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Simulation of actual evapotranspiration from agricultural landscapes in the Canadian Prairies

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ABSTRACT

Study region: This study was carried out in southwestern Manitoba, in the prairie region of Canada.
Study focus: Mathematical models are routinely used to estimate evapotranspiration (ET) when measurements are lacking. This study was conducted to select the most relevant models for estimating ET in the Canadian Prairies. Eight reference ET models (i.e., Penman-Monteith, Priestley-Taylor, Makkink, Turc, Maulé et al., Blaney-Criddle, Hargreaves-Samani, and Hamon models) were evaluated. This study also assessed the applicability and transferability of the growing degree day (GDD)-based crop coefficients for estimating crop ET in the Canadian Prairies.
New hydrological insights: The equation developed by Maulé et al. (2006) was found to be the best reference ET alternative to the Penman-Monteith equation with a mean relative error of 11%. However, when models were validated against measured crop ET, the simpler radiation-based Turc and Makkink models were found to be the most useful models with daily mean relative errors ranging from 16% to 49%, outperforming the widely accepted Penman-Monteith model. Discrepancies in the GDD-based crop coefficients were found to also contribute to errors; however, results show the potential transferability of GDD-based coefficients across different locations and climatic conditions.

1. Introduction

Evapotranspiration (ET) is a key component of the hydrological cycle due to the vital role it plays in energy-moisture exchanges between the earth and the atmosphere. It is a combined process where water is lost from the soil surface through evaporative processes as well as water transpired through growth and temperature regulation processes of plants. Since more than 99% of the water taken by plants is lost through transpiration (Lambers et al., 2008), ET is often used to determine crop water requirement as part of regional water resource planning and management exercises. However, despite numerous methods available for its measurement and calculation, obtaining accurate estimates of ET remains challenging (Amatya et al., 2016).

Direct measurements of ET include weighing lysimeters and eddy covariance methods. These techniques can be difficult to successfully employ and expensive to install, maintain, and operate (Allen et al., 1998; Shi et al., 2008; Gebler et al., 2015). High costs and time-consuming tasks associated with these methods make them unsuitable for routine measurements (Allen et al., 1998); however, they remain useful for the evaluation of ET estimated from indirect methods such as the residual energy balance (Halldin

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and Lindroth, 1992), Bowen ratio energy balance (BREB) (Bowen, 1926; Angus and Watts, 1984), soil water balance (Ritchie, 1985), and other (predictive) mathematical models (see also Rana and Katerji, 2000 for more details).

Rates of evapotranspiration are determined through various climatic factors that describe the energy available to evaporate water (e.g., radiation and temperature) and those that affect the movement of the evaporated water away from the evaporating surface (e.g., wind speed and humidity). Thus, when field ET measurements are not available, mathematical models built around those factors are employed to estimate ET using climate and land surface data. A common approach to simulate crop ET (ET_c) is the crop coefficient technique presented in FAO56 (Allen et al., 1998); with this approach ET_c is estimated using the (average) ET of a reference crop [ET_o (ET_r in this study)] and an adjusting crop coefficient (K_c) for the crop grown. The effect of climate on ET is reflected by the ET_r while the effect of crop growth and development is given by the coefficient K_c.

The K_c values are derived from measured crop characteristics and, thus, vary throughout the season in correspondence to the growth stage of the crop. Crop coefficient curves can be developed as a function of time (Irmak et al., 2013b; Reddy et al., 2015), plant growth stage (Allen et al., 1998; Piccinni et al., 2009), thermal unit or growing degree days (GDD) (Irmak et al., 2013a; Alberta Agriculture and Forestry, 2017b), and leaf area index or canopy cover (Irmak et al., 2013b). While Irmak et al. (2013b) found that different base scales show no significant differences when predicting crop coefficients for soybeans in Nebraska, other studies suggested that GDD-based crop coefficients should be transferable to other locations with different climatic conditions with an assumption that differences in plant development characteristics are related mainly to temperature (Sammis et al., 1985; Irmak et al., 2013a).

The ET_r estimate, on the other hand, is independent of crop type and management practices as it only accounts for climate effects. It is defined as the ET rate from a reference surface of a uniform and actively growing vegetation, not short of water, and having specified height and surface resistance (ASCE, 2005). The two standards for “reference evapotranspiration” are: (1) a short crop with an approximate height of 0.12 m and a daily surface resistance of 70 s/m (similar to clipped grass), and (2) a tall crop with an approximate height of 0.5 m and a daily surface resistance of 45 s/m (similar to full cover alfalfa) (ASCE, 2005).

Reference evapotranspiration models can be generally categorized into temperature-based models (e.g., Blaney-Criddle, Hargreaves-Samani, Hamon, Thornthwaite, Baier-Robertson, and Linacre equations); radiation-based models (e.g., Makkink, Priestley-Taylor, and Turc equations); mass-transfer-based models (e.g., Rohwer and Trabert-Mahringer equations); and combinations of the above modeling approaches (e.g., Penman, Monteith, Kimberly-Penman, and Penman-Monteith equations). Due to the differences in assumptions, data requirements, and climatic conditions in which these ET_r models were developed, they may result in inconsistent values (Grismer et al., 2002; Lu et al., 2005). Thus, several studies attempted to calibrate and validate these models under local conditions. Most of these studies (e.g., Alexandris et al., 2008; Bogawski and Bednorz, 2014; Djaman et al., 2015) calibrated and validated these models against the Penman-Monteith equation, which is the globally recognized and accepted standard equation for estimating ET_r (Allen et al., 1998). The Penman-Monteith equation requires detailed climatic parameters that are not always available in historical weather station records (e.g., relative humidity, wind speed, incoming solar radiation) in Canada. Although relative humidity, wind speed, and solar radiation are now being routinely measured by many Canadian weather stations, only humidity and wind speed data are readily available across the country. Solar radiation measurements have been made by provincial agricultural weather networks in Alberta (Alberta Agriculture and Forestry, 2017a) and Manitoba (Manitoba Agriculture, 2017) over the past decade or so which has recently increased the availability of this important parameter for modeling ET in those specific regions of Canada.

However, it may not be advisable to validate ET models using another model as other studies (Xu and Singh, 2005; Guo et al., 2017) indicated that different ET_r models (including the widely accepted Penman-Monteith model) perform differently in different climatic conditions. Also, when validation is done against measured crop ET, correction factors for crop characteristics and water availability have to be applied.

A number of studies have attempted to validate ET_r models for the different climatic and agricultural conditions in Canada. De Jong and Tugwood (1987) compared different ET_r models for locations across the country and evaluated models against Class A pan evaporation data. Though the authors also estimated actual ET_c, they did not compare the results to measure ET_c. More recently, Maulé et al. (2006) developed ET_r models for the agricultural conditions of the Canadian Prairies using regression against the Penman-Monteith equation, but also did not validate model outputs against measured data. Xing et al. (2008) compared the accuracy of three ET_r models (i.e., Penman-Monteith, Priestley-Taylor, and Penman equations) in estimating ET from a non-irrigated potato crop field in New Brunswick using BREB data. However, there might have been a bias in the comparison as different K_c values were employed for the different models. Moreover, ET_c estimates, which were not adjusted for water availability, were compared to actual measurements, which might have been influenced by soil moisture content. Gervais et al. (2012) compared two ET_r models [i.e., Penman-Monteith model and second generation Prairie Agrometeorological Model (PAMII)] for their performance in estimating ET from various sites in Saskatchewan and Manitoba. Although actual ET_c estimates were used for comparison, they were compared to ET_c measured indirectly from the difference between the change in soil moisture storage and precipitation (soil water balance method), with an assumption that runoff and deep drainage were negligible. Brimelow et al. (2010), however, evaluated the ability of the PAMII to simulate actual daily ET against eddy covariance measurements at a grassland and a cropland site in southern Alberta. In that study, the authors found that the model underestimated ET (i.e., significant negative bias) in both ecosystems (Brimelow et al., 2010), which underscores the need for further ET model comparisons with actual ET measurements on the Canadian Prairies for model and technique refinement. Further, as the Canadian Prairies or the Northern Great Plains in general are vast, it is important to have more studies from different locations comparing models to measurements.

