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Modeling of Soybean Plant Sap Flow

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Abstract

Soybean (*Glycine max*. (L.) Merr.) sap flow during the growth stages in relation to soil moisture, nutrition, and weather conditions determine the plant development. Modeling this process helps to better understand the plant water-nutrition uptake and improve the decisions of efficient irrigation management and other inputs for effective soybean production. Field studies of soybean sap flow took place in 2017-2021 at Marianna, Arkansas using heat balance stem flow gauges to measure the sap flow during the reproductive growth stages R3-R7. Plant water uptake was measured using the lysimeter-container method. The uniform sap flow-based hydraulic system in the soil-root-stem-leaf pathway created negative water tensions with osmotic processes and water surface tensions in stomata cells as water evaporation layers increase are the mechanism of the plant water uptake. Any changes the factors like soil water tension, solar radiation, or air relative humidity immediately, within a few seconds, affect the system's balance and cause simultaneously appropriate reactions in different parts of the system. The plant water use model was created from plant emergence, vegetative to final reproductive growth stages depending on soil-weather conditions, plant morphology, and biomass. The main factors of the model include solar radiation, air temperature, and air relative humidity. The effective sap flow uptake occurs around 0.8 KPa VPD. Further research is needed to optimize the model's factors to increase the plant growth dynamics and yield productivity.

Keywords

Sap Flow, Water Potential, Solar Radiation, Air Relative Humidity, Vapor Pressure Deficit, Evapotranspiration

1. Introduction

Sap flow modeling helps to better understand the soybean (*Glycine max* L.

Merr.) plant water uptake process for further control and improve the plant development. Predicting the sap flow dynamics, which strongly depend on soil moisture content and weather conditions, will improve the water management, irrigation scheduling, irrigation initiation, and termination timings during the plant growth stages.

The water demand of soybean plants varies with growth stage and weather conditions [1]. In every moment of the plant life cycle, nutrients in soil water are absorbed through the plant root system and transported to stems, leaves, and pods by osmosis hydraulic potentials created by xylem and phloem microcapillaries and leaf evapotranspiration. Soil water resistance and hydraulic conductance of the plant regulate the amount of sap flow. Some authors found that hydraulic conductance is a major limiting factor to water flow in the soybean plant and is not flow-dependent [2]. Sap flow is regulated by soil moisture, solar radiation, air temperatures, and vapor pressure deficit (VPD) [3] [4].

In controlled environment studies, transpiration rates of soybean and maize (Zea mays, L.) declined rapidly at high soil matric potential and then dropped more slowly as the soil dried [5]. Although measured transpiration rate declined by nearly 30% following a reduction of soil matric potential to −0.1 MPa, differences in leaf water potential and CO_2 assimilation rate were low and less than the measurement techniques' sensitivity. Total system resistance to water flow increased as the soil dried. Whether or not these patterns occur in actual real field conditions is unclear.

Other researchers detail sap flow regulation by soil moisture, solar radiation, air temperatures, and VPD [5] [6]. Sap flow rates of soybeans and upland cotton (Gossypium hirsutum, L.) were lower in humid conditions than in arid conditions in both species [7]. The leaf temperature of the soybean cultivar changed almost in parallel with the air temperature during the daytime. On the other hand, the leaf temperatures of cotton were higher than the air temperatures until mid-noon. Under the arid condition, the leaf temperatures of cotton were higher than that of soybean and the air temperature. There was no significant difference in leaf temperature among the cotton and soybean cultivars under humid conditions. The flow rates of stem sap in the cotton cultivars under the arid condition were consistently higher than that in the soybean cultivar and were largely affected by VPD. Under the humid condition, however, the flow rates of stem sap were lower in the cotton cultivars than in the soybean cultivars. The research predicts the importance of soybean water use measurements for different climates and soils [8]. Soil water resistance and hydraulic conductance of the plant regulate the amount of sap flow. Researchers show that the energy rate attributed to water evaporation in the leaf energy balance is from 20% to 40% [9] [10].

VPD is considered an important environmental factor that might affect plants' leaf expansion and transpiration rate. The leaf expansion rate of different variety soybeans in the high (2.8 - 3 kPa) VPD treatment chamber was significantly less than in the low (1.2 - 1.6 kPa) VPD treatment chamber [11]. Research is needed to examine these relationships in field conditions.

It has been a well-accepted conceptual model to explain the complex water and solute flows across the root that has been related to the composite anatomical structure. There are three parallel pathways involved in transporting water and solutes in roots—apoplast, symplast, and transcellular paths [12]. Many studies have shown that the usual driving force across roots is the tension, which is created by transpiration from the shoot and propagated into the root xylem. Therefore, the driving force across the root is a hydrostatic pressure gradient [13] [14]. Evaporation inside the leaves occurs predominantly from damp cell wall surfaces surrounded by a network of air spaces. Menisci form at this air-water interface, where apoplastic water contained in the cell wall capillaries is exposed to the air of the sub-stomatal cavity. Driven by the sun's energy to break the hydrogen bonds between molecules, water evaporates from menisci, and the surface tension at this interface pulls water molecules to replace those lost to evaporation. This force is transmitted along with the continuous water columns down to the roots, where it causes an influx of water from the soil [15]. The mechanism of creating and calculating water tension forth and affecting it to the stem-root system water potential is not provided.

Sap flow measuring methods include stomatal conductance [16], plant chambers [17], lysimeters [18], and field water balance [19]. Lysimeters or weigh controlling containers with plants imposed in the environment are a simple method to get the initial sap flow information of the plants. The thermal calculation method [20], using plant stem electric heaters and temperature sensors, is more dynamic and timing-sensitive to deeper analyzing the flow dynamics.

