

## DYNAMIC SIMULATION OF DIURNAL COURSE OF STEM DIAMETER OF APPLE TREE (*MALUS DOMESTICA* BORKH. CV. 'FUJI')

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### Abstract

Using soil-plant-atmosphere continuum (SPAC) theory and stem volume equation, dynamic changes in stem diameters of apple trees (*Malus domestica* Borkh. Cv. 'Fuji') were simulated. Numerical simulation results indicate that stem water potential fluctuated sinusoidally and gently on sunny and cloudy days, respectively. Fluctuations in the amplitude and trend were caused by sap flow and storage resistance, respectively. The change in stem-stored water was proportional to the change rate in water potential. Stem diameter increased with fluctuations in clear day; moreover, it varied slightly on cloudy days. Changes in stem diameter were caused by changes in water potential, which was determined by meteorological factors, soil water potential, and characteristics of plants.

### Introduction

Information on a crop's water status, which is required when planning irrigation programs, is best provided by physiological indicators. In the diurnal course of tree, stem diameter is a direct indicator of water status of a tree (Yatapanage and So 2001, Köcher *et al.* 2013). Micromorphometric method is most widely used for automatic irrigation of crops (Link *et al.* 1998, Ortuño *et al.* 2010, Coccozza *et al.* 2015). By establishing a diurnal course model of stem diameter, an in-depth study of stem variation as well as precision irrigation were conducted. Based on stem structure, Génard *et al.* (2001) constructed a model and simulated diurnal courses of stem with respect to different temperatures, diameters, and water potentials. John (1999) simulated diurnal and annual courses of stem under different densities and temperatures according to the law of dry matter distribution. However, aforementioned models require dozens of equations and many parameters, bringing difficulties in the applications of actual production. Moreover, currently available models usually cannot simulate daily variations in stem diameter due to environmental conditions. In this study, soil-plant-atmosphere continuum (SPAC) theory was integrated with tree diameter growth model, and then it was simulated with diurnal course of stem diameter. Thus, a new strategy was developed to simulate dynamic growth of stem diameter.

### Materials and Methods

Experiments were conducted at the experimental station of Beijing Vocational College of Agriculture in 2017. Test materials were 4-year-old potted apple trees (*Malus domestica* Borkh. cv. 'Fuji'). The rootstock was *M. micromalus* Makino. Cultivation management measures were same for all test trees, which had approximately the same crown size and stem thickness. The pot size was 0.3 m × 0.3 m × 0.5 m; all pots were wrapped with reflective films to prevent evaporation of water from soil. Soil moisture and nutrient conditions were favorable for the growth of potted apple trees. Soil moisture was controlled by quantitative irrigation, which was based on soil water potential.

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A single plant with 32 replications was included in normal treatment. Step-by-step drought treatment was done on a single plant with 16 replications. These plants were fully irrigated on May 15, 2017 and ended in June 5. Soil water potential of  $-4$  MPa was maintained. Soil water potential was measured daily by gypsum-block method. From late May to early June each tree was sampled thrice separately; eight replicates were used each time. Furthermore, water potentials of leaves and stems were determined. To measure the stem water potential, the leaves from the sprout stem at their base were wrapped tightly with plastic bags, balanced for 2 hrs before measuring the leaf water potential, and then it was used to represent the stem water potential (Simonin *et al.* 2015). Stem water capacitance was represented by water capacitance of a 3-year-old branch (Hunt and Nobel 1987, Salomón *et al.* 2017). Furthermore, storage hydraulic resistance was measured (Nobel and Jordan 1983). Sap flow was recorded with a sphygmomanometer, which was based on heat pulses (Dauzat *et al.* 2001). Water potential was measured with a water potential instrument, which was developed by Scholander. Conduit resistance for moisture transfer was ignored. Resistance of root system ( $R_{root}$ ) was determined by the method developed by Nobel and Jordan (1983). Daily growth of tree stem was the average daily growth of tree stem in May and June. The diameter of stem base was recorded by DD-L diameter dendrometer. Solar radiation, atmospheric temperature, atmospheric humidity, and wind speed were measured with a small-field weather station AZWS-001,  $39^{\circ} 42' N$ ,  $116^{\circ} 13' E$ , 30 m in altitude.

Based on the analogy between moisture transfer and a resistor-capacitor circuit (Lhomme *et al.* 2001), stem water potential was determined from equation (1):

$$\psi_{soil} + S \cdot R_{root} - q \cdot R_{stem} + \psi_{stem} = 0 \quad (1)$$

where  $\psi_{soil}$  and  $\psi_{stem}$  are water potential (MPa) of soil and stem, respectively;  $S$  is the sap flow (g/hr);  $q$  is the change rate of stored water in stem (g/hr), which is calculated from equation (2):

$$q = C_{stem} \frac{d\psi_{stem}}{dt} \quad (2)$$

Equations 1 and 2 were used to calculate the change rate of stem water potential and water storage, respectively.

