Canopy Cover and Leaf Area Index Relationships for Wheat, Triticale, and Corn

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ABSTRACT

Previously collected data sets that would be useful for calibrating and validating AquaCrop contain only leaf area index (LAI) data but could be used if relationships were available relating LAI to canopy cover (CC). The objective of this experiment was to determine relationships between LAI and CC for corn (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), and spring triticale (×*Triticosecale* spp.) grown under dryland or very limited irrigation conditions. The LAI and CC data were collected during 2010 and 2011 at Akron, CO, and Sidney, NE, using a plant canopy analyzer and point analysis of above-canopy digital photographs. Strong relationships were found between LAI and CC that followed the exponential rise to a maximum form. The relationship for corn was similar to a previously published relationship for LAI <2 $m^2 m^{-2}$ but predicted lower CC for greater LAI. Relationships for wheat and triticale were similar to each other.

In semiarid regions where environmental conditions (particularly highly variable precipitation) make production decisions uncertain about which crops to plant, how often to fallow, and which crop sequence should be used, cropping systems simulation models have been successfully used to analyze the effects on productivity of varying cropping intensity, crop sequence, N management, and plant population (Lyon et al., 2003; Saseendran et al., 2004, 2010), as well as effects due to varying location, weather, and soils (Saseendran et al., 2009). There are often difficulties in extending field research results from a specific season and site to other situations. The use of models may assist in this process if they are validated and if specific growth parameters are adequately predicted. Lyon et al. (2003) noted that field research results can sometimes be limited to the period of time in which they were conducted, potentially leading to some inaccurate conclusions. Crop modeling with long-term climate data provides the opportunity to reduce the occurrence of these inaccurate conclusions that may result from short-term field studies conducted during a period that does not adequately represent the true climate variability (Lyon et al., 2003; Staggenborg and Vanderlip, 2005). Models have been used to extend field research results to make management decisions in the central Great Plains (Saseendran et al., 2010), including optimal planting date, crop rotation sequencing, crop–fallow decisions, evaluating profitability of alternative crops, and limited irrigation management. Additionally, modeling is a tool that can be used by producers to avoid the risks encountered in the adoption of new crops (e.g., canola [*Brassica napus* L. ssp. *napus*]) and new crop rotation sequences (Nielsen et al., 2012; Staggenborg and Vanderlip, 2005).

AquaCrop (FAO, 2012) is a computer model developed by the Land and Water Division of the FAO with the goal of increasing water use efficiency in food production (Araya et al., 2010). AquaCrop was designed to simulate biomass and seed yield responses of crops to water, especially under conditions where water is the liming factor (Steduto et al., 2009). It has been used to simulate production for barley (*Hordeum vulgare* L.; Araya et al., 2010), corn (Hsiao et al., 2009), cotton (*Gossypium hirsutum* L.; Farahani et al., 2009), onion (*Allium cepa* L.) and potato (*Solanum tuberosum* L.) (Domínguez et al., 2011), quinoa (*Chenopodium quinoa* Willd.; Geerts et al., 2009), and wheat (Andarzian et al., 2011; Salemi et al., 2011).

AquaCrop uses a relatively small number of parameters that can be separated into four categories: climate, crop, management, and soil (Raes et al., 2009). In the crop category, AquaCrop simulates green-crop CC as opposed to LAI to describe growth and canopy development. There are only a few previously reported relationships between LAI and CC for crop species. Hsiao et al. (2009) reported the following relationship for corn:

$$CC = 100.5\left[1 - \exp\left(-0.60\ \mathrm{LAI}\right)\right]^{1.2} \quad [1]$$

No details were given regarding how LAI and CC were measured.

Farahani et al. (2009) reported the following relationship for cotton:

$$CC = 100\left[1 - \exp\left(-0.77\ \mathrm{LAI}\right)\right] \quad [2]$$

Abbreviations: CC, canopy cover; LAI, leaf area index.

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The LAI was measured by passing the green leaves of two plants through a moving-belt leaf area meter. Canopy cover was calculated from measurements of above- and below-canopy photosynthetically active radiation taken near solar noon with a quantum bar sensor or calculated from weekly digital photographs of canopy development. No details were given as to how those photographs were taken or analyzed for CC except that "visual estimates" of CC were made from the photographs.