This study was conducted to (1) qualitatively and quantitatively compare a selection of ET_r models and assess their ability to estimate ET from annual crops in the Canadian Prairies with respect to accuracy in comparison to measured ET_c and (2) assess the

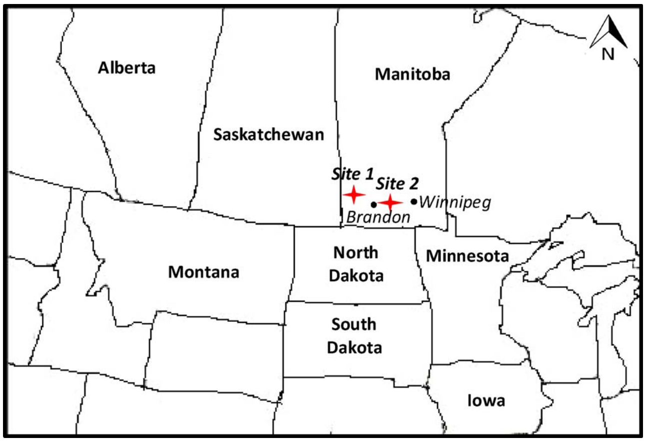

Fig. 1. Map of the Northern Great Plains region showing the locations of the two study sites (Site 1 is the organic site; latitude: 50°01'16" N, longitude: 100°34'26" W and Site 2 is the conventional site; latitude: 49°54'22" N, longitude: 99°20'49" W) near Brandon, Manitoba, Canada.

applicability and transferability of GDD-based crop coefficients to the climatic conditions of the Canadian Prairies.

2. Methodology

2.1. Study sites and measurements

This study was carried out at two experimental sites in southwestern Manitoba, Canada (Fig. 1) as part of a larger multi-year study investigating the water, carbon, nitrogen, and phosphorus balance components of contrasting cropping systems in the area. The sites are characterized by semi-arid to sub-humid climatic conditions. The 30-year (1981–2010) normal mean temperature and relative humidity around Brandon, Manitoba is 13.1 °C and 69.4%, respectively, with mean precipitation of 353 mm from May to October (Environment Canada, 2016).

The first site was an annual crop production field on a private organic farm situated 50 km northwest of Brandon, Manitoba (latitude: 50°01'16" N, longitude: 100°34'26" W, elevation: 477 m). It was sown with millet and hemp in June of 2013 and 2014, respectively, and with fall rye in September 2014. Extreme rainfall events that occurred in late June and early July of 2014 at the site destroyed the hemp crop; thus, the data for the 2014 growing season was excluded from this analysis. The second site was a conventional crop production field at the Canada − Manitoba Crop Diversification Centre − Carberry located approximately 45 km east of Brandon, Manitoba (latitude: 49°54'22" N, longitude: 99°20'49" W, elevation: 382 m). This site was planted with soybean, spring wheat, and canola in the 2013, 2014, and 2015 growing seasons, respectively.

The soils at the two sites have clay loam surface textures and were classified as Black Chernozem according to the Canadian System of Soil Classification. The soil water retention parameters (i.e., field capacity and wilting point) used for the organic site were taken from the soil measurement data (see Del Grosso et al., 2011) as there were no better data available for this site (Table 1). The field capacity of each layer [layer depths based on Canadian Soil Information Service (CanSIS) data and within the upper 1 m depth soil profile] was assumed to be the maximum soil water content measured after a rain, just when soil water started draining to the next lower layer, which can be observed from the fluctuations in soil moisture content depth profiles. The field capacity of the last layer in the 1 m profile was determined when there was drainage water collected in a lysimeter (G2 Drain Gauge, Decagon Devices Inc., Pullman, USA) installed at the 0.5 m to 1.2 m depth. The wilting point of each layer (layer depths from CanSIS data and also within 1 m depth soil profile) was chosen as the lowest soil moisture content observed after a long period (~2 weeks) without a significant amount of rain (< 3 mm). For the conventional site, the field capacity and wilting point used were taken from a soil survey conducted for the site (Mills and Haluschak, 1995). The other soil hydraulic parameters (i.e., saturation and saturated hydraulic conductivity) used for the two sites were estimated using the Soil-Plant-Air-Water (SPAW) model (Saxton, 2009) and the soil physical

Table 1
Assumed soil water characteristics for two field sites near Brandon, Manitoba, averaged over 1-m depth.

Site (Soil texture, series)	Field capacity (mm/m)	Wilting point (mm/m)	Saturation (mm/m)	K_{sat}[a] (mm/d)
Organic site (Clay loam, Newdale)	244[b]	154[b]	439[c]	127[c]
Conventional site (Clay loam, Ramada)	326[d]	132[d]	499[c]	114[c]

[a] Saturated hydraulic conductivity.
[b] Determined from soil moisture measurements.
[c] Estimated using the Soil-Plant-Air-Water (SPAW) model.
[d] Mills and Haluschak (1995).

characteristics from CanSIS as inputs to the SPAW model.

Three years (2013, 2014, and 2015) of climate data were used in this study. Daily meteorological data, which included maximum and minimum temperature (Model CS500, Campbell Scientific Inc., Edmonton, Canada), maximum and minimum relative humidity (Model CS500, Campbell Scientific Inc.), incoming solar radiation (Model SP-110, Apogee Instruments Inc., Logan, USA), wind speed (Model 05103, R.M. Young Company, Traverse City, USA) at 2 m high, and precipitation (Model TR525, Texas Electronics Inc., Dallas, USA) were recorded by data loggers (Model CR1000, Campbell Scientific Inc.) on automated weather stations located at the two sites. All sensors were purchased new from the manufacturers in 2011 and 2012 so had very recent factory calibrations performed on them with the exception of the CS500 temperature and relative humidity probes, which were older sensors but upgraded with new relative humidity chips prior to the beginning of the study. The tipping bucket rain gauges were checked for accuracy with a field calibration device (Model FCD, HyQuest Solutions Pty Ltd, Warwick Farm, Australia) either annually or every second year in the early spring and were sent for factory calibration at the end of the study (during winter 2015–2016). The solar radiation data from both sites were evaluated against theoretical clear sky values for the latitude, elevation, and other conditions for each site (following ASCE, 2005: Appendix D: Weather Data Integrity Assessment) and found to always fall within ± 5% on clear days during all growing seasons studied. All parameters used in the study for modeling ET from the primary weather stations were verified against data collected by secondary stations (Decagon Devices, Inc.) located at each field site. As well, for the conventional crop production field near Carberry, Manitoba, meteorological parameters (air temperature, relative humidity, wind speed, rainfall) were compared to data from weather stations independently operated by Environment and Climate Change Canada and Manitoba Agriculture located less than 1 km away.

