supplemental lighting is provided by four 80-W fluorescent bulbs and eight 100-W incandescent bulbs placed 50.8 cm above the top of the bath. The lighting system can be adjusted up or down and moved to a different position while data are collected.

To expedite removal of the boxes for data collection, a derrick was installed as illustrated in Figure 1. By means of a pulley, a bar with four hooks is lowered and attached to the iron bar on which the three acrylic boxes are attached. The tier of three boxes is then hoisted up until the full length of the box is exposed.

To record data, color slides are taken with a 35-mm camera equipped with a 50-mm lens. The camera is mounted on a stand. The height and angle of the camera are adjusted to minimize any distortion due to the convex lens. The distance between the camera and the acrylic box is such that the box completely fills the viewing field of the camera. To assure consistent pictures of each box, a grid was drawn on the floor, with a specific stand location for each box (Figure 1). To achieve sufficient resolution of the root system, supplemental light and a black backdrop are used. To minimize reflections, it is necessary to take the photographs when the sun is obscured or not overhead, usually at sunrise or sunset. Lifting a tier of three boxes and photographing them takes approximately 3 minutes.

To interpret the data, the slides are projected onto a grid, which is the same size as the acrylic box, and rectangular coordinates of the roots are recorded.
PERFORMANCE

There was no detectable temperature spatial variability at any given time within the water bath at temperature settings ranging from 5°C to 35°C. Fluctuations in temperature over time periods up to 25 days were within the control limits of the heat-exchanging unit, ± 0.3°C. The water bath has been used at ambient temperatures ranging from 15°C to 38°C.

Temperature gradients within the immersed acrylic boxes have been measured for water bath temperature settings of 17°C, 21°C, 25°C, and 29°C. Thermistor probes were installed in representative acrylic boxes at depths of 0.0 cm (soil surface-insulation interface), 2.5 cm, 5.0 cm, 7.5 cm, 10.0 cm, and 15.0 cm. Temperature profiles of the extremes in ambient temperature encountered for each setting are presented in Figure 5. At the high extreme, the temperature at 2.5 cm deviated less than or equal to 2.5°C from the water bath setting. At the low extreme, the temperature at 2.5 cm deviated less than 1.0°C from the water bath setting.
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Figure 2. Schematic drawing of plumbing for circulation and temperature control of water bath.
C = water filter. D = ball valve which regulates flow to filter. E = water circulation
pump. F = hose for height adjustment of inflow and outflow manifolds. G = outflow
manifold. H = inflow manifold
Figure 3. Acrylic box in which plants are grown. A = lead weight. B = aluminum flange. C = clamp which fastens flange to iron bar. D = vacuum drainage tube. E = glass wool drainage filter. F = access hole to facilitate emptying of boxes.
Figure 5. Temperature vs. depth in acrylic boxes at four water bath settings. o = minimum surface temperature encountered. △ = maximum surface temperature encountered.
SECTION II. THE EFFECT OF TEMPERATURE ON THE DEVELOPMENT OF THE TAPROOT AND LATERAL ROOTS OF SOYBEANS
The Effect of Temperature on the Development of the Taproot and Lateral Roots of Soybeans

J. A. Stone

H. M. Taylor

ABSTRACT

Modification of soybean (Glycine max (L.) Merr.) root systems to increase the depth of root penetration can be achieved by cultivar selection and changes in soil temperature. Beeson, Hawkeye 63, Wayne, and Harosoy 63 soybean cultivars were grown at root-zone temperatures of 17°C, 21°C, 25°C and 29°C to evaluate the effect of temperature on the development of the taproot and lateral roots and to describe the results in a manner adaptable to a root growth simulation model. Temperature treatments were imposed upon the soybean cultivars with the constant temperature water bath system designed by Stone and Taylor (1982). The constant temperature bath was located in a temperature modified greenhouse. Air temperature was in the range of 20°C to 35°C over the course of the 12 month experiment. Serial measurements of taproot and lateral root location and frequency of primary nodes by depth were recorded on alternate days until 19 days after emergence.

The rate of taproot extension increased with temperature, decreased with time and averaged over time was greater for the Beeson and Hawkeye 63 cultivars than for the Wayne and Harosoy 63 cultivars. The rate of lateral root extension increased with temperature, generally increased with time, and averaged over time was greater for the Beeson and Hawkeye 63 cultivars than for the Wayne and Harosoy 63 cultivars at temperature treatments greater than 17°C. Within the time and temperature range of this experiment the taproot and lateral root rates of extension can be expressed by an equation of the form \( L' = -A + Bt + (C-Dt)T + ET^2 \). \( L' \) is the rate of extension; \( A, B, C, D, \) and \( E \) are constants; \( t \) is the
time; and T the temperature. The frequency of primary nodes varied with depth, time and cultivar. The greatest frequency of nodes occurred 2.5-7.5 cm below the soil surface. The initiation of primary nodes with time was different above and below the planting depth of 2.5 cm. In the 0-2.5 cm depth, the initiation of nodes increased with time up to 19 days. This is most evident at 25°C and 29°C. In the depth increments below 2.5 cm, the initiation of primary nodes decreases with time. The Beeson and Hawkeye 63 cultivars had fewer primary nodes than the Wayne and Harosoy 63 cultivars.
INTRODUCTION

Modification of root systems by soil and crop management practices to increase the depth which roots penetrate can be beneficial during periods of water stress. Taylor et al. (1978) and Kaspar et al. (1978) have shown cultivar differences in the depth of soybean (*Glycine max* (L.) Merr.) root penetration. Taylor et al. (1972) and Arndt (1945) have shown temperature differences in taproot extension for cotton (*Gossypium hirsutum* L.). A viable method of evaluating the effects of management practices on rooting depth is by computer simulation of root growth. However, data required to construct simulation models for soybean root development to an appreciable depth are lacking.

The objectives of this experiment were 1) to evaluate the effect of root-zone temperature on the development of the taproot and lateral roots of soybeans grown to an appreciable depth, 2) to evaluate the cultivar-temperature interactions for taproot and lateral root development, and 3) to describe the results in a manner adaptable to a root growth simulation model.
MATERIALS AND METHODS

Beeson, Hawkeye 63, Wayne, and Harosoy 63 soybean cultivars were grown in medium grade horticultural vermiculite using the constant temperature water bath designed by Stone and Taylor (1982). The system consists of a 137.2 x 100.3 x 121.9 cm deep constant-temperature water bath, twelve 2.5 x 30.5 x 121.9 cm immersed acrylic plastic plant-growth containers, movable lighting, and a derrick for removing the growth containers. The acrylic containers are lifted from the bath in tiers of three and the root development data recorded with photographs. The soybeans were grown at constant root temperatures of 17°C, 21°C, 25°C and 29°C. The constant temperature bath was located in a temperature modified greenhouse. Air temperature ranged from approximately 20°C to 35°C over the course of the 12 month experiment. A 16 hour photoperiod was provided with the supplemental light source. Total radiation incident upon the soybean plants varied depending on the solar elevation.

The experimental design was a split-plot with the whole plots being temperature and the split-plots cultivars. Measurements in time were treated as repeated measures and were analyzed as an additional split-plot treatment. The design for the whole plots was three replications of a randomized block design. Each whole plot replication consisted of four constant temperature runs, one at each of the four temperature treatments. Three replications of each cultivar was randomly assigned to the 12 acrylic growth containers. Serial measurement of root parameters were taken on alternate days for 19 days resulting in 10 measurements in time.
Uninoculated seeds were planted 2.5 cm deep in moist vermiculite at the treatment temperature. The vermiculite was kept near field capacity by watering with approximately 250 ml of double strength modified Hoagland solution (Epstein, 1972) daily. Excess nutrient solution was removed daily by applying suction. Water use could be estimated by monitoring the amount of nutrient solution in the collection flask.

Serial root measurements were begun when 50% of the plants had emerged. Data were recorded from slides projected onto a graduated screen. The rates of taproot and lateral root extension were determined from the rectangular coordinates of the root tips. An attempt was made to record data from five roots, the taproot and four primary lateral roots. The rectangular coordinates were transferred to computer cards and the actual rates in cm/day calculated using a computer program. Serial measurements of the frequency of the primary nodes were recorded in 5 cm depth increments measured from the soil surface. To be counted as a node, the corresponding lateral root was required to attain a length greater than or equal to 5 cm by the 19th day after emergence. For analysis, the node frequency data was grouped into the following depth increments: 0-2.5 cm, 2.5-7.5 cm, 7.5-12.5 cm, 12.5-17.5 cm, 17.5-27.5 cm, and 27.5-57.5 cm. No primary nodes were observed below 57.5 cm at any of the four temperature treatments. Serial measurements of plant height and growth stage were also recorded.

At the end of each run, the plant tops were removed and the roots carefully separated from the vermiculite. The plants were dried at 65°C and the dry weights recorded.
The complete data sets and analysis of variance tables are provided elsewhere.

---

RESULTS

Figure 1 shows that the rate of taproot extension varied with time, temperature, and cultivars. The effects of temperature, cultivar, and time were all highly significant (.01 level). Within each temperature the Beeson and Hawkeye 63 cultivars responded differently (.01 level) from the Harosoy 63 and Wayne cultivars. This cultivar difference decreased with temperature.

The significant linear component of time (.01 level), temperature (.01 level), the quadratic component of temperature (.05 level), and the linear time-linear temperature (.01 level) interaction allowed the rate of taproot extension to be expressed as a function of these effects at any given time and temperature within the range of this experiment. Table 1 lists the equations for the rate of taproot extension. The intercepts and coefficients were obtained with a least squares regression analysis.

Missing data were a problem in the analysis of the lateral root data due to the nature of the development of lateral roots with time and to the method of root observation. In many cases, lateral roots did not emerge adjacent to the acrylic plate resulting in variability in the number of roots that could be measured and in the time at which measurements could begin. As a result it was necessary to average the rates of all lateral roots for each plant at a given time together and to eliminate the first 3 days of data. The result is illustrated in Figure 2.

The effects of temperature, cultivar, and time were all highly
significant (.01 level). By graphical analysis, it was determined that an equation of the same form as was used for the taproot data would adequately describe the rate of lateral root extension with changes in time and temperature. Comparison of regressions using this equation showed that the Beeson and Hawkeye 63 cultivars were significantly different (.01 level) from the Wayne and Harosoy 63 cultivars. However, this cultivar difference decreased with temperature and at 17°C the relationship was reversed. Table 2 lists the equations which describe the rate of lateral root extension for a given time and temperature within the range of this experiment. The intercepts and coefficients were obtained with a least squares regression analysis.

Measurements were made on alternate days for 19 days, therefore, the rate of extension (cm/day) for a given day in Figures 1 and 2 is actually the average of 2 days growth. Figures 1 and 2 and the equations in Tables 1 and 2 are not continuous but stepwise functions proceeding in steps of 48 hours. For example, the rate for day 19 on Figures 1 and 2 is plotted as day 18 because it is the average rate for 18 days after emergence ± 24 hours.

Analysis of variance of the node data showed that the frequency of the primary nodes varied significantly (.01 level) with changes in cultivar, depth and time but not with changes in temperature. Further analysis of the data was performed by depth increments and the form of the equation determined graphically because of the unbalanced nature of the data set. Examination of Figure 3 shows that the overall effect of depth was sigmoidal, the greatest frequency of nodes occurring in the 2.5 to 7.5 cm depth increment.
Table 3 summarizes the F tests of the node data for temperature, cultivar, and time at the chosen depth increments. The temperature effect was not conclusive. Closer examination of the data has shown that the frequency of the nodes at a given depth generally decreased linearly with increases in temperature. There was a significant increase in the frequency of nodes with increases in time at all depths. Figure 3 illustrates that the major component of the time effect was quadratic except for the 0 to 2.5 cm depth where it seemed to be linear. It was determined that the frequency of the primary nodes at a given depth could be expressed by an equation of the same form as was used to describe the taproot and lateral root extension rates. Using this model, the effect of cultivars illustrated in Table 3 was examined for the top four depth increments. The Beeson and Hawkeye 63 cultivars had significantly fewer (.01 level) nodes than the Wayne and Harosoy 63 cultivars. The difference was most pronounced in the upper depths at higher temperatures. The cultivar effect is illustrated for the 0 to 2.5 cm and the 2.5 to 7.5 cm depths in Figures 4 and 5. While different in magnitude, Figure 5 is similar to the graphs of lower depths. Figure 4 is quite different. This is interesting to note because Figure 4 is the zone above the planting depth and Figure 5 below.