Andarzian et al. (2011) showed a graph of AquaCrop simulations of CC vs. measured CC for spring wheat in Iran but omitted details of how the CC measurements were obtained except to state that the maximum CC was determined using LAI. Likewise, no details were given about how LAI was measured.

Literature reports of plant growth have generally reported LAI and not CC. For those data to be useful for calibrating and validating AquaCrop, relationships need to be developed between LAI and CC. Therefore, the objective of this study was to define the relationship between LAI and CC for corn, winter wheat, and spring triticale while providing specific details about how both LAI and CC were measured.

MATERIALS AND METHODS

Field studies were conducted in 2010 and 2011 at the High Plains Agricultural Laboratory of the University of Nebraska (41°12′ N, 103°0′ W, 1315 m elevation asl) located near Sidney, NE, and at the USDA-ARS Central Great Plains Research Station (40°9′ N, 103°9′ W, 1383 m elevation asl) located near Akron, CO. The soil texture at both locations was a silt loam (Aridic Argiustolls) (National Cooperative Soil Survey, 2006a, 2006b). Two fixed no-till crop rotations were established in 2008 at each location (winter wheat–corn–fallow and winter wheat–corn–triticale), with crops in each rotation grown under both dryland (rainfed) and limited supplemental irrigation conditions.

Planting dates, seeding rates, and cultivars used for 2010 and 2011 are given in Table 1. Row spacing was 0.76 m for corn at both locations. Row spacing for wheat and triticale was 0.19 m at Akron and 0.25 m at Sidney. Each phase of each rotation was present each year in a randomized complete block experimental design with four replications per location. This resulted in 16 corn plots and 16 wheat plots (two rotations, two irrigation treatments, four replications) and eight triticale plots (one rotation, two irrigation treatments, four replications) each year at each location. The plot size was 18.3 by 9.1 m at Sidney and 12.4 by 6.1 m at Akron. Plots were fertilized to eliminate nutrient stress. For all three crops at Akron, 17 kg P_2O_5 ha^{-1} and 67 kg N ha^{-1} were applied at planting, which is a typical rate of fertilizer application for dryland production systems in this region. At Sidney, 38 kg N ha^{-1} was applied in April 2009 and no supplemental fertilizer was applied in 2010, as determined by soil testing done on soil samples taken in the fall of 2008 and 2009 to a depth of 122 cm and according to University of Nebraska fertilizer recommendations (Shapiro et al., 2008; Hergert and Shaver, 2009; Dr. G.W. Hergert, personal communication, 2008, 2009). Glyphosate [*N*-(phosphonomethyl)glycine] was used for weed control during the fallow periods. During the cropping season, weeds were controlled by hand weeding.

The supplemental irrigations (Table 2) were applied at the beginning and midpoint of each month from March through October whenever the previous 2-wk period had less precipitation than the 30-yr normal precipitation for that period of time. Only enough water was applied to bring the total precipitation plus irrigation up to the 30-yr normal for the previous 2-wk period. The supplemental irrigation was applied with lateral-move drop-nozzle irrigation systems at both locations.

The LAI measurements were made at various times during the growing season at both locations (Table 3) using a plant canopy analyzer (LAI-2000, Li-Cor Inc.) This instrument uses a radiative transfer model to calculate LAI from measurements of intercepted solar radiation. Four sets of readings were taken at a single location in each plot at each sampling date at Sidney and at two locations in each plot in Akron, generally when the sun was low on the horizon. The instrument operator stood with the sun to his or her back and used a 90° view cap (270° open) to block his or her body and the sun from the sensor. Observations of corn LAI were adjusted by recomputing with the fifth-ring sensor reading ignored, as recommended by the manufacturer and using the manufacturer's FV2000 data processing software. No LAI or CC observations were taken for corn at Sidney during 2011.

