WHEN TO IRRIGATE?

by
G. S. Campbell and R. Kunkel

The question of how to measure plant water needs is probably as old as history. Ancient people irrigated crops, and they probably asked themselves "How do I know when the plant needs water." Modern irrigators are also concerned with this question, but it is becoming increasingly important that we have the correct answer. Yields and quality of produce are strongly dependent on irrigation scheduling. Land can be damaged and water supplies wasted by improper irrigation.

Two approaches have been used to determine when to irrigate. One is the empirical approach in which one applies water in various quantities and at various times and then sees how the crop responds. This is the approach which has been used by irrigators for centuries, and is the approach used by most irrigation researchers today. Modern analysis and measurement techniques have improved the accuracy and reliability of this method, but it still has one fundamental limitation. The results do not apply to new soils, new climates, or new varieties for which data has not been collected. It is impossible to predict the response of the crop when grown under different conditions. For each new area, new variety, or new fertility level a new series of experiments must be performed to determine the best irrigation practice.

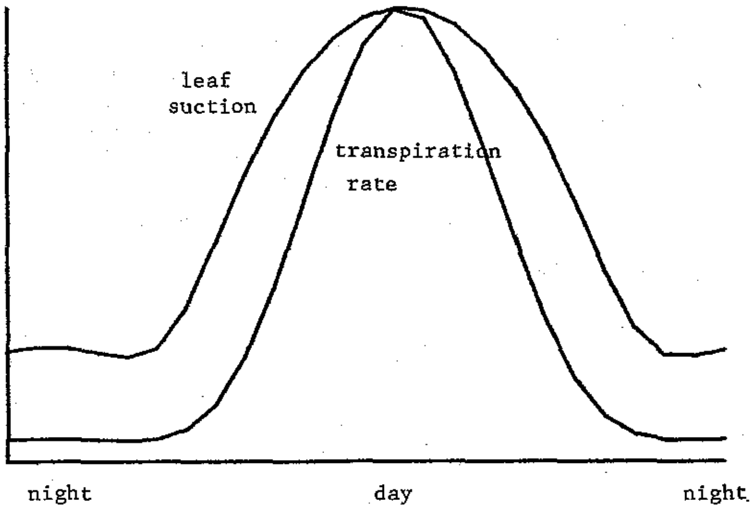
The second method for determining when to irrigate is based on fundamental relationships between the plant and its environment. If this approach is properly followed, the response of the plant to a given irrigation regime can be predicted no matter what new variables are introduced. Thus, changes in soils, climate, fertility, variety, planting density, etc. are all taken into account. The fundamental relationships, taken as a body and used to predict plant response from environmental conditions and plant characteristics, are called a model. The big disadvantage of this approach is already obvious. We don't know enough about the plant or its environment to make a comprehensive model. Such a model would be extremely complex and would take a computer to handle all of the computations to determine the interactions.

Since both approaches have advantages and disadvantages, we might look for a combination that would give the best answer. If we were to use simple models that we understand for parts of the system and then interpret the outcome of our empirical experiments using these models we could solve some of the problems. This is probably the best answer. We could also use the simple models to extend our empirical data to new conditions. A simple water relations model for potatoes shows how the plant responds to water stress and what factors are important in determining the degree of stress. We will also indicate from the model and field measurements the potato responses which are most sensitive to water stress and, therefore, are good indicators of water need. This model, coupled with empirical studies, can provide a means for proper irrigation scheduling to give maximum yield and tuber quality without land damage, waste of water, or nutrient leaching.

