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POTATO

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ABSTRACT

Precision irrigation requires a method of quantifying the crop water status or root zone depletion of water to determine when and how much water to apply to the soil. Changes in canopy resistance (r_c) and canopy temperatures have the potential of being used as a crop water status indicator for irrigation management. A study was conducted on potato (*Solanum tuberosum* L.) grown in northern Egypt at Shibin El-Kom on an alluvial loamy soil for winter (20 Sept. 2001 through 20 Jan. 2002) and spring (1 Feb. 2002 through 20 May 2002) seasons to determine if r_c derived from energy balance and plant parameters could be used to determine the onset of water stress and the amount of water required to refill the soil profile. Diurnal r_c was determined for well-watered conditions and achieved minimum values of 20 and 10 s m^{-1} at noontime during winter and spring periods, respectively. A power relationship of -0.86 for well-watered conditions was developed between r_c and net radiation (R_n) at various plant growth stages. In deficit soil water conditions, r_c increased linearly with decreasing available soil water (ASW), with a change in potato r_c of 0.75 and 0.39 s m^{-1} per percentage ASW for 1 and 2 MJ m^{-2} h^{-1} of R_n at midgrowth, respectively. A ratio of actual/potential canopy resistance (r_c/r_{cp}) was derived to normalize the meteorological differences between growing seasons. This ratio was 2.5 when 50% of ASW was removed and can be used as a parameter to determine the need for irrigations using weather factors and canopy temperature. Canopy resistance increased linearly with increasing soil solution salinity, electrical conductivity, when the soil solution was above the threshold soil salinity value. A ratio of r_c/r_{cp} was found to normalize the effects of different environments across saline and water deficit conditions.

ESTIMATION OF PLANT WATER status provides a basis for more efficient irrigation management. There are several different methods of estimating plant water status, e.g., leaf water potential, leaf or canopy temperature, or r_c (Stewart, 1984). Of these methods, one of the least explored terms has been canopy resistance. Canopy resistance represents a bulk resistance to water vapor or mass transfer from the collection of leaves. Canopy resistance was proposed by Monteith (1965) as an expansion of the energy balance equation to more closely link the biological factors with meteorological conditions. An examination of the Penman–Monteith equation shows the direct relationship between evapotranspiration (ET) and canopy resistance as depicted in Eq. [1]:

$$\lambda E = \frac{\Delta (R_n - G) + \rho c_p \{e_s[T(z)] - e(z)\}/r_a}{\Delta + \gamma(r_a + r_c)/r_a} \quad [1]$$

where λE is the latent heat of vaporization (J m^{-2} s^{-1}), Δ the change of saturation vapor pressure with temperature, γ the psychrometric constant (kPa K^{-1}), R_n the net radiation (J m^{-2} s^{-1}), G the soil heat flux (J m^{-2} s^{-1}), ρ the density of dry air (kg m^{-3}), c_p the specific heat of air (J kg^{-1} K^{-1}), e_s the saturation vapor pressure (kPa), $T(z)$ the air temperature at position z (K), $e(z)$ the vapor pressure of water in atmosphere at position z, r_a the aerodynamic resistance (s m^{-1}), and r_c the canopy resistance (s m^{-1}).

The dependence of canopy resistance on environmental factors offers the potential for feedback control of irrigation. Irrigation management requires that the interrelationships among plant, soil, and weather factors be quantified to determine when to irrigate and how much water to apply. Canopy resistance determined from leaf or canopy temperatures represents a plant parameter affected by plant characteristics, e.g., leaf area index (LAI), height, and maturity. Soil factors (ASW content and soil solution salinity) and weather factors (R_n and wind speed) also affect canopy resistance. The companion term in Eq. [1], r_a, can be determined using plant height and wind speed. These terms represent a combination of both plant and weather factors directly affecting crop water use.

Monteith (1965) showed that transpiration rate physically depends on relative changes of surface temperature and r_a. He concluded that r_a depends on Reynolds number of air and can be determined from wind speed, characteristic length of plant surface, and the kinematic viscosity of air. For Reynolds numbers between 10^3 and 3×10^3, r_a ranges between 20 to 2 s m^{-1}. From field studies, he found barley (*Hordeum vulgare* L.) r_c increased from 30 s m^{-1} in mid-June to 70 s m^{-1} at the end of July. During this period, total LAI decreased from 10 to 6. The increase of r_c was caused by a decrease in total leaf area, by an increase in the resistance of individual leaves due to senescence, or by a combination of both effects. He also revealed that an increase of Sudan grass (*Sorghum hordense* L.) r_c was related to an increase of stomatal resistance in leaves that had reached maturity. An increase of stomatal resistance for grass at O'Neill, NE, was correlated with decreasing soil moisture content. On 13 August, when soil moisture was 6% of wet weight, the surface resistance was 200 s m^{-1}, but after 18 d without rain, soil moisture decreased

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Abbreviations: ASW, available soil water; DOY, day of year; EC, electrical conductivity; ET, evapotranspiration; LAI, leaf area index; r_a, aerodynamic resistance; r_c, canopy resistance; r_{cp}, potential canopy resistance; $T_l - T_a$, leaf–air temperature differences.

to 3%, and the stomatal resistance increased to about 1500 s m^{-1}.