To estimate the CC, digital photographs were taken above the crop canopy on the same date as the LAI measurements (Table 3) using an inexpensive (<US$175) digital camera. At Akron, a Panasonic Lumix DMC-FS3 camera was used in 2010 and a Panasonic DMC-FP1 camera was used in 2011 (JPEG image format, 2048 by 1536 pixels, 180 points per inch, ppi). At Sidney, a Sony Cyber-Shot DSC-S780 camera was used in both years (JPEG image format, 3264 by 2448 pixels, 314 ppi). Photographs were taken with the digital camera held level with

Table 1. Planting dates and seeding rates for corn, winter wheat, and spring triticale at Akron, CO, and Sidney, NE, in 2010 and 2011.

Location	Year	Crop	Planting date	Seeding rate	Cultivar or hybrid
Akron, CO	2010	corn	10 May 2010	34,600 seeds ha^{-1}	DK 5259 RR
		wheat	28 Sept. 2009	67 kg ha^{-1}	Pronghorn
		triticale	na†	na	na
	2011	corn	17 May 2011	34,600 seeds ha^{-1}	DK 5259 RR
		wheat	22 Sept. 2010	67 kg ha^{-1}	Pronghorn
		triticale	1 Apr. 2011	100 kg ha^{-1}	Trical 2700
Sidney, NE	2010	corn	10 May 2010	34,600 seeds ha^{-1}	DK 5259 RR
		wheat	10 Sept. 2009	67 kg ha^{-1}	Pronghorn
		triticale	30 Mar. 2010	120 kg ha^{-1}	Trical 2700
	2011	corn	na	na	na
		wheat	9 Sept. 2010	56 kg ha^{-1}	Pronghorn
		triticale	1 Apr. 2011	100 kg ha^{-1}	Trical 2700

† na, not available. Triticale unavailable at Akron, CO, in 2010 due to planting error. Corn not planted at Sidney, NE, in 2011.

Table 2. Growing-season precipitation and supplemental irrigation amounts for corn, winter wheat, and spring triticale at Akron, CO, and Sidney, NE, in 2010 and 2011.

Location	Year	Crop	Growing-season precipitation	Supplemental irrigation
			mm	
Akron, CO	2010	corn	163	108
		wheat	263	51
		triticale	na†	na
	2011	corn	273	89
		wheat	371	25
		triticale	222	25
Sidney, NE	2010	corn	252	166
		wheat	461	48
		triticale	225	10
	2011	corn	na	na
		wheat	484	83
		triticale	270	66

† na, not available. Triticale unavailable at Akron, CO, in 2010 due to planting error. Corn not planted at Sidney, NE, in 2011.

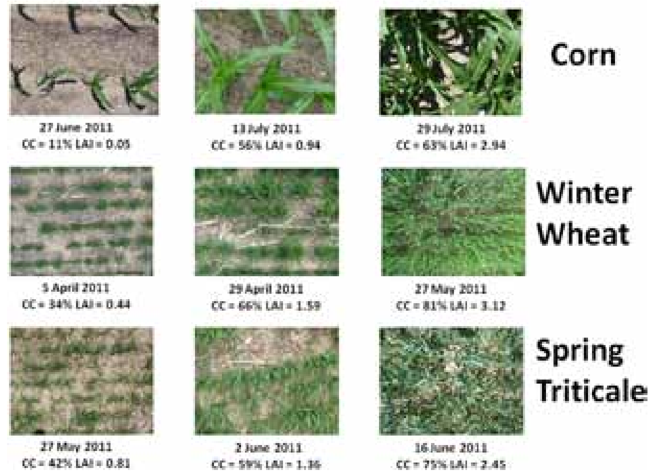

Fig. 1. Representative photographs of corn, winter wheat, and spring triticale at Akron, CO, and the associated measured canopy cover (CC) and leaf area index (LAI).

the horizon and at arm's length to the south of the photographer at midday to minimize shadows. Photographs were taken above the canopy at four locations per plot. For photographs of corn taken after 12 July, the photographer climbed a stepladder to get above the canopy. Each digital image was subsequently analyzed using SamplePoint measurement software version 1.53 (Booth et al., 2006; http://www.samplepoint.org/). The SamplePoint software was set to select 64 randomly located points in each image. The software operator classified each of the 64 points as either leaf or soil. The CC percentage was calculated as the fraction of sampled points that contacted the crop canopy. The results from the four areas photographed in each plot were averaged to give the average CC per plot at each sampling time.