How the potato plant senses water stress

Before we can discuss responses of plants to water, we must agree on some measurement which tells us the water condition in the plant. We could measure the water content of the tissue, but different tissues with widely different water contents exhibit similar responses. Such a measurment would, therefore, have little value. Water in plant tissues and in soil is held in the pores, in cells in the plant, and on particles or molecule surfaces. The pores and surfaces attract water so that water in plants and soils is at a negative pressure, or suction. A measure of this suction is presently almost universally accepted as a proper measure of the water status of soils and plants. Suctions are generally measured in units of bars, a bar being equal to 14.5 pounds per square inch (psi). Free water, of course, has a suction of 0 bars. Most plant leaves have suctions of 10 bars. (145 psi). Some molds can live at suctions as high as 300 bars (4,350 psi), and the atmosphere at 50% relative humidity is around 1000 bars (14,500 psi). Water moves along suction gradients from the soil to the atmosphere. Since the suction in the atmosphere is so much higher than in the soil, the water moves readily from the soil, through the plant, and into the atmosphere. Once the water reaches the leaf, it must evaporate from the cell surfaces and diffuse through the small pores or stomates in the leaf. Once outside the leaf, the wind carries the water vapor away. The rate at which water evaporates from the leaf is therefore determined by the energy available from the sun to evaporate the water in the leaf, the opening of the stomates to let the water out of the leaf, and the wind to carry the water vapor away from the leaf. Generally, the stomates are open during the day, so, as the sun gets hotter, the rate of water loss increases. Figure 1 shows a typical water loss curve for a day.

Figure 1: Representation of typical transpiration rate and leaf suction over the period of a day.



There is resistance to water flow within the soil and plant. As the water loss from the leaves becomes greater, the suction in the leaves must become greater in order to supply water from the soil at the required rate. Figure 1 also shows the leaf suction over a day. The suction does not go to zero during the night and tends to have a rather broad maximum during the day because the plant resistance to water flow changes. At high transpiration rates the resistance decreases and at low transpiration rates it increases. Both the fact that leaf suction changes from day to night and the fact that the resistance to water flow increases at night are important to production and the way the plant senses even slight moisture stress, as will be shown later.

In addition to the biochemical machinery which carries on cell metabolism, each plant cell contains solutes such as sugars and salts. Because the cell membrane is permeable to water but not to these solutes, the solutes have a suction for water. We call this suction osmotic suction. It is generally greater than the leaf suction, so water from the transpiration stream tends to move into the cells. The cell walls are rigid, so as water moves in a pressure builds up which opposes the inward movement. This is called turgor pressure. When the cell is in equilibrium with the transpiration stream, the osmotic suction minus the turgor pressure must equal the leaf water suction. The cell wall is rigid, so the change in cell volume with pressure is slight. The osmotic suction therefore remains almost constant. This means that turgor pressure will undergo large diurnal fluctuations just as the leaf suction does. This is shown in Figure 2a. Figure 2b shows how the situation changes when the soil becomes drier. The turgor pressure is still about zero through the middle of the day, but the nighttime recovery is considerably reduced.

Nighttime recovery of turgor is extremely important to plant growth. For a cell to grow and multiply it is necessary that pressure inside the cell force the cell to expand. If there is no internal pressure, the cells do not grow. This dependence of growth on turgor pressure is shown in Figure 3. Of course cells also require new materials for cell walls, protoplasm, membranes, etc. Indications are, however, that for usual summertime conditions these are not the limiting factors. Evidence for this is that reduction in growth due to reduced turgor is observed long before either photosynthesis or transpiration are reduced (Hsiao, 1973). However, one could visualize conditions such as low light levels (cloudy weather) or low nutrient levels where factors other than reduced turgor pressure could limit growth.

Figure 2: Representation of typical osmotic suctions, leaf suctions, and turgor pressures over a day showing the effect of reduced water availability on leaf suction and turgor pressure.