As water uptake by plant roots lags behind the loss of water from leaves, water stress increases during the day. Therefore, the minimum value of diurnal stomatal resistance observed by many researchers (Monteith, 1965; Idso et al., 1981; Sharma, 1984) occurs around midday. Then, it increases gradually until stomata completely closed at sunset. This interpretation is consistent with an increase of surface resistance when transpiration rate decreases. The decrease of resistance after sunrise shows a slow opening of stomata in response to increasing irradiance (R_n); or an increase of permeability in plant roots as the soil warms near the soil surface. Sharma (1984) found that diurnal minimum stomatal resistance of Jarrah tree (*Eucalyptus marginata* Donn ex Sm.) was 25 and 50 s m^{-1} for plants under non-water stress and water stress, respectively.

Jackson et al. (1981) derived a ratio of r_c/r_{cp} based on measured values of R_n, canopy and air temperature, and vapor pressure deficit. They found that under potential ET, canopies had resistance of 5 s m^{-1} and canopy resistance increased with decreasing soil water availability. Denmead (1984) verified that an increase of forest canopy resistance in Australia was correlated with a decrease of soil moisture content. After irrigation, when soil was wet, the surface resistance was 116 and 235 s m^{-1}, but after 6 d without rain, when soil was dry, the resistance increased to about 520 and 1000 s m^{-1} for winter and spring periods, respectively. Canopy resistance is responsive to soil water availability and increases with decreasing soil water availability.

Hatfield (1985) determined canopy resistance using energy balance techniques and found that canopy resistance obtained under optimal ASW did not decline gradually with increasing solar radiation (>0.5 MJ m^{-2} h^{-1}). He also found that canopy resistance was 20 s m^{-1} when the canopy was near potential ET and increased linearly with decreasing ASW with change in crop resistance of 0.4 and 2.1 s m^{-1} per percentage of ASW for 2.9 to 3.1 MJ m^{-2} h^{-1} and 1.3 to 1.4 MJ m^{-2} h^{-1}, respectively. He also stated that canopy resistance was not affected until 10% of the ASW was removed at solar irradiances greater than 0.5 MJ m^{-2} h^{-1}.

Walker and Hatfield (1983) found kidney bean (*Phaseolus vulgaris* L.) yield decreased with increasing crop water stress. They found that yield decrease was related to the increasing resistance of water-stressed canopy. Wanjura et al. (1992) studied the effect of crop development on crop water stress as related to canopy resistance and found that crop yield decreased with increasing plant water stress. Idso et al. (1981) showed that infrared thermometry was a useful measurement to detect the changes in plant water potential caused by soil water deficits in alfalfa (*Medicago sativa* L.)

Van Bavel (1967) studied alfalfa throughout an irrigation cycle and found that resistance became measurable when actual ET declined below potential ET. He showed that canopy resistance increased linearly with decreasing soil water potential. He stated that alfalfa canopy resistance was 8 s m^{-1} at 100% and 130 s m^{-1} at 20% ASW. Szeicz and Long (1969) compared several

Table 1. Chemical analysis of fresh irrigation water for the experimental site.

		Soluble ions							
		Cations				Anions			
pH	EC†	Ca^{++}	Mg^{++}	Na$^+$	K$^+$	CO$_3^-$	HCO$_3^-$	Cl$^-$	SO$_4^-$
	dS/m				cmol/L				
8.2	0.65	13.1	19.5	31.0	1.4	0.00	21.0	39.0	5.0

† EC, electrical conductivity.

methods of measuring canopy resistance and concluded that they all agreed closely when applied to different species. They also found that when actual ET was equal to potential ET, the canopy resistance for alfalfa was about 25 s m^{-1}.

The objective of this study is to evaluate the response of canopy resistance in potato to soil water content and to determine if these responses depend upon the growing season conditions. A goal of the study is to determine if the ratio of r_c/r_{cp} can be used as an indicator for irrigation control.

MATERIALS AND METHODS

Diamant potato was planted for two seasons in an arid site in northern Egypt (Shibin El-Kom area, 17.9 m above sea level; 30°32′ N, 31° 03′ E). Soil in the study area was classified as alluvial loamy soil with 1.3 g cm^{-3} soil bulk density. Soil particle sizes for 0.3 m of soil profile were distributed as 5.86% coarse sand, 35.46% fine sand, 30.70% silt, and 27.80% clay. Chemical analyses of the soil are shown in Table 1. The volumetric water content values were 44, 28, and 15% at saturated, field capacity, and wilting points, respectively. Irrigation water was uniformly distributed all over the field. Fresh irrigation water with 0.56 dS m^{-1} was applied using basin system when soil water was reduced to 50% of available water, and analyses of the water are shown in Table 2.

The winter season crop was planted on 20 Sept. 2001 and harvested on 20 Jan. 2002. The spring season crop was planted on 1 Feb. 2002 and harvested on 20 May 2002. Plants emerged 20 d after planting for both seasons. Plot size was 4.2 by 10 m with 0.70-m row width and a 0.3-m spacing between plants. Meteorological instruments were positioned 2 m above the potato canopy surface and collected data every 10 s into 30- and 60-min averages using Campbell Scientifics' CR-23X datalogger[1] (Campbell Scientific Inc., Logan, UT). Net radiation, soil heat flux, soil temperature, and wind speed were measured over the treatments with air temperature, relative humidity, and leaf temperatures positioned in each replicate. Instruments used were CS500 temperature and relative humidity probes, 03001-5 cup anemometer, and quantum model 7 net radiometer. Two fine-wire (0.125-mm diam.) thermocouples

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[1] Mention of a specific product or trade name does not imply endorsement.

