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Comparison of Methods for Estimating Crop Water Use: Sap Flow, FAO-56 Penman-Monteith, and Weather Parameters

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Abstract

Knowing crop water uptake each day is useful for developing irrigation scheduling. Many technologies have been used to estimate daily crop water use. Sap flow is one of the technologies that measure water flow through the stem of a plant and estimate daily crop water uptake. Sap flow sensor is an effective direct method for measuring crop water use, but it is relatively expensive and requires frequent maintenance. Therefore, alternative methods, such as evapotranspiration based on FAO 56 Penman-Monteith equation and other weather parameters were evaluated to find the correlation with sap flow. In this study, Dynamax Flow 32-1K sap flow system was utilized to monitor potato water use. The results show sap flow has a strong correlation with evapotranspiration (RMSE = 1.34, IA = 0.89, MBE = −0.83), solar radiation (RMSE = 2.25, IA = 0.72, MBE = −1.80), but not with air temperature, relative humidity, wind speed, and vapor pressure. It is worth noting that the R^2 between sap flow and relative humidity was 0.55. This study has concluded that daily evapotranspiration and solar radiation can be used as alternative methods to estimate sap flow.

Keywords

Crop Water Use, Irrigation, Sap Flow, Evapotranspiration, Weather Parameter

1. Introduction

Understanding crop water use is important to develop irrigation scheduling, which will improve irrigation water use efficiency and maximize crop production and quality. Common methods to estimate crop water use are based on reference evapotranspiration [1] [2] [3] [4]. Reference evapotranspiration (ET) assumes a 4-inch grass-covered surface that is well-watered and unshaded. Actual crop evapotranspiration can be calculated using a crop coefficient, which is a multiplier. The crop coefficient depends on the crop type and its development stage. Food and Agricultural Organization (FAO) of the United Nations (UN) has crop coefficients for the specific development of crops [5]. Many previous studies have proven to estimate crop water use using evapotranspiration, which can improve irrigation water use efficiency and increase crop production and quality. For example, according to a study conducted in Florida, ET-based irrigation scheduling for papaya reduced water use by 65% [6]. In addition, a study of head lettuce and broccoli found that irrigating based on evapotranspiration data resulted in the same crop yield while using well below the amount of water that was previously being applied [7]. A study conducted in Texas, have found that irrigation scheduling based on evapotranspiration in a corn field, resulted in greater grain yield with less water [8]. Evapotranspiration-based irrigation scheduling is an indirect method to estimate the crop water use. Direct measurements of crop water use can help increase the accuracy of measuring crop water use.

The heat balance method is a direct method to measure crop water use. The sap flow measurement is based on the amount of heat carried by the sap through the stem of a plant. Sap flow is the measurement of the water, nutrients, and hormones in the water that flows through the stem of a plant. In addition to the heat balance method, the heat pulse velocity method has been used by sap flow sensors. This method requires calibration and stem intrusion, which are two drawbacks compared to the heat balance method [9]. Utilizing SAP flow sensor is effective for evaluating the crop water uptake [10], however, these sensors are relatively expensive and require high maintenance [11]. Previously, SAP flow sensors have been mostly used in woody plants [12]-[22], and a few studies utilized the sap flow sensors for row crops [23] [24] [25]. Thus, assessing sap flow in row crops and finding its relationship with other environmental parameters is worth exploring. The purpose of this study is to investigate the correlation between sap flow and various weather parameters (ET-based FAO-56 Penman-Monteith equation, solar radiation, air temperature, wind speed, humidity, vapor pressure) in row crops.

2. Materials and Methods

2.1. Field Experiment Setup

This study was conducted at Michigan State University Montcalm AgBio Research Center in 2022 (Lakeview, Michigan, USA). The research plot has the Mackinac (MSX540-4) potato variety. Soil samples were collected at 6-, 12-, and 18-inch depths using a soil ring. The samples were sent to Michigan State University Soil and Plant Nutrient Lab (East Lansing, MI) for analysis. The soil characteristic of the plot is shown in **Table 1**.