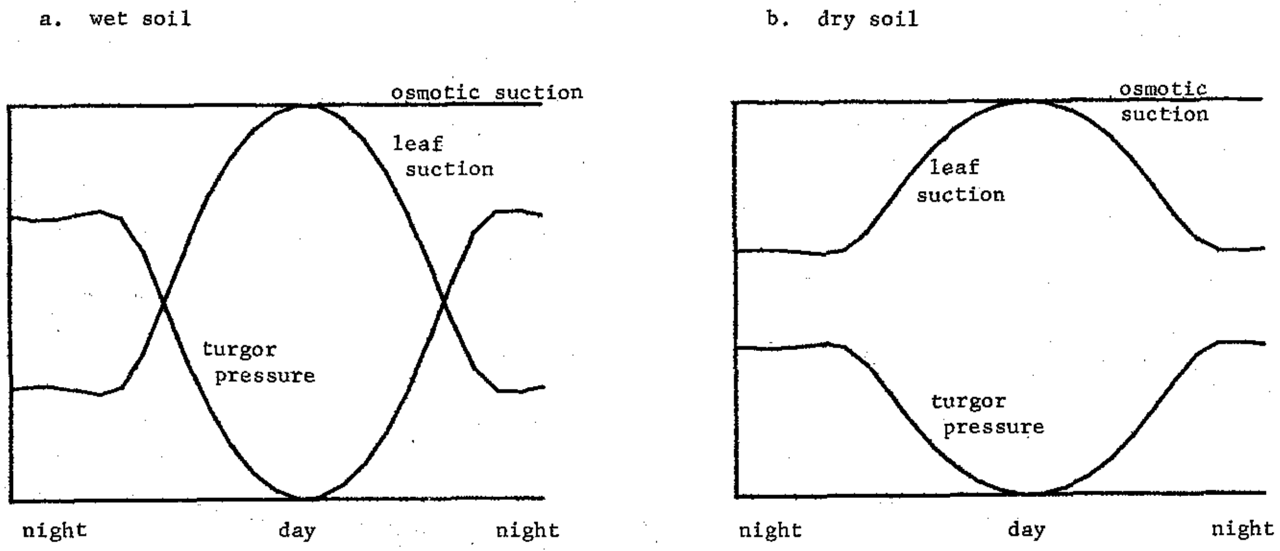
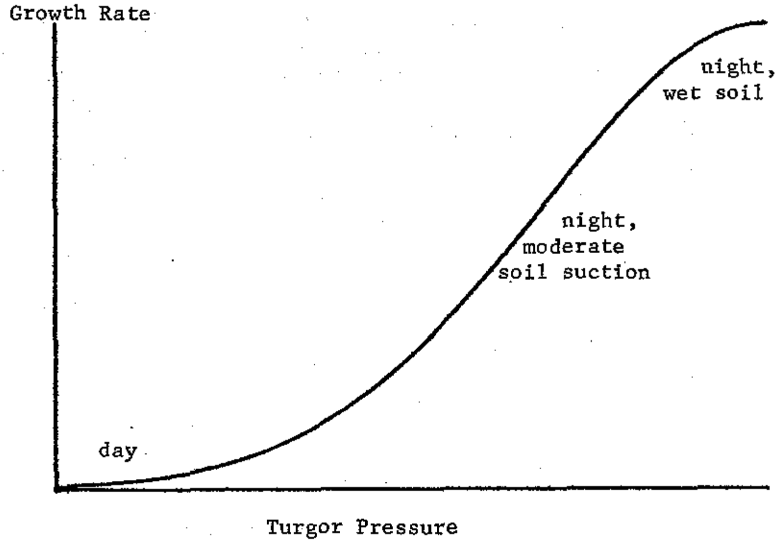


Figure 3: Hypothetical growth vs. turgor pressure curve for a potato leaf.