Table 2. Soil chemical properties for the experimental site.

			Soluble ions							
			Cations				Anions			
Depth	pH	EC†	Ca^{2+}	Mg^{2+}	Na$^+$	K$^+$	CO$_3^{-2}$	HCO$_3^-$	Cl$^-$	SO$_4^{-2}$
cm		dS/m				cmol/kg soil				
0–30	7.73	0.30	0.64	0.31	1.45	0.31	0.00	0.92	1.11	0.68
30–60	7.85	0.28	0.49	0.32	1.85	0.23	0.00	1.12	1.05	0.72
60–90	7.92	0.29	0.34	0.38	2.23	0.15	0.00	1.44	0.86	0.8

† EC, electrical conductivity.

(copper-constantan) were used to measure leaf temperatures and connected to the CR23X datalogger. The closed fine-wire leads of thermocouple were inserted into the veins of the backside of the leaves to avoid potential heating from direct radiation. These thermocouples were moved as the canopy developed to obtain leaf temperature data in fully expanded leaves in direct sunlight. This approach was used because of the lack of infrared thermometers for the large number of treatments in this study. Soil temperature and soil heat flux were measured with two soil CS108 temperature probes (Campbell Scientific Inc., Logan, UT) and HFT-3 heat flux plates placed 0.1 m below the soil surface. To measure soil volumetric water content, a CS615-L water content reflectometer (Campbell Scientific Inc., Logan, UT) with two parallel rods of 30 cm long was inserted at a depth of 30 cm. The datalogger was programmed to collect 30-min and hourly averages of weather (air temperatures, relative humidity, R_n, and wind speed), soil (volumetric soil water content, soil temperature, and soil heat flux), and plant (canopy temperature) data. Data collection commenced the day after planting and continued until harvest for both seasons.

Plant measurements for the study were height and leaf area. Canopy height was measured from the ground surface to the upper most expanded leaf once a week. Leaf area was measured using a planimeter. Leaf area index was determined by dividing area of plant leaves per projected area of an individual plant. Two replicates and three plants from each replicate were sampled for height and leaf area measurements.

To study the effect of soil solution salinity (electrical conductivity, EC) on canopy resistance, five plots of early growing potato (two replicates, 2 by 2 m) were irrigated with different saline of water using basin system (0.6, 1.1, 2.3, 3.5, and 4.6 dS m^{-1}) until the end of both growing seasons. At noontime on day of year (DOY) 333 in winter 2001 and DOY 107 in spring 2002, both plant and energy balance measurements were taken from the plot area. On those days, soil water in root zone for 30-cm soil surface depth and two samples of the treatments was extracted using ceramic cups after 24 h of irrigation. Then, soil solution was measured using EC meter. The average of soil solution EC for 30 cm of surface soil depth was around 0.92 dS m^{-1} at the beginning of both experiments.

Estimation of Canopy Resistance

The surface energy balance for crop has been expressed (Jackson, 1982) as:

$$R_n = G + H + \lambda E \qquad [2]$$

where R_n is net radiation in MJ m^{-2} s^{-1}, G is soil heat flux in MJ m^{-2} s^{-1}, H is sensible heat flux in MJ m^{-2} s^{-1}, and λE is latent heat flux in MJ m^{-2} s^{-1}.

Sensible heat flux, H, in MJ m^{-2} s^{-1}, was determined as described by Jackson (1982) as:

$$H = -\rho C_\rho \left[\frac{T_s - T_a}{r_a} \right] \qquad [3]$$

where T_a and T_s are the air and surface temperatures in °C, respectively.

Latent heat flux, λE, in MJ m^{-2} s^{-1}, was determined using the equation described by Jackson (1982) as:

$$\lambda E = -\frac{\rho C_\rho}{\gamma} \left[\frac{e_s - e_a}{r_a + r_s} \right] \qquad [4]$$

where r_s is the surface resistance in s m^{-1} and e_a and e_s are the air and saturation vapor pressure at the leaf surface temperature in kPa, respectively.

Surface resistance of dense crops cannot be obtained by simply averaging stomatal resistance because the driving force (vapor pressure deficit) is not constant within the canopy. Simple averages will also produce negative values of canopy resistance. Aerodynamic resistance, r_a, in s m^{-1}, was computed from the top of the canopy height, h_c, to the reference height, z, based on Alves et al. (1998) as:

$$r_a = \frac{\ln\left(\dfrac{z-d}{h_c-d}\right)\ln\left(\dfrac{z-d}{z_o}\right)}{k^2 u} \qquad [5]$$

where z is the reference height (m) of measurement of air temperature, wind speed, and water vapor; h_c the crop height (m); d the displacement height (m); z_o the roughness height (m); k the von Karman's constant (0.41); and u the wind speed (m s^{-1}). Values for roughness and displacement height were assumed to be 0.13 and 0.67 of canopy height, respectively, for the potato crop and were assumed to be applicable in this canopy shape.