No consistent relationship was found between the dry weight top/root ratio and temperature; therefore, the root and top dry weights were examined separately. Averaged over blocks in time and cultivars, root and top dry weight increased with temperature. At 17°C, there was not much variability in the root and top dry weights between blocks in time averaged over cultivars indicating that root temperature was limiting.
At 21°C, 25°C, and 29°C, there was considerable variability between blocks in time averaged over cultivars. Due to this variability, further analysis was not performed.
Figures 1 and 2 show that the time-temperature interaction of the extension rate was different for the taproot and lateral roots at temperatures greater than 17°C. The amount of the decrease in the taproot rate with time increased with temperature. The opposite seemed to be true for the lateral root rate. The similar rates at 17°C indicated that at 17°C temperature was the limiting factor in the extension rate for both the taproot and lateral roots. When the temperature was increased above 17°C, it is postulated that there was competition for carbohydrates between the taproot and lateral roots after the initiation of branching, the lateral roots evidently being the better competitor. Interpretation of the lateral root rate data is difficult because it represents the average of several different primary lateral roots on one plant without accounting for possible differences in rate due to morphological parameters. At 25°C and 29°C, the taproot extension rate (Figure 1) shows a characteristic decrease approximately 3 days after emergence. This is very similar to the data of May et al. (1967) for buckwheat. This "dip" may represent the depletion of endosperm reserves.

Figures 1 and 2 show similar cultivar differences for the taproot and lateral root extension rates. The overall extension rates of the Beeson and Harosoy 63 cultivars were greater than the Wayne and Harosoy 63 cultivars. This agreed with the cultivar differences reported by Kaspar et al. (1978) and Taylor et al. (1978). However, at 17°C the cultivar separation was small for the taproot and reversed for the lateral root extension rates suggesting that temperature rather than
the cultivar was limiting root extension.

Figure 3 shows that the total number of primary nodes decreased with increases in temperature. Evidently roots were more efficient at higher temperatures so that fewer roots were sufficient to satisfy the nutrient and water requirements of the plant. It is interesting to note that while the depth of the root system at 25°C and 29°C was approximately twice that of soybeans grown at 17°C, no nodes were found below 57.5 cm at any temperature.

Perhaps the most interesting observation that can be made from the primary node data is its relationship with depth and cultivars. The initiation of nodes with time was different above and below the planting depth of 2.5 cm. In the 0 to 2.5 cm depth (Figure 4), the initiation of nodes was increasing with time up to 19 days. This was most evident at 25°C and 29°C. At the 2.5 to 7.5 cm depth (Figure 5), the initiation of nodes decreased with time. Figures 4 and 5 also show that the cultivars with the faster extension rate, Beeson and Hawkeye 63, had fewer primary nodes than the cultivars with the slower extension rate, Wayne and Harosoy 63. The change in the number of primary nodes with depth and cultivars implied a distribution of available carbohydrate between the processes of root extension and primary root initiation. It is postulated that the Beeson and Hawkeye 63 cultivars diverted more carbohydrate to the process of root extension resulting in fewer primary laterals than the Wayne and Harosoy 63 cultivars in which more carbohydrate was used for primary lateral development resulting in a slower extension rate. The difference in root distribution near the surface with changes in temperature, cultivar, and depth may have practical significance if these
roots are functional in absorption and support.

The lack of a consistent relationship between root and top dry weight and temperature at 21°C, 25°C and 29°C indicates that the root temperature was not limiting and that top and root dry weight accumulations were limited by unregulated factors, presumably air temperature, light intensity or experimental error in measuring such small weights (approximately .1 gm). Although supplemental light was supplied, radiation incident upon the plants in the greenhouse varied due to changes in solar elevation. An attempt was made to correlate total incoming radiation measured outside the greenhouse with top and root dry weights, but no meaningful relationship could be found.

Although the error increased with increasing temperature there was very good reproducibility between blocks in time for the rate data. This suggests that the rates of taproot and lateral root extension were limited by soil temperature. If root dry weight accumulation is dependent on light intensity (Rufty et al., 1981; Earley and Cartter, 1945), perhaps the growing tips are strong enough sinks to be able to obtain carbohydrates at the expense of other root functions or development.
CONCLUSIONS

The rate of taproot and lateral root extension of soybeans increased with temperature. The rate of taproot extension decreased with time. The rate of lateral root extension generally increased with time. At a given temperature the taproot and lateral root rates varied among cultivars. The frequency of primary nodes varied with cultivar, depth and time. At a given temperature the root system consisted primarily of lateral roots that developed from the upper 0-7.5 cm of the taproot.

These results show that modification of soybean root systems to increase the depth of root penetration can be achieved by cultivar selection and changes in soil temperature.
ACKNOWLEDGMENTS

The authors would like to thank Dr. P. N. Hinz, Department of Statistics, Iowa State University, Ames, Iowa, for his assistance with the data analysis.
LITERATURE CITED


Table 1. Prediction equations for the rate of taproot extension

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Equation$^a$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wayne</td>
<td>$L' = -11.0679 + .2582t + (1.0136 - .01468t)T - .01410T^2$</td>
<td>.75</td>
</tr>
<tr>
<td>Harosoy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beeson</td>
<td>$L' = -14.6974 + .2262t + (1.3202 - .01216t)T - .01991T^2$</td>
<td>.83</td>
</tr>
<tr>
<td>Hawkeye</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^aL' = \text{rate of taproot extension; } t = \text{time; } T = \text{temperature.}$
Table 2. Prediction equations of the rate of lateral root extension

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Equation</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wayne Harosoy</td>
<td>$l' = -11.4984 + .0854t + (1.019 - .0017t)T - .0168T^2$</td>
<td>.73</td>
</tr>
<tr>
<td>Beeson Hawkeye</td>
<td>$l' = -13.2367 + .1237t + (1.0800 - .0036t)T - .0155T^2$</td>
<td>.81</td>
</tr>
</tbody>
</table>

*a* $l'$ = rate of lateral root extension; $t$ = time; $T$ = temperature.
Table 3. Summary of F tests from analysis of primary node data

<table>
<thead>
<tr>
<th>Depth</th>
<th>Temperature</th>
<th>Cultivar</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2.5</td>
<td>3.49</td>
<td>17.04**</td>
<td>155.60**</td>
</tr>
<tr>
<td>2.5-7.5</td>
<td>2.05</td>
<td>11.64**</td>
<td>389.78**</td>
</tr>
<tr>
<td>7.5-12.5</td>
<td>9.17*</td>
<td>4.41*</td>
<td>63.15**</td>
</tr>
<tr>
<td>12.5-17.5</td>
<td>4.35</td>
<td>9.90**</td>
<td>39.42**</td>
</tr>
<tr>
<td>17.5-27.5</td>
<td>1.51</td>
<td>3.18*</td>
<td>37.23**</td>
</tr>
<tr>
<td>27.5-57.5</td>
<td>1.69</td>
<td>2.08</td>
<td>3.93**</td>
</tr>
</tbody>
</table>

* = Significant at the .05 level.

** = Significant at the .01 level.
Figure 1. Rate of taproot extension vs. time at 17°C, 21°C, 25°C, and 29°C. Each point represents the rate for ± 1 day. • = Beeson, o = Hawkeye, △ = Harosoy, and □ = Wayne soybean cultivars.
Figure 2. Rate of lateral root extension vs. time at 17°C, 21°C, 25°C, and 29°C. Each point represents the rate for + 1 day. ● = Beeson, ○ = Hawkeye, △ = Harosoy, and □ = Wayne soybean cultivars. The average 95% LSD was used because the sample size increased from day 9 to day 19. The 95% LSD ranged from 0.45 to 0.78 at 17°C, 0.68 to 0.78 at 21°C, and 1.11 to 1.49 at 25°C and 1.25 to 1.44 at 29°C.
Figure 3. The number of primary nodes vs. time for 17°C, 21°C, 25°C, and 29°C. ● = 0 to 2.5 cm, ○ = 2.5 to 7.5 cm, △ = 7.5 to 12.5 cm, □ = 12.5 to 17.5 cm, ▲ = 17.5 to 27.5 cm and ■ = 27.5 to 57.5 cm. The 95% LSD is calculated from the top four depth increments.
Figure 4. The number of primary nodes vs. time for 0 to 2.5 cm at 17°C, 21°C, 25°C and 29°C. • = Beeson, o = Hawkeye, A = Harosoy, and □ = Wayne soybean cultivars
Figure 5. The number of primary nodes vs. time for 2.5 to 7.5 cm at 17°C, 21°C, 25°C and 29°C. • = Beeson, ○ = Hawkeye, △ = Harosoy, and □ = Wayne soybean cultivars.
SECTION III. COMPUTER SIMULATION OF SOYBEAN ROOT GROWTH BASED ON TEMPERATURE
Computer Simulation of Soybean Root Growth Based on Temperature

J. A. Stone
H. M. Taylor

Contribution from the Department of Agronomy, Iowa State University,
Journal Paper No. J- of the Iowa Agriculture and Home Economics
Experiment Station, Ames, Iowa. Project No. 2354.
ABSTRACT

A two dimensional root growth simulation model has been developed from data which describe the effects of root-zone temperatures on root development. The major inputs are equations which describe taproot and lateral root extension, primary node development, and the rooting angle as a function of time and temperature. The model predicts the extension of the taproot and 10 primary lateral roots for two groups of soybean cultivars. The output consists of a listing of serial rectangular coordinates for each root tip and a computer plot of the entire root system. The rooting depths predicted by the model agree well with the greenhouse and field experimental data. This illustrates the importance of soil temperature in determining the depth of soybean root penetration and in extrapolating greenhouse root extension data to a field situation.
INTRODUCTION

Several different approaches have been used to develop root growth models. Lungley (1973) and Hackett and Rose (1972) developed models from experimentally derived root initiation and extension data. Others have estimated root growth as a function of physical processes (Dexter, 1978; Page and Gerwitz, 1974; Römken and Miller, 1971) or by simulating physiological processes (Narda and Curry, 1981; Bar-Yosef and Lambert, 1977). Major limitations in root growth models result from uncertainties about extrapolation of laboratory data to field situations and incorporation of the effects of soil physical conditions such as temperature.

The objective of this experiment was to illustrate the importance of soil temperature in modeling soybean root development and in extrapolating greenhouse root extension data to a field situation.
METHODS

This model is based on the equations presented by Stone and Taylor (1983) and from the data presented by Stone (1982)\(^1\) and Kaspar et al. (1981).

The model has been designed to illustrate the effects of time, temperature and cultivar on the depth of soybean root penetration. The time and temperature inputs were chosen to correspond with the data collected by Stone and Taylor (1983) and Kaspar (1982)\(^2\). The cultivar effect was either 1) Beeson and Hawkeye 63 or 2) Wayne and Harosoy 63.

The model predicts the extension of the taproot and 10 lateral roots. It is assumed that the 4 lateral roots emerge from the primary nodes in a single plane, orientated at 90° to each other. The model predicts lateral root extension in one quadrant. Lateral roots are allowed to emerge from the taproot in 3 depth increments, 0-2.5 cm above, 0-5 cm below, and 5-10 cm below the planting depth.

The program is written in standard FORTRAN. Copies may be obtained from the authors.

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THE MODEL

A flow chart of the root growth simulation model and definitions of the subroutines are presented in Figure 1.