Short-term changes in tree stem diameter ( $D$ ) are generally caused by changes in water storage. The specific gravity of stem was represented by  $\rho$ . In a short period of time, it was found that all changes in  $D$  were caused by variations in water storage. Therefore, if a stem has length  $h$  and volume  $V_0$ , then water potential is 0 and volume is  $V(t)$  at time  $t$

$$V(t) - V_0 = \rho \cdot \frac{\pi}{4} \cdot h \cdot (D(t)^2 - D_0^2) \quad (3)$$

In equation 3,  $D(t)$  is stem diameter at time  $t$ . According to the definition of water capacitance (Nobel and Jordan 1983), equation 4 was

$$V(t) - V_0 = C \cdot \frac{\pi \cdot D_0^2 \cdot h}{4} (\psi(t) - \psi_0) \quad (4)$$

Here  $\Psi(t)$  is stem water potential at time  $t$ , which is determined by equations 1 and 2.  $\Psi_0$  is set to 0. Using equations 3 and 4, the following expression was

$$D(t) = D_0 \sqrt{1 + C \cdot \psi(t) / \rho} \quad (5)$$

Equation 5 is dynamic simulation equation for short-term change in stem diameter. In fact,  $D$  keeps increasing steadily. If stem diameter grows linearly in a short period of time, the rate of

increase per unit time is  $a$ .

$$D(t) = (D_0 + \Delta t \cdot a) \sqrt{1 + C \cdot \psi(t) / \rho} + \Delta t \cdot a \quad (6)$$

Equation 6 is dynamic simulation of stem growth over a long period of time. If dynamic pattern of annual stem growth is known, better simulation results can be obtained by replacing  $D_0$ . Under different water conditions, dynamic growths are determined by  $a$  and  $\Psi(t)$  together. If  $dD(t)/dt$  is set to 0, critical water potential for stem growth can be calculated, which is, the water potential required to stop stem growth.

### Results and Discussion

Diurnal variation in stem water potential is caused by changes in stem transpiration, which is related to meteorological factors. According to water diffusion theory, transpiration in a plant is primarily determined by solar radiation, temperature, humidity, and wind speed. Figs 1 and 2 illustrate that sinusoidal variations were observed in solar radiation and temperature during a single day, with higher values at noon and lower ones at evening; however, humidity varied in opposite direction. On cloudy days, radiation and temperature were relatively stable while wind speed variation was random.

Stored water does not affect sap flow significantly given suitable conditions of soil moisture. Sap flow was primarily determined by transpiration. Fig. 3 illustrates that diurnal course of sap flow was compliant with that of solar radiation. Sap flow was much greater on sunny days than on cloudy days. Moreover, sap flow fluctuated during noon, which was caused by the closure of stomata. Sap flow was basically undetectable at night. In fact, sap flow was weak because of the presence of storage tissues; however, weak sap flow could not be detected as it was beyond instrumental sensitivity.

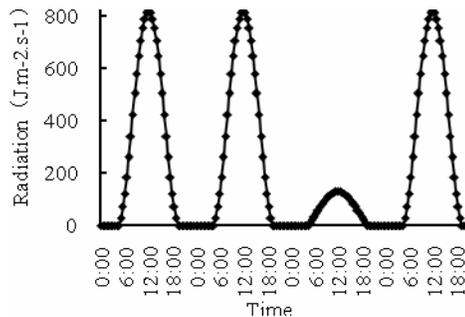


Fig.1. Diurnal course of solar radiation from June 15 to 18.

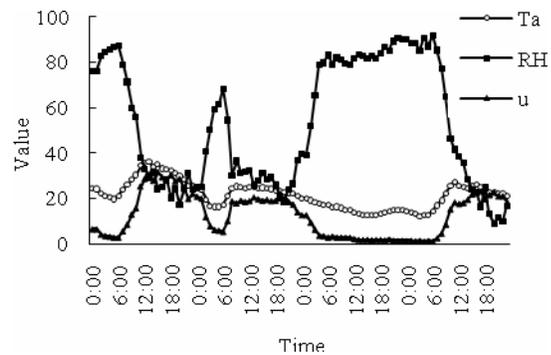


Fig. 2. Diurnal course of temperature, humidity and wind speed from June 15 to 18.