The volumetric soil moisture content in each field was measured (Model 5TM, Decagon Devices Inc.) at 0.2, 0.5, and 1.0 m depths. Daily ET_c rates from the two sites were measured indirectly using the residual energy balance (REB) technique (Amiro, 2009; Bawazir et al., 2014). Previous studies conducted in Canadian boreal forest sites (Amiro, 2009) indicated that REB ET measurements agree well with the eddy covariance technique on daily, weekly, and seasonal scales. Data from the organic site in the present study has also shown excellent agreement between REB ET measurements and eddy covariance values at a daily time-step during growing season conditions (Glenn and Wilson, 2014). Using the REB technique, ET_c was estimated as the latent heat flux (LE) calculated from the residual of net radiation (R_n), soil heat flux (G), and sensible heat flux (H):

$$LE = R_n - G - H \tag{1}$$

Net radiation was calculated as the average measurement of two net radiometers (Model NR Lite2, Kipp & Zonen B.V., Delft, The Netherlands) installed in each field. Soil heat flux was measured from four points at each site using heat flux transducers [Model HFT3, Campbell Scientific Inc.] installed at 0.08 m below the soil surface and corrected for energy storage in the upper soil layers (Liebethal et al., 2005) using measurements from temperature and volumetric moisture probes (Model 5TM, Decagon Devices Inc.) installed at a depth of 0.05 m below the surface. Sensible heat flux was measured directly at each site using sonic anemometer-thermometers (81,000, R.M. Young Company at site 1; CSAT3, Campbell Scientific, Inc., Logan, USA at site 2) and the eddy covariance technique (Burba and Anderson, 2010).

The surface energy fluxes (R_n, G, H, and LE) were calculated as 30-min means and summed to obtain daily totals after gap-filling missing values. Gaps in the surface energy flux data occurred due to instrument and data-logger maintenance, malfunctions, inclement weather (e.g., rain or heavy dew on the sonic anemometers), and quality-control filtering. Small data gaps (< 2 h or four consecutive half-hours) were filled by linear interpolation for all variables. There were no gaps larger than 2 h for R_n or G for the datasets used in this analysis. Gaps longer than 2 h for H were filled based on linear relationships with available energy ($R_n - G$). The regression coefficients used to fill these gaps were adjusted over the growing season using a moving-window approach where fits of 240 observations at a time were incrementally solved in steps of 48 points for the half-hour datasets from each of the sites (Amiro, 2009; Eichelmann et al., 2016). For periods where available energy ($R_n - G$) was calculated to be less than zero, LE was forced to zero (Amiro, 2009). Daily ET_c was calculated by dividing the daily LE sums by the latent heat of vaporization for water.

2.2. Reference evapotranspiration models

Eight ET_r models with different degrees of complexity and data requirements were evaluated in this study (Table 2). The eight models include two combination models (i.e., FAO56 Penman-Monteith and Maulé et al. models), three radiation-based models (i.e.,

Table 2
Parameters required by the eight reference evapotranspiration (ET_r) models.

Model	Radiation	Humidity	Wind speed	Temperature
FAO56 Penman-Monteith (1998)	X	X	X	X
Priestley-Taylor (1972)	X			X
Makkink (1957)	X			X
Turc (1961)	X	X		X
Maulé et al. (2006)		X	X	X
Blaney-Criddle (1950)				X
Hargreaves-Samani (1985)				X
Hamon (1963)				X

Priestley-Taylor, Makkink, and Turc models), and three temperature-based models (i.e., Blaney-Criddle, Hargreaves-Samani, and Hamon models). Descriptions of the eight models are found in the Appendix A in supplementary file.

2.3. Simulation of crop evapotranspiration

The daily ET_c was estimated using the crop coefficient approach presented in FAO56 (Allen et al., 1998), which is expressed as:

$$ET_c = K_c ET_r \tag{2}$$

where ET_c is in mm/d and K_c is dimensionless. The K_c used in this study was a fourth order function of the cumulative GDD given in the form (Alberta Agriculture and Forestry, 2017b):

$$K_c = a + bx + cx^2 + dx^3 + ex^4 \tag{3}$$

where x is the cumulative GDD and a, b, c, d, and e are coefficients specific to the crop grown. Growing-degree days were estimated using the equation:

$$GDD = \left(\frac{T_{max} + T_{min}}{2}\right) - T_{base} \tag{4}$$

where T_{base} is the base temperature (°C) below which crop growth ceases. The reported base temperatures for most crops range from 0 °C to 10 °C (de Beurs and Henebry, 2010). The base temperature used in this study was 5 °C, assumed to be a reasonable base temperature for all crops at these study sites (Gordon and Bootsma, 1993; Alberta Agriculture and Forestry, 2017b). Since other studies (Sammis et al., 1985; Irmak et al., 2013a) suggested the potential transferability of GDD-based K_c to different locations with different climatic conditions assuming that temperature is the main factor affecting plant development characteristics, GDD-based K_c were used in this study.

Two sets of K_c values were employed in this study (Table 3). In the first set, the K_c for spring wheat, canola, and fall rye were adopted from AIMM (Alberta Agriculture and Forestry, 2017b) while values for millet and soybean were derived for this study. The derivation for millet and soybean K_c values used the growth stage-based crop coefficients and crop development stages presented in FAO56 (Allen et al., 1998) and the daily normal temperature of Beaver City, Nebraska, USA (National Oceanic and Atmospheric Administration, 2016). Beaver City was chosen to represent the climatic region where these crop parameters would generally be applicable (Allen et al., 1998). The crop coefficients used in AIMM were derived using the BREB method and the data for each crop were collected for two years in southern Alberta, Canada [Harms (personal communication)], while the base data for the FAO56 crop coefficients were obtained from across the world. The second set of K_c were the coefficients of the best fit fourth order polynomial curve for the ratio of observed ET_c to the product of ET_r estimated from the Penman-Montieth model and K_s estimated from measured soil moisture content [$K_c = ET_{c\text{-obs}}/(ET_{r\text{-PM}}{*}K_s)$; K_s is defined in the succeeding section]. We are aware, however, that comparing observed ET_c to the ET_c estimates using this second set of K_c would have a bias, yet, this was done for comparison purposes.

For method consistency, the AIMM crop coefficients that are based on alfalfa as the reference crop (Alberta Agriculture and Forestry, 2017b) were converted to grass-based coefficients (Eq. (5); Allen et al., 1998):

$$K_{c\,grass} = K_{ratio} K_{c\,alfalfa} \tag{5}$$

where K_{ratio} is 1.05 for humid and calm conditions, 1.20 for arid and moderately windy conditions, and 1.35 for arid and windy conditions (Allen et al., 1998). Accordingly, the value chosen for the study sites was 1.20.

2.4. Soil moisture considerations for actual crop evapotranspiration

As mentioned earlier, crops may experience various levels of moisture stress through their growth stages; thus, a dimensionless soil moisture stress coefficient (K_s) was introduced to Eq. (2) to account for the available water in the root zone:

Table 3
Values for the coefficients a, b, c, d, and e required to calculate growing degree day driven crop coefficients (K_c). The first set were taken from the AIMM model[x] or derived for this study[y] while the second set (values inside parenthesis) were the coefficients of the 4th order polynomial regression curve describing the ratio of observed ET_c to the product of ET_c from the Penman-Monteith equation and K_s from observed soil moisture content.