Surface resistance, r_s, in s m^{-1}, was determined by rearranging Eq. [4] and solving as:

$$r_s = -\frac{\rho C_\rho}{\gamma} \left[\frac{e_a - e_s}{\gamma E} \right] - r_a \qquad [6]$$

Canopy resistance (mean stomata resistances of crop), r_c, in s m^{-1}, can be determined by dividing r_s by effective LAI as defined by Szeicz and Long (1969), Denmead (1984), and Hatfield and Allen (1996). For well-watered crops, canopy resistance, r_c, in s m^{-1}, can be estimated as follows:

$$r_c = \frac{0.3\text{LAI} + 1.2}{\text{LAI}} r_s \qquad [7]$$

where LAI is in m^2 m^{-2}. This approach was verified in this study by comparing measured stomatal resistance values with a porometer to estimated r_c values from Eq. [7] at several times during the season and soil salinity treatments. Canopy resistance is a calculated value based on the energy balance components and represents the sum of the errors within each parameter; however, within this study, we estimated the error to be ±15% for the range of conditions encountered.

RESULTS AND DISCUSSION

Crop Growth and Meteorological Conditions

Canopy height and LAIs were different between the fall and spring growing seasons (Fig. 1). These data are expressed as a percentage of the growing season to
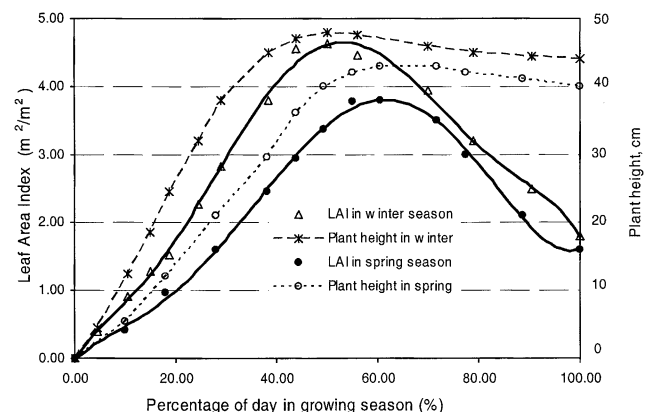

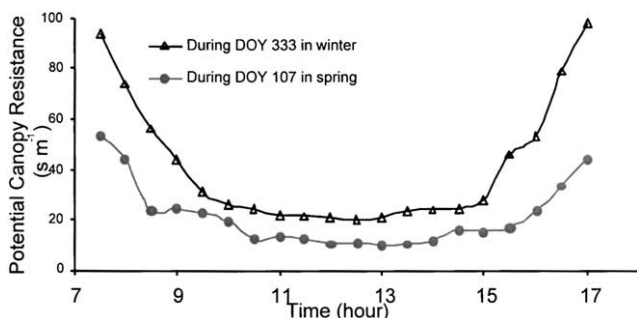**Fig. 1. Potato leaf area index (LAI) and height changes during the winter and spring seasons.**

Table 3. Net radiation (R_n), canopy resistance (r_c), aerodynamic resistance (r_a), air temperature (T_a), and leaf temperature (T_l) for days with available soil water >90% and leaf area index >2.5.

	Winter season (2001) midday values						Spring season (2002) midday values				
DOY†	R_n	r_c	r_a	T_a	T_l	DOY	R_n	r_c	r_a	T_a	T_l
	MJ m^{-2} h^{-1}	—— s m^{-1} ——		—— °C ——			MJ m^{-2} h^{-1}	—— s m^{-1} ——		—— °C ——	
318	1.03	22.00	5.27	25.95	25.09	85	1.30	17.80	5.54	19.03	18.35
323	1.12	18.8	3.71	20.52	19.78	92	1.37	11.65	4.78	19.75	18.71
324	1.01	21.14	6.50	21.53	20.45	93	0.86	22.80	6.06	19.82	18.91
325	1.04	21.05	23.63	23.67	20.87	101	2.04	10.50	20.25	26.10	22.23
333	0.92	20.2	12.65	22.34	20.70	106	1.74	12.12	6.67	28.39	27.96
334	0.93	21.01	5.33	22.32	21.45	107	2.02	10.20	10.58	25.68	23.30
338	1.01	20.45	2.39	17.94	17.45	113	1.85	12.83	8.25	26.68	24.73
339	0.99	21.20	3.73	19.94	19.23	116	1.92	9.80	6.57	25.63	24.07
343	1.12	22.00	2.42	20.64	20.10	117	1.99	10.80	8.94	24.62	22.50
344	1.00	21.30	12.77	21.40	21.8	118	2.03	9.70	4.25	25.74	24.53
350	1.08	17.50	7.31	19.78	18.41	119	1.98	9.80	4.62	24.27	22.98

† DOY, day of year.