2. Materials and Methods

Soybean plant sap flow was measured using Dynamax (https://www.dynamax.com) sensors installed at different maturity group varieties of Dyna-Gro (http://www.dynagroseed.com) and Pioneer (https://www.pioneer.com/) brands planted in various planting timings and treated different irrigation regimes have taken place at the Lon Mann Cotton Research Station, Marianna, Arkansas USA (34.732800, −90.766239) during 2017-2021. The cultivation and pest control practices were performed according to recommendations of the University of Arkansas Extension Service. Soybean seeds were planted 0.96 m wide row spacing with 320 K seeds/ha density, and the final plant stand was between 280 K - 310 K plants/ha. Potential evapotranspiration (ET) was recorded hourly using digital atmometers (https://www.etgage.com, Loveland Colorado, CO, USA) installed at the edges of the plots. WaterMark™ soil moisture sensors were installed at 15, 30, 45, and 76 cm depths and connected to a 900 M Watermark data logger (https://www.irrometer, Riverside, CA, USA), which recorded soil moisture in centibars (Cbs) every hour. Gravimetric soil moisture content (g/g) and soil bulk density (g/cm^3) were measured to a depth of 90 cm in 15 cm intervals once in each growth stage. Soil temperature (˚C) was measured at 3 and 15 cm depths by iBWetL temperature data loggers and WaterMark™ temperature sensors. Plant height, width, number of nodes, leaves, and stem diameter were measured daily. Plant leaf and pod areas and plant moisture content were measured randomly at the growth stages [4]. Weather parameters were recorded with Watchdog 2900ET Weather Station (https://www.specmetr.com, Aurora, IL, USA) installed adjacent to the field. Two similar stations improved remote air temperature and relative humidity sensors installed under and above the canopy. SGA-5 and SGB-9 WS sap flow sensors (https://dynamax.com/, Houston, TX, USA) were installed on random plants using 5 mm and 9 mm collars when stem diameter growth allowed. Sensors are installed approximately 10 - 20 cm above the soil surface and wrapped with several isolators to keep the heat energy in the plant stem. Each sensor was equipped with heater and temperature sensors that recorded upcoming and outgoing sap stream temperatures. Sap flow was calculated and recorded in 10-minute time intervals. Sap flow was expressed as the average grams of water per plant measured and adjusted to cm of water transpired using the average plant density of the field (plants/ha) determined from a nearby row of 10 m length, where at least three random plants were sampled. A soybean leaf and canopy temperature measurement system was created based on infrared temperature (IR) transmitters OS136A-1-MA and OS137A-1-MA (https://omega.com/ Norwalk, CT, USA).

Experimental measurements of plant water evapotranspiration and soil evaporation were accomplished using 19 L multiple lysimeter-containers filled with 17 kg each with clay, loam, and sandy soils. The experiment was set up with 27 containers planted with soybeans, cotton, and corn seeds with three replications in each soil type. In addition, 3 containers of each soil were prepared and left bare. The container experiment was conducted at the Lon Mann Cotton Research Station in Marianna, AR, during 2014-2015. Four 2 mm holes were drilled through each side to dry the soil in the container, and three 2 mm holes were drilled through each container base. Infiltrated water was collected underneath the containers. All containers were placed in a sunny grass area and weighed daily at 0800 CST on a Cen-Tech 130 Lb. Electric Platform Scale (Cen-Tech Inc., Camarillo, CA). In addition, nine containers of each soil were equipped with EC-5 Decagon https://metergroup.com) and WaterMark™ soil moisture sensors [21], and data loggers.

To evaluate the process of water evapotranspiration or sap flow uptake, we recommend solar radiation efficiency (*SRE*) value defined as the ratio between hourly solar energy received by the plant and the amount of sap flow [4]:

$$SRE = SF/SRD \,. \tag{1}$$

where, *SF*—evapotranspiration water or sap flow amount in certain moment of the day;

SRD—solar radiation received by the plant in the same moment of the day.

Collected variable data was analyzed using scattered diagram method, regression analyses, calculating the coefficient of determination (R^2) and p-value to evaluate the functional relations using SAS (SAS Inst., Cary, NC), R and EXCEL data analyses ToolPak.

3. Results and Discussions

The initial lysimeter-container experiment shows that the period of higher water demand of soybean plants appears to be 40 and 80 days after planting. A soybean plant's water use averaged 138.4 grams per day during this period. However, maximum water use may increase up to 320.1 grams per day depending on weather conditions, particularly solar radiation and ET [22]. The average cumulative water loss in containers with different bare soils is 3.1 times less than in containers with soybean plants during the reproductive growth stage. However, considering that the soil surface between plant rows in the field conditions will be under canopy shade, the water lost differences could be higher. The average cumulative moisture loss between shaded lysimeter-containers with different bare soils and the containers with the soybean plants is 10.4. The ratio between ET and soil water evaporation is given for each soil type in **Figure 1**. The lower relative water loss is in the clay soils with a ratio of 13.0, and the higher relative water loss is in sandy soils with a ratio of 7.3. The relative air humidity is constantly 100% 10 cm under the soybean canopy at night and almost 5% to 10% higher than 10 cm above the canopy in the daytime (**Figure 2**). Humidity changes slightly during the day after irrigation events. Rainfall, in contrast to irrigation, sharply increases the air humidity in all positions, and it also significantly affects the following day's humidity conditions. The high humid condition under the canopy reduces the water evaporation from the soil surface. Furthermore, some part of air-water returns to the soil because of higher dew point temperature and low air temperature at night, especially around 5:00 in the early morning. We may consider from these measurements that the soybean plants utilize around 90 percent of soil water in the field as sap flow through the