Crop	a	b	c	d	e
Canola[x]	8.71×10^{-2}	7.13×10^{-3}	-1.96×10^{-5}	2.31×10^{-8}	-9.63×10^{-12}
	(5.22×10^{-1})	(-2.00×10^{-3})	(1.00×10^{-5})	(-1.00×10^{-8})	(5.00×10^{-12})
Fall rye[x]	-2.03×10^{-2}	2.65×10^{-3}	6.30×10^{-8}	-2.18×10^{-9}	2.76×10^{-13}
	(4.14×10^{-1})	(3.40×10^{-3})	(-9.00×10^{-6})	(1.00×10^{-8})	(-4.00×10^{-12})
Millet[y]	4.79×10^{-2}	2.98×10^{-3}	-1.34×10^{-6}	-5.84×10^{-10}	-4.15×10^{-13}
	(7.01×10^{-1})	(4.00×10^{-4})	(9.00×10^{-7})	(-2.00×10^{-9})	(9.00×10^{-13})
Soybean[y]	3.40×10^{-1}	1.67×10^{-3}	-1.29×10^{-6}	5.85×10^{-10}	-1.43×10^{-13}
	(3.56×10^{-1})	(1.40×10^{-3})	(-8.00×10^{-7})	(8.00×10^{-10})	(-6.00×10^{-13})
Spring wheat[x]	4.79×10^{-2}	2.98×10^{-3}	-1.34×10^{-6}	-5.84×10^{-10}	-4.15×10^{-13}
	(4.09×10^{-1})	(-2.00×10^{-4})	(6.00×10^{-6})	(-8.00×10^{-9})	(3.00×10^{-12})

$$ET_{ca} = K_s K_c ET_r \tag{6}$$

where ET_{ca} is the actual ET_c, which is the crop evapotranspiration rate (mm/d) corrected for the availability of water in the root zone. Soil moisture stress coefficient was estimated as a logarithmic function of the actual available water (AW) and the total available water (TAW) (Alberta Agriculture and Forestry, 2017b):

$$K_s = \frac{log\left[\left(\frac{AW}{TAW}\right)100 + 1\right]}{\log(101)} \tag{7}$$

where values for K_s could range from 0 (maximum water stress) to 1 (minimum or no water stress). In this current study, the minimum value for K_s was set at 0.1 similar to what is applied in AIMM (Alberta Agriculture and Forestry, 2017b). Total available water is defined as the amount of water available to plants at field capacity, and was estimated as the difference between field capacity (FC) and wilting point (WP):

$$\mathrm{TAW} = \mathrm{FC} - \mathrm{WP} \tag{8}$$

Similarly, AW was calculated as:

$$\mathrm{AW} = \mathrm{SW} - \mathrm{WP} \tag{9}$$

where SW (mm) is the actual soil water content in the root zone. The daily SW was estimated using the water balance approach:

$$\mathrm{SW_t} = \mathrm{SW_{t-1}} + \mathrm{P} - \mathrm{ET_{ca}} - \mathrm{RO} - \mathrm{DP} \tag{10}$$

where P is precipitation (mm), RO is surface runoff (mm), and DP is the soil water that exceeds field capacity, and thus, percolates downward out of the root zone (mm) on day t. Runoff was estimated using the Soil Conservation Service (SCS) curve number procedure (SCS, 1972). It should be noted that no irrigation was applied to both fields during the period considered in this study.

2.5. Statistical analysis

Statistical approaches were used to quantitatively assess the performance of the models by comparing the measured ET_c fluxes against simulated actual ET_c fluxes. The statistical measures implemented include Nash–Sutcliffe model efficiency coefficient (NSE), root mean square error (RMSE), mean absolute error (MAE), mean percentage relative error (MRE), and coefficient of determination (R^2):

$$NSE = 1.0 - \frac{\sum_{i=1}^{N} (ET_{ca\,obs,i} - ET_{ca\,mod,i})^2}{\sum_{i=1}^{N} (ET_{ca\,obs,i} - \overline{ET_{ca\,obs}})^2} \tag{11}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N} (ET_{ca\,obs,i} - ET_{ca\,mod,i})^2\right]^{0.5} \tag{12}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |ET_{ca\,obs,i} - ET_{ca\,mod,i}| \tag{13}$$

$$MRE = \frac{1}{N}\sum_{i=1}^{N} \left\{\left(\frac{|ET_{ca_{obs},i} - ET_{ca_{mod},i}|}{ET_{ca_{obs},i}}\right)(100)\right\} \tag{14}$$

where subscripts *obs* and *mod* refer to the observed and modeled values, respectively, N is the number of observations, and the overbar indicates mean value. The indices RMSE, MAE, and MRE summarize the mean difference between measured and predicted values and the smaller the difference, the better is the agreement between measured and predicted results. The value of NSE ranges from negative infinity to 1.0 where higher values indicate better agreement. A value of 0 for NSE indicates that the observed mean is as good as the model prediction, while negative values indicate that the observed mean is better than the model prediction.

3. Results and discussion

3.1. Summary of measurement results

The mean temperatures and relative humidity at the two sites were comparable to growing season normals (1981–2010), except in 2015 which was relatively warmer (Table 4). The wind speeds were slightly lower than the height-adjusted normal value of 3.0 m/s. There may have been a bias caused by the measurement height correction itself or real differences in the surface roughness characteristics upwind of the cropland site weather stations. The seasonal precipitation values at the sites were generally higher than the normal except for 2015 at the organic farm which was slightly lower than normal for the area (Table 4). The 2014 and 2013 growing seasons were the wettest during the study for the organic and conventional sites, respectively, with 108–114 mm exceeding the normal. The normal solar radiation and ET_r values for the area were not available; however, the values for both sites compared

Table 4
Daily climate averages[a] (1st May to 31st October) in 2013, 2014, and 2015 at the two experimental sites in comparison to the 1981–2010 climate normal at a weather station in Brandon, Manitoba.

Parameter	Organic farm			Conventional farm			30-year normal[b]
	2013	2014	2015	2013	2014	2015	(1981–2010)
T_{mean} (°C)	13.9	13.8	14.2	13.5	13.5	14.1	13.1
RH_{mean} (%)	67.1	69.4	68.8	68.8	68.8	66.9	69.4
u_2 (m/s)	2.4	2.7	2.5	2.4	2.5	2.2	3.0[c]
R_s [MJ/(m^2 d)]	17.6	16.9	17.4	17.1	16.8	17.2	–
ET_r (mm/d)[d]	3.5	3.3	3.5	3.4	3.3	3.5	–
$Precip_{acc}$ (mm)	379.1	467.5	325.8	461.0	430.9	421.2	353.1

T_{mean} − mean temperature; RH_{mean} − mean relative humidity; u_2–wind speed at a 2 m height; R_s − solar radiation.
[a] Climate parameters are daily averages except precipitation (precip) which is the accumulated amount from 1st May to 31st October.
[b] Measurements taken at a weather station in Brandon, Manitoba (latitude: 49°54’36” N, longitude: 99°57’7” W, elevation: 409.40 m; http://climate.weather.gc.ca).
[c] Corrected for a height of 2 m.
[d] Reference evapotranspiration for short crop estimated using the Penman-Monteith equation.

well with each other.

The measured daily ET_c was found to have positive correlations with solar and net radiation, maximum and minimum temperature, vapour pressure deficit, and maximum relative humidity and negative correlations with minimum relative humidity and wind speed (Table 5). Higher correlations were obtained from radiation (net and solar radiation) and temperature (maximum and minimum temperature), which also agreed with the results obtained from the best fit curve regressions (Fig. 2). This verifies that the measured ET_c at the study sites was mostly driven by the energy available to evaporate water (e.g., radiation and temperature) and less so by the factors that removed water vapour from the vegetation surfaces (e.g., relative humidity and wind speed), as has been observed by other studies (Priestley and Taylor, 1972; Wang et al., 2007; Shi et al., 2008; Yang et al., 2014). It is surprising that ET had a negative relationship with wind speed; however, other studies (El Bably, 2003) also found similar result.

