Environmental Responses and Modeling of Leaf Stomatal Conductance in Apple Trees on the Loess Plateau (Postprint)

Authors: Miao Yu

Date: 2021-04-14T00:00:00+00:00

Abstract

Stomatal conductance (gs) is a crucial parameter for quantifying the exchange rates of water, CO2, and other substances between plants and the external environment, and its observation and simulation can effectively indicate the status of material exchange and various physiological parameters. Using the LI-6400 portable photosynthesis system, we observed various physiological parameters of apple tree leaves on the Loess Plateau, analyzed the diurnal variation characteristics of gs and its response relationships with environmental factors, and simulated gs using the Jarvis model and the Ball-Woodrow-Berry (BWB) model. The results demonstrate: (1) The diurnal variation of gs in apple trees on the Loess Plateau exhibited a bimodal curve during observation days in August and September when temperatures were high and radiation was intense. In the morning (8:00–12:00), as solar radiation gradually intensified, stomata opened, and gs reached its first peak at 11:00–13:00; at noon (12:00–14:00), due to increased air temperature (Ta), stomata closed to prevent excessive water loss from cells, resulting in a brief "midday depression of photosynthesis" phenomenon; in the afternoon (14:00–18:00), as Ta and photosynthetically active radiation (PAR) decreased, gs gradually increased and reached its second peak at 15:00–17:00. (2) Through grey correlation analysis, the correlation degree between gs and environmental factors was found to be in the following order: PAR (0.731) > CO2 concentration (Ca, 0.712) > vapor pressure deficit (VPD, 0.702) > Ta (0.689) > relative humidity (hs, 0.673). The response relationship between gs and environmental factors manifested as: gs increased with increasing PAR, Ta, Ca, and hs, and decreased with increasing VPD. (3) The simulation results of gs indicate that the coefficient of determination (0.678), modified coefficient of efficiency (0.335), and modified coefficient of agreement (0.803) of the Jarvis model were all superior to the corresponding values of the BWB model (0.329, -1.630, 0.138), while the mean absolute error (0.103) was smaller than that of the BWB model (0.143), demonstrating that the Jarvis model provided superior simulation performance. This analytical study of the environmental response and simulation of gs in apple tree leaves on the Loess Plateau holds significant importance for understanding temporal variations in water demand of apple tree leaves throughout the day and for further improving water resource utilization efficiency in apple cultivation in this region.