normalize the difference in growing season length. The two plant parameters were expressed as polynomial functions for both winter and spring seasons (Fig. 1). Height and leaf area showed rapid increases in early growth stages. Leaf area decreased in maturity stage because of senescing leaves in the lower part of the canopy. Vegetative growth was larger during winter, which had less radiation and shorter daylengths compared with the spring planting. Plant height increased more rapidly in the winter compared with the spring season (Fig. 1). Maximum LAI was achieved near midpoint of the winter growing season but delayed until later in the spring season. Yields for the potato crop averaged 24 t ha^{-1}, with the higher yields in the winter crop compared with the spring planting.
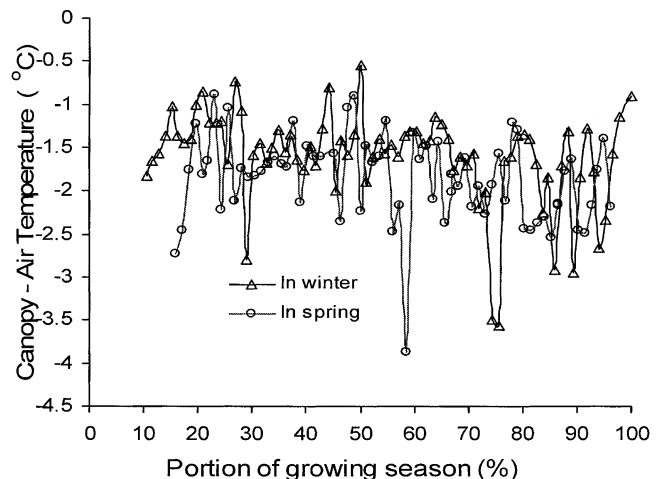
Air temperature varied throughout each day and among days depending on the intensity of solar radiation. Leaf temperature for typical days under well-watered conditions is shown in Table 3. Variations in meteorological factors, e.g., R_n or vapor pressure deficit, which are responsible for plant evaporation demand, affect canopy temperature. Leaf temperatures at midday under well-watered conditions were around 21°C for the winter period and 24°C for the spring period. Wind speed affects leaf temperature through the indirect effect on r_a (O'Toole and Hatfield, 1983). Aerodynamic resistance values for the canopies were calculated via Eq. [5], and values for z_o and d were calculated as 0.13h and 0.67h, respectively for this study. Since these are fairly dense canopies, this approximation was considered acceptable for this study. These data were then

used to estimate the r_{cp} during conditions of unlimited soil water availability, defined as ASW ≥ 90%, using Eq. [6] and [7]. Canopy resistance determined from measurable canopy temperature varied diurnally (Fig. 2). Under well-watered conditions, r_{cp} values at noon were 20 s m^{-1} during winter and 10 s m^{-1} for spring conditions. The total error in this study was 15% of the average canopy resistance values and indicates that the difference between spring and winter conditions was different. The diurnal change of r_{cp} during two typical days, DOY 333, representing winter conditions, and DOY 107 for spring conditions, shows that the minimum values are present for 4 to 6 h per day (Fig. 2). These potential r_c values are similar to values reported for a range of crops (Hatfield, 1985; Jackson, 1982; Szeicz and Long, 1969).

Leaf–Air Temperature Patterns

Leaf–air temperature differences ($T_l - T_a$) from 1130 to 1230 h were used to represent noontime conditions when r_c values were minimal over the two study periods (Fig. 3). Values of $T_l - T_a$ under the well-watered conditions showed differences of 1.0 to 1.5°C over the study period, with the larger variation in the spring growing season (Fig. 3). There was good agreement (less than 0.2°C difference) between the two thermocouples within

Fig. 2. Diurnal canopy resistance, r_{cp}, for well-watered treatments for potato during full canopy cover in the winter and spring seasons. DOY, day of year.

Fig. 3. Leaf–air temperature differences, $T_l - T_a$, at midday during the winter and spring seasons under well-watered conditions.
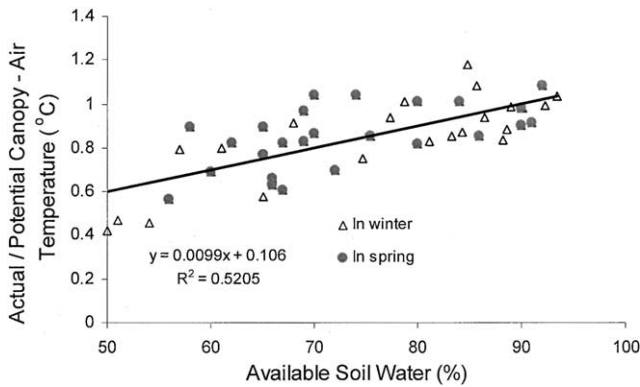
Fig. 4. Ratio of actual leaf–air temperature under various soil water availability conditions relative to leaf–air temperature under well-watered conditions for potato in the winter and spring environments.

the leaves in a treatment. This variation could be due to wind speed differences as suggested by O'Toole and Hatfield (1983). Seasonal averages of $T_1 - T_a$ for the well-watered treatments were $-1.7°C$ and $-2.35°C$ in winter and spring, respectively. A comparison was made between the ratio of the actual $T_1 - T_a$ to values obtained under the well-watered relative to soil water depletion (Fig. 4). Inconsistencies of $T_1 - T_a$ over the study period were caused by variations in relative humidity, wind speed, and solar radiation. The relationship of $T_1 - T_a$ with ASW showed differences with relative humidity, wind speed, and R_n. Segregating the data into both winter and spring seasons when LAI was greater than 2.5 showed the $T_1 - T_a$ values formed a linear relation (Fig. 4) with low correlation ($r^2 = 0.52$). Due to low correlation of $T_1 - T_a$ with ASW, canopy resistance that can be determined from weather and leaf measurements was selected to be a more accurate method to quantify water stress in potato.