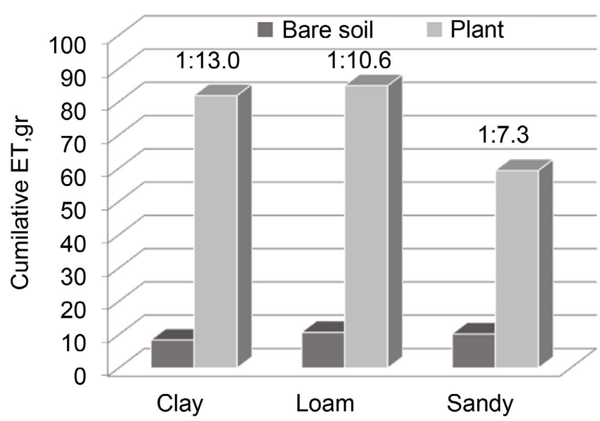

Figure 1. Cumulative soybean ET and bare soil water evaporation in the lysimeter containers filled three different types of soils.

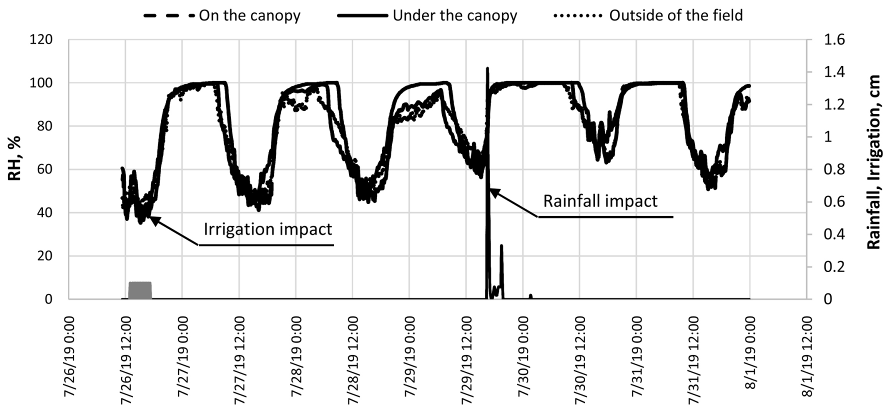

Figure 2. The air humidity above 5 cm and under 15 cm of the soybean canopy and outside of the field.

plant evapotranspiration processes.

The initial plant-soil-water experiment analyses help create the plant sap flow model (**Figure 3**). Rainfall and irrigation water amounts as the soil water sources, soil structure with nutrients and plant root system, and stem and leaves are the main components of the model. Leaves in the sunlight utilize carbon dioxide and produce oxygen. Solar radiation and air parameters, including temperature, relative humidity, and vapor pressure, determine the soil water evaporation and leaf evapotranspiration amounts. The soil water uptake occurs through the root hairs around the tap and secondary roots. Water molecules move to xylem cells because of negative osmotic potential Ψo. The osmotic potential of sap flow depends on solute concentration and volume of the root xylem cells in the root zone. Water molecules penetrating plant root epidermal cells begin to restructure with solute elements that make a vacuum in sap flow, and the water potential in the root system drops [16]. As a result, the root hairs began to soak more water. Irrigation water potential Ψ_w is 0. Saturated soil water potential near the water zone is also close to 0. However, as the soil gets dryer farther from the water source, the soil water potential drops down, and this negative water potential increases moisture transport from the higher moisture zones. The moisture movement between different moisture content zones depends on water potential, soil type, and driving gradient. Our measurements show that the soil moisture from the 5 Cb to 60 Cb moisture zone moves at 2 - 4 cm/hour speed in the silt loam soils, depending on their compaction. Therefore, dry soil layers apart 25 - 30 cm from the wet part of the soil will take 10 or more hours to equilibrate. After irrigation or rainfalls, the soil moisture on the topsoil layers where the plant root system existed, balanced within the day or night. Excess water beyond the soil water holding capacity will be lost as runoff from the field or percolate to the deeper soil layers.

The watermark sensors indicated that the average soil water potential is 30 Cb or −30 KPa in the early morning at 7:00 (**Figure 4** and **Figure 5**). However, sap flow sensors revealed little to no sap flow because of similar water potentials

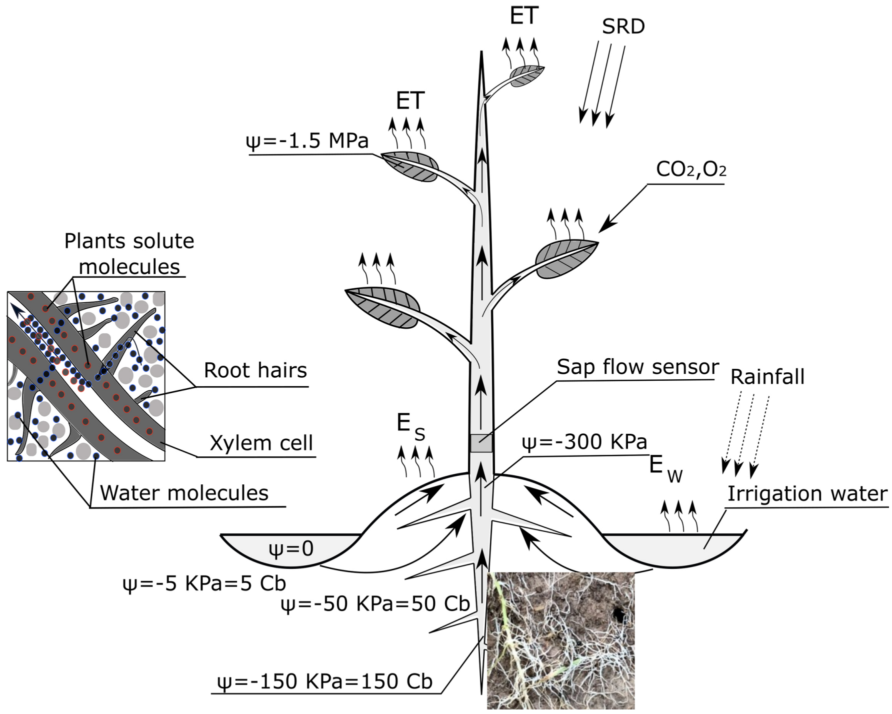

Figure 3. Soybean plant water uptake, sap flow movement, and evapotranspiration model.