Table 1. Soil characteristics of the site.

Depth (inch)	pH	Organic Matter (%)	Sand (%)	Silt (%)	Clay (%)	Texture
6	4.6	2.1	74.5	13.8	11.7	Sandy Loam
12	4.4	2.1	73.5	14.8	11.7	Sandy Loam
18	4.6	1.1	78.5	10.8	10.7	Sandy Loam

2.2. Sap Flow Measurement

The Flow 32-1K system, manufactured by Dynamax Inc. (Houston, Texas, USA), was used in this study to measure the sap flow of the potato plants. The datalogger enclosure was mounted to a 3.81 cm (1.5-inch) PVC pipe which was mounted onto a T-post driven into the ground. Three SGA9 sensors were then installed.

The installation entails:

1) Locating a section of the potato stem large enough to fit the sensor.

2) Smoothing the surface using sandpaper.

3) Spraying 100% pure natural oil onto the stem to prevent the sensor from sticking to the plant.

4) Insulating compound was applied to the inside of the sensor.

5) Wrapping the sensor and around the stem, which were installed on the bottom part of the stem. This can be seen in **Figure 1**.

(a) (b)

Figure 1. (a) Installed SAP flow sensors on potato plant stems; (b) installed sap flow data-logger and solar panel.

Parameters had to be set for each sensor using the PC400 software. The sensor type, SGA9, was selected. The thermocouple gap was set to 4 mm. The cross-sectional area of the stem was calculated using the stem diameter and was specified in the software. The plants' stem constant was selected to the recommended value of 0.54. The data for each sensor will then be collected and exported to excel files. The data was calculated in grams of water per hour.

SAP Flow is calculated using Equation (1) [26].

$$F = \frac{P_{in} - Q_v - Q_r}{C_p \cdot dT} \tag{1}$$

where, F is sap flow (g/s); P_{in} is the power of the heater (W); Q_v is the vertical conduction; Q_r is the radial conduction; C_p is the specific heat of water (4.186 J/(g·˚C)); dT is temperature increase of sap (˚C).

2.3. Reference Evapotranspiration

Reference ET data was obtained from Michigan State University Enviroweather weather station (**Figure 2**). This station is located at Michigan State University Montcalm AgBio Research Center (Lakeview, MI). The weather station provides 5-min, hourly, and daily weather data such as air temperature, humidity, leaf wetness, soil moisture (0 - 60 cm), precipitation, soil temperature, total solar flux, wind speed, and wind direction. Reference ET was calculated using the FAO 56 Penman-Monteith, which is shown in Equation (2) [5].

Figure 2. Michigan state university enviroweather station at montcalm agibio research center (Lakeview, MI).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where, ET_0 is reference evapotranspiration (mm/day); R_n is net radiation at the crop surface (MJ/(m^2·day)); G is soil heat flux density (MJ/(m^2·day)); T is air temperature at 2 m height (˚C); u_2 is wind speed at 2 m height (m/s); e_s is saturation vapor pressure (kPa); e_a is actual vapor pressure (kPa); $e_s - e_a$ is saturation vapor pressure deficit (kPa); Δ is slope vapor pressure curve (kPa/(˚C)); Δ is psychrometric constant (kPa/(˚C)).

Once the reference ET was obtained, the crop coefficient was used to calculate the actual crop ET. Equation (3) describes the calculation for the actual crop coefficient. Potato crop coefficient changes as potatoes grow. When a potato is in the reproductive stage, the crop coefficient is 1.27 [27], which was used in this study.

$$ET_C = K_C * rPET \tag{3}$$

where, ET_c is Actual Crop Evapotranspiration (in/day); K_c is Crop Coefficient (unitless multiplier); $rPET$ is Reference ET (in/day).