The seasonal ET_c of the crops (cumulative ET_c for the entire growing period) grown in southwestern Manitoba for this study was generally comparable to those published in the literature (Table 6). Literature values of growing season water-use for fall rye and canola tended to be lower than those measured in the current study (Table 6), however, the former studies were conducted in parts of Saskatchewan which have a more arid climate. The published values for soybean ET were higher than what were obtained in the current study, particularly for fields under irrigation (Table 6). However, those studies were conducted with longer season soybean cultivars under a warmer and wetter climate (Nebraska) than southern Manitoba. In the current study, soybean had the largest ET_c (Table 6), which also had the longest growing period (143 days) and millet had the lowest ET_c, which also had the shortest growing period (80 days).

3.2. ET_r models comparison

Using the FAO56 Penman-Monteith equation as the benchmark, errors (MRE) in the ET_r estimates by the other seven models ranged from 11% to 34% with the Maulé et al. equation producing the least error and the Blaney-Criddle model providing the largest (Table 7). The Maulé et al. equation, which accounts for the effects of radiation, humidity, and wind speed, showed the best fit probably because it was developed using climate data from the Canadian Prairies. The 0.87 NSE value obtained in this study was comparable to the 0.93 value obtained by Maulé et al. (2006) for their equation against the Penman-Monteith equation. De Jong and Tugwood (1987) obtained errors up to 20% by the Penman-Monteith equation and up to 25% by the Priestley-Taylor equation against adjusted Class A pan data collected from eight weather stations across Canada. Under a semi-arid climate in Iran, Tabari (2010) found errors up to 37% by various models (i.e., Turc, Priestley-Taylor, Makkink, and Hargreaves-Samani) against the Penman-Monteith equation with the Hargreaves-Samani model providing the best fit. When contrasted against the Penman-Monteith equation, the Priestley-Taylor (NSE of 0.96) and Hargreaves-Samani (NSE of 0.97) models were found to work best in a semi-arid region in China (Gao et al., 2017). In this current study, the Hargreaves-Samani model ranked fourth among the seven models with a NSE value of 0.70 (18% error), which is comparable to the 0.74 obtained by Maulé et al. (2006). The relatively good performance of the Hargreaves-Samani model, in comparison to the Penman-Monteith model, for the semi-arid to sub-humid climate of the Canadian

Table 5
Pearson correlation coefficients between measured daily ET_c and meteorological parameters for two sites near Brandon, Manitoba, in the years 2013–2015.

Meteorological parameters	T_{max}	T_{min}	RH_{max}	RH_{min}	VPD	u_2	R_s	R_n
ET_c	0.59**	0.50**	0.17**	−0.15**	0.44**	−0.31**	0.76**	0.82**

** Correlation is significant at the 0.01 level.
ET_c − crop evapotranspiration; T_{max} and T_{min} − maximum and minimum temperature, respectively; RH_{max} and RH_{min} − maximum and minimum relative humidity, respectively; VPD − vapour pressure deficit; u_2–wind speed at 2 m above surface level; R_s − solar radiation; R_n − net radiation.

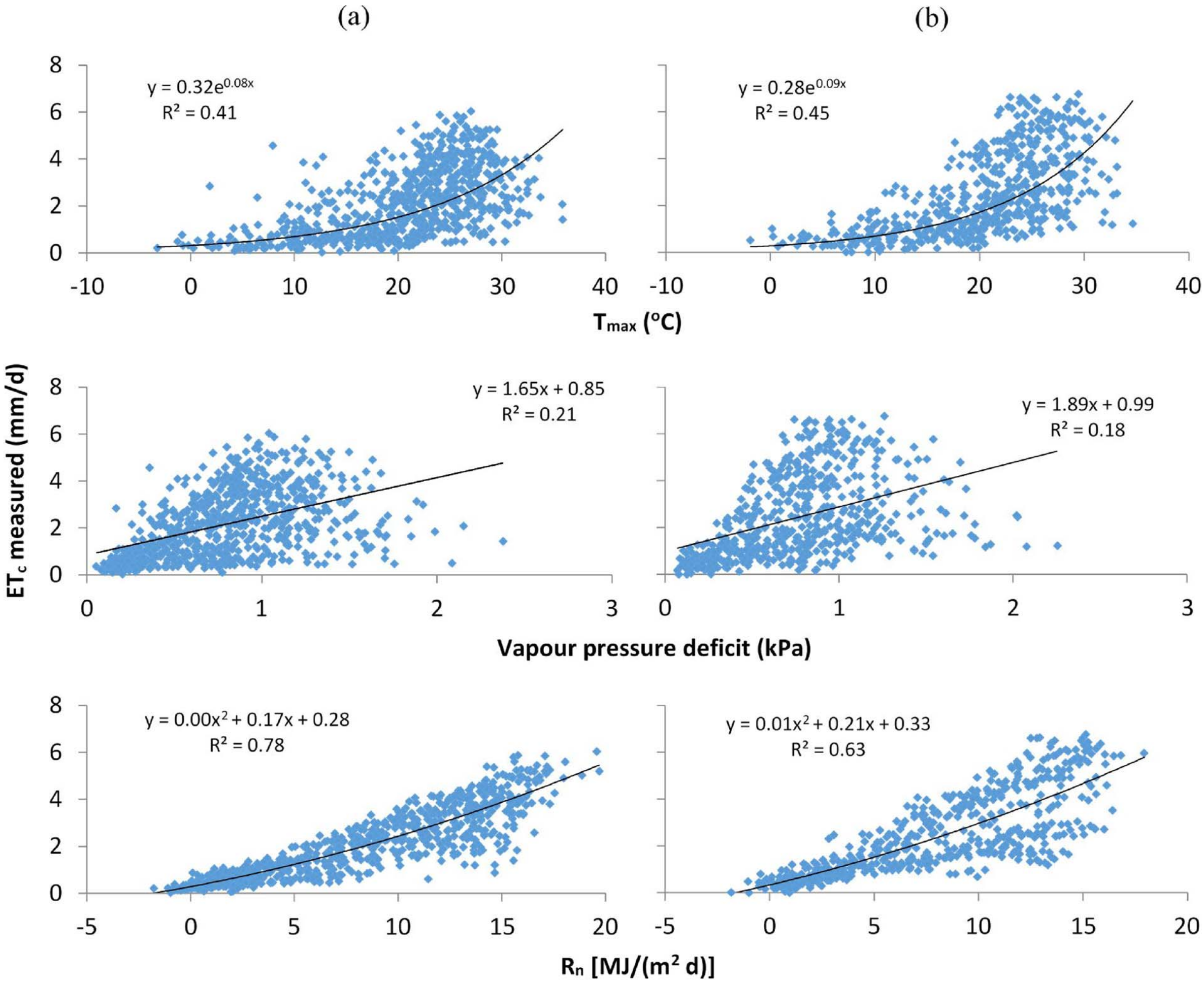

Fig. 2. Best fit curves for the relationship between daily measured ET_c and some of the climatic parameters [i.e., maximum temperature (T_{max}), vapour pressure deficit, and net radiation (R_n)] measured at the (a) organic site and (b) conventional site.

Table 6
Measured and literature reported seasonal crop evapotranspiration (ET_c) for five crops grown at two sites near Brandon, Manitoba, in the years 2013–2015.

Crop	ET_c (mm)		
	From the current study	From the literature (location)	Reference
Proso millet	243	202[a]–372[a] (Colorado)	Shanahan et al. (1988)
Fall rye	367	143–287[a] (Saskatchewan)	Gan et al. (2000)
Soybean	404	431[a]–452[b] (Nebraska); 514–535[b] (Nebraska)	Suyker and Verma (2009); Irmak et al. (2013b)
Spring wheat	350	281–345[a] (Saskatchewan); 350–450[a] (Saskatchewan, Manitoba); 420–480[c] (Alberta)	Kröbel et al. (2014); Gervais et al. (2012); Alberta Agriculture and Forestry (2016)
Canola	353	264–286 (Saskatchewan); 250–450 (Alberta, Saskatchewan, and Manitoba); 400–480[c] (Alberta)	Cutforth et al. (2006); Cardillo (2014); Alberta Agriculture and Forestry (2016)

[a] Rainfed.
[b] Irrigated.
[c] Crop water requirement under optimal conditions.