$T_a$ : temperature ( $^{\circ}\text{C}$ ), RH: humidity (%),  $R_a$ : total radiation ( $\text{J}/\text{m}^2/\text{s}$ ),  $u$ : wind speed (0.1 m/s). It was cloudy on Jun 17 and clear on all other days.

As shown in equations 1 and 2, changes in stem water potential of apple trees were caused by sap flow variations (Fig. 4); moreover, volume of water storage was proportional to the change rate of water potential. Numerical simulation results indicate that stem water potential varied in a sinusoidal pattern, with higher values at morning and lower values at afternoon; fluctuations in stem water potential were significantly less on cloudy days than on sunny days (Fig. 4).

Fluctuations were determined by the amplitude of water potential and stem water capacitance (Zweifel *et al.* 2001). It can also be seen from Fig. 4 that minimum value of stem water potential lagged significantly (for 3-4 hrs) beyond the peak value of sap flow, which was caused by regulating stem water storage.

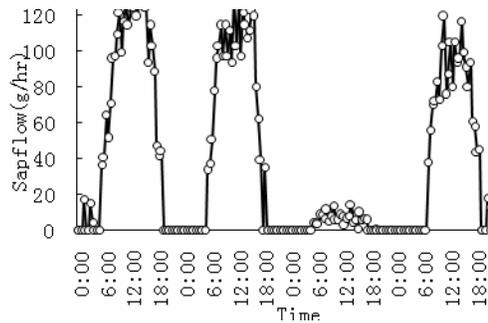


Fig. 3. Diurnal course of sap flow from June 15 to 18.

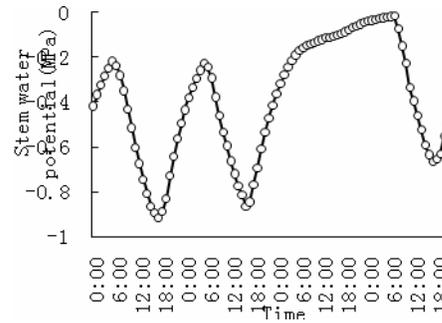


Fig. 4. Diurnal course of stem water potential from June 15 to 18.

As shown in Fig. 5, stored water flowed into transpiration stream from the stem in the morning. Then, stored water flowed back into the stem in the afternoon and evening and it varied to a greater extent during daytime, but it was more stable at night. In fact, fluctuations in stored water were gentler on cloudy days than on sunny days. These variations were associated with sap flow. Changes in sap flow were mainly caused by meteorological factors, such as radiation, temperature, humidity, and wind speed at day time. At night, sap flow was basically related to water storage tissues and water capacitance. With an increase in storage tissues and water capacitance, sap flow rate also increased at night. Variations in the range of sap flow were primarily determined by water storage resistance. Larger the resistance, smaller would be the range and gentler would be the change. Meanwhile, less water flowed into storage tissues per unit time.

In a short period of time, stem volume of apple tree changed due to changes in water storage; moreover, volume change caused changes in stem diameter. Fig. 6 shows that stem diameter had a diurnal course like that of water potential; changes in stem diameter increased with fluctuations. On cloudy days, fluctuations in stem diameter were significantly less than on sunny days. Sap flow fluctuated to a less extent on cloudy days. The daily increment in diameter was significantly less than the diurnal amplitude of diameter. Sap flow fluctuations were caused by diurnal variations of meteorological factors.

The variation in diurnal diameter was caused by diurnal changes in stored water, which is related to tissue water potential; therefore, the growth of tree stem would be different under drought stress. As shown in Fig. 7, stem growth fluctuated because of small changes in water potential during the early period of drought. At a later stage, stem growth dropped sharply. Stem stopped growing when soil water potential reached  $-0.45$  MPa. The decrease in stem diameter was mainly caused by the exponential correlation between soil water potential and water content. In detail, soil water potential decreased exponentially with decrease in water content during drought. Stem water potential was reduced by the drop in soil water potential. A large amount of water discharged for transpiration, and normal physiological processes of plants were maintained. In fact, actual growth of plants was hampered under step-by-step drought stress, which lasts for various lengths of time due to randomness and discontinuity of rainfall.

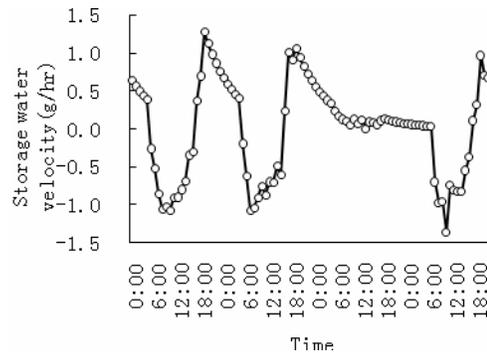


Fig. 5. Diurnal course of stored water diameter in stem from June 15 to 18.