Canopy Resistance Patterns

Thirty-minute canopy resistance values for the 1130- to 1200-h and 1200- to 1230-h intervals were combined to form an average daily canopy resistance at noon. Minimum values of canopy resistance (r_{cp}) during winter were about twice of those during spring (Fig. 5). Canopy resistance values responded to the drying of the soil and decreased rapidly once the plants began to cover the soil surface when LAI values increased above 1, and
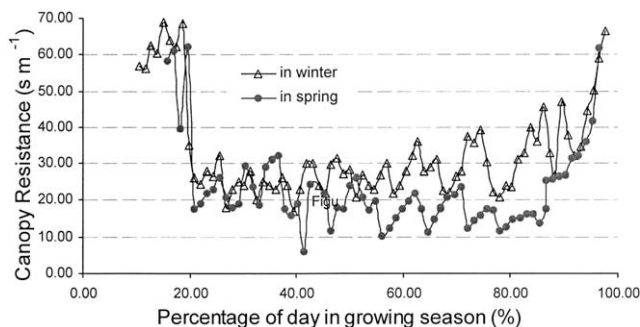

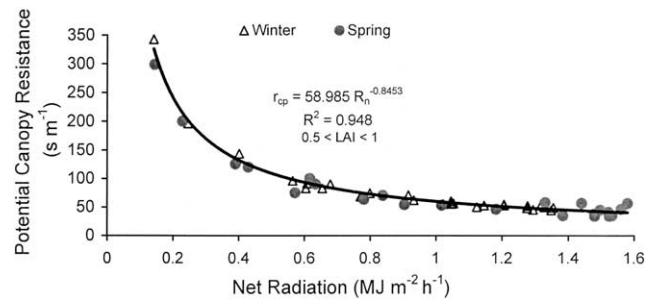Fig. 5. Potato canopy resistance, r_c, during the winter and spring seasons at midday.

Fig. 6. Potato canopy resistance, r_{cp}, vs. net radiation, R_n, for the early growth stages for both winter and spring conditions. LAI, leaf area index.

the trends across the days showed the responsiveness to the depletion of soil water (Fig. 5). The responsiveness of r_c to changes in the ambient conditions and soil water availability was evident throughout the growing season. The changes in r_c throughout the growing season are in agreement with those found by Hatfield (1985). Similar values for potato were reported by Kjelgaard and Stockle (2001) based on their calculations of canopy resistance from energy balance observations. Canopy resistance values gradually increased due to soil water depletion throughout both seasons. Values of r_c exhibited consistency throughout the growing season with variation induced by soil and meteorological factors. As the plants began to mature, the r_c values began to increase; for the winter period, this was in the last 20% of the growing season while in the spring season, the last 15% of the growing season showed this response (Fig. 5). In maturity stage, r_c increased due to leaf senescence and reduced ET by the maturing canopy as explained by Hatfield (1985).

The differences between the two growing seasons were related to the change in R_n of the canopy and the effect of canopy temperature. For well-watered conditions, r_{cp} increased when R_n increased (Fig. 6, 7, and 8). To examine the changes over the growing season, the season was divided into three parts to represent the early growth stages, the period of complete ground cover, and the senescing portion of the season. For the early portion of the growing season and the full-cover part, the values for r_{cp} showed the same relationship for the spring and winter periods (Fig. 6 and 7); however, for the
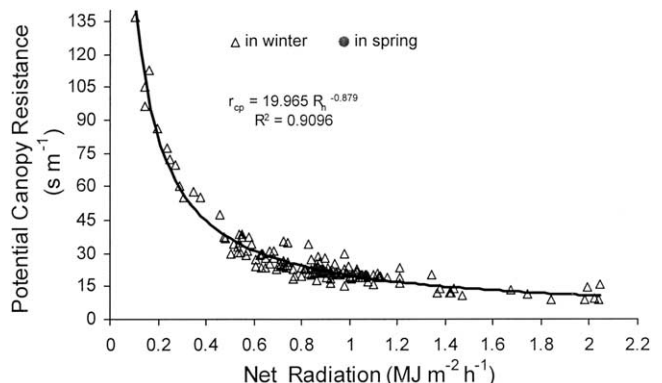

Fig. 7. Potato canopy resistance, r_{cp}, vs. net radiation, R_n, for the complete ground cover phase of growth for both winter and spring conditions.
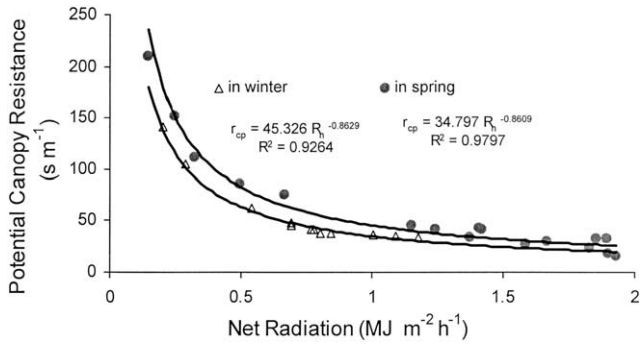
Fig. 8. Potato canopy resistance, r_{cp}, vs. net radiation, R_n, for the maturity phase of growth stages for both winter and spring conditions.

maturing stage of development, there was a separation between the winter and spring periods (Fig. 8). At all stages when R_n was less than 0.2 MJ m^{-2} h^{-1}, values of canopy resistance increased rapidly, and values exceeded 150 s m^{-1}. There was a rapid decrease in r_{cp} from 0.2 to 0.5 MJ m^{-2} h^{-1}. For all growth stages, r_{cp} was related to R_n in a power equation that was similar to that achieved using solar radiation instead of R_n by Denmead and Millar (1976) and Hatfield (1985) for wheat. The constant value in the equation increased when LAI decreased, but the power (-0.86) was almost the same. At 1 MJ m^{-2} h^{-1} of R_n, r_{cp} was 60 when LAI was less than 1 (Fig. 6) and decreased to 20 s m^{-1} when LAI was between 2.5 to 4 (Fig. 7). During the maturity stage when LAI was 2.5 and R_n was 1 MJ m^{-2} h^{-1}, r_{cp} was 45 and 35 s m^{-1} during winter and spring, respectively (Fig. 8). The power function obtained in well-watered conditions between r_{cp} and R_n could be used as potential reference to the actual canopy resistance, r_c. Actual canopy resistance obtained under deficit water and salinity conditions could be used to manage irrigation systems with different rates and intervals.