The dew point was obtained using air temperature and relative humidity from the Enviroweather station and Equation (4) [28]. The vapor pressure was obtained from the dewpoint using Equation (5) [29].

$$t_d = \frac{B_1\left(\ln\left(\frac{RH}{100}\right)+\frac{A_1 t}{B_1+t}\right)}{A_1-\ln\left(\frac{RH}{100}\right)-\frac{A_1 t}{B_1+t}} \tag{4}$$

where, t_d is dewpoint temperature (˚C); B_1 = 243.04 (˚C); A_1 = 17.625; RH is relative humidity (%).

$$e = 6.11\times 10^{\frac{7.5\cdot t_d}{237.3+t_d}} \tag{5}$$

where, e is vapor pressure (mb); t_d is dewpoint temperature (˚C).

2.4. Statistical Analysis

Coefficient of determination (R^2), Root Mean Squared Error (RMSE), Index of Agreement (IA), and Mean Bias Error (MBE) were used to compare the sap flow measurement with weather parameters. RMSE measures the difference between the measured and predicted value and is defined in Equation (6), IA is defined in Equation (7), and MBE is defined in Equation (8) [30].

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(M_i - P_i\right)^2} \tag{6}$$

$$\text{IA} = 1 - \frac{\sum_{i=1}^{N}\left(M_i - P_i\right)^2}{\sum_{i=1}^{N}\left(\left|P_i - \bar{M}\right| + \left|M_i - \bar{M}\right|\right)^2} \tag{7}$$

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N}\left(P_i - M_i\right) \tag{8}$$

where, N is sample size; M is measured value; P is predicted value; $\bar{M}$ is average measured value.

3. Results and Discussion

3.1. Sap Flow Observation

Figure 3 shows the sap flow measurement using Flow 32-1K system. The data shows the changes in potato water uptake throughout each day. Sap flow peak during the middle of each day, then drops to zero overnight. Days 8 and 13 were cloudy, resulting in a low sap flow rate. On sunny days, the sap flow rate was high.

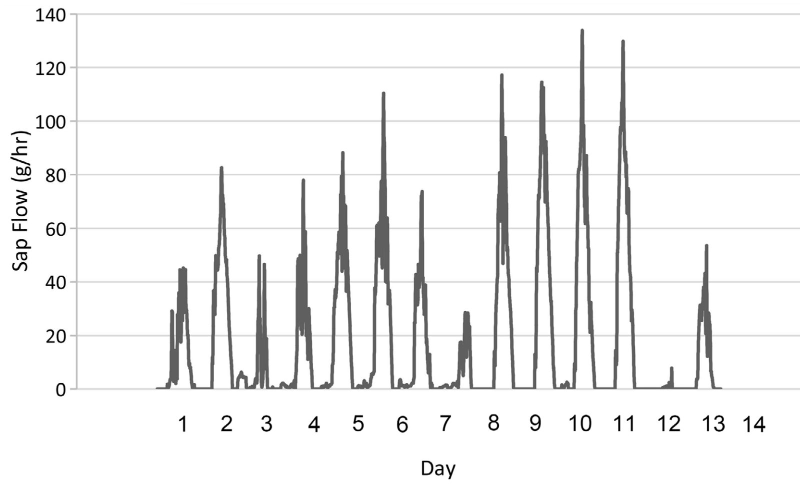

Figure 3. The changes in sap flows of Mackinac (MSX540-4) potato at reproductive stage.

3.2. Comparison of Sap Flow and Reference Evapotranspiration

The total hourly sap flow of potato was compared to the hourly ET obtained from the Michigan State University Enviroweather station. Based on **Figure 4**, there is a strong correlation between sap flow and ET, indicated by the R^2 of 0.94. This result shows a strong correlation between potato sap flow and ET. A previous study shows that the sap flow of a tree was equivalent to ET when normalized via leaf area [31].