Prairies would be important, particularly for those weather stations that have temperature measurement only.

3.3. Simulated actual crop evapotranspiration

As similar K_c and K_s values were applied across all the models, variations among the actual ET_c estimates would be due only to the

Table 7
Comparison of the reference evapotranspiration (ET_r) models against the Penman-Monteith equation.

ET_r model	NSE (−)	RMSE (mm/d)	MAE (mm/d)	MRE (%)	Rank
PT	0.74	0.68	0.48	14	3
MK	0.48	0.95	0.81	24	5
TR	0.77	0.63	0.44	15	2
ML	0.87	0.47	0.36	11	1
BC	0.27	1.13	0.86	34	7
HS	0.70	0.72	0.57	18	4
HM	0.31	1.09	0.90	25	6

PT − Priestley-Taylor; MK − Makkink; TR − Turc; ML − Maulé et al.; BC − Blaney- Criddle; HS − Hargreaves-Samani; HM − Hamon.

ET_r inputs from the different models. Comparison of daily simulated actual ET_c from the different ET_r models (and using the first set of K_c) against observed ET_c produced errors (MRE) ranging from 23% to 68% with the Makkink model having the least error and the Blaney-Criddle model providing the largest error (Table 8). The other statistical indices (NSE, RMSE, and MAE), however, show the best fit of the Turc model. Overall, on a daily basis, the Turc model produced the smallest error (RMSE) among the eight models, followed by the Makkink, Priestley-Taylor, and Penman-Monteith models. This indicates that simpler models such as the Makkink and Turc models can provide estimates comparable to those of the Penman-Monteith model for the crops and agroclimatic conditions at the sites. The better performance of the radiation-based models agrees with the high correlation found between measured ET_c and radiation (Table 5; Fig. 2). When compared against the Penman-Monteith equation, Tabari (2010) found the Turc model as the best model (RMSE = 0.284–1.106 mm/day) in estimating ET in cold humid and arid climates, similar to the climates under which the model was developed. However, it was also found to perform well for the semi-arid climate of southern Greece (Xystrakis and Matzarakis, 2011) and the sub-humid climate of Kharagpur, India (RMSE ranging from 0.39 to 0.53 mm/day) (Srivastava et al.,

Table 8
Quantitative measures on the performance of the eight reference evapotranspiration models employed in the simulation of crop evapotranspiration (using the first set of K_c) at two sites near Brandon, Manitoba, in the growing periods of 2013–2015 on daily time step.

Statistical index	PM	PT	MK	TR	ML	BC	HS	HM
R^2 (−)								
Millet	0.34	0.35	0.34	0.36	0.24	0.11	0.19	0.08
Fall rye	0.42	0.50	0.57	0.54	0.37	0.25	0.38	0.42
Soybean	0.81	0.84	0.87	0.87	0.68	0.55	0.71	0.54
Spring wheat	0.50	0.54	0.71	0.64	0.36	0.06	0.40	0.37
Canola	0.41	0.50	0.60	0.57	0.34	0.04	0.24	0.29
Rank	*4*	*3*	*1*	*2*	*5*	*8*	*6*	*7*
NSE (−)								
Millet	−0.19	−0.28	−0.22	−0.21	−0.29	−0.94	−0.59	−0.61
Fall rye	0.08	0.07	0.16	0.12	0.01	−0.11	−0.02	0.04
Soybean	0.75	0.77	0.68	0.79	0.61	0.54	0.68	0.48
Spring wheat	0.32	0.30	0.43	0.46	0.20	−0.56	0.20	0.13
Canola	0.34	0.44	0.55	0.53	0.29	−0.28	0.11	0.20
Rank	*3*	*3*	*2*	*1*	*5*	*8*	*6*	*7*
RMSE (mm/d)								
Millet	1.16	1.20	1.18	1.17	1.21	1.48	1.34	1.35
Fall rye	1.40	1.41	1.34	1.36	1.45	1.53	1.48	1.43
Soybean	0.78	0.74	0.87	0.70	0.96	1.05	0.87	1.12
Spring wheat	1.38	1.40	1.26	1.23	1.50	2.09	1.49	1.55
Canola	1.37	1.26	1.12	1.15	1.42	1.90	1.58	1.50
Rank	*4*	*3*	*2*	*1*	*5*	*8*	*6*	*7*
MAE (mm/d)								
Millet	0.87	0.94	0.77	0.87	0.86	1.15	1.02	1.00
Fall rye	1.03	1.09	0.99	1.02	1.09	1.16	1.09	1.06
Soybean	0.63	0.56	0.69	0.56	0.79	0.84	0.68	0.91
Spring wheat	1.06	1.12	0.93	0.90	1.22	1.66	1.18	1.31
Canola	1.11	1.00	0.90	0.88	1.17	1.63	1.35	1.24
Rank	*3*	*4*	*2*	*1*	*5*	*8*	*6*	*7*
MRE (%)								
Millet	33	36	26	32	32	49	41	37
Fall rye	46	49	43	44	51	64	49	48
Soybean	32	23	26	26	38	54	34	47
Spring wheat	38	38	29	30	50	68	47	50
Canola	41	41	32	35	45	63	54	51
Rank	*4*	*3*	*1*	*2*	*5*	*8*	*6*	*7*

PM − Penman-Monteith; PT − Priestley-Taylor; MK − Makkink; TR − Turc; ML − Maulé et al.; BC − Blaney- Criddle; HS − Hargreaves-Samani; HM − Hamon.

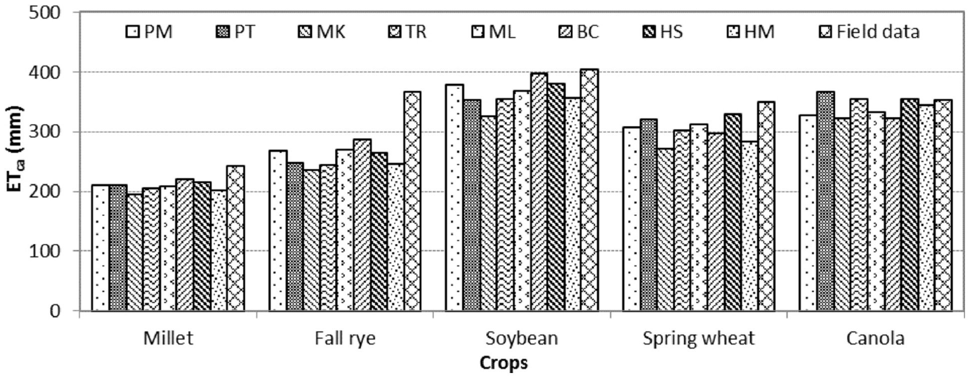

Fig. 3. Cumulative measured ET_c compared to estimated growing season actual ET_c (using the first set of K_c) for millet, fall rye, soybean, spring wheat, and canola grown at two sites in Southern Manitoba, using different ET_r models (PM − Penman-Monteith; PT − Priestley-Taylor; MK − Makkink; TR − Turc; ML − Maulé et al.; BC − Blaney-Criddle; HS − Hargreaves-Samani; HM − Hamon).