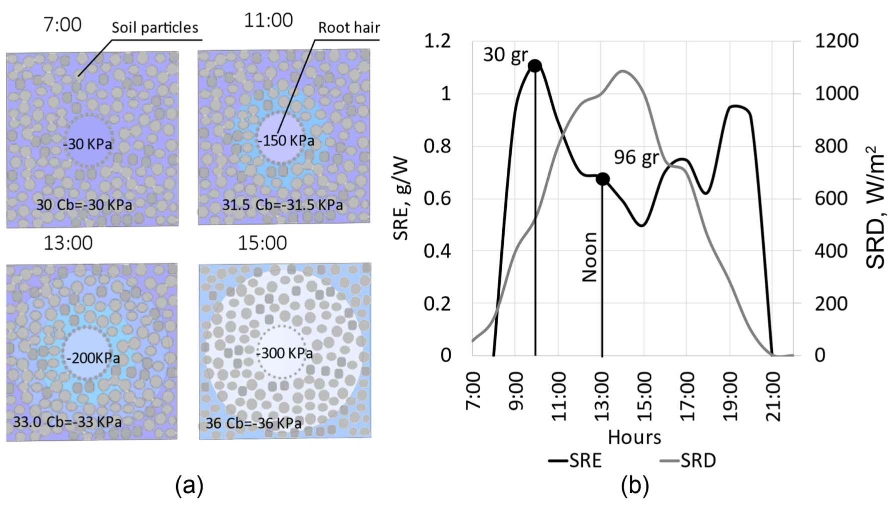

Figure 4. Water potential in the soil and the soybean plant root (a), and graphs of coefficient of SRE and solar radiation SRD (b) at the daytime of 17 June 2019.

existing in the plant root and nearby soil layers. At this time of the year, sunrise at approximately 05:50 and solar beams fully began to touch the plant canopy from around 06:30 in the morning. The existing dew on the leaves' surface delays the water evaporation from the leaf cells until the surface becomes dry. Similarly, during rainfalls, plant evapotranspiration is significantly reduced when the leaves get wet. Sensors indicated the beginning of the sap flow around 08:00 in the morning, which means the water potential began to drop down in the

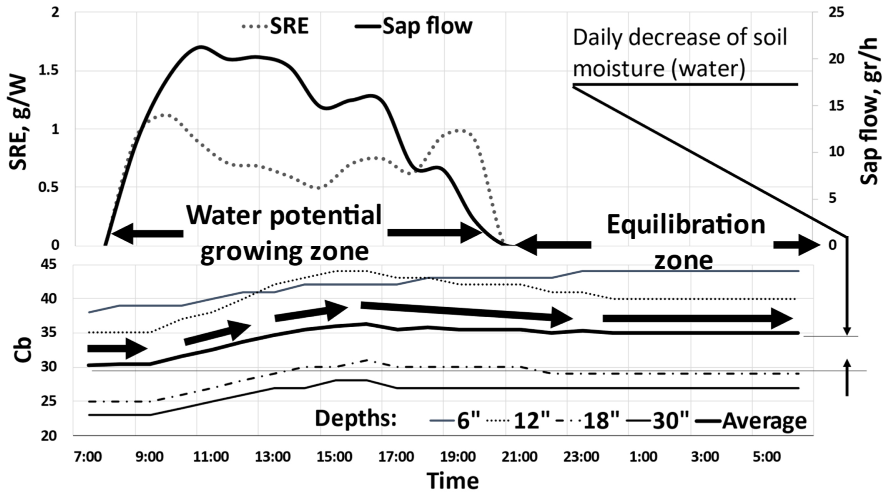

Figure 5. Soil water potential, SRE, and sap flow in 24 hours of plant water uptake and soil moisture equilibration period.

root cells relative to soil water potential near the root zone. The water and nutrient molecules began to penetrate to the root xylem cells, and this sap with plant solute molecules began to move to the upper parts of the plant where the water potential is lower than in the root system area. The solar radiation increases 536 W/m^2 around 10:00, and the water potential in the root system is about half of the minimal (−300 KPa) water potential, which is −150 KPa. As a result, the sap flow movement intensifies.

Sap flow reaches its maximum level—more than 20 grams per hour, between 11:00 and solar noon hours of the day, when the solar radiation also close to its maximum −1100 W/m^2. Increasing water uptake from the root zone area can lower water potential in the soil. For example, the average root zone volume of soybean plants in R5 growth stage with 20.3 cm depth and 30.5 cm width equals 4939.7 cubic cm. Assuming the dry mass of the soil in this volume is 5927.7 grams, at 20% of soil moisture it holds 1185.5 grams of water. The plant used 96 grams of water from morning to noon solar, and as a result, the soil near the root zone dropped to 18.4%. Lowering water potential increases soil moisture movement from nearby and deeper soil layers. Soil water potential in the plant-soil system usually becomes fully balanced from evening hours until the next morning. We call these hours the soil moisture equilibration period.