The following integer constants must be read into the model initially; the number of days growth, the cultivar, the planting depth (cm), and the time increment of growth (days). The model will distinguish between the following groups of soybean cultivars; 1) Beeson and Hawkeye 63 and 2) Wayne and Harosoy 63. The time increment of growth is the length of time the values determined by the root growth equations for a given time and temperature remain constant. The model is not continuous but "grows" in steps of one day. Temperature (°C) is defined by empirically derived equations representing the temperature at a given time and depth.

The root extension equations presented by Stone and Taylor (1983) are applicable only after emergence. They defined emergence as the time at which 50% of the plants had emerged. To use Stone and Taylor's equations in the model, an algorithm was required which would predict the depth of the taproot at emergence, per their definition, regardless of the planting depth.

Prediction of the depth of the taproot at emergence is accomplished by determining the preemergence taproot extension in the following manner. First, the number of days to emergence (DTG) is predicted as a function of temperature using the following equation derived from data presented
by Stone (1982)

\[ DTG = 9.72 - 0.23T \]

Next, the percent (PERC) that one day's growth is of DTG is determined and summed. Now the depth of the taproot tip below the planting depth at the time of emergence (DE) for a given temperature is determined from the following equations derived from the data of Stone.

\[ DE = 2.10 + 0.54T \]

The preemergence taproot extension is determined by dividing DE (cm) by DTG (days) and multiplying by one day. Lastly, the taproot depth is found by adding the preemergence taproot extension to the previous preemergence taproot depth. Initially, the preemergence taproot depth is the planting depth. The procedure is now repeated using the new temperature at the preemergence taproot depth. The depth of the taproot at emergence is the depth at which the summation of PERC is greater than or equal to 95%.

The model determines the rectangular (X and Y) coordinates of the taproot and lateral roots from the rate of taproot extension (TAPEXT) and lateral root extension (LATEXT) at a given time and temperature. The rates of extension are based on the temperature at the root tips. Time is not allowed a value greater than or equal to 19 days after

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emergence, the limits of Stone and Taylor's (1983) equations, to avoid excessive extrapolation of the effect of time. Horizontal deviations resulting from soil resistance were accounted for by introducing a tortuosity factor (TORT). TORT was set equal to .5 cm and randomly assigned in the '+' or '-' X direction. The equations for determining the rectangular coordinates of the taproot and lateral roots are described below:

Taproot: 
\[
X = X_{j-1} + \text{TORT} \\
Y = Y_{j-1} + (\text{TAPEXT}^2 - \text{TORT}^2)^{1/2}
\]

Lateral roots: 
\[
X = X_{j-1} + (\text{LATEXT} \cdot \cos(\text{RAD})) + \text{TORT} \\
Y = Y_{j-1} + \text{LATEXT} \cdot \sin(\text{RAD})
\]

\(j\) represents the time (days) and \(\text{RAD}\) the rooting angle of the lateral roots measured from the horizontal in radians.

The rooting angle of the lateral roots at a given temperature (T) is determined from the following equations derived from the data of Kaspar et al. (1981). The rooting angle is based on the temperature at the root tip.

\[
T \leq 21.1^\circ C \quad \text{RAD} = .19 + .01T \\
T > 21.1^\circ C \quad \text{RAD} = .43 - .003T
\]

The horizontal distance (cm), measured from the taproot, at which the lateral roots turn downward (TRNDWN) as a function of temperature was determined from observations made in the greenhouse and during field experiments. The equations describing this relationship are listed below.
The turning downward of the first lateral root is assumed to correspond to some plant stimulus causing all lateral roots to grow vertical. However, all lateral roots must grow some minimum horizontal distance before turning downward. This was estimated to be 7.5 cm based on greenhouse observations.

Primary nodes are randomly assigned in 3 depth increments; 0-2.5 cm above, 0-5 cm below, and 5-10 cm below the planting depth. These depths were chosen to correspond with the data of Stone (1982)\(^1\). Equations which define the number of primary nodes at a given time and temperature for each depth increment are presented in Table 1. These were derived from the data of Stone. The number of lateral roots is limited to 10; 2, 6, and 2 laterals 0-2.5 cm above, 0-5 below, and 5-10 cm below the planting depth, respectively. This distribution corresponds with the observed distribution of nodes in the 3 depth increments. The actual depths of the nodes within each depth increment are determined by a system random number generator.

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RESULTS AND DISCUSSION

Table 2 compares the predicted values with the original experimentally observed values of the taproot depth recorded by Stone (1982)\(^1\) for soybeans grown at constant temperatures for 19 days after emergence. Lateral roots were not compared because of alteration in the rooting angle caused by the growth container. The predicted taproot depth agreed well with the experimental data. Changes in the precision of the predicted values and cultivar differences with changes in temperature agree with the observations presented by Stone and Taylor (1983).

Figure 2 compares the predicted values of the taproot and lateral root depth with the experimental data obtained by Kaspar (1982)\(^2\). Kaspar sampled soybean roots using the soil core method. The experiment was conducted at the Western Iowa Experimental Farm, Castana, Iowa in 1981. The soil was an Ida silt loam (fine, silty, mixed (calcareous) mesic family of typic Udorthents). Equations for the temperature at any given time and depth were derived from temperature observations made during the course of Kaspar's experiment. The actual temperature data is presented by Stone (1982)\(^1\). Kaspar did not grow the same cultivars as distinguished between in the present model, however, he did make a separation between fast and slow elongating soybean cultivars. In Figure 2, predicted values for Beeson and Hawkeye 63 are compared with

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the fast elongating soybean cultivars and Wayne and Harosoy 63 with the slow elongating soybean cultivars. Figures 3 and 4 are plots of the root systems predicted by the model for the two groups of soybean cultivars 76 days after planting. The planting depth was 8 cm.

In Figure 2, the predicted values of the lateral root depth fit the experimental data better than the predicted values of the taproot depth. This may be explained by the increased chances of intersecting the path of a lateral root when taking root samples in the field by the soil core method.

Figures 2, 3, 4, and Table 3 illustrate that the model is sensitive to cultivar differences even under the changing temperature regime experienced in the field. However, the cultivars with the slowest taproot extension rate had the deepest lateral root penetration and vice versa. This was consistent with the cultivar differences described by the equations presented by Stone and Taylor (1983). They found that for lateral roots grown at 17°C the relationship between fast and slow cultivars was reversed. This illustrates the uncertainty of extrapolating cultivar differences in root extension rates to lower temperatures and probably accounts for some of the difficulty in extrapolating greenhouse root extension data to a field situation.

The lateral roots in Figures 3 and 4 seem to be moving downward as a "rooting front" in spite of the fact that the individual roots were initiated at different depths and times. Examination of the serial coordinates which comprise Figures 3 and 4 show that roots which initiate later experience warmer temperatures and as a result, grow faster. Therefore, the lateral roots tend to move downward in a "rooting
front" which becomes more definitive with time and depth. Output from the model also shows that the root tips tend to collect at, and follow the 16-17°C heat wave downward.

Table 3 presents the predicted rooting depths 76 days after planting if the temperature observed during Kaspar's\textsuperscript{1} experiment were increased and decreased by 1°C. Such a change is of a magnitude which may be induced by varying the tillage treatment (Griffith et al., 1973). The 1°C deviation caused an approximately 15 cm change in rooting depth as well as a change in the magnitude of the cultivar differences.

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CONCLUSIONS

The soybean root growth model based solely on temperature effects presented in this paper predicts soybean rooting depths which agree well with the rooting depths observed in the field (Kaspar, 1982). This illustrates the importance of soil temperature in determining the depth of soybean root penetration and in extrapolating greenhouse root extension data to a field situation.

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ACKNOWLEDGMENTS

The authors would like to thank T. C. Kaspar for his cooperation in obtaining the field soil temperature data used in this model.
LITERATURE CITED


Table 1. Equations describing the number of primary nodes as a function of time (days after emergence), temperature (°C), and depth relative to the planting depth. \( Y \) = the number of primary nodes, \( t \) = the time, and \( T \) = the temperature

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Cultivar</th>
<th>Equation</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above</td>
<td>Beeson Hawkeye 63</td>
<td>( Y = -0.73 + 0.18t + (0.03 - 0.003t)T )</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Wayne Harosoy 63</td>
<td>( Y = 0.24 - 0.01t - (0.03 - 0.01t)T )</td>
<td></td>
</tr>
<tr>
<td>Below</td>
<td>Beeson Hawkeye 63</td>
<td>( Y = -6.93 + (1.62 - 0.02t)t + (0.27 - 0.04t)T )</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Wayne Harosoy 63</td>
<td>( Y = -8.02 + (2.22 - 0.03t)t + (0.31 - 0.05t)T )</td>
<td>0.75</td>
</tr>
<tr>
<td>Below</td>
<td>Beeson Hawkeye 63</td>
<td>( Y = -2.70 + 0.68t + (0.10 - 0.02t)T )</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Wayne Harosoy 63</td>
<td>( Y = -3.97 + 1.11t + (0.15 - 0.04t)T )</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Table 2. Comparison of the predicted and experimentally observed values of taproot depth for soybean cultivars grown for 19 days after emergence at constant temperatures

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Cultivar</th>
<th>Depth of taproot (cm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Predicted</td>
<td>Experimental&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>29°</td>
<td>Beeson</td>
<td>119.0</td>
<td>111.3 (4.3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hawkeye 63</td>
<td>105.8</td>
<td>102.8 (3.4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wayne</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harosoy 63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25°</td>
<td>Beeson</td>
<td>108.7</td>
<td>104.6 (3.1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hawkeye 63</td>
<td>96.5</td>
<td>96.9 (4.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wayne</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harosoy 63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21°</td>
<td>Beeson</td>
<td>86.7</td>
<td>88.7 (1.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hawkeye 63</td>
<td>78.9</td>
<td>78.4 (2.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wayne</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Harosoy 63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17°</td>
<td>Beeson</td>
<td>52.7</td>
<td>51.1 (2.8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hawkeye 63</td>
<td>52.9</td>
<td>52.4 (1.7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wayne</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Harosoy 63</td>
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</tbody>
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<sup>a</sup>The number in parentheses is the 95% confidence interval.
Table 3. Predicted depths of root penetration 76 days after planting for temperatures observed during Kaspar’s (1982) experiment and for the observed temperatures increased and decreased by 1°C

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<tr>
<td>Wayne</td>
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<td>178.7 (1.4)</td>
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^The number in parentheses is the 95% confidence interval.

SUBROUTINE ZER05 initializes the arrays used throughout the program by setting all components equal to zero.

Call ZEROS

Call TEMP

Call EMERGE

SUBROUTINE EMERGE determines the depth of the taproot at emergence.

SUBROUTINE TEMP determines the temperature at any given time and depth.

Call TAPRAT

SUBROUTINE TAPRAT calculates the rate of extension of the taproot and determines its coordinates.

Call NODE

SUBROUTINE NODE determines the number of primary nodes in a given depth increment.

Call LATRAT

SUBROUTINE LATRAT calculates the rate of extension of each lateral root and determines its coordinates.

Call PRINT

SUBROUTINE PRINT prints out the rectangular coordinates of the taproot and lateral roots for each day's growth.

SUBROUTINE RTPLOT plots the coordinates of the root tips.

SUBROUTINE RESIST sets the horizontal deviations due to soil resistance.

SUBROUTINE TEMP

SUBROUTINE NNODE determines the location of the primary node within a given depth increment.

SUBROUTINE TEMP

SUBROUTINE ANCLE determines the angle at which the lateral root grows and when it turns downward.