2016). Although the Makkink model was developed under temperate humid conditions, Schneider et al. (2007) also found it to give accurate estimates for ET (RMSE = 0.59–0.69 mm/day) in a semi-arid region of northern China.

On a seasonal scale, all the eight models resulted in relatively smaller errors as uncertainties tended to balance out on longer time scales; however, the temperature-based Hargreaves-Samani and Blaney-Criddle models produced the least errors (Fig. 3). The daily overestimates by the Blaney-Criddle model were compensated by daily underestimates, which were more evident throughout the growth period of the millet (Fig. 4a) and spring wheat (Fig. 4d) crops; hence, it provided similar seasonal totals (Fig. 3). Although the Hargreaves-Samani and Blaney-Criddle models performed well on longer time scales, more studies are required to better understand the differences on the performance of these models under different time scales and to verify if this would hold under other conditions and crops.

Results from the ET_c comparison (Table 8) were slightly different from those of the ET_r comparisons (Table 7), except for the Turc model which showed good performance in both analyses. The equation developed by Maulé et al. (2006), which provided the most accurate estimates for the Penman-Monteith equation (Table 7), did not perform any better than the radiation-based models (i.e., Turc, Makkink and Priestley-Taylor models) (Table 8). The differences observed in the outcomes could be caused by a number of reasons. First, validating a model with another model may not always be preferable, as mentioned earlier. Although the Penman-Monteith model is the widely accepted standard procedure for ET calculation and has shown to be the most accurate ET_r model in many studies, it can sometimes be outperformed by other models. Douglas et al. (2009) found the ET estimates of the Priestley-Taylor and Turc equations more accurate than those of the Penman-Monteith model (the older version) when compared against eddy covariance and Bowen ratio data collected over a variety of land cover types in Florida. In addition, the Hargreaves-Samani and Makkink equations were also found to perform better than the Penman-Monteith equation when actual ET_c estimates from the Soil and Water Assessment Tool (SWAT) using these models were compared to eddy flux measurements collected in a semi-arid watershed area in northern China (Schneider et al., 2007). A second reason is that inaccuracies in the actual ET_c estimates are also affected by the discrepancies in K_c and K_s values. Thus, the larger errors observed in the ET_c comparisons (Table 8) were probably due to the errors in the K_c and K_s estimates.

When actual ET_c values were estimated using the second set of K_c [$K_c = ET_{c\text{-}obs}/(ET_{r\text{-}PM}*K_s)$], errors were smaller and most other statistical indicators of model performance were substantially improved (Table 9) compared to those obtained using the first set of K_c (Table 8). This difference was expected as the second set of K_c values was based on trends in the actual ET observations made at the study sites. However, both K_c approaches produced similar model ranking results with the Turc model providing the best fit and the Blaney-Criddle model giving the poorest estimate, which could indicate the transferability of GDD-based K_c, though, more studies are needed to further investigate this. While the accuracy of the K_s values could also affect the actual ET_c estimates, given that soil properties were not varied in both comparisons (Tables 8 and 9) and that both used similar ET_r inputs, any differences/similarities in the outputs of both analyses could only be due to the K_c values. The relatively large errors obtained using both sets of K_c values (Tables 8 and 9) might be a reflection of the limited amount of measurement data used in their derivation. The one-year data used for the derivation of the second set of K_c, the two-year data for AIMM K_c, and the climate normal used in the derivation for millet and soybean K_c might not have been sufficient to establish accurate K_c.

The discrepancies in the first set of K_c values can also be seen in the inconsistencies between measured and modeled actual ET_c observed after planting and before harvest (Fig. 4). These differences would increase if precipitation amounts would differ from the setting from which the crop coefficients were developed. Since the first set of crop coefficients used in this study take into account the combined effects of evaporation and transpiration, the variation in evaporation rates, particularly during the start and towards the end of the growing period where evaporation is dominant, might not have been fully accounted for in the coefficients. For example, prior to planting the proso millet crop on June 25, 2013, the organic site received 60 mm of rainfall over June 22 and 23, as well as, an additional 36 mm from June 25 to June 26 following seeding. This precipitation (96 mm total) around the seeding of the crop evidently lead to high rates of evaporation under the conducive thermal and radiative regimes of late June and early July that were not captured by the crop coefficient used (Fig. 4a). Correction factors could probably help rectify this problem; however, there is none

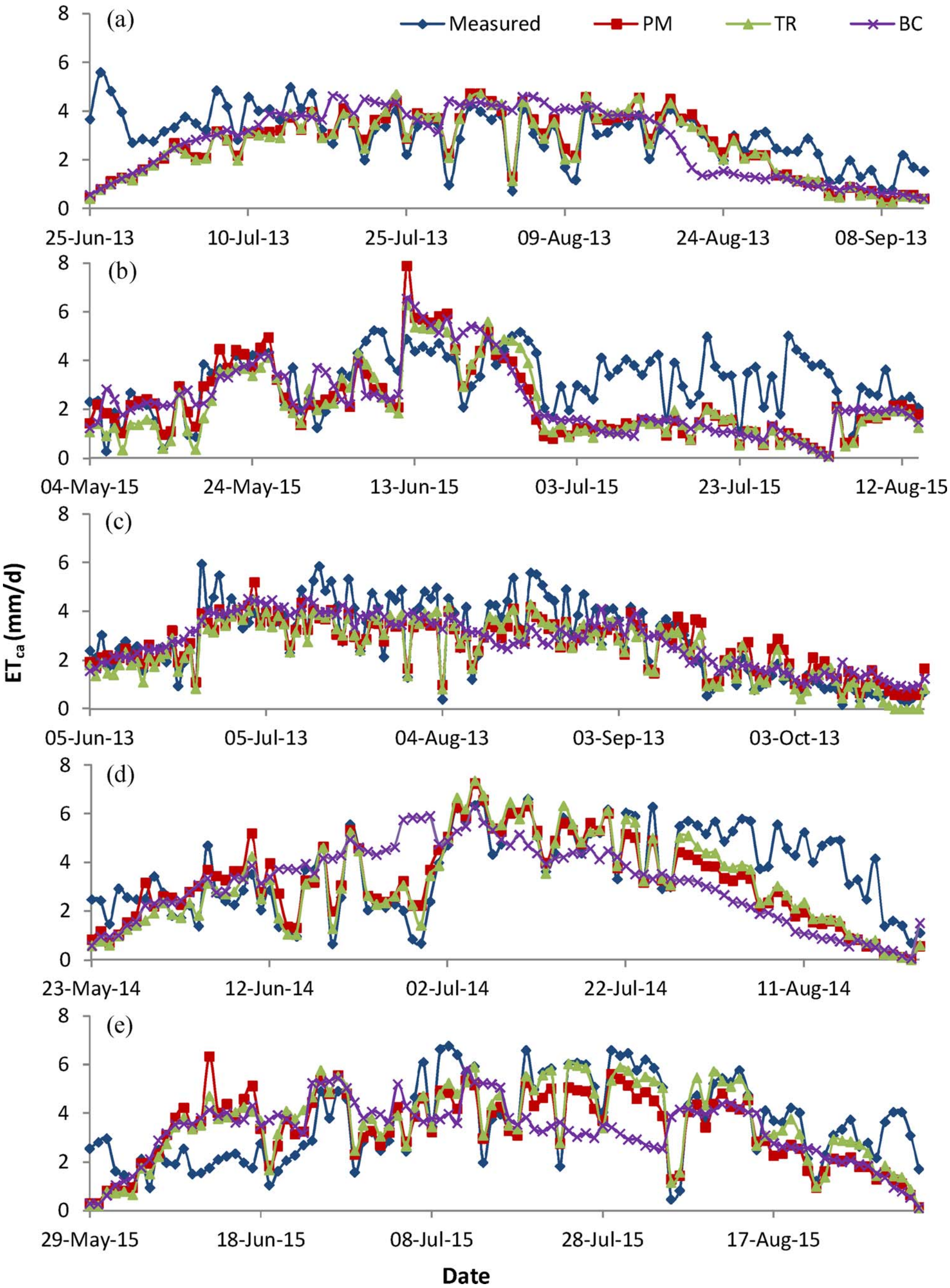

Fig. 4. Measured and estimated actual ET_c (using the first set of K_c) for (a) millet, (b) fall rye, (c) soybean, (d) spring wheat, and (e) canola. Actual ET_c estimates used the ET_r values calculated from the Penman-Monteith (PM), Turc (TR), and Blaney-Criddle (BC) models.