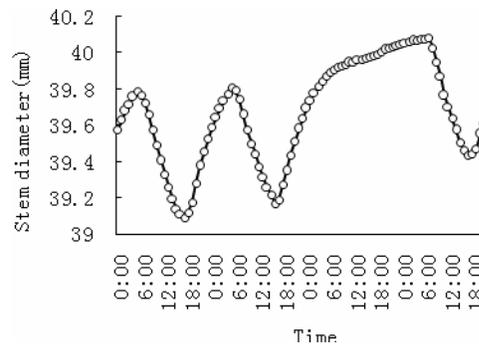


Fig. 6. Diurnal course of stem from June 15 to 18.

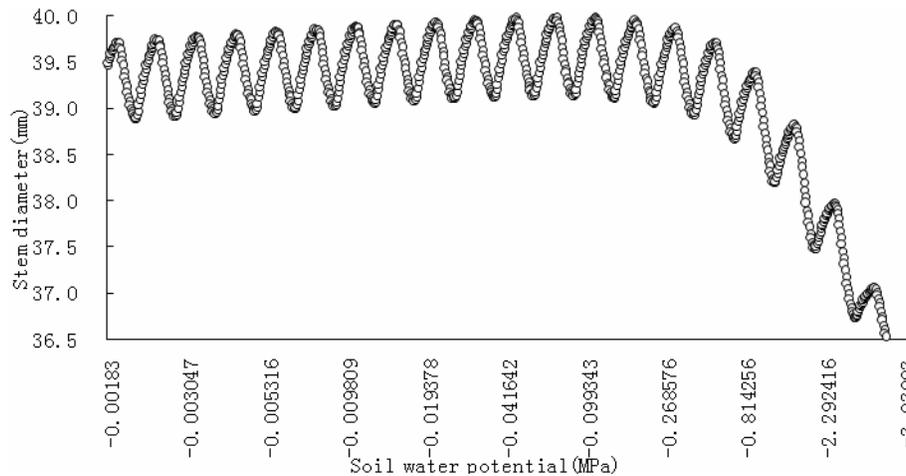


Fig. 7. Stem diameter of apple tree under gradual drought.

Using soil-plant-atmosphere continuum (SPAC) theory and stem volume equation, the diurnal course of apple tree diameter was simulated. The present simulation results were similar to those reported by Link *et al.* (1998), Yatapanage and So (2001) and Manoli *et al.* (2017). Numerical simulation results indicate that tree stem diameter increased with fluctuations, which were caused by changes in stem water storage. Furthermore, change in water storage was attributed to variations in water potential, which was ultimately determined by meteorological factors (Köcher *et al.* 2013). Simulation results also indicate that tree stem diameter was highest at dawn; moreover, tree stem diameter was least in the afternoon (Fig. 6). Furthermore, tree stem diameter increased slowly at night. Stronger the transpiration at daytime, drier would be the soil and lower would be the stem water potential (Cocozza *et al.* 2015). Stem diameter declined consequently. The underlying reason was water potential and water storage resistance, which eventually depended on environmental factors and nature of plants. In the present model, the impact of various meteorological factors and soil moisture on tree diameter was associated with variations in sap flow. Properties of sap flow were exhibited by water capacitance and water storage resistance. Compared with the model proposed by John (1999) and Génard (2001), fewer parameters were included in the model. These

parameters were simple and easy to use. They could be applied directly to the simulation of diurnal courses of branch and root diameters.

The diurnal courses of plant organs are primarily associated with the entry and exit of water, which is actually related to water potential (Zweifel *et al.* 2001, Coccozza *et al.* 2015). Changes in water potential are caused by stem sap flow, which is mainly caused by transpiration. The results are simulated by PM equation (Bauerle *et al.* 2002). By combining PM equation with tree growth model, diurnal courses of stem diameter were simulated under different weather conditions. Using soil-water movement model, diurnal courses of stem diameter were simulated under different aquatic conditions (Huang *et al.* 2017). By integrating the annual growth pattern of tree diameter, diurnal courses of tree diameters were simulated in different years. There was a significant relationship between log QT (tree transpiration) and log DBH (diameter at breast height) ( $r^2 = 0.66$ ,  $p < 0.001$ ) because of the strong dependence of sapwood area on DBH. The study confirmed the applicability of the relationship for the stand transpiration (EC) estimates even in a multi-specific broadleaved forest with a wide variation in DBH (Chiu *et al.* 2016).

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