SUBROUTINE TEMP

SUBROUTINE RESIST

SUBROUTINE PRINT

SUBROUTINE TEMP

SUBROUTINE LATRAT

SUBROUTINE RESIST

SUBROUTINE TEMP

Figure 1. Flow chart of the temperature based root growth simulation model.
Figure 2. Depth of root penetration versus time for the predicted values of the taproot (---) and lateral roots (-----) for 1) Beeson and Hawkeye 63 and 2) Wayne and Harosoy 63 soybean cultivars. ● = the means for maximum rooting depth taken from Kaspar (1982).1

---

Beeson and Hawkeye 63

Wayne and Harosoy 63

TIME (DAYS AFTER PLANTING)
Figure 3. Plot of the root system predicted by the root growth model for Beeson and Hawkeye 63 soybean cultivars 76 days after planting.
BEESON AND HAWKEYE 63
CULTIVARS
Figure 4. Plot of the root system predicted by the root growth model for Wayne and Harosoy 63 soybean cultivars 76 days after planting.
GENERAL SUMMARY AND DISCUSSION

Three experiments were designed to evaluate the role of soil temperature in soybean root extension. In the first experiment, a constant temperature water bath system was designed which was capable of controlling root-zone temperatures while allowing serial observations of taproot and lateral root development to a depth of 120 cm. In the second experiment, the constant temperature water bath was used to evaluate the effect of root-zone temperature on the development of the taproot and lateral roots of soybeans. Beeson, Hawkeye 63, Wayne, and Harosoy 63 soybean cultivars were grown at root-zone temperatures of 17°C, 21°C, 25°C, and 29°C. In the third experiment, a root growth simulation model was developed which was based on the temperature response data. The following conclusions can be derived from the three experiments.

1) The constant temperature water bath designed in this study was an effective technique for observing the effects of temperature on taproot and lateral root development of soybeans to a depth of 120 cm.

2) The rate of taproot extension increased with temperature, decreased with time, and averaged over time was greater for the Beeson and Hawkeye 63 cultivars than for the Wayne and Harosoy 63 cultivars.

3) The rate of lateral root extension increased with temperature, generally increased with time, and averaged over time was greater for the Beeson and Hawkeye 63 cultivars than for the Wayne and Harosoy 63 cultivars at temperature treatments greater than 17°C.

4) The taproot and lateral root rates of extension can be expressed by an equation of the form \( L' = -A + Bt + (C -Dt)T + ET^2 \)
within the time and temperature range of this experiment. \( L' \) is the rate of extension; \( A, B, C, D, \) and \( E \) are constants; \( t \) is the time; and \( T \) the temperature.

5) The number of primary nodes varied with depth, time, and cultivar. The Beeson and Hawkeye 63 cultivars had fewer primary nodes than the Wayne and Harosoy 63 cultivars.

6) The temperature based root growth simulation model predicted rooting depths which agreed well with those observed in the field.

The general increase in the lateral root rate of extension and the decrease in the taproot rate of extension with time at temperatures greater than 17°C suggested that there was competition for carbohydrates between the taproot and lateral roots, the lateral roots evidently being the better competitor. However, the similar taproot and lateral root extension rates at 17°C indicated that at 17°C temperature was the limiting factor. The overall cultivar separation in the taproot and lateral root extension rates agreed with the cultivar separation reported by Kaspar et al. (1978) and Taylor et al. (1978).

Competition for available carbohydrate between the processes of root extension and primary root initiation was also suggested by the change in the number of primary nodes with depth and cultivar. It is postulated that the Beeson and Hawkeye 63 cultivars diverted more carbohydrate to the process of root extension than the Wayne and Harosoy 63 cultivars resulting in fewer primary laterals.

The agreement of the rooting depths predicted by the root growth simulation model with rooting depths observed in the field demonstrate the importance of soil temperature in determining the depth of soybean
root penetration and in extrapolating greenhouse root extension data to a field situation.

Collectively, the research performed in this dissertation shows that root-zone temperature plays a major role in the rate of soybean root extension.
GENERAL LITERATURE CITED


Jones, L. R., J. Johnson, and J. Dickson. 1926. Wisconsin studies upon the relation of soil temperature to plant disease. Wisc.


ACKNOWLEDGMENTS

I wish to thank Dr. H. M. Taylor, Dr. R. M. Cruse, Dr. P. N. Hinz, Dr. R. H. Shaw, and Dr. H. P. Johnson for serving on my graduate committee.

I am especially indebted to Dr. H. M. Taylor, my major advisor, and Dr. R. M. Cruse, who acted as my major advisor during Dr. Taylor's absence, for their help, advice, and support.

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A special thanks is extended to my wife, Rebecca, for her support and assistance throughout my Ph.D. program.
APPENDIX A: CONSTANT TEMPERATURE WATER BATH

Blueprints of the Water Bath
Figure A1. Side cross section of water bath
Figure A2. Top cross section of water bath
Temperature Gradient Data

Tables A1 through A4 are a composite of the temperature observations taken at 6 depths within the acrylic plant growth boxes for the first 2 replications of each of the 4 temperature treatments. The column headings are defined below.

Date — date of observation, month-day-year.
Time — time of observation.
Run — data is listed for 8 runs, 2 replications of each of the 4 temperature treatments.
AAT — average ambient air temperature (°C).
AWT — average water temperature (°C).
Surf — temperature at soil surface (°C).
2.5 — temperature at 2.5 cm below soil surface (°C).
5.0 — temperature at 5.0 cm below soil surface (°C).
7.5 — temperature at 7.5 cm below soil surface (°C).
10.0 — temperature at 10.0 cm below soil surface (°C).
15.0 — temperature at 15.0 cm below soil surface (°C).
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Table A1. Temperature gradients within the acrylic boxes at the 17°C treatment with varying ambient air temperatures
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| 31181 | 1515 | 6.0 32.0 17.4 21.4 19.3 18.4 17.9 17.6 17.4 |
| 101680 | 1345 | 2.0 30.3 17.2 21.4 18.9 18.5 18.0 18.6 17.4 |
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| 101780 | 1330 | 2.0 28.6 17.2 21.7 18.7 17.9 17.5 17.9 17.4 |
| 102080 | 1715 | 2.0 27.7 17.3 21.8 18.5 16.3 17.9 18.0 17.4 |
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| 101580 | 1430 | 2.0 28.3 17.4 23.3 18.5 18.2 17.8 17.9 17.4 |
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| 100780 | 1430 | 2.0 37.1 17.4 29.8 20.0 19.1 18.4 18.2 17.5 |
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Table A2. Temperature gradients within the acrylic boxes at the 21°C treatment with varying ambient air temperatures

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APPENDIX B: TAPROOT AND LATERAL ROOT RATE OF EXTENSION DATA

Taproot Data Statistical Analysis

Table Bl. Analysis of variance of the taproot rate of extension data. The "fast" cultivars are Beeson and Hawkeye. The "slow" cultivars are Harosoy and Wayne.

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<td>(31.68 )</td>
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<td>(.01 )</td>
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<td>(29.10)</td>
<td>(115.81)**</td>
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<td>(.48 )</td>
<td>( 1.91 )</td>
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<td>(10.31)</td>
<td>(41.03)**</td>
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<td>( 4.28)**</td>
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<td>( 55.42)</td>
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<td>( 1.28)</td>
<td>( 8.26)**</td>
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<td>( .35)</td>
<td>( 2.26)**</td>
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<td>( 1.58)</td>
<td>(10.15)**</td>
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* = significant at the .05 level.
** = significant at the .01 level.
Table B2. Analysis of variance of the taproot rate of extension data by temperature

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<tr>
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* = significant at the .05 level.
** = significant at the .01 level.
Lateral Root Data Statistical Analysis

Table B3. Analysis of variance of the rate of lateral root extension data

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** Significant at the .01 level.

Table B4. Comparison of regressions for Beeson and Hawkeye (F) vs. Harosoy and Wayne (S) cultivars for the rate (l') of lateral root extension data. The regression model used was l' = A + Bt + (C + Dt)T + ET^2, where A, B, C, D and E are constants, t time and T temperature

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<th>Source</th>
<th>df</th>
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<th>MS</th>
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<td>2.32</td>
<td>10.55**</td>
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<td>4.57</td>
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Table B5. Analysis of variance of the lateral root rate of extension data by temperature

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<td>5.47</td>
<td>1.82</td>
<td>8.27**</td>
</tr>
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<tr>
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* = significant at the .05 level.
** = significant at the .01 level.
Original Data

The original serial data which is presented in the following pages was recorded from the projected slides. The data are grouped by temperature treatments. Repetition refers to the block in time of which were 3. The time period refers to the order in which the treatments were applied within each repetition (block). The column headings are defined below.

BOX — the number of the acrylic box in which the plant was grown.
DAY — days after emergence.
TIME — time of observation.
DATE — date of observation, day-month-year.
HT — height of plant, measured from the soil surface to petiole.
GS — growth stage
COND CODE — Code which refers to the condition of the plant or error in making observation.

0 or blank — healthy plant
1 — chlorotic areas on leaves, no brown spots on edges, edges may be cupped.
2 — chlorotic areas on leaves, few brown spots on edges.
3 — chlorotic areas, brown spots on edges common.
4 — insect damage.
5 — physical damage to plant.
6 — deformed or notably stunted plant.
7 — mechanical problem with equipment which may have affected plant.

9n— Possible error in observation taken from projected slide, n refers to the root.
91 — ALAT1
92 — LAT2
93 — TAP
94 — LAT3
95 — ALAT4

ALAT1, LAT2, LAT3, ALAT4 — the x and y coordinates of the 4 lateral roots.
TAP — the x and y coordinates of the taproot.
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**TIME PERIOD - 2**

**TEMPERATURE - 17 C**

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| 6   | 7   | 1745 | 111100 | 9.5 | VC | 12.0 | 15.6 | 15.2 | 22.6 | 42.0 | 0.0 | 0.0 |
| 6   | 9   | 1645 | 111300 | 9.5 | V1 | 10.9 | 22.2 | 14.1 | 18.0 | 22.2 | 49.1 | 26.8 | 20.6 |
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| 6   | 17  | 1700 | 112100 | 17.0 | V3 | 9.3 | 49.8 | 14.2 | 39.9 | 23.5 | 70.2 | 27.5 | 44.1 |
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| 7   | 17  | 1700 | 112100 | 17.0 | V3 | 0.0 | 0.0 | 34.6 | 57.2 | 20.3 | 70.6 | 30.7 | 60.7 |
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TEMPERATURE - 21 C

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**Variety: Hawkeye**

**Temperature: 21°C**

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**Note:** The table contains data on various environmental conditions and measurements for different days and times.
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| 12  | 5   | 1730 | 040301 | 8.2 | VC |       | 0.0 | 0.0 | 0.0 | 19.9 | 34.8 | 0.0 | 0.0 | 0.0 |
| 12  | 7   | 1800 | 040501 | 10.5 | VC |       | 0.0 | 0.0 | 0.0 | 19.9 | 34.8 | 0.0 | 0.0 | 0.0 |
| 12  | 9   | 1815 | 040701 | 12.0 | V1 |       | 0.0 | 0.0 | 0.0 | 19.9 | 34.8 | 0.0 | 0.0 | 0.0 |
| 12  | 11  | 1815 | 040901 | 15.0 | V2 |       | 0.0 | 0.0 | 0.0 | 19.9 | 34.8 | 0.0 | 0.0 | 0.0 |
| 12  | 13  | 1815 | 041101 | 16.5 | V2 |       | 0.0 | 0.0 | 0.0 | 19.9 | 34.8 | 0.0 | 0.0 | 0.0 |
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| 12  | 17  | 1815 | 041501 | 23.5 | V4 |       | 0.0 | 0.0 | 0.0 | 19.9 | 34.8 | 0.0 | 0.0 | 0.0 |
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**TIME PERIOD - 3**