If we proceed on the assumption that turgor is the growth limiting process and combine the information in figures 2 and 3, we can show how the plant grows over a period of a day or more. This is shown in Figure 4. Growth is primarily at night since turgor is high then. During the day the growth rate is low, and when the soil is dry, even the nighttime rate is low. It is easy to see from Figure 4 why the plant is so sensitive to water stress. The reduction in growth each day is fairly small, but this effect accumulates over time until the final result is much larger. It is probable, though yet unproven, that most of the stomatal closure observed in field potatoes during the day is an indirect rather than a direct response to water stress. If nighttime turgor pressures are too small for growth to use up all of the carbohydrate produced during the previous day's photosynthesis, then there is less need for photosynthesis the following day. The plant, therefore, produces enough photosynthate to build its stores back up and then closes its stomates to prevent unnecessary water loss. (One could state this without invoking teleology by saying there is feedback inhibition by the photosynthate causing a slowdown of the photosynthetic mechanism and buildup of CO_2 in the stomatal cavities thus closing the stomates.)

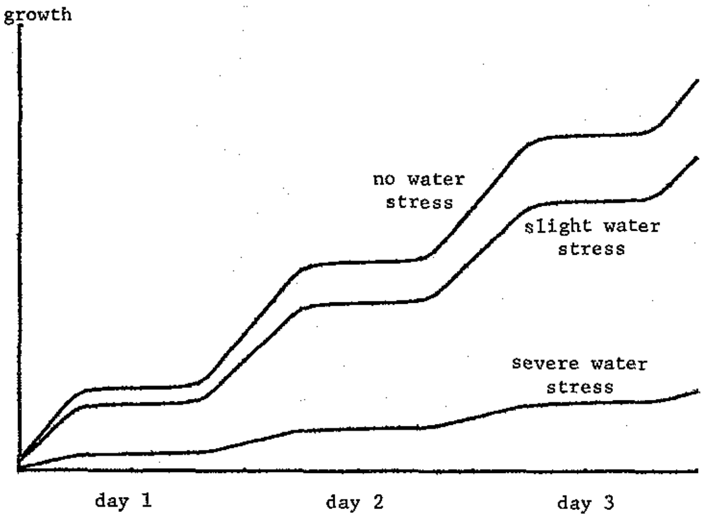


Figure 4: Diagram of growth over a three day period obtained using the growth curve from Figure 3 and the turgor curves of Figure 2. Growth during the day is essentially zero for all conditions, but nighttime growth rate is strongly dependent on turgor recovery.

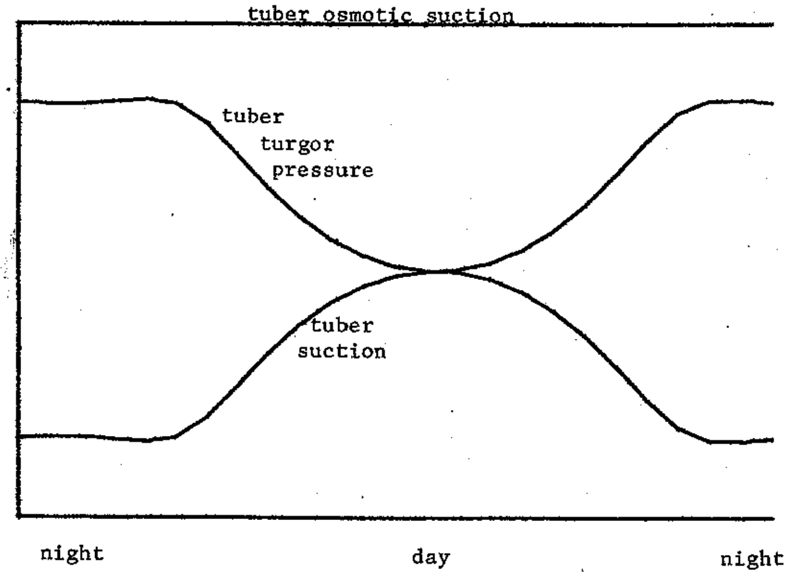
In growing potatoes we are primarily concerned with the harvestable portion, so let's focus attention on the response of tubers to water stress. The principles just discussed apply also to growth of tubers, but since they are further down in the transpiration stream, their fluctuations in suction are not as great as those shown in Figure 2 for leaves. Typical tuber suction, osmotic suction, and turgor pressure changes over a period of a day are shown in Figure 5. We do not, as yet, have a curve similar to Figure 3 for tubers, but Kunkel and Gardner (1965) and Meinel (1965) have measured diurnal fluctuations in tuber mass or volume, some of which look about like Figure 4. This would indicate that tuber growth responds to turgor pressure similar to leaves but is somewhat more sensitive to slight reductions in turgor pressure.