As transpiration increases during the day, the soil matric potential measured by sensors near the root zone generally increases, resulting in a lower SRE in afternoon periods (Figure 5). The daily high SRE was around 1 g/W when soil moisture is high (the average is 31 Cb) and around 0.5 g/W when the water potential is higher (35 Cb). Higher rates of sap flow between 11:00-13:00 hours when the solar radiation is close to daily maximum and soil water potential near the root zone increase not more than 2 - 3 Cbs from the initial level. When the SRE is less than 0.3 - 0.1 g/W in dry soil (<120 Cb), sap flow is sharply reduced. Daily plant water transpiration is 0.7 cm in high, 20% - 25%, and 0.2 cm in low, 10% - 15% of silty-loam soil moisture conditions at R4-R6.5 growth stages and 0.5 - 0.6 cm daily ET rates.

Calculations showed that the maximum sap flow speed in the plant stem is 78 cm/h or 1.3 cm/min. However, our previous experiments [4] show that cutting the main plant stem near the ground causes an immediate, in a few seconds, the sharp increase in the leaf surface temperature, presumably due to the leaf surface temperature being exposed to the sun with the termination of sap flow in the new portions of cooler sap from the ground instead of evaporated water molecules in stomata cells of the leaves. According to Pascal's law, a change in pressure at any point in an enclosed fluid system is transmitted equally throughout the fluid. The enclosed hydraulic pressure connection from leaves to the far ends of the root xylem cells works as a nerve system of the leaving creatures for the plant: creating the immediate plant reaction to even small temperatures, moisture, or nutrition changes in the soil around the root system.

Immediate temperature reaction in the plant system also shows that the sap flow energy comes not only from osmotic water potential in the plant also because of creating the negative hydraulic sap-water pressure by evapotranspiration in the leaf stomata cells. Stomata cells varied widely in size, with mean guard cell length ranging from 19.1 to 71.5 μm [23]. The stomata opening looks oval, and the average size is 316 μm² [24] [25]. There are more than 2.000.000 stomata cells of plant leaves in the higher biomass period—R5 growth stage when the LAI is 3-3.6 /4/.

With an hourly 20 g sap flow at 11:00, the single stomata cell gets 0.856 μm³ water in a second. The evaporation reduces the water in the stomata openings and increases the water surface tension. We recommend the following formula to calculate the vertical component of the surface tension forces that create the negative water potential in the plant:

$$P = \pi\left(\frac{ah}{a^2+h^2}+\frac{bh}{b^2+h^2}\right)*\sqrt{2\left(a^2+b^2\right)}\sigma\left(\frac{T_c-T}{T_c-T_1}\right)^R, \quad (2)$$

where, a and b—stomata cell opening ellipse's sizes,

h—water evaporation depth in stomata opening,

σ—surface tension,

T_c—critical temperature,

T_1—Kalvin temperature, $T_1 = 273˚C$,

T—leaf temperature,

R—correction coefficient.

The average size of the ellipse-shaped stomata opening is 32 × 16 μm. The calculated water potential in the plant stem created by surface tension force and water surface tension in stomata depending on evaporation depth are depicted in **Figure 6**. It is seen from the graphs that just in 4 μm stomata water evaporation causes −1 MPa negative water pressure in the plant stem. Evaporation of 0.1 grams of water from the plant leaves is enough to create this water pressure, and

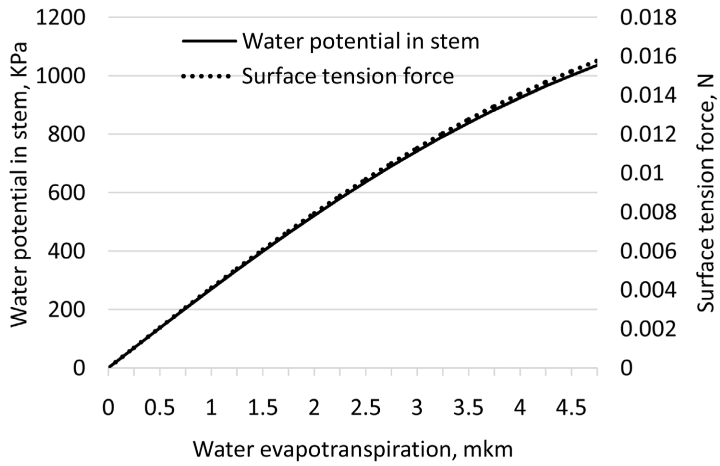

Figure 6. Surface water tension force in stomata cells and water potential in soybean stem depending on water evaporation layer.

it occurs in 10 - 15 seconds in high water demand hours. This shows that any changes of soil water tension, solar radiation, or air relative humidity immediately, within a few seconds, affect the system's balance and causes the simultaneously appropriate reactions in different parts of the system.

The leaf stomata opening, and accordingly the intensity of water evapotranspiration depend on whether parameters, including solar radiation, air temperature, air relative humidity, ET, and VPD. Figure 7 shows the relations between sap flow, solar radiation, and VPD in soybean planted in 23rd of April 2021 during R4-R6 reproductive stages in every 10 minutes intervals. The highest correlation $R^2 = 0.67$ observed between sap flow and solar radiation.

Relation between sap flow and VPD seems low due to widespread measuring units in continuous time in different growth stages. Analyses show that the correlation between parameters is significantly higher within growth stages. Noticeably, sap flow rates are higher in certain intervals of VPD. However, VPD is hard to control in field conditions. These relations could predict plant development in forecasting weather conditions and regulate planting timings or irrigation regimes (Figure 8) As seen from the graph, 97.6% of all sap flow occurs between 0.5 - 1.1 kPa VPD, and 76.1% of sap flow uptake occurs between 0.7 - 0.9 kPa VPD intervals. The best effective for sap flow uptake vapor pressure is 0.8 kPa, allowing 56.7% of all sap flow uptake in R4-R7 growth stages.