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**REPEITION - 3**

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**Time Period - 4**

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**REPLICATION - 3**

**TIME PERIOD - 2**

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| 10  | 7   | 0700 | 070281 | 7.3 | V1 | 0.0  | 0.0   | 6.1  | 29.0 | 21.4 | 51.8  | 0.0   |
| 10  | 9   | 0745 | 070461 | 8.5 | V1 | 0.0  | 0.0   | 6.7  | 40.0 | 22.0 | 63.4  | 25.7  |
| 10  | 11  | 0445 | 070661 | 11.5 | V2 | 0.0  | 0.0   | 4.8  | 50.1 | 22.2 | 72.5  | 26.6  |
| 10  | 13  | 0445 | 070881 | 14.0 | V3 | 0.0  | 0.0   | 3.5  | 60.7 | 21.6 | 82.5  | 26.3  |
| 10  | 15  | 0615 | 071081 | 17.0 | V4 | 3.5  | 66.6  | 5.0  | 71.0 | 23.0 | 91.7  | 25.1  |
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**PERIOD - 20°C**

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**TAP**

**LAT3**

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**VARIETY - WAYNE**

**REPEITION - 3**

**TIME PERIOD - 3**

**TEMPERATURE - 29 C**
FORTRAN Program

The following is a listing of the FORTRAN program used to transform original data to extension rates in cm/day.
C THIS PROGRAM CALCULATES THE RATE OF EXTENSION IN CM/DAY OF THE
C TAPROOT AND 4 LATERAL ROOTS. IT ALSO CALCULATES THE
C HORIZONTAL RATE OF EXTENSION (MOVEMENT ALONG THE X AXIS)
C OF THE TAPROOT AND 4 LATERAL ROOTS.
C
C THE MAJOR VARIABLES ARE DEFINED AS FOLLOWS:
C VARiev TP=TIME PERIOD (RUN). TMP=TEMPERATURE. BX=BOX.
C D Y= DAYS AFTER EMERGENCE. TI=TIME. DT=DATE. HT=PLANT HEIGHT.
C GSTAGE=GROWTH STAGE. ALI+L2+L3+AL4=THE X AND Y COORDINATES OF THE
C LATERAL ROOTS. THE "A" PREFIX DENOTES POSSIBLE ADVENTITIOUS ROOTS.
C TAPX AND Y COORDINATES OF THE TAPROOT. DXN(J) AND DYN(J)=THE
C X AND Y COMPONENT OF EXTENSION FROM DAY J-1 TO DAY J.
C DNL(J)=THE EXTENSION RATE FROM DAY J-1 TO DAY J.
C DXDTN(J)=THE HORIZONTAL RATE FROM DAY J-1 TO DAY J.
C T=TIME INCREMENT BETWEEN SAMPLING IN DAYS.
C NTPS=THE NUMBER OF TIME PERIODS. NBXS= THE NUMBER OF BOXES.
C
C GRAPH PRINTED IN COLUMNS 76-80 INDICATE CARDS ADDED TO FACILITATE
C USE OF SIMPLOT, A SYSTEM GRAPHING SUBROUTINE AT ISU.
C PUNCH PRINTED IN COLUMNS 76-80 INDICATE CARDS ADDED TO PUNCH
C OUTPUT.
C
C INTEGER TP,TMP,BX,DY,II,DT,CC
REAL ALI(2*10),L2(2*10),TAP(2,10),L3(2,10),AL4(2,10)
REAL XLI(5),LBI(5),LAB2(5),LAB3(5)
REAL XAS(5),LAS(5)
REAL XAS1(5),XAS2(5),XPI(5)
REAL LAS1(5),LAB2(5)
CHARACTERO VAR
CHARACTER GSTGE
COMMON/A/OY(10),TI(10),DT(10),HT(10),TP(10),TMP(10),BX(10),CC
COMMON/B/DL1(10),DL2(10),DL3(10),DL4(10),DL5(10)
COMMON/C/DX1(10),DX2(10),DX3(10),DX4(10),DX5(10),DY1(10),DY2(10),
DY3(10),DY4(10),DY5(10),AL1(10),AL2(10),AL3(10)
COMMON/D/VAR,GSTGE
COMMON/E/DXDT1(10),DXDT2(10),DXDT3(10),DXDT4(10),DXDT5(10)
COMMON/F/DR(10)
C
C READ IN NTPS AND NBXS TO SET UP DO LOOPS
C CALL ZEROS
READ(5,100)NTPS,NBXS
DO 15 NT=1,NTPS
READ(5,150)MLAB1,LAB2,LAB3
DO 10 NT=1,NBXS
WRITE(6,200)
WRITE(6,300)
CALL ZEROS
DO 5 J=1,10
READ(5,400)VAR,TP,TMP,BX,DY(J),TI(J),DT(J),GSTGE,CC,AL1(1:J),
AL2(1:J),L2(1:J),TAP(1:J),TAP(2:J),L3(1:J),L3(2:J),
...
CALL HTCORR
CALL PRINT
IF (J.EQ.1) GO TO 5
DX1(J)=AL1(1,J)-AL1(1,J-1)
DY1(J)=AL2(1,J)-AL2(1,J-1)
DX2(J)=L2(1,J)-L2(1,J-1)
DY2(J)=L2(2,J)-L2(2,J-1)
DX3(J)=TAP(1,J)-TAP(1,J-1)
DY3(J)=TAP(2,J)-TAP(2,J-1)
DX4(J)=L3(1,J)-L3(1,J-1)
DY4(J)=L3(2,J)-L3(2,J-1)
DX5(J)=AL4(1,J)-AL4(1,J-1)
DY5(J)=AL4(2,J)-AL4(2,J-1)
CALL CHECK
CALL TIME
DL1(J)=SORT(DX1(J)**2+DY1(J)**2)/T
DL2(J)=SORT(DX2(J)**2+DY2(J)**2)/T
DL3(J)=SORT(DX3(J)**2+DY3(J)**2)/T
DL4(J)=SORT(DX4(J)**2+DY4(J)**2)/T
DL5(J)=SORT(DX5(J)**2+DY5(J)**2)/T
DXDT1(J)=DX1(J)/T
DXDT2(J)=DX2(J)/T
DXDT3(J)=DX3(J)/T
DXDT4(J)=DX4(J)/T
DXDT5(J)=DX5(J)/T
CALL PRINT
5 CONTINUE
WRITE(6,500)
10 CONTINUE
WRITE(6,501)
15 CONTINUE
WRITE(6,502)
200 FORMAT(*VARIETY = VARIETY OF SOYBEAN PLANTED*)
FORMAT(5X,*'DAY = DAYS AFTER EMERGENCE*)
FORMAT(5X,*'TIME,DATE = DATE AND TIME DATA WAS COLLECTED*)
FORMAT(5X,*'HT = HEIGHT OF PLANT: SOIL SURFACE TO PETIOLE*)
FORMAT(5X,*'GSTGE = GROWTH STAGE OF PLANT*)
FORMAT(5X,*'CC = CODE OF PLANT CONDITION*)
FORMAT(5X,*'LAT1 - LAT2 = ELONGATION RATE OF 4 CHOSEN LATERAL ROOTS
 6 A PREFIX DENOTES POSSIBLE BASAL ROOT*)
FORMAT(5X,*'TAP = ELONGATION RATE OF TAP ROOT*)
FORMAT(5X,*'X1 - X5 = RATE OF HORIZONTAL MOVEMENT OF RESPECTIVE ROOT
  TO THE RIGHT(+) OR LEFT(-)*)
STOP
END
SUBROUTINE ZEROS*INITIALIZES THE ARRAYS CONTAINING THE RATES OF
EXTENSION (DXN(J)) AND THE ARRAYS CONTAINING THE HORIZONTAL
RATES OF EXTENSION (DXDTN(J)) BY FILLING THEM WITH ZEROS.
SUBROUTINE ZEROS
COMMON/E/DXDT1(10),DXDT2(10),DXDT3(10),DXDT4(10),DXDT5(10)
DO 10 J=1,10
  DL1(J)=0.
  DL2(J)=0.
  DL3(J)=0.
  DL4(J)=0.
  DL5(J)=0.
  DXDT1(J)=0.
  DXDT2(J)=0.
  DXDT3(J)=0.
  DXDT4(J)=0.
  DXDT5(J)=0.
CONTINUE
RETURN
END
SUBROUTINE PRINT*PRINTS AND PUNCHES CALCULATED VALUES.
SUBROUTINE PRINT
CHARACTER8 VAR
CHARACTER=2 GSTGE
INTEGER TP,TMP,BX,DT,CC
COMMON/A/DY(10),TI(10),HT,TP,TMP,BX,CC
COMMON/B/DL1(10),DL2(10),DL3(10),DL4(10),DL5(10)
COMMON/VAR,GSTGE
COMMON/E/DXDT1(10),DXDT2(10),DXDT3(10),DXDT4(10),DXDT5(10)
WRITE(6,500) VAR,TP,TMP,BX,DY(J),TI(J),HT,GSTGE,CC,
  6DL1(J),DXDT1(J),DL2(J),DXDT2(J),DL3(J),DXDT3(J),DL4(J),DXDT4(J),
  6DL5(J),DXDT5(J)
WRITE(7,600) VAR,TP,TMP,BX,DY(J),HT,GSTGE,CC,
  7DL1(J),DXDT1(J),DL2(J),DXDT2(J),DL3(J),DXDT3(J),DL4(J),DXDT4(J),
  7DL5(J),DXDT5(J)
500 FORMAT(9*I4) PUNCH
500 FORMAT(9*F4.1) PUNCH
RETURN
END
SUBROUTINE "TIME" calculates the number of days between sampling times for use in calculation of the rates of extension in cm/day.

Note that this subroutine converts minutes to hundredths, i.e., 1715 is converted to 1725.

```fortran
SUBROUTINE TIME
INTEGER TP, TMP, BX, DY, TI, DT, HT, TP, TMP, BX, J, CC
COMMON/A/DY(10), TI(10), DT, HT, TP, TMP, BX, J, CC
COMMON/0/VAR, GSTGE
CHARACTER*8 VAR
CHARACTER*2 GSTGE
DAYS=(DY(J)-DY(J-1))/2400-2400
LTRUNC=TI(J-1)/100./100.
MTRUNC=TI(J)/100./100.
FRAC1=(TI(J-1)-LTRUNC)/60.*100.
FRAC2=(TI(J)-MTRUNC)/60.*100.
CT1=(FLOAT(LTRUNC)+FRAC1)
CT2=(FLOAT(MTRUNC)+FRAC2)
T=((2400.-CT1)*CT2+DAYS)/2400.
RETURN
END
```

SUBROUTINE "CHECK" checks and makes corrections for missing data which would result in errors in calculation of extension rates by interpreting the missing data as a zero coordinate.

```fortran
SUBROUTINE CHECK
REAL AL1(2,10), L2(2,10), TAP(2,10), L3(2,10), AL4(2,10)
COMMON/A/DY(10), TI(10), DT, HT, TP, TMP, BX, J, CC
COMMON/O/VAR, GSTGE
DIMENSION OOR(10)
OOR(L)=FLOAT(DY(L))
10 CONTINUE
```

SUBROUTINE "REALDY" puts the values for the day (DY(J)) into a real array and adds a factor to position the point facilitating the use of the SIMPLOT graphing subroutine.

```fortran
SUBROUTINE REALDY
INTEGER TP, TMP, BX, DY, TI, DT, CC
COMMON/A/DY(10), TI(10), DT, HT, TP, TMP, BX, J, CC
COMMON/F/DR(10)
DIMENSION OOR(10)
DO 10 L=1,10
OOR(L)=FLOAT(DY(L))
10 CONTINUE
```
DR(1)=1
DO 20 K=2,10
DR(K)=DDR(K-1)+(DDR(K)-DDR(K-1))/2
20 CONTINUE
RETURN
END

SUBROUTINE HTCORR
COMMON/A/DY(10),TI(10),DT,T,HT,TP,TMP,BX,J,CC
IF(TP.EQ.3.AND.T(J).LE.7)HT=HT-.75
IF(TP.EQ.3.AND.T(J).GE.9)HT=HT-2.0
IF(TP.GE.4)HT=HT-2.0
IF(TP.GE.5)HT=HT-2.5
RETURN
END

DATA CARDS
$STOP
C JOB CONTROL CARDS FOR SIMPLOT GRAPHING SUBROUTINE.
//GO..F14.0 .DO DSNAME=6SM.UNIT=SCRATCH.DISP=(NEWPASS).
//SPACE=(600),(120.15).DCE=(RECFM=VB..LRECL=796..BLKSIZE=800)
//SMPLTTR EXEC PLOT, PLOTTER=PRINTER
Transformed Data

The original serial data which was transformed to rates in cm/day are presented in the following pages. The data are grouped by temperature treatments. Repetition refers to the block in time of which there were 3. The time period refers to the order in which the treatments were applied within each repetition (block). The column headings are defined below.