Both LAI and CC values were averaged across the four replicate plots for each combination of the two crop rotations and two irrigation levels. Relationships between CC and LAI were created with SigmaPlot for Windows version 11.0 graphing and analysis software (Systat Software) using the nonlinear regression wizard to fit a curve to the data. The regression wizard used the Marquardt–Levenberg algorithm in an iterative process to find the regression coefficients (parameters) that gave the best fit between the equation and the data (SigmaPlot, 2008, p. 667–670; Marquardt, 1963). Several equation forms were evaluated (two-, three-, and four-parameter versions of exponential rise to a maximum, logarithmic, and power forms), with the R^2 value used to determine goodness-of-fit. There was no functional difference between the forms, but the R^2 value was maximized with the exponential rise to a maximum form. There was no difference in the R^2 value among the two-, three-, and four-parameter versions of this equation form. We therefore decided to use the three-parameter version so that the fitted parameters could be directly compared with the parameters given by Hsiao et al. (2009) for corn as shown in Eq. [1] above.

RESULTS AND DISCUSSION

Representative photographs of corn, wheat, and triticale canopies on three dates for each crop are shown in Fig. 1, with the measured CC and LAI noted. The SamplePoint software

Table 3. Dates of leaf area index measurements and canopy cover photographs and associated crop growth stage for corn, winter wheat, and spring triticale at Akron, CO, and Sidney, NE, in 2010 and 2011. Triticale data are unavailable for Akron, CO, in 2010 due to a planting error, while corn was not planted at Sidney, NE, in 2011.

Location	Year	Crop	Sampling date (growth stage†)							
Akron, CO	2010	corn	11 June (V5)	18 June (V6)	24 June (V8)	1 July (V9)	29 July (R1)			
		wheat	14 April (pseudostem)	27 April (jointing)	13 May	25 May (boot)	3 June (anthesis)	11 June (milk)		
	2011	corn	21 June (V5)	28 June (V6)	5 July (V8)	12 July (V10)	20 July (V13)	29 July (V19)		
		wheat	5 April (pseudostem)	29 April (jointing)	5 May	13 May	20 May (boot)	27 May	6 June (anthesis)	10 June (watery ripe)
		triticale	9 May	20 May	27 May	2 June (jointing)	10 June (boot)	16 June (heading)		
Sidney, NE	2010	corn	30 June (V8)	27 July (anthesis)						
		wheat	28 April (jointing)	18 May	4 June (anthesis)					
		triticale	1 June (jointing)	22 June (heading)						
	2011	wheat	3 May (jointing)	9 June (anthesis)						
		triticale	1 June (jointing)	22 June (heading)						

† Corn growth stages as defined by Ritchie and Hanway (1986). Wheat and triticale growth stages as defined by Nelson et al. (1988).

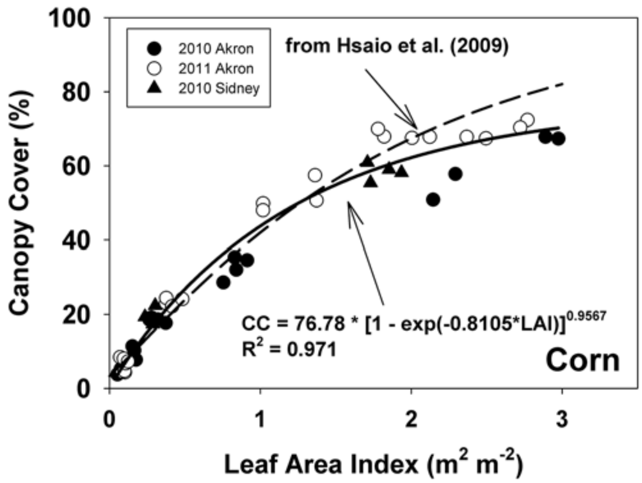

Fig. 2. Relationship between leaf area index (LAI) and canopy cover (CC) for dryland corn grown at Akron, CO, and Sidney, NE (Eq. [3]).

made classification of the points in each image relatively quick and simple because the software automatically moved to and zoomed in on a new location in the photograph after each point was classified as either soil or leaf by the software operator. The 64 points in a single photograph could be analyzed in <2 min.