We might summerize to this point by saying there are large diurnal fluctuations in leaf suction in response to high rates of water loss during the day and low rates of water loss at night. These fluctuations result in large diurnal fluctuations in turgor pressure of the plant and ultimately in relatively rapid growth at night and slower growth during the day. Tuber growth follows this same pattern because turgor fluctuations in the tuber, though smaller than those in leaves, still modulate growth.

Measurements which indicate water stress

Irrigation for maximum production and highest quality potatoes requires that water is applied before the crop is injured by water stress. From our discussion so far we see that the plant is designed to maintain a slight positive turgor pressure under all conditions. If the plant is stressed until wilting of leaves can be seen the plant is beyond its design capability and one can be fairly certain that some damage occurred. Around midday on high evaporative demand days the leaf suction will be about equal to the osmotic suction, and the osmotic suction stays almost constant. The plant can apparently operate this way without damage. Thus, a measure of daytime leaf suction apparently would be a very poor indicator of water stress since the plant tends to maintain this constant relationship. Experiments we have conducted tend to confirm this. We grew potatoes under irrigation at Othello and without irrigation at Pullman during the summer of 1973. The Pullman potatoes were obviously water stressed since most of the older leaves had been shed and the younger leaves were small and thick. The rate of growth of the Pullman plants was much slower than that of the Othello plants, and the soil moisture in Pullman was depleted to about 6 bars suction to a depth of 3 feet. The suction in the root zone of the Othello potatoes was 0.5 bar or above for the entire season. We measured midday leaf water suctions in the Othello plants of around 12 bars while the suction in the Pullman plants was around 11 bars. The difference might have been due to the higher fertility level at Othello, since we have observed on other occasions that high fertility allows the leaves to go to higher suctions. In any case, the water stress of the Pullman plants was not reflected in their daytime suctions. Nighttime suctions were around 2 to 3 bars at Othello and 6 to 7 bars at Pullman. Figure 3 indicates that growth would be quite rapid at 3 bars, but very slow at 7 bars. Stomatal diffusion resistances were around 1.2 sec/cm at Othello in the morning and began increasing during the afternoon to around 4 or 5 sec/cm. At Pullman the lowest diffusion resistance reached was 2.5 sec/cm at 8:00 in the morning and it quickly increased to around 6 sec/cm and higher in the afternoon. The indication from these measurements is that nighttime leaf suction and afternoon stomatal diffusion resistance might be good indicators of water stress. The first response to reduced water availability is decreased turgor pressure, followed by decreased growth, and finally stomatal closure. Any of these could probably be used to indicate need for irrigation if interfering factors were taken into account. Our current thinking then, is that nighttime leaf suctions greater than 2 or 3 bars probably cause decreased growth. This should be reflected in afternoon diffusion resistances of 4 to 5 sec/cm.

Figure 5: Representation of tuber osmotic suction, tuber suction, and turgor pressure, over the period of a day. The tuber turgor pressure always remains high, but it is hypothesized that even such small changes in tuber turgor reduce growth.



With these ideas in mind, one immediately wonders whether environmental conditions which would maintain high turgor during the day and still not reduce sunlight could increase growth even more. Misting or frequent daytime irrigation might provide this condition. To establish this hypothesis more research is needed. It should be pointed out, however, that more than one factor is involved. The effects of such treatments on diseases and insects as well as nutrient uptake must also be considered.