BOX — the number of the acrylic box in which the plant was grown.
DAY — days after emergence.
HT — height of plant measured from the soil surface to petiole.
GS — growth stage.
ALAT1, LAT2, LAT3, ALAT4 — the extension rates in cm/day for the lateral roots. This is the average rate from day j-1 to day j.
TAP — the extension rate in cm/day for the taproot.
X1, X2, X3, X4, X5 — the horizontal extension rate from day j-1 to day j for ALAT1, LAT2, TAP, LAT3, and ALAT4, respectively. "+" or "-" indicate the direction of extension on a rectangular coordinate system.
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| 7   | 3   | 4.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
| 7   | 5   | 5.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
| 7   | 7   | 6.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 1.0 | 0.1 | 0.0  | 0.0 | 0.0  | 0.0 |
| 7   | 9   | 6.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.3 | 0.1 | 0.0  | 0.0 | 0.0  | 0.0 |
| 7   | 11  | 10  | V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.3 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
| 7   | 13  | 10  | V/ | 1.0 | 0.0 | 0.0  | 0.0 | 2.1 | 0.3 | 0.0  | 0.0 | 0.0  | 0.0 |
| 7   | 15  | 12  | V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.2 | 0.1 | 0.0  | 0.0 | 0.0  | 0.0 |
| 7   | 17  | 14  | V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.2 | 0.1 | 0.0  | 0.0 | 0.0  | 0.0 |

| 12  | 1   | 2.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 0.0 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
| 12  | 3   | 4.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.6 | 0.2 | 0.0  | 0.0 | 0.0  | 0.0 |
| 12  | 5   | 6.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.4 | 0.2 | 0.0  | 0.0 | 0.0  | 0.0 |
| 12  | 7   | 7.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.0 | 0.2 | 0.0  | 0.0 | 0.0  | 0.0 |
| 12  | 9   | 9.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.1 | 0.1 | 0.0  | 0.0 | 0.0  | 0.0 |
| 12  | 11  | 11.5| V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.5 | 0.2 | 0.0  | 0.0 | 0.0  | 0.0 |
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| 12  | 15  | 13  | V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.9 | 0.4 | 0.0  | 0.0 | 0.0  | 0.0 |
| 12  | 17  | 14  | V/ | 0.0 | 0.0 | 0.0  | 0.0 | 2.3 | 0.1 | 0.0  | 0.0 | 0.0  | 0.0 |

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**VARIETY - HAWKEYE**

**REPLICATION - 1**

**TIME PERIOD - 3**

**TEMPERATURE - 21°C**

*Note: The table contains data for various parameters measured in the experiment.*
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| 3   | 14  | 15.5| V3 | 0.0  | 0.0 | 0.0  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
| 3   | 16  | 17.0| V3 | 0.0  | 0.0 | 0.0  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
| 3   | 18  | 19.0| V4 | 0.0  | 0.0 | 0.0  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
| 3   | 20  | 20.0| V4 | 0.0  | 0.0 | 0.0  | 0.0 | 0.0 | 0.0  | 2.2  | 0.0 | 0.0   | 0.0 |

| 4   | 1   | 4.5 | VE | 5.0  | 0.0 | 0.0  | 0.0 | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
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| 4   | 23  | 25.0| V4 | 0.0  | 0.0 | 3.7  | 0.0  | 0.0 | 0.0  | 0.0 | 0.0  | 0.0 |
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TIME PERIOD - 1
TEMPERATURE - 21 C
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**VARIETY** - HARCSDY

**REPETITION** - 1

**TIME PERIOD** - 4

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**Note:** The table above shows the percentage of a certain substance or condition at different temperatures. The values are constant across all temperatures indicated, suggesting a stable or non-temperature-dependent characteristic.
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**VARIETY - DEESON**
**REPLICATION - 2**
**TEMPERATURE - 25°C**

**TIME PERIOD - 4**
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**Variety: Wayne**

**Replication: 2**

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**TEMPERATURE - 29 C**

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| 11  | 9   | 11.5| VI | 0.0  | 0.0 | 4.4    | -0.6| 4.4  | 0.0 | 2.8  | -0.5| 4.1    | -0.4|
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APPENDIX C: FREQUENCY OF PRIMARY NODES DATA

Primary Node Data Statistical Analysis

Table Cl. Analysis of variance of the frequency of primary nodes data for depth 0-2.5 cm, 2.5-7.5 cm, 7.5-12.5 cm and 12.5-17.5 cm

<table>
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<th>F</th>
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<td>139.36</td>
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<td>11.91**</td>
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* = significant at the .05 level.

** = significant at the .01 level.
Table C2. Analysis of variance of the frequency of primary node data by depth

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</tr>
<tr>
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</tr>
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<td>.35</td>
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<td>.26</td>
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* = significant at the .05 level.
** = significant at the .01 level.
Table C3. Comparison of regressions for Beeson and Hawkeye (F) vs. Harosoy and Wayne (S) cultivars by depth for the primary node data. The regression model used was \( y = A + Bt + (C + Dt)T \) where \( A, B, C, \) and \( D \) are constants; \( t \) is time; and \( T \) temperature and depth.

<table>
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<th>Depth</th>
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<td>(134.05)</td>
<td>(134.05)</td>
<td>(176.38)**</td>
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<td>( 4.78)</td>
<td>( 6.29)**</td>
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<td>(105.27)</td>
<td>( 34.42)</td>
<td>( 45.29)**</td>
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<td>( 2.31)</td>
<td>( 3.04)</td>
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<td>(194.22)</td>
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<td>( 8.88)</td>
<td>( 2.24)</td>
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<td>( 74.32)</td>
<td>( 24.77)</td>
<td>( 8.04)**</td>
</tr>
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<td>(6)</td>
<td>(122.48)</td>
<td>( 20.41)</td>
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<td>11.08**</td>
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<td>( 41.81)</td>
<td>( 41.81)</td>
<td>( 32.16)**</td>
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<td>( 70.79)</td>
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<td>( 1.13)</td>
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<td>39.42</td>
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<td>( 33.34)</td>
<td>( 33.34)</td>
<td>( 39.32)**</td>
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<td>( 1.64)</td>
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<td>( 40.02)</td>
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</table>

** = Significant at the .01 level.
Primary Node Data

The original serial primary node data which was recorded from projected slides are presented in the following pages. The data are grouped by temperature treatments. Repetition refers to the block in time of which there were 3. The time period refers to the order in which the treatments were applied within each repetition (block). The column headings are defined below.

BOX — the number of the acrylic box in which the plant was grown.
DAY — days after emergence.
HT — height of plant, measured from the soil surface to petiole.
GS — growth stage.
5 through 60 — indicates the depth increment in which the primary nodes were counted measured from the top of the acrylic box. The soil surface was at 2.5 cm. For example, 5 represents the number of primary nodes in the top 0-5 cm of the acrylic box. Since the soil surface is 2.5 cm below the top, this represents the top 2.5 cm of vermiculite. A primary node was counted if the primary lateral was greater than or equal to 5 cm.
NOTES — Comments pertinent to the data.
### VARIETY - HAWKNE
#### REPEITION - 3
#### TIME PERIOD - 6
#### TEMPERATURE - 17°C

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### VARIETY - WAYNE

**REPETITION - 2**

**TIME PERIOD - 1**

**TEMPERATURE - 29°C**

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TEMPERATURE - 29°C
## APPENDIX D: DRY WEIGHT DATA

### Dry Weight Data Statistical Analysis

Table D1. Analysis of variance of the root dry weight data

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<td>1.81</td>
<td>0.60</td>
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<td>SK x T</td>
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<td>1.46</td>
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<tr>
<td>Cultivar(C)</td>
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<td>0.08</td>
<td>0.03</td>
<td>4.44**</td>
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Table D2. Analysis of variance of the top dry weight data

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<td>12.86**</td>
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Dry Weight Data

Table D3 lists the dry weight data. Each value represents the average of 3 plants. The data are listed by cultivars (varieties) for each of the 12 runs (run = TP). Basal roots were defined as roots greater than 5 cm emerging from the hypocotyl. The large laterals (LGLAT) were defined as lateral roots greater than 15 cm. The taproot (TAP WT) was the root below the hypocotyl minus the basal (BASAL WT) and large laterals (LGLAT WT).
### Table D3. Dry Weight Data

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<th>VARIETY</th>
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<th>TP</th>
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<th>AVERAGE</th>
<th>AVERAGE</th>
<th>TOP/GOT</th>
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<td>LGAL WT</td>
<td>TAP WT</td>
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| BEESCN  | 17   | 2  | 0.5111  | 0.0097  | 0.3637  | 0.0566  | 4.114   | 0.1241  |
| HAROSOY | 17   | 2  | 0.7208  | 0.0285  | 0.2066  | 0.0851  | 3.002   | 0.2421  |
| MAWKeye | 17   | 2  | 0.4794  | 0.0095  | 0.0590  | 0.0712  | 3.432   | 0.1297  |
| WAYNE   | 17   | 2  | 0.6056  | 0.0152  | 0.1128  | 0.1077  | 2.369   | 0.2256  |

| BEESCN  | 21   | 3  | 1.1050  | 0.0590  | 0.2279  | 0.1001  | 2.855   | 0.3270  |
| HAROSOY | 21   | 3  | 1.3031  | 0.0664  | 0.2521  | 0.0686  | 3.051   | 0.4271  |
| MAWKeye | 21   | 3  | 1.1891  | 0.0462  | 0.2274  | 0.1102  | 3.046   | 0.3836  |
| WAYNE   | 21   | 3  | 1.2273  | 0.0290  | 0.2152  | 0.1127  | 2.517   | 0.5022  |

| BEESCN  | 25   | 4  | 1.6600  | 0.3009  | 0.2146  | 0.0864  | 4.975   | 3.3344  |
| HAROSOY | 25   | 4  | 1.6816  | 0.0955  | 0.2232  | 0.0515  | 4.841   | 0.3742  |
| MAWKeye | 25   | 4  | 1.4602  | 0.0320  | 0.2329  | 0.0753  | 4.244   | 0.3401  |
| WAYNE   | 25   | 4  | 1.5279  | 0.0686  | 0.2247  | 0.0501  | 3.546   | 0.4134  |
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<th>AVERAGE LCLAT WT</th>
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<tr>
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<td>0.0326</td>
<td>0.2304</td>
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<td>0.2063</td>
<td>0.0976</td>
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<td>0.0329</td>
<td>0.2501</td>
<td>0.1064</td>
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</table>
APPENDIX E: COMPUTER SIMULATION OF SOYBEAN ROOT GROWTH

FORTRAN Program

The following is a listing of the root growth simulation model based on temperature.
THIS FORTRAN PROGRAM IS A COMPUTER SIMULATION OF
SOYBEAN ROOT GROWTH BASED ON THE
RESPONSE TO CONSTANT ROOT-ZONE TEMPERATURES. THE TEMPERATURE
RESPONSE DATA IS PRESENTED BY STONE AND TAYLOR (1981). THE
PURPOSE OF THE MODEL IS TO ILLUSTRATE THE IMPORTANCE OF ROOT-ZONE
TEMPERATURES ON SOYBEAN ROOT DEVELOPMENT.