The exponential equation form given by Hsiao et al. (2009) in Eq. [1] fit the CC and LAI data well for corn for all three site-years ($R^2 = 0.971$) (Fig. 2):

$$\mathrm{CC} = 76.78\left[1-\exp\left(-0.8105\ \mathrm{LAI}\right)\right]^{0.9567} \qquad [3]$$

This relationship was not greatly different from the Hsiao et al. (2009) relationship for corn until LAI exceeded about 2.0 $m^2\ m^{-2}$. As stated above, the details about how the CC and LAI data were obtained, as well as corn seeding rates and row spacing, were not given explicitly by Hsiao et al. (2009). It is likely that their data came from some of the experiments they referenced, with higher plant populations (69,800–119,000 plants ha^{-1}) than obtained from the relatively low corn seeding rates (34,600 seeds ha^{-1}) appropriate for dryland production used in this experiment. In the current study, no data were acquired for LAI >3.0 $m^2\ m^{-2}$ because of the water-limited growing conditions and low dryland plant populations used. At LAI = 3.0 $m^2\ m^{-2}$, CC appeared to be maximized at about 70%. We anticipate that with higher seeding rates, corn CC values >70% are probable, and a different relationship between CC and LAI would need to be established. This new relationship would probably shift the curve upward to be more consistent with the Hsiao et al. (2009) relationship above LAI = 3.0. Saseendran et al. (2005) reported a maximum LAI of 5 $m^2\ m^{-2}$ for a 109-d relative maturity corn hybrid grown under irrigation with a final plant population of 73,910 plants ha^{-1}. With an LAI of 5 $m^2\ m^{-2}$, Eq. [1] from Hsiao et al. (2009) predicted a CC value of 94.5%, while Eq. [2] from the current study predicted a much lower CC value of 75.5%.

The relationship between CC and LAI for winter wheat (Fig. 3) was likewise found to be well described by the equation form given by Hsiao et al. (2009):

$$\mathrm{CC} = 94.00\left[1-\exp\left(-0.43\ \mathrm{LAI}\right)\right]^{0.52} \qquad [4]$$

and fit the data from all four site-years well ($R^2 = 0.957$). Even though the growth and structure of wheat (Fig. 3) and triticale (Fig. 4) are much different than corn (Fig. 2), we included the corn relationship reported by Hsiao et al. (2009) in all three figures as a point of reference. For any given wheat LAI value <2 $m^2\ m^{-2}$, the relationship given in Eq. [4] predicted CC values much higher than was predicted by the corn relationships given by Eq. [1] and [3]. This may be due to the narrower row spacing used with wheat (0.19 or 0.25 m) compared with the corn row spacing (0.76 m). Equation [4] predicted a maximum CC of about 85%.

The relationship between CC and LAI for spring triticale (Fig. 4) was found to be

$$\mathrm{CC} = 94.00\left[1-\exp\left(-0.37\ \mathrm{LAI}\right)\right]^{0.53} \qquad [5]$$

which was very similar to the relationship found for wheat (Eq. [4]). Equation [5] fit the data from all three site-years well ($R^2 = 0.898$), although not quite as well as the fit found for the corn and wheat data. At any given LAI value, the CC values