If the water status of the plant is to be monitored to the extent we suggest is necessary for maximum production, we need simple and accurate techniques for determining leaf suction and stomatal diffusion resistance in the field. We are working on such techniques and feel that progress is being made. The pressure chamber apparatus of Scholander et al. (1965) has been successfully used on potatoes throughout the past growing season. It is probably not suited to general farm use, but could be used successfully by a trained operator for an irrigation scheduling service. We are currently working on a simpler version which, if successful, would probably be inexpensive and simple enough to find general usage.

We have also been working on a simple and accurate diffusion resistance meter. We have modified the steady state meter of Beardsell et al. (1972) for field use, and found it to work very well on potatoes. Again, at this stage it is probably best suited to use by someone trained specifically for that, but may also develop into something which could be routinely used by the grower.

Relating leaf water suction to soil suction

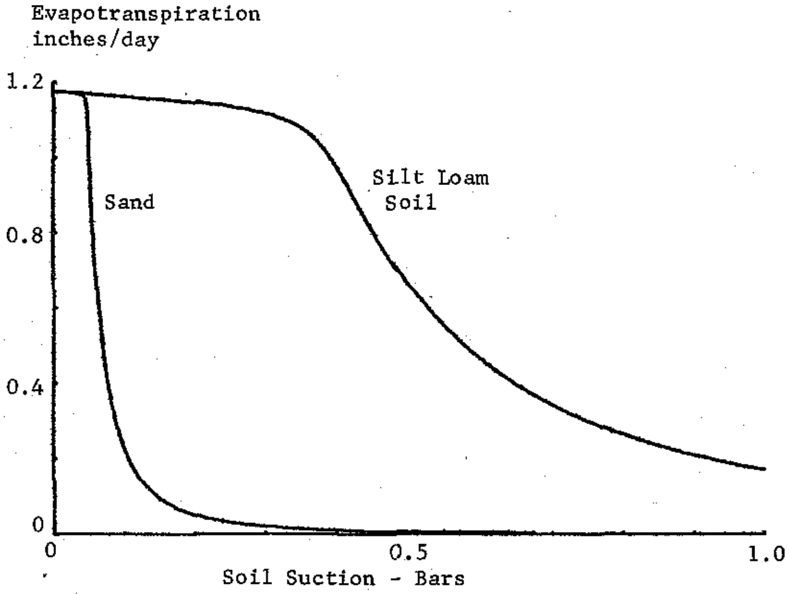
Current irrigation scheduling methods are generally based on some measurement of soil moisture, either the suction (tension) as measured with a tensiometer or the percent of "available moisture" determined from water content measurements and some estimate of the moisture holding capacity of the soil. As we have seen, it is the suction in the leaf that is important to the plant, not the suction in the soil. These are, of course, related, and we need to look at this relationship in greater detail.

Campbell (1972) derived a mathematical model which predicts the maximum rate at which the plant can supply water to the atmosphere. He showed that this maximum rate is determined by the resistance to water flow in the plant and soil, and the highest suction the plant is capable of attaining without stomatal closure. The resistance to water flow in the soil is determined by properties of the soil, the rooting depth and density of the crop, the transpiration rate, and the soil moisture suction. From this analysis it is clear that there can be no unique relationship between soil suction (or "available moisture") and leaf suction. However, if we have information about the soil, the rooting habit of the plant, and the highest expected transpiration rate we can easily determine the highest soil suctions at which peak evaporative demands can be met. Figure 6 shows the maximum rate at which transpiration can occur as a function of soil suction. At midsummer, average evaporative demands are around 0.3 to 0.4 in/day. The peak water loss at midday is probably double this or more. For a sandy soil (Figure 6) we might therefore pick 0.1 bar as the lower limit where for a silt loam we could allow the soil suction to go to 0.5 bar before irrigation. In the spring and fall when evaporative demand is lower, soil suctions could be allowed to go to higher levels without causing stomatal closure due to inability of the plant to get water fast enough.