STONE, J.A. AND H.M. TAYLOR. 1982. THE EFFECT OF TEMPERATURE ON
TAPROOT AND LATERAL ROOT DEVELOPMENT OF SOYBEANS.
AGRON.J.

NDSG= THE NUMBER OF DAYS GROWTH. CULT= CULTIVAR.1=BEESON AND
HAWKEYE.2=HAROS0Y AND WAYNE. TI=THE TIME INCREMENT OF GROWTH IN
DAYS. T=TEMPERATURE(C). DAY=_DAYS AFTER PLANTING.
TAPD=DEPTH OF TAPROOT. THE INITIAL VALUE OF TAPD IS THE PLANTING
DEPTH WHICH IS STORED AS PDPTH. THE REMAINING VARIABLES ARE
DEFINED IN THE SUBROUTINES IN WHICH THEIR VALUES ARE
CALCULATED.

INTEGER CULT
REAL LAT,NDSG
COMMON /TAP(Z,100),LAT(10,2,100),DY(100)
COMMON DAY
DATA T,GERM,DAY/0.0,0.0,0.0/
CALL ZEROS
WRITE(6,200)
WRITE(6,300)
READ(5,100) NDSG,CULT,TAPD, TI
PDPTH=TAPD
10 DAY=DAY+TI
CALL TEMP(DAY,TAPD,T)
CALL EMERGE(T,TI,TAPD,GERM)
WRITE(6,400) DAY,T,TAPD,GERM
IF(GERM.LT.95.0)GO TO 10
WRITE(6,500)
TAP(2,1)=TAPD
NDSG=NDSG-DAY
DY(1)=1.0
INT=IFIX(NDSG)
DO 20 J=2,INT
DY(J)=J
CALL TAPRAT(J,TI,CULT)
IF(J.LE.19)CALL NNODE(J,PDPTH,CULT)
CALL LATRAT(J,T,CULT,T)
20 CONTINUE
CALL PRINT
CALL RTPLOT
100 FORMAT(F4.0,F4.1,F3.1)
200 FORMAT("1"*10X,"DAY"*10X,"TEMP"*10X,"TAPDEPT"*10X,"GERM")
300 FORMAT("0")
400 FORMAT("*"*10X,F2.0,12X,F3.0,13X,F4.1,11X,F5.1)
500 FORMAT("1")
STOP
END

C

SUBROUTINE TEMP DETERMINES THE TEMPERATURE AT ANY DEPTH AND
C TIME.
C DDY= DAY(RELATIVE TIME COUNTER). DEPTH= DEPTH. T= TEMPERATURE (C).
C
SUBROUTINE TEMP(DDY,DEPTH,T)
COMMON/E/DAY
TY=DDY+DAY
T=19.7*(.192*CTY)-(.057*DEPTH)+((.00000536*DEPTH)
   -.00224)*TY+.057*DEPTH
RETURN
END

C

SUBROUTINE EMERGE DETERMINES THE DEPTH OF THE TAPROOT AT EMERGENCE.
C THIS IS ACCOMPLISHED BY SUMMING THE PERCENT THAT TI DAYS GROWTH
C IS OF THE TOTAL TIME TO EMERGENCE UNTIL IT IS > 95%.
C DTG=DAYS TO EMERGENCE. PERC=PERCENT THAT TI DAYS GERMINATION IS OF
C THE TOTAL TIME TO EMERGENCE. GERM= SUMMATION OF PERCENT FOR EACH
C TI. DE=DEPTH OF THE ROOT TIPS BELOW PLANTING DEPTH AT THE TIME
C OF EMERGENCE. TAPEXT=THE VERTICAL EXTENSION OF THE PRE-
C EMERGENCE TAPROOT FOR TI DAYS GROWTH AT THE GIVEN
C TEMPERATURE.
C
SUBROUTINE EMERGE(T,TI,TAPD,GERM)
DTG=9.72 -.23*TI
PERC=(TI/DTG)*100.
GERM=GERM + PERC
DE=2.10+(.54*TI)
TAPEXT=(DE/DTG)*TI
TAPD=TAPD + TAPEXT
RETURN
END

C

SUBROUTINE ZEROS Initializes TAP(2,100). LAT(10,2,100). AND DY(100).
C BY FILLING THEM WITH ZEROS.
C
SUBROUTINE ZEROS
INTEGER*4 TN, TN1, TN2, TN3
COMMON/A/ TAP(2,100), LAT(10,2,100), DY(100)
COMMON/B/NODES(3,25)
COMMON/C/LTN, TN1, TN2, TN3
COMMON/D/RAD
DATA TN, LTN, TN1, TN2, TN3/O, 0, 0, 0, 0/
DO 20 I = 1, 2
DO 10 J = 1, 100
TAP(I,J) = 0.
10 CONTINUE
20 CONTINUE
DO 50 I = 1, 10
DO 40 J = 1, 2
DO 30 K = 1, 100
LAT(I,J,K) = 0.
30 CONTINUE
40 CONTINUE
50 CONTINUE
DO 60 I = 1, 100
DY(I) = 0.
60 CONTINUE
DO 80 I = 1, 3
DO 70 J = 1, 25
NODES(I,J) = 0.
70 CONTINUE
80 CONTINUE
RAD = 0.
RETURN
END

C SUBROUTINE PRINT PRINTS OUT THE DAYS AFTER EMERGENCE AND THE C COORDINATES OF THE ROOT TIPS STORED IN DY(100), TAP(2,100), C AND LAT(10,2,100) RESPECTIVELY.
C
SUBROUTINE PRINT
REAL C: LAT
COMMON/A/ TAP(2,100), LAT(10,2,100), DY(100)
WRITE(6,100)
WRITE(6,200)
WRITE(6,300)
DO 10 L = 1, 100
WRITE(6,400) DY(L), TAP(L,1), TAP(L,2), LAT(L,1), LAT(L,2), LAT(L,3), LAT(L,4), LAT(L,5), LAT(L,6), LAT(L,7), LAT(L,8), LAT(L,9), LAT(L,10)
10 CONTINUE
WRITE(6,500)
100 FORMAT('1*40X*RECTANGULAR COORDINATES OF THE ROOT TIPS*)
200 FORMAT('1*12X*DAY*7X*TAP*7X*LAT1*6X*LAT2*6X*LAT3*6X*LAT4*6X*LAT5*6X*LAT6*6X*LAT7*6X*LAT8*6X*LAT9*6X*LAT10')
300 FORMAT('0*)
400 FORMAT('1*11X*F5.1*3X*11(F4.1*,*,F5.1))
500 FORMAT('*:*')
SUBROUTINE TAPRAT CALCULATES THE RATE OF EXTENSION FOR THE TAPROOT AND DETERMINES ITS COORDINATES. THE RATE FOR DAY J IS BASED ON THE TEMPERATURE AT THE ROOT TIP ON DAY J-1.

\[ \text{TRATE} = \text{THE TAPROOT RATE OF EXTENSION. } \]
\[ \text{TAPEXT} = \text{TAPROOT EXTENSION IN CM FOR } \text{TI DAYS.} \]

SUBROUTINE TAPRAT(J, TI, CULT)
COMMON/A/ TAP(2, 100), LAT(10, 2, 100), DY(100)
INTEGER*4 CULT
CALL TEMP(DY(J-1), TAP(2, J-1), T)
D = FLOAT(T)
IF(DGT.19) D = 19.
IF(CULT .EQ. 2) TRATE = -11.0579 + (1.0136 - 0.01468.T) + T - 0.0140692
IF(CULT .EQ. 1) TRATE = -14.6974 + (0.3202 - 0.01260.T) + T - 0.01990902
TAPEXT = TRATE * TI
CALL RESIST(J, TORT)
IF(J .NE. 2) GO TO 10
TAP(1, J-1) = TORT
TAP(2, J) = TAP(2, J-1) * SQRT(TAPEXT * 2 - TORT * 2)
TAP(1, J) = TORT + TAP(1, J-1)
RETURN
END

SUBROUTINE RESIST(J, TORT)
INTEGER*4 IR(100), K, NR
DOUBLE PRECISION DSEED
DATA K, NR / 50, 100 /
CALL CLOCK(IC)
DSEED = IC
CALL GGUD(DSEED, K, NR, IR)
LTRUNC = IR(J) / 2
IF(FLOAT(LTRUNC) .LT. FLOAT(IR(J)) / 2.) DIR = 1.
IF(FLOAT(LTRUNC) .EQ. FLOAT(IR(J)) / 2.) DIR = -1.
TORT = 50 * DIR
RETURN
SUBROUTINE NNODE DETERMINES THE NUMBER OF NODES IN A GIVEN DEPTH INCREMENT AND BY CALLING NEWNDS DETERMINES THE DEPTH AT WHICH THE NODE APPEARS.

NODES(K,J) = THE NUMBER OF NODES IN THE K DEPTH INCREMENT AT DAY J.

O(N) = THE MEAN DEPTH OF THE INCREMENT. TNN = THE TOTAL NUMBER OF NODES. NN(K) = A LIMIT ON THE NUMBER OF NODES WHICH CAN APPEAR IN ANY DEPTH INCREMENT. K = A COUNTER CORRESPONDING TO THE NUMBER OF DEPTH INCREMENTS. ADPTH = THE TEMPERATURE IN THE MIDDLE OF THE DEPTH INCREMENT.

SUBROUTINE NNODE(J,PDEPTH,CULT)
COMMON/A/ TAP(2,100),LAT(10,1,2,100),DY(100)
COMMON/B/NODES(3,25)
INTEGER*4 TNN,CULT,NNO,TN
REAL*4 D(3),LAT,DIRECT*10)
DATA 0<1),0(2),043)/-1.25=2.5=7.5/
DATA NN(l),NN(t),NN(3)/2.6,2/
DO 10 K=1,3
ADPTH=PDEPTH+D(K)
CALL TEMP(DY(J),ADPTH,T)
S=FLOAT(J)
IF(D(K).EQ.1.25.AND.CULT.EQ.1)NODES(K,J)=-73+(.1805)*
6(.03-(.003*S))*T
IF(D(K).EQ.1.25.AND.CULT.EQ.2)NODES(K,J)=-24+(.0105)*
6(.03-(.003*S))*T
IF(D(K).EQ.2.5.AND.CULT.EQ.1)NODES(K,J)=-6.93+(1.62-(.0205))*S+
6(.27-(.0375))*T
IF(D(K).EQ.2.5.AND.CULT.EQ.2)NODES(K,J)=-8.02+(2.22-(.0305))*S+
6(.31-(.0555))*T
IF(D(K).EQ.7.5.AND.CULT.EQ.1)NODES(K,J)=-2.70+(.6805)*
6(.10-(.0205))*T
IF(D(K).EQ.7.5.AND.CULT.EQ.2)NODES(K,J)=-3.27+(1.1105)*
6(.10-(.0405))*T
IF(NODES(K,J).GT.NN(K))GO TO 5
IF(NODES(K,J).EQ.NODES(K,J-1))GO TO 10
IF(NODES(K,J).LT.NODES(K,J-1))GO TO 10
CALL NEWNDS(J,K,PDEPTH)
GO TO 10
5 NODES(K,J)=NN(K)
10 CONTINUE
RETURN
END
C J-1. TN=THE SUMMATION OF THE TOTAL NUMBER OF NODES.
C TNK=THE SUMMATION OF THE TOTAL NUMBER OF NODES FOR DEPTH
C INCREMENT K=1, 2, OR 3. LTN=THE SUMMATION OF THE TOTAL
C NUMBER OF NODES FOR DAY J-1.
C
SUBROUTINE NEWNOS(J,K,PDPTH)
COMMON/A/ TAP(2,100),LAT(10,2,100),DY(100)
COMMON/B/NODES(3,25)
COMMON/C/TN,LTN,TN1,TN2,TN3
INTEGER K1,K2,NR,N,C1,C2,C3,C4
REAL LAT
DOUBLE PRECISION DSEED,ESEED
DATA K1,K2,NR/24,50,100/
CALL CLOCK(IC)
CALL CLOCK(KC)
DSEED=1C
ESEED=KC
LTNN=NODES(K,J-1)
TNN=NODES(K,J)
IF(NODES(2,J).GT.0)TN2=NODES(2,J)
IF(NODES(3,J).GT.0)TN3=NODES(3,J)
IF(NODES(1,J).GT.0)TN1=NODES(1,J)
TN=TN1+TN2+TN3
LTN=TN-(TNN-LTNN)
N=LTN+1
DO 20 I=N,TN
20 IF(K.GT.I)GO TO 9
CALL GGUD(DSEED,IC,NR,IR)
LAT(I,2,J-1)=PDPTH*FLOAT(IR(J))/10.
GO TO 15
9 CONTINUE
CALL GGUD(ESEED,K2,NR,IR)
IF(K.EQ.2)LAT(I,2,J-1)=PDPTH+FLOAT(IR(J))/10.
IF(K.EQ.3)LAT(I,2,J-1)=PDPTH+5.+FLOAT(IR(J))/10.
15 DIRECT(I)=1.
20 CONTINUE
RETURN
END