The relationship of actual canopy resistance, r_c, with ASW showed differences with R_n (Fig. 9). Segregating the data into R_n conditions of 1 and 2 MJ m^{-2} h^{-1} when LAI was greater than 2.5 showed two distinct relationships for winter and spring conditions (Fig. 9). These values for R_n were selected because they were most prevalent of the conditions in each of the seasons for the midday period when r_{cp} values were most consistent. Canopy resistance values were similar in both seasons when ASW > 90% (Fig. 9). Canopy resistance changed
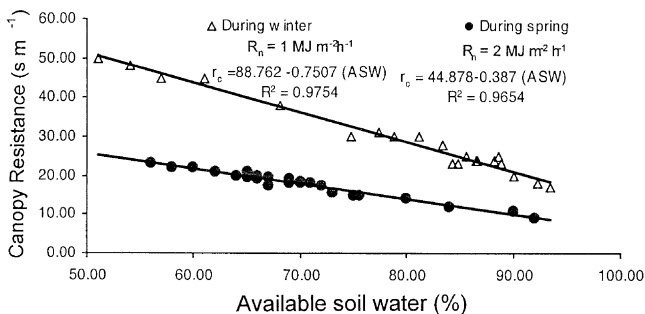

Fig. 9. Changes in canopy resistance, r_c, in relation to available soil water (ASW) during the winter and spring growing seasons. R_n, net radiation.
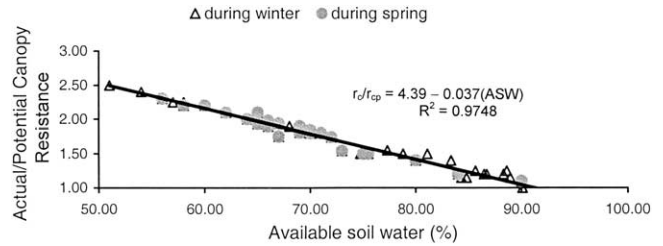

Fig. 10. Canopy resistance normalized to the well-watered soil treatment during the winter and spring growing seasons. r_c, actual canopy resistance; r_{cp}, potential canopy resistance; ASW, available soil water.

at a rate of 0.75 s m^{-1} per percentage ASW for 1 MJ m^{-2} h^{-1} of R_n in the winter season and 0.39 s m^{-1} per percentage ASW for 2 MJ m^{-2} h^{-1} of R_n in the spring season (Fig. 9). Forming the ratio of r_c to r_{cp} to normalize the relationship of r_c/r_{cp} for the range of ASW between 50 and 90% created a unifying relationship for both seasons (Fig. 10). This relationship could potentially be used as an indicator to determine when to irrigate and how much water to apply. For example, a value of $r_c/r_{cp} = 2$ would represent 35% removal of ASW. If the canopy resistance can be determined from weather and leaf measurements, then program control tables can be developed to control irrigation times. This concept would need to be tested relative to other methods for irrigation management for a range of soils and growing seasons.

Soil Salinity Effects on Canopy Resistance

As irrigation water applied with 0.6, 1.1, 2.3, 3.5, and 4.5 dS m^{-1} in potato field, average soil solution salinity for 30-cm surface depth in root zone was increased to 0.94, 1.72, 3.40, 5.20, and 6.70 in winter and 1.04, 1.83, 3.84, 5.14, and 6.45 in spring, respectively. Canopy resistance was affected by reducing soil water, and r_c was also affected by the soil salinity, EC, when the soil solution exceeded the threshold value of 1.75 dS m^{-1} and less than 7 dS m^{-1} (Fig. 11). Canopy resistance linearly increased with EC at a rate of 11.2 and 7.2 s m^{-1} per 1 dS m^{-1} of EC for 1 and 2 MJ m^{-2} h^{-1} of R_n, respectively. The determined r_c was correlated with the measurable r_c using r_c values from Table 4 after adjusting via Eq. [7]. The correlation between these values was 0.95. By normalizing r_c, as affected by soil solution EC, to the corresponding r_{cp}, the relationship of r_c/r_{cp} during full-
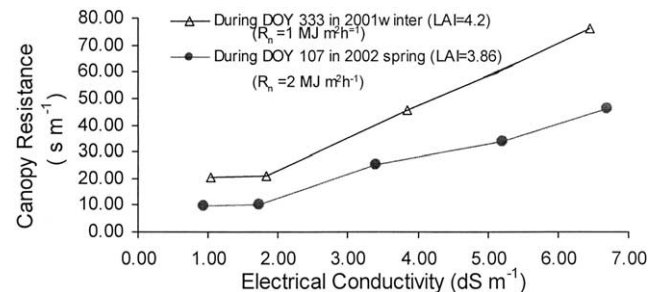

Fig. 11. Canopy resistance as affected by soil solution for full canopy cover conditions under winter and spring growing conditions. DOY, day of year; LAI, leaf area index; R_n = net radiation.