Aggregated data across the 2017-2021 years show that sap flow is related to growth stage, plant biomass, solar radiation, evapotranspiration, air temperature, and relative humidity. As expected, sap flow increases relative to increasing average daily maximum and minimum temperatures within the same growth stage. A relationship between solar radiation and air relative humidity was developed for R4, R5, and R6, where a large enough dataset existed. The sap flow (SF) multiple regression equation at the R4 growth stage is defined as: $SF = 17.86 + 0.039SRD - 0.178HMD$. Here, SRD: solar radiation, and HMD: relative air humidity. The residual standard error for R4 was found to be 5.284 with

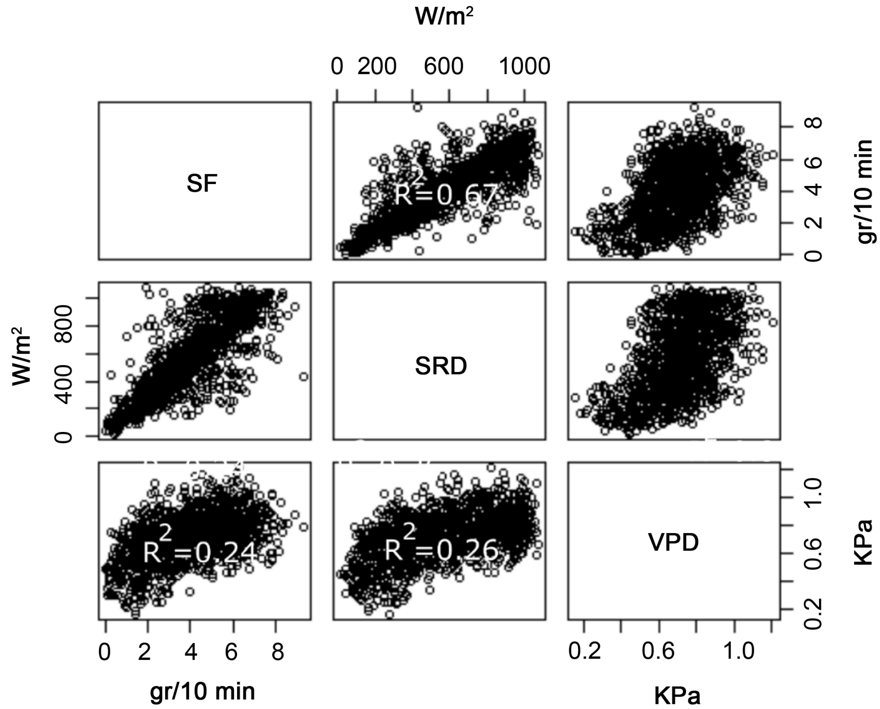

Figure 7. Relations every 10 minute-intervals between sap flow (SF), solar radiation (SRD), VPD during the R4-R6 reproductive stages of soybeans planted on 26th of April 2021.

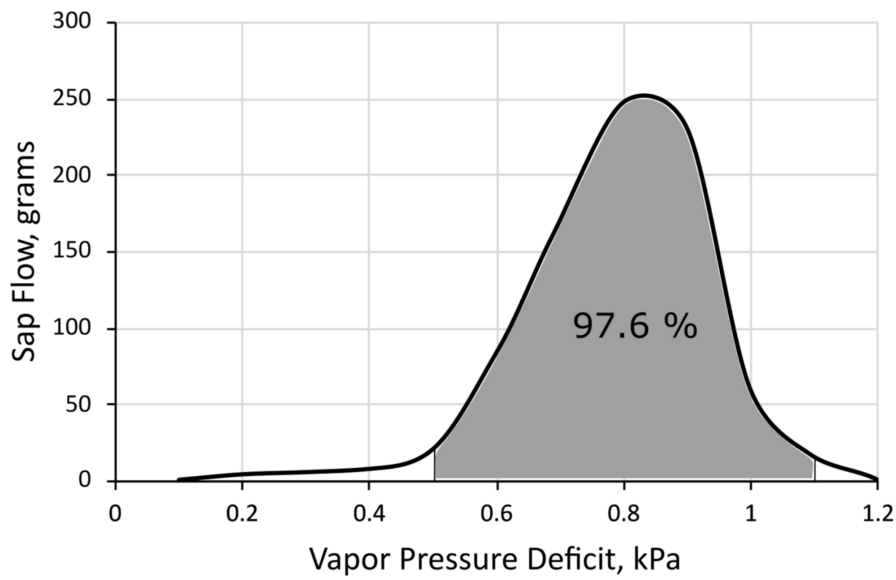

Figure 8. Sap flow and vapor pressure deficit relations.

213 degrees of freedom (DF). Multiple R-squared goodness of fit was found to be 0.922, P-value < 0.001. The effect of SRD and HMD are shown in Figure 9.