We need to interpret the information just presented in light of the previous discussion on sensitivity of the plant to turgor loss. On the one hand, if the soil becomes so dry that the plant is forced to close its stomates during the day to prevent dessication, growth will be reduced. Figure 6 would therefore predict the highest soil suction permissable. On the other hand, the plant may well already have reduced growth before drought induced stomatal closure occurs. In fact it is likely that when stress is introduced gradually enough for the plant to respond through reduced growth and leaf shedding, the plant will seldom if ever allow drought induced stomatal closure. Thus the soil suctions at which irrigation should occur are probably somewhat higher than those predicted from Figure 6. The model needs to be extended to reliably predict nighttime turgor recovery and some other details of plant response to water stress need to be included. This work is going on at the present time, but no definitive answer is yet available.

One point should be made in passing. When the soil suctions are as high as those shown here for irrigation, deep percolation of water below the root zone is rapid unless irrigation amount and frequency are matched to the soil and evaporative loss. Careful attention needs to be paid to this aspect of design and scheduling to prevent losses of water, nutrients, and yield.

Figure 6: Maximum transpiration rate which can be supported by a typical potato crop on soils of two textures.



Water in relation to other management variables

It is often the case in agriculture that a farmer adopts a new management practice only to find that it works no better, and sometimes worse than the old practice. He is then tempted to give up the new practice even though the "experts" think it is better than the old one. The reason the new practice often fails is that it is used in conjunction with old varieties or practices which limit its effect. High fertility levels with older wheat varieties fail to improve yields in many cases, but the combination of high fertility, new varieties, and improved cultural practices has doubled or tripled wheat yield in some cases. This also applies to potato irrigation practice. If we fertilize for 600 cwt/ac. and continue irrigating the way we did for 300 cwt/ac. the plant gets confusing signals and may well end up with poor quality tubers. This is illustrated by an experiment we did at Othello in 1972. The results of the experiment are shown in Table 1. When both fertility and irrigation were adequate high yields of high quality potatoes were produced. When both irrigation and fertility were reduced, yield was reduced but quality remained high. (The low irrigation treatment in this experiment was still too high to show yield reduction.) When fertility was high but irrigation inadequate, yields remained high but the market quality and specific gravity of the tubers were reduced.

This principle tends to apply to any management variable. Improvement of one management variable is not likely to help much without concomitant improvement in other variables. Thus high yields of high quality potatoes require not only good irrigation management, but good fertility and pest management and proper maintainence of soil physical condition to provide adequate aeration and root growth. Ignoring one or more of these areas will likely reduce yield, quality of tubers, or both.

Table 1: Yield and quality of potato tubers grown at two irrigation levels (I) and two fertility levels (F).

Treatment	Yield cwt/ac.	No. 1's Percent	Specific Gravity
Hi I, Hi F	588	74	1.078
Hi I, Lo F	548	67	1.080
Lo I, Hi F	591	58	1.073
Lo I, Lo F	553	70	1.080

Literature Cited

Beardsell, M. F., P. G. Jarvis, and B. Davidson. 1972. A null-balance diffusion porometer suitable for use with leaves of many shapes. J. Appl. Ecol. 9:677-690.

Campbell, M. D. 1972. The lower limit of soil water potential for potato growth. Ph. D. thesis, Washington State University, Pullman.(University Microfilm #73-35).

Hsiao, T. C. 1973. Plant responses to water stress. Ann. Rev. of Plant Physiol. 24:519-570.

Kunkel, R. and W. H. Gardner. 1965. Potato tuber hydration and its effect on blackspot of Russet Burbank potatoes in the Columbia Basin of Washington. Amer. Potato J. 42:109-124.

Meiml, G. 1965. The growth and water supply of individual organs of the potato. In B. Slavik, ed., Water Stress in Plants, W. Junk, Publishers, The Hague, p. 223-226.

Scholander, P. F., H. T. Hammel, E. D. Bradstreet, and E. A. Hemmingsen. 1965. Sap pressure in vascular plants. Science 148: 339-346.