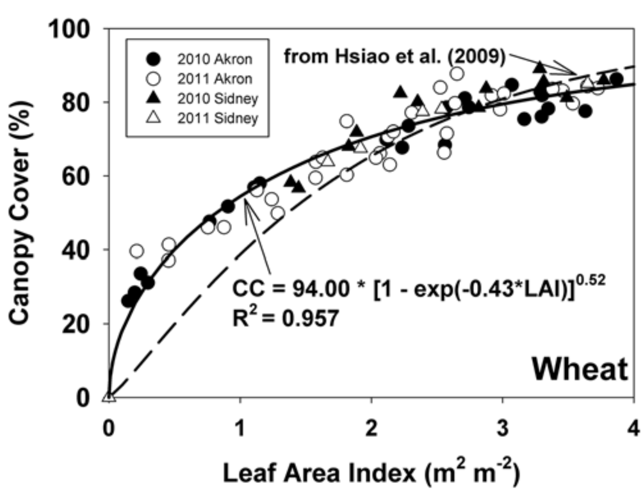

Fig. 3. Relationship between leaf area index (LAI) and canopy cover (CC) for dryland winter wheat grown at Akron, CO, and Sidney, NE (Eq. [4]).

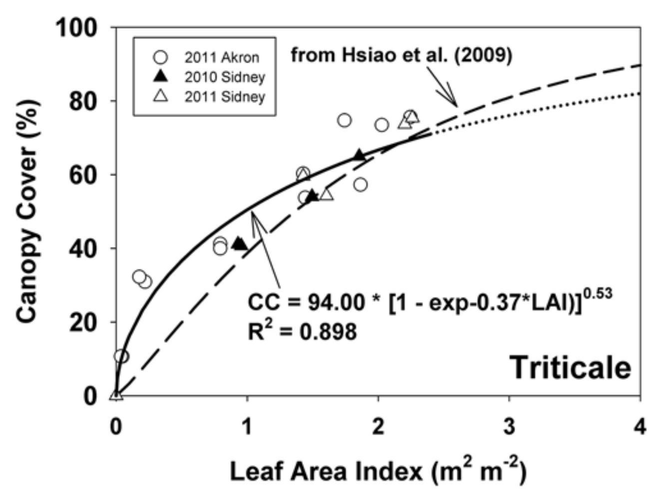

Fig. 4. Relationship between leaf area index (LAI) and canopy cover (CC) for dryland spring triticale grown at Akron, CO, and Sidney, NE (Eq. [5]).

predicted by Eq. [5] for triticale were about 93% of the CC values predicted by Eq. [4] for wheat. Data were only available for LAI values up to 2.25 $m^2 m^{-2}$, so we are somewhat unsure about what the maximum CC value for triticale would be at higher LAI values. It is probable that the data at higher LAI values would show a relationship very similar to what was found for winter wheat because the structure of these two grasses is similar and the row spacing was the same. The relationship for triticale should be further investigated, however, and confirmed with data for situations with LAI > 2.5 $m^2 m^{-2}$.

Prediction of CC from LAI using Eq. [3], [4], and [5] can enable data from completed experiments to be used to calibrate and validate AquaCrop or other models that rely on values of CC to quantify plant development. Additionally, the relationships given in Eq. [3], [4], and [5] can be rewritten solving for LAI so that researchers who only have a relatively inexpensive digital camera available to them can quantify treatment effects on LAI development for these three crops without having to invest in more expensive equipment or time-consuming destructive sampling. For example, Eq. [3] would become:

$$\mathrm{LAI} = \frac{\ln\left(1 - \sqrt[0.9567]{\mathrm{CC}/76.78}\right)}{-0.8105} \qquad [6]$$

CONCLUSIONS

Data collected on corn, winter wheat, and spring triticale during 2 yr at two locations from two cropping systems and two water treatments were analyzed to determine predictive relationships between LAI and CC. The relationship for corn was found to be similar in form (exponential rise to a maximum) to one previously given in the literature and predicted similar values of CC when LAI was <2 $m^2 m^{-2}$. At greater LAI values, however, the new relationship predicted lower CC values than the relationship from the literature. The difference may have to do with stand density differences. The relationships found for winter wheat and spring triticale were similar to each other and predicted greater canopy cover values at LAI <2 $m^2 m^{-2}$ than the relationship found for corn. The relationships will be valuable to individuals that wish to use AquaCrop to model data sets that had only LAI recorded. Additionally, the relationships can be rewritten such that LAI is a function of CC so that LAI can be quickly and inexpensively estimated from digital photographs of CC made with a low-cost digital camera.

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