available yet in the literature for GDD-based crop coefficients. For growth stage-based coefficients, FAO56 outlines a method to correct the crop coefficient for the initial stage; however, it seems difficult to adapt this approach to the GDD-based coefficients as length of growth stages varies with heat units. It is also worth mentioning that the K_c for fall rye in both sets were derived using data collected from May 1st until harvest (the same year) only; however, the derived K_c was applied to the entire growth period (mid-September to mid-August the following year). This means that the K_c for fall rye was derived using a portion only of its total growth period. This limitation might have caused the discrepancy between modeled and observed ET_c towards the end of its growth period (Fig. 4b).

Table 9
Quantitative measures on the performance of the eight reference evapotranspiration models employed in the simulation of crop evapotranspiration (using the second set of K_c) at two sites near Brandon, Manitoba, in the growing periods of 2013–2015 on daily time step.

Statistical index	PM	PT	MK	TR	ML	BC	HS	HM
R^2 (−)								
Millet	0.76	0.68	0.84	0.79	0.64	0.31	0.47	0.38
Fall rye	0.41	0.57	0.67	0.60	0.31	0.21	0.34	0.50
Soybean	0.77	0.75	0.90	0.85	0.68	0.50	0.62	0.65
Spring wheat	0.65	0.67	0.86	0.78	0.53	0.08	0.52	0.51
Canola	0.85	0.79	0.89	0.85	0.74	0.33	0.59	0.45
Rank	*4*	*3*	*1*	*2*	*5*	*8*	*6*	*7*
NSE (−)								
Millet	0.63	0.54	0.47	0.63	0.48	0.04	0.36	0.15
Fall rye	0.25	0.33	0.38	0.36	0.13	0.01	0.14	0.28
Soybean	0.76	0.69	0.85	0.82	0.65	0.45	0.58	0.62
Spring wheat	0.62	0.61	0.72	0.73	0.52	−0.31	0.49	0.45
Canola	0.70	0.78	0.83	0.83	0.57	0.27	0.57	0.42
Rank	*3*	*4*	*2*	*1*	*5*	*8*	*6*	*7*
RMSE (mm/d)								
Millet	0.64	0.72	0.78	0.65	0.77	1.04	0.85	0.98
Fall rye	1.26	1.20	1.15	1.17	1.36	1.45	1.36	1.23
Soybean	0.77	0.86	0.61	0.67	0.91	1.15	1.01	0.96
Spring wheat	1.03	1.04	0.88	0.87	1.15	1.91	1.20	1.24
Canola	0.92	0.78	0.70	0.69	1.10	1.43	1.10	1.28
Rank	*4*	*3*	*2*	*1*	*5*	*8*	*6*	*7*
MAE (mm/d)								
Millet	0.50	0.56	0.66	0.53	0.61	0.82	0.66	0.79
Fall rye	0.92	0.84	0.84	0.84	1.01	1.09	0.98	0.94
Soybean	0.59	0.68	0.48	0.53	0.72	0.87	0.78	0.77
Spring wheat	0.79	0.78	0.66	0.61	0.93	1.46	0.93	1.04
Canola	0.76	0.63	0.53	0.54	0.90	1.16	0.91	0.98
Rank	*4*	*3*	*2*	*1*	*5*	*8*	*6*	*7*
MRE (%)								
Millet	18	22	22	19	21	36	27	29
Fall rye	47	38	34	38	54	63	48	46
Soybean	25	32	22	27	30	44	36	37
Spring wheat	27	25	19	19	37	60	36	41
Canola	23	22	16	18	29	44	34	39
Rank	*4*	*3*	*1*	*2*	*5*	*8*	*6*	*7*

PM − Penman-Monteith; PT − Priestley-Taylor; MK − Makkink; TR − Turc; ML − Maulé et al.; BC − Blaney- Criddle; HS − Hargreaves-Samani; HM − Hamon.

4. Summary and conclusions

The mean temperatures and relative humidity at the two sites compared well with the growing season normals (1981–2010), except in 2015 which was relatively warmer. The growing season precipitation totals at the measurement sites were generally higher than the normal, with 2014 and 2013 being the wettest during the study for the organic and conventional fields, respectively. Correlations between measured ET_c at the sites and climate variables indicated that ET during the study period was mostly driven by the energy available to evaporate water (e.g., radiation and temperature) and less so by the factors that removed water vapour from the vegetation surfaces (e.g., relative humidity and wind speed). The seasonal cumulative ET_c of the crops grown in southwestern Manitoba for this study fell within the expected range of previously published values.

Comparison of the seven models against the FAO56 Penman-Monteith equation showed the Maulé et al. equation as the best alternative to the Penman-Monteith equation for estimating reference ET in the study sites. However, results were different when actual ET_c estimated using the eight models (including the Penman-Monteith equation) were evaluated against measured ET_c. Applying two sets of K_c values, which were derived using data from different locations and climatic/environmental conditions, showed the Turc model as the most accurate and the Blaney-Criddle model as the least accurate on a daily time scale. The comparability of the model ranking results from the two sets of K_c could indicate the transferability of GDD-based K_c to various locations and climatic conditions; however, more studies are needed to further investigate this. The errors obtained in this study were contributed not only by the approaches and meteorological parameters accounted for by the ET_r models but also by the inaccuracies of the K_c values as a result of limited data used in their derivation. Further, as the GDD-based K_c did not account separately for the evaporation and transpiration components; larger errors were observed after planting and prior to harvest when evaporation was the dominant process. Discrepancies became more pronounced when there were more rainfall events. Correction factors could probably help rectify this problem; however, there is none available yet in the literature for GDD-based K_c. Separate accounting for evaporation and transpiration could also help address this issue, however, additional data is needed to develop the method.

In general, the radiation-based models performed better than the temperature-based models on a daily time step. However, further studies on longer time scales are needed to assess the relevance of the temperature-based Hargreaves-Samani and Blaney-

Criddle models for calculation of ET in the Canadian Prairies as they may be important for locations having temperature measurement only.

Results of this study provide additional insights on which models to consider that could give accurate ET estimates in the Canadian Prairies. Accurate ET models are important components in estimating regional water balances, for efficient water resources planning and management, and for better understanding of environmental impacts of water use in agriculture. This study also shows the potential transferability of GDD-based K_c across different locations and climatic conditions; however, more studies with validated GDD-based K_c are needed to further investigate this finding. As it was found that K_c coefficients derived using data collected from the study sites produced better fit, it is recommended to collect more data in the region to establish more accurate GDD-based K_c. If reliable GDD-based K_c for various crops were made available and their application to various locations and climatic conditions were proven meaningful by more studies, then crop water use calculations in various related applications would be fairly straightforward.

Conflict of interest

The authors declare that there are no conflicts of interest associated in this manuscript.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ejrh.2017.11.010.

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