The high daily water use period of early (from April to the first week of May) planted soybeans was observed in the late-R3-R6.5 growth stages. The high daily water use period shifted to earlier-R2-R6 growth stages in middle-term (until the end of May) planted soybeans. Water use is high very early and decreases

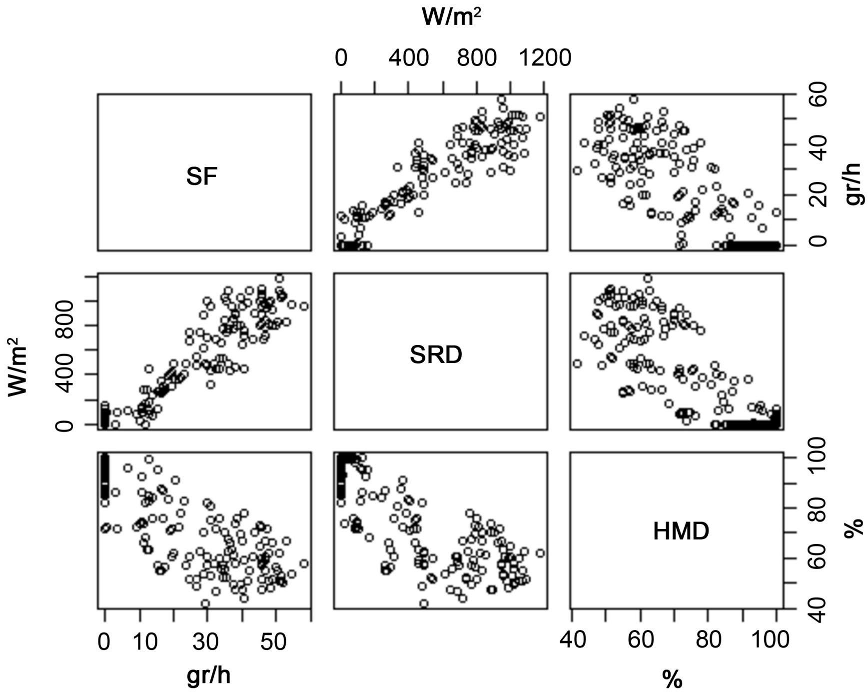

Figure 9. SRD: solar radiation (W^*h/m^2) and HMD: relative air humidity (%) impact to the soybean plant sap flow SF (g/h) at the R4 growth stage.

from R5 growth stages in late term (late June) planted soybeans (**Figure 10**). ET trends explain these differences. High ET occurs in the June-July-August months in the Arkansas climate zone with varying patterns from year to year. Conformity of plant high water use growth stages of different soybean maturity group variates to the ET trend help to maximize the plant sap flow uptake. Long-term forecasting of solar radiation, air temperature, and ET trends of oncoming vegetation season could be essential to choosing the soybean varieties and planting timings for the soybean production year.

Sap flow has a good correlation with the plant development. Our calculations show a small portion of sap as the water and nutrients contributed to increases in plant biomass. 0.5% - 0.8% of sap flow in R5 growth and 0.8% - 1.2% in R6 growth stages utilizes as a plant biomass. Accordingly, the higher plant sap flow rates correspond to maximum rates of biomass, W_b, calculated as a volume of the plants per row foot:

$$W_b = kHBL, \tag{3}$$

where, *k*—coefficient depending on the vertical profile of the soybean plant that vary for different varieties and usually changes from 0.65 to 0.85,

H—height of the plant,

B—width of the plant,

L—length of the row.

The relationship between sap flow per cubic biomass and plant age can be represented by the following equations:

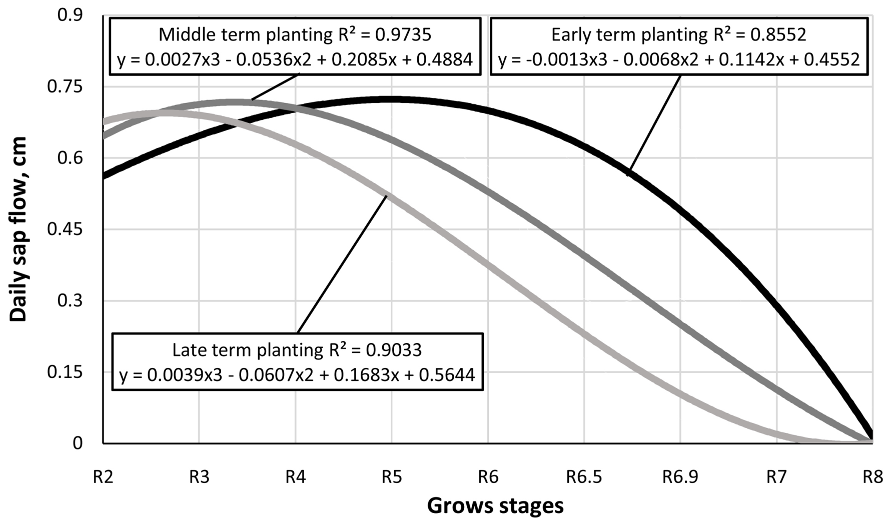

Figure 10. Soybean daily sap flow (water use) planted in different timings.

$$SF_1 = -0.0003N + 0.0516, \quad (4)$$

$$SF_2 = -0.0006N + 0.0709, \quad (5)$$

where, SF_1, SF_2—sap flow per cubic foot biomasses respectively of soybeans planted 1st and 28th of May 2019, N—days after emergence of the plants.