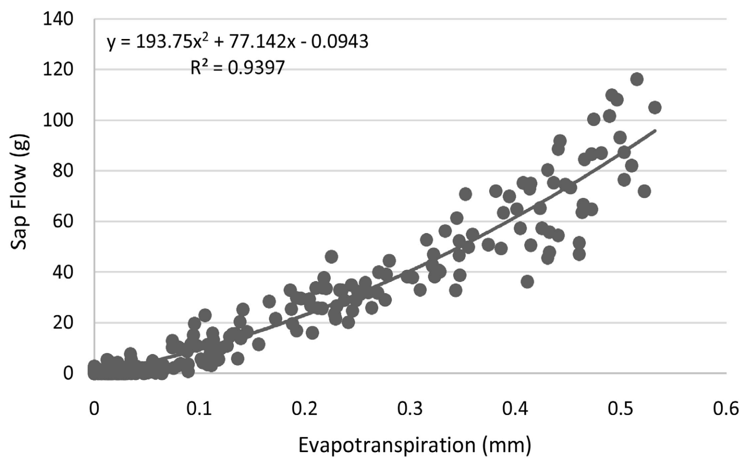

Figure 4. Comparison of total hourly sap flow with hourly ET (N = 335).

3.3. Comparison of Sap Flow and Solar Radiation

Figure 5 shows the comparison of total hourly sap flow and hourly solar radiation. The correlation between sap flow and solar radiation was significant, with an R^2 of 0.93. This indicates a strong relationship between sap flow and solar radiation and is comparable to other studies that have found a similar correlation. Gordon *et al.* (1999) found the correlation coefficients between sap flow and solar radiation were between 0.54 and 0.78 [32]. Oogathoo *et al.* (2020)

found the correlation coefficients between sap flow and solar radiation were between 0.68 and 0.76 [33]. This study, potatoes at the reproductive stage, shows much higher R^2 than the other studies. In addition, the R^2 of solar radiation and sap flow (0.93) is similar to the R^2 of ET and sap flow (0.94). This result indicates the potential use of solar radiation to estimate potato sap flow. A previous study also confirmed that solar radiation was among the main variables controlling sap flow in a forest.

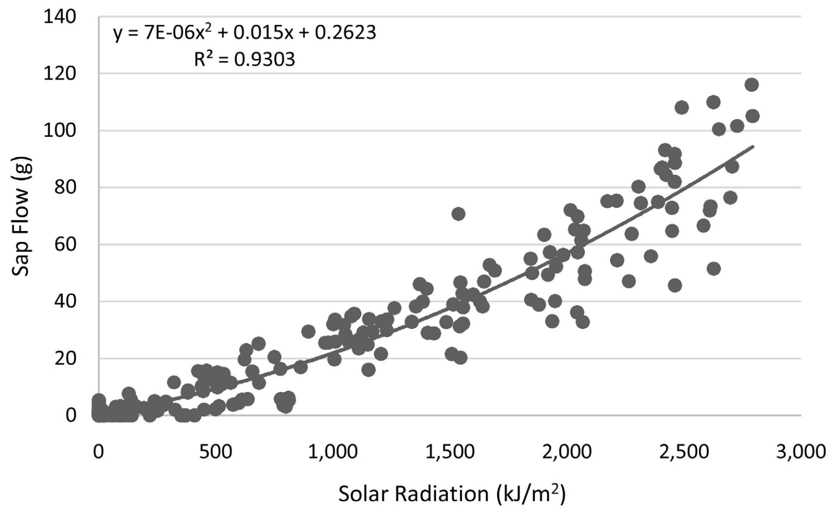

Figure 5. Comparison of total hourly sap flow and hourly solar radiation ($N = 335$).

3.4. Comparison of Reference Evapotranspiration and Solar Radiation

Figure 6 shows the correlation between solar radiation and ET. This comparison was made because of the strong correlation between ET and sap flow, and solar radiation and sap flow. Solar radiation has a strong correlation with ET in the growing season in Michigan, as indicated by the R^2 value of 0.98.