C SUBROUTINE LATRAT CALCULATES THE RATE OF EXTENSION FOR EACH
C OF THE LATERAL ROOTS AND DETERMINES ITS COORDINATES.
C IT ALSO SETS THE MINIMUM LENGTH A LATERAL ROOT MUST
C GROW BEFORE IT IS ALLOWED TO TURN DOWNWARD.
C LRATE=THE LATERAL ROOT RATE OF EXTENSION (CM/DAY).
C LATEXT=THE AMOUNT OF LATERAL ROOT EXTENSION (CM)
C FOR TI DAYS.
C SAVE=A VARIABLE USED FOR TEMPORARILY STORING RAD.
C L=THE NUMBER OF THE LATERAL ROOT FOR WHICH EXTENSION
C IS BEING CALCULATED.
C
SUBROUTINE LATRAT(J,TI,CULT,T)
COMMON/A/ TAP(2,100),LAT(10,2,100),DY(100)
COMMON/C/TN,LTN,TN1,TN2,TN3
COMMON/D/RAD
INTEGER T,N,CULT
REAL LAT, LATEXT, LRATE, LAT
IF(T.N.EQ.0) RETURN
DO 10 L=1,TN
CALL TEMP(DY(J), LAT(L,2,J-1), T)
CALL ANGLE(J,T,L,RAD2)
E=FLOAT(J)
IF(E.GT.19.)E=19.
IF(CULT.EQ.1) LRATE=-13.2367+(1.1237*E)+(1.08-(.0036*E)*T
6-(.0155*T**0.2)
IF(CULT.EQ.2) LRATE=-11.4948+(.0854*E)*T
6-(.0168*T**0.2)
CALL RESIST(J,TORT)
LATEXT=LRATE*T1
SAVE=RA0
IF(LAT(L,1,J-1).LT.7.5) RAD=RA02
M=J-1
DO 5 KK=1,M
IF(LAT(L,1,KK).GE.7.5) RAD=SAVE
5 CONTINUE
LAT(L,1,J)=LAT(L,1,J-1)+(LATEXT*COS(RAD)*TORT
LAT(L,2,J)=LAT(L,2,J-1)+(LATEXT*SIN(RAD)*TORT
RAD=SAVE
10 CONTINUE
RETURN
END

C
C SUBROUTINE ANGLE DETERMINES THE ANGLE THAT THE LATERAL ROOT
C GROWS AT AND WHEN IT TURNS DOWNWARD.
C RAD=THE ROOTING ANGLE MEASURED FROM THE HORIZONTAL IN RADIANS.
C RAD2=RAD2, IT IS USED TO DETERMINE THE ROOTING ANGLE
C OF THE LATERALS WHICH EMERGE AFTER PRECEDING LATERALS
C HAVE TURNED DOWNWARD, IE. WHEN RAD=1.5708.
C TRNDWN=THE HORIZONTAL DISTANCE AT WHICH THE LATERAL ROOTS TURN
C DOWNWARD MEASURED FROM THE TAPROOT.
C
C SUBROUTINE ANGLE(J,T,L,RAD2)
COMMON/A/ TAP(2,100)*LAT(10,2,100)*DY(100)
COMMON/D/RAD
REAL LAT
IF(RAD.EQ.1.5708) GO TO 10
IF(T.LT.15.) TRNDWN=7.8
IF(15.LE.T.AND.T.LE.27.) TRNDWN=-38.7+3.1*T
IF(T.GT.27.) TRNDWN=45.
IF(T.LE.21.) RAD1=1.933+.008*T
IF(T.GT.21.) RAD2=4336-.0034*T
IF(LAT(L,1,J-1).GT.TRNDWN) RAD=1.5708
10 IF(T.LE.21.) RAD2=1.933+.008*T
IF(T.GT.21.) RAD2=4334-.0034*T
RETURN
END

C
C SUBROUTINE RTPLOT PLOTS THE COORDINATES OF THE ROOT TIPS BY UTILIZING
C SIMPLOT, A SYSTEM PLOTTING SUBROUTINE AT ISU.
SUBROUTINE RTPLOT
COMMON/A/ TAP(2,100), LAT(10,2,100), DY(100)
REAL TPX(100), LX1(100), LX2(100), LX3(100), LX4(100),
    LX5(100), LX6(100), LX7(100), LX8(100), LX9(100), LX10(100),
    TPY(100), LY1(100), LY2(100), LY3(100), LY4(100),
    LY5(100), LY6(100), LY7(100), LY8(100), LY9(100), LY10(100),
    LAT
DO 10 J=1,100
   TPX(J)=TAP(1, J)
   TPY(J)=TAP(2, J)
   LX1(J)=LAT(1, 1, J)
   LX1(J)=LAT(1, 2, J)
   LX2(J)=LAT(2, 1, J)
   LX2(J)=LAT(2, 2, J)
   LX3(J)=LAT(3, 1, J)
   LX3(J)=LAT(3, 2, J)
   LX4(J)=LAT(4, 1, J)
   LX4(J)=LAT(4, 2, J)
   LX5(J)=LAT(5, 1, J)
   LX5(J)=LAT(5, 2, J)
   LX6(J)=LAT(6, 1, J)
   LX6(J)=LAT(6, 2, J)
   LX7(J)=LAT(7, 1, J)
   LX7(J)=LAT(7, 2, J)
   LX8(J)=LAT(8, 1, J)
   LX8(J)=LAT(8, 2, J)
   LX9(J)=LAT(9, 1, J)
   LX9(J)=LAT(9, 2, J)
   LX10(J)=LAT(10, 1, J)
   LX10(J)=LAT(10, 2, J)
10 CONTINUE
CALL GRAPH(100, TPY, TPX, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY1, LX1, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY2, LX2, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY3, LX3, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY4, LX4, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY5, LX5, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY6, LX6, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY7, LX7, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY8, LX8, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY9, LX9, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL GRAPH(100, LY10, LX10, 0.4, 12, 0.6, 0, 20.0, 0, 20.0, -60.0,
   6*DEPTH (CM); WIDTH (CM);)
CALL LETTERS(1, 0, 2, 125, 'SEASON AND HAYEYE 63; *, 90; 0; 21)
CALL LETTERS(1, 25, 2, 125, 'CULTIVARS; *, 90; 0; 9)
RETURN
END
Example of Output from FORTRAN Program

Tables E1 and E2 are copies of the computer printout produced by the root growth simulation model. The column headings are defined below.

DAY — number of days after emergence.
TAP — the rectangular coordinates of the taproot. The x and y coordinates are separated by a comma.
LAT1 through LAT10 — the rectangular coordinate of 10 separate lateral roots. The x and y coordinates are separated by a comma.
<table>
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<tr>
<th>DAY</th>
<th>TAP</th>
<th>LATT</th>
<th>LATT2</th>
<th>LATT3</th>
<th>LATT4</th>
<th>LATT5</th>
<th>LATT6</th>
<th>LATT7</th>
<th>LATT8</th>
<th>LATT9</th>
<th>LATT10</th>
</tr>
</thead>
<tbody>
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<td>20.6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
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<td>24.1</td>
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<td>0.0</td>
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</tr>
<tr>
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</tr>
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Table E1. Example printout produced by the root growth simulation model. The inputs are as follows: NDS = 76 days, CULT = 1, TAPD = 8.0 cm, and T = 1 day. Equations for the temperature at any given time and depth were derived from temperature observations made during the course of Kaspar's (1981) experiment.
|     | 36.0 | 37.0 | 38.0 | 39.0 | 40.0 | 41.0 | 42.0 | 43.0 | 44.0 | 45.0 | 46.0 | 47.0 | 48.0 | 49.0 | 50.0 | 51.0 | 52.0 | 53.0 | 54.0 | 55.0 | 56.0 | 57.0 | 58.0 | 59.0 | 60.0 | 61.0 | 62.0 | 63.0 | 64.0 | 65.0 | 66.0 | 67.0 | 68.0 | 69.0 | 70.0 | 71.0 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|     | 5.04 | 3.22 | 7.01 | 5.89 | 3.97 | 5.61 | 5.38 | 7.95 | 5.61 | 5.38 | 5.04 | 3.22 | 7.01 | 5.89 | 3.97 | 5.61 | 5.38 | 7.95 | 5.61 | 5.38 | 5.04 | 3.22 | 7.01 | 5.89 | 3.97 | 5.61 | 5.38 | 7.95 | 5.61 | 5.38 | 5.04 | 3.22 | 7.01 | 5.89 | 3.97 | 5.61 |

Table E2. Example printout produced by the root growth simulation model. The inputs are as follows: NDSG = 76 days, CULT = 2, IAPD = 8.0 cm, and T = 1 day. Equations for the temperature at any given time and depth were derived from temperature observations made during the course of Kaspar's (1981a) experiment.

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Data Used to Determine the Number of Days to Emergence

Table E3. Data used to develop equations which describe the number of days to emergence. Emergence was defined as the time at which 50% of the plants had emerged. The planting depth was 2.5 cm

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Field Temperature Data

The following is a listing of the soil temperature data recorded during the course of Kaspar's (1981)\(^1\) experiment. The data are grouped by the day of observation. The column headings are defined below.

- **DAY** - days after planting.
- **DATE** - date of observation.
- **PROBE** - the number of temperature probe to which the thermistors were attached. Data for probe number 0 were obtained from National Weather Service records.
- **DEPTH** - the depth below the soil surface for which temperature was recorded.
- **TEMP** - the temperature (°C).

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APPENDIX F: PRELIMINARY VARIABLE TEMPERATURE EXPERIMENT

Additional preliminary experiments were performed to provide information about the affects of changing temperatures on the rates of taproot and lateral root extension. These experiments were carried out in cooperation with T. C. Kaspar.

Two experiments were performed. The procedures and cultivars were the same as described in Section II of this dissertation except that root measurements and PAR were recorded daily and the temperature was changed approximately every four days.

In experiment number 1, the seeds were planted and kept at 17°C until emergence. The temperature was then increased to 25°C, decreased to 17°C, and increased again to 25°C (Figures F1 and F3). In experiment 2, the seeds were planted and kept at 25°C until emergence. The temperature was then decreased to 17°C and increased to 25°C (Figures F2 and F3).
Figure F1. Rate of taproot extension, rate of lateral root extension, and PAR versus time for preliminary experiment number 1. Each point represents the average of 12 plants, 3 each of Beeson, Hawkeye 63, Wayne, and Harosoy 63 soybean cultivars.
Figure F2. Rate of taproot extension, rate of lateral root extension, and PAR versus time for preliminary experiment number 2. Each point represents the average of 12 plants, 3 each of Beeson, Hawkeye 63, Wayne, and Harosoy 63 soybean cultivars.
Figure F3. Rate of root extension versus time comparing preliminary experiments number 1 and 2. □ = the taproot. ○ = the lateral root.