The sap flow per cubic foot biomass is higher in the younger and smaller plants than in the older and larger plants. Higher sap flow rate and biomass in younger plants due to better sun exposure and air movement and higher moisture content of plant structures of younger plants. Lower leaves of the bigger plants, especially when LAI ≥ 1, were not exposed to full solar radiation, and limited wind speed in lover plant layers decreases the evaporation rates from their surface. The air temperature and humidity differences under and above the canopy increase as the biomass of the soybean rows rises. Due to intensive evapotranspiration rates of the plant, the higher air humidity under the canopy significantly decreases the water evapotranspiration from the lower leaves. The sap flow model of the soybean variety Pioneer P31A06L planted on the 1st of May 2019 (**Figure 11**) shows that the soybean plant in vegetative stages uses a little more than 2% of the total water required during the entire soybean growing season. The total water needs are 10.4% or 4.1 cm. of water required during the R1 and R2 growing stages. 14.3% or 5 cm. of water needed during the R3 growth stage. In our experiments, sap flow measurements with other varieties and planting timings show that the water use in R2 and R3 growth stages may require as much as 6.4 - 8.9 cm., especially in mid-and late-planted soybean during these growth stages. 23.4 cm. or 65.7% of soybean plant water demand in the reproductive stage is required during the R4 to R6 growth stages. Water use is 3.3 cm. in the final R7 and R8 stages. It is noticeable that lower rates of ET slow the biological activity of the plant development and increase the time a plant resides in a growth stage. This is seen in the longer length of R4 growth stage than the

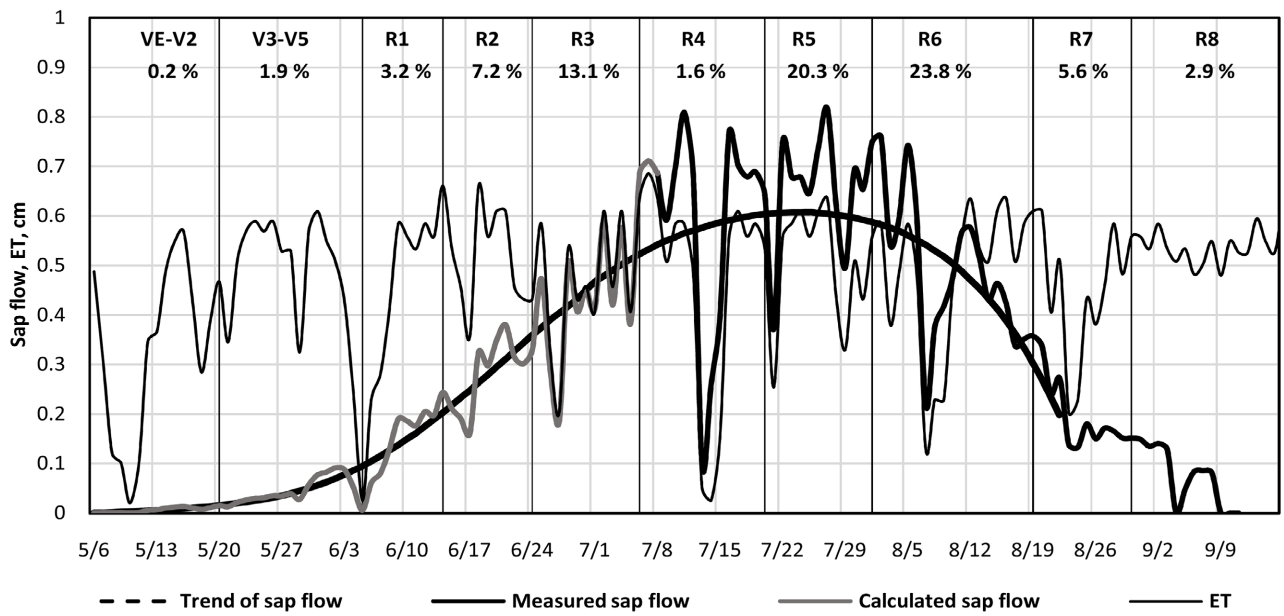

Figure 11. Soybean water use as the measured and calculated plant sap flow and evapotranspiration (ET) during the whole soybean vegetative and reproductive growth stages.

lengths of R3 and R5 growth stages. It should be noted that the data is highly variable from year to year, depending on the contrast of weather and soil moisture trends.

4. Conclusion

In a high-water use period, soybean plants in reproductive stages utilize around 90 percent of soil water in the field as a sap flow. Soil water evaporation and evapotranspiration from the lower leaves are less due to shading and high air relative humidity under the crop canopy in the daytime. Air relative humidity under the plant canopy can increase following rainfall events compared to irrigation events. Modeling sap flow movement in the plant shows the uniform soil moisture around the root zone in the early morning hours when the plant sap flow is zero. After evaporation of dew or wet layers on the leaf surface, if rainfall occurs, stomata cells opening begin the evapotranspiration and sap flow movement from the root to the leaves. The water potential dropped −150 KPa and more in the root's inner layers because of osmotic potential and created negative potential by the surface water tension forces in every stomata cell as the water evaporation layer increases. SRE is high in the morning hours when the soil water potential near the root zone is low. Relations between water surface force and stomata parameters show that water tension in the plant stem could drop until −1 MPa in 15 - 20 seconds in high sap flow rates. Higher rates of sap flow between 11:00-13:00 hours when the solar radiation is close to daily maximum and soil water potential near the root zone increase not more than 2 - 3 Cbs from the initial level. As the water evapotranspiration increases, the soil water potential near the root zone increases, and SRE decreases as a result-decreases the sap flow intensity in the afternoon hours. A higher water potential zone near the root system causes moisture movement from the high moisture zone, including the deeper soil layers, to the root zone until the moisture in the soil layers is balanced-equilibrated for 5 - 10 evening and nighttime hours. A strong correlation exists between sap flow and solar radiation established. More than 97.6% of all sap uptakes occur between 0.5 and 1.1 KPa VPD and 76.1% between 0.7 and 0.9 KPa VPD intervals. Multifunctional model coefficients in different reproductive growth stages between sap flow, and significant influential factors: solar radiation, vapor pressure deficit, and relative air humidity are described. Relations between biomass and sap flow allow finding precise soybean water demands from emergence, and vegetative to final reproductive growth stages that help accurately predict the irrigation initiation, scheduling, and termination dates.

Conflicts of Interest

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

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