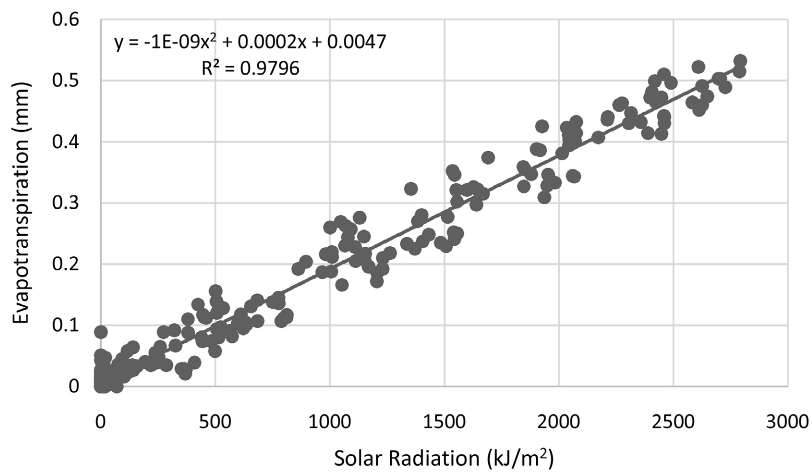

Figure 6. Comparison of hourly total ET to hourly solar radiation ($N = 335$).

3.5. Comparison of Sap Flow and Other Weather Parameters

The hourly sap flow data was compared to hourly air temperature, relative humidity, and wind speed, which were obtained from the Michigan State University Enviroweather weather station (Figure 7). The correlations between sap flow with air temperature, relative humidity, wind speed, and vapor pressure were not significant. For sap flow and air temperature, the R^2 was 0.28. For sap flow and relative humidity, the R^2 was 0.55. For sap flow and wind speed, the R^2 was 0.12. For sap flow and vapor pressure, the R^2 was 0.03. Although the correlation was not significant, a relationship between sap flow and humidity (R^2 = 0.55) was interesting to be noted. The result showed when the humidity was decreased, the sap flow was increased. This is consistent with the finding of Huang *et al.* (2015), who found the correlation coefficient between sap flow and relative humidity to be 0.48 and 0.63 in 2012 and 2013, respectively [34].