Table 4. Soil solution salinity (electrical conductivity, EC), leaf–air temperature difference ($T_l - T_a$), and canopy resistance (r_c), for both day of year (DOY) 333 and DOY 107 in full cover stages.†

DOY 333 in 2001 winter midday values			DOY 107 in 2002 spring midday values		
EC	$T_l - T_a$	r_c	EC	$T_l - T_a$	r_c
dS/m	°C	s/m	dS/m	°C	s/m
1.04	−1.64	28	0.95	−2.38	16
1.83	−1.90	38	1.72	−2.48	18
3.84	−2.24	75	3.42	−3.30	43
5.14	−2.37	96	5.24	−3.49	55
6.45	−2.44	132	6.70	−3.76	76

† These measurements were taken on the fourth and fifth leaves using Steady State Promoter. On DOY 333, average measurable parameters were almost as: leaf area index (LAI) = 4.2, T_a = 22.35°C, relative humidity (RH) = 65%, wind speed (WS) = 0.69 m/s, net radiation (R_n) = 0.95 MJ m^{-2} h^{-1}, and aerodynamic resistance (r_a) = 12.65 s/m. On DOY 107, LAI = 3.86, T_a = 25.68°C, RH = 54%, WS = 1.06 m/s, R_n = 2 MJ m^{-2} h^{-1}, and r_a = 10.12 s/m.

cover stages in winter coincided with that achieved in spring. The increase rate was 0.6 per 1 dS m^{-1} of EC for both growing seasons (Fig. 12) when salinity of soil solution was greater than 1.75 dS m^{-1}. Changing canopy temperature was observed in cotton (*Gossypium hiursutum* L.) by Howell et al. (1984). They showed that increasing soil salinity changed the canopy temperature, and by inference, canopy resistance increased with salinity, and the response was not detected in the leaf water potential measurements.

To evaluate the potential for irrigation management under conditions of changing soil water and potential saline conditions, a new ratio was developed using the rate of change in r_c/r_{cp} as a normalizing parameter. The relationship for soil water deficit was $r_c/r_{cp} = 4.39 - 0.037\text{ASW}$, and for salinity of soil solution, it was $r_c/r_{cp} = 0.6\text{EC}$. Then, potato canopy resistance, r_{cs}, as affected by both saline and water deficit can be formulated as: $r_{cs}/r_{cp} = 0.6\text{EC} \times (4.39 - 0.037\text{ASW})$. For example, if the growers want to irrigate when 35% of ASW was reached and 5 dS m^{-1} EC existed in soil solution, then the feedback will be done when the r_{cs}/r_c reaches a value of 6.

CONCLUSIONS

Canopy resistance provides an indication of the canopy response to water status in the soil, with the values dependent upon the soil and weather conditions. Diurnal values of canopy resistance in potato under well-watered conditions achieved minimum value of 20 and 10 s m^{-1} at noon during winter and spring periods, respectively, and these minimum values were present for 4 to 6 h around noon. A relationship between R_n and r_c for the different portions of the growing season and for different growing seasons was described using a power law function. The coefficient for these different times was consistent at –0.86 for all stages, but the equation constantly differed for the early-growth and late-maturity stages. In a deficit soil water condition, canopy resistance linearly increased with declining availability of soil water, with a decrease in potato canopy resistance of 0.75 and 0.39 s m^{-1} per percentage ASW for 1 and 2 MJ m^{-2} h^{-1} of R_n at midgrowth, respectively. Ratio of r_c/r_{cp} provided a unifying relationship that accounted for the seasonal differences in R_n for a wide range of ASW. The ratio could be effectively used as a parameter to automatically schedule irrigations using meteorological data combined with canopy temperatures. Canopy resistance linearly increased by increasing soil solution salinity, EC, when salinity levels exceeded a threshold value of 1.75 dS m^{-1} in this work and confirmed the earlier results reported by Hanson et al. (1999) for potato. A ratio of r_c/r_{cp} of 6 for use for potato irrigation scheduling covers both saline (5 dS m^{-1}) and soil water deficit conditions (ASW of 65%). Canopy resistance can be an effective method for assessing crop water needs under a range of soil water and R_n conditions and could be used in automatic irrigation management programs.

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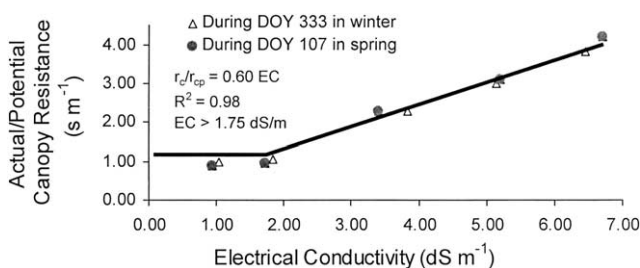

Fig. 12. Normalized canopy resistance relative to well-watered treatments in relation to soil solution salinity (electrical conductivity, EC) for complete ground cover in winter and spring conditions. DOY, day of year; r_c, actual canopy resistance; r_{cp}, potential canopy resistance.

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