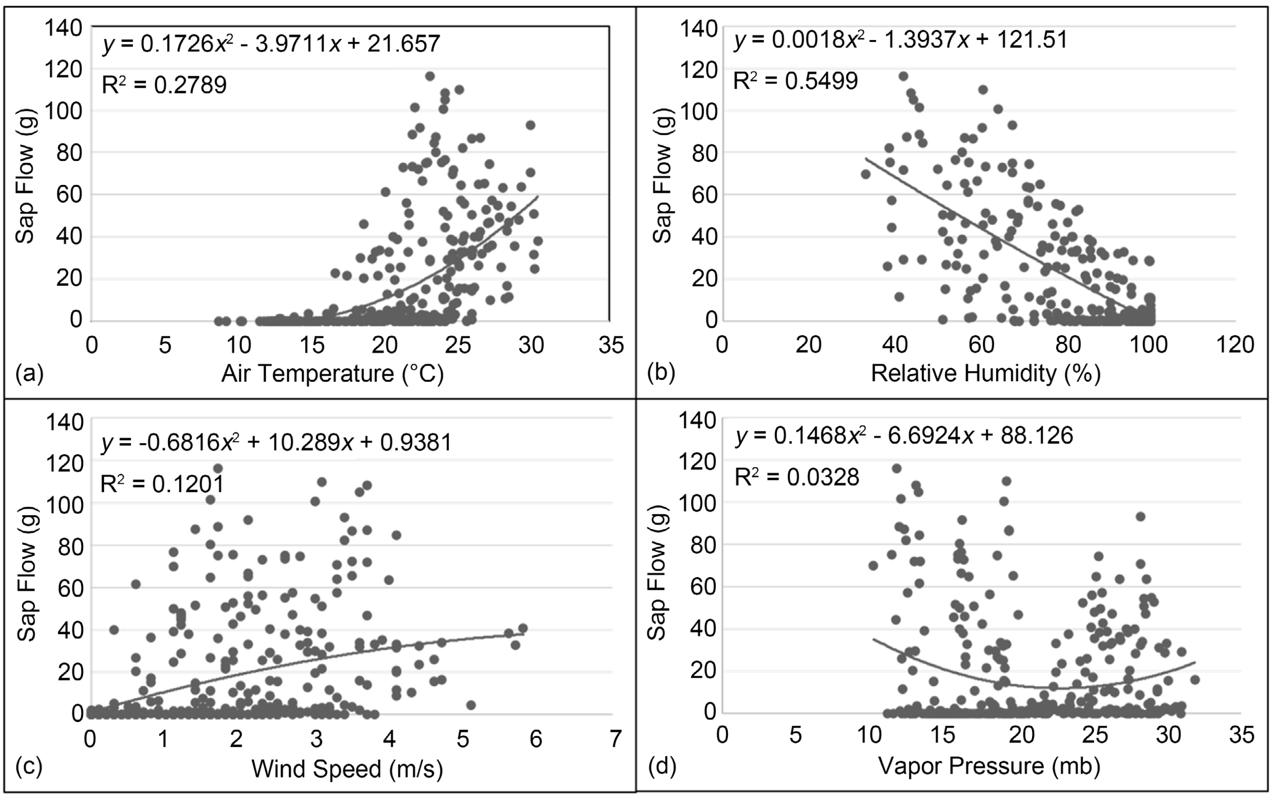

Figure 7. Comparison of hourly total sap flow and (a) hourly average air temperature, (b) hourly average relative humidity, (c) hourly average wind speed, (d) hourly vapor pressure (N = 335).

3.6. Comparison of Daily Sap Flow, Estimated Crop Water Use Based on Reference Evapotranspiration and Solar Radiation

Comparison of the daily sap flows with estimated crop water use based on reference ET and solar radiation was compared. Sap flow typically outputs in grams. Thus, sap flow values were converted from gram to mm by multiplying sap flow by the number of potatoes in an acre, and dividing by the acre area. Solar radiation was converted to ET using the second-degree polynomial equation based on the relationship between ET and solar radiation (**Figure 6**). **Table 2** shows RMSE, IA, and MBE to evaluate how well daily ET and solar radiation predicted daily sap flow. **Table 2** shows that ET from the weather station has the best fit with daily sap flow (RMSE = 1.34; IA = 0.89; MBE = −0.83). The solar radiation-based method shows an acceptable fit with daily sap flow (RMSE = 2.25; IA = 0.72; MBE = −1.80). This result indicates that daily ET and solar radiation values can be used to estimate daily sap flow, which is useful in managing irrigation to determine when and how much to irrigate the crop [35].

Table 2. RMSE, IA, and MBE for sap flow as measured value and ET and solar radiation as the predicted value.

Measured	Predicted	RMSE	IA	MBE
Sap Flow	Evapotranspiration	1.34	0.89	−0.83
Sap Flow	Solar Radiation	2.25	0.72	−1.80

4. Conclusion

This study evaluated the relationship between sap flow and various environmental parameters such as ET, solar radiation, air temperature, wind speed, relative humidity, and vapor pressure. The predictions of crop water use using ET and solar radiation from a weather station have strong correlations with sap flow. This study also shows the potential use of solar radiation to estimate plant water use. Ultimately, it can be used for irrigation management, when and how much to irrigate. In a future study, validation of this methodology with other crop types should be conducted. Comparing sap flow, reference ET, and solar radiation methods with weighing lysimeters, which are direct methods of measuring crop water use [36] [37] [38], should also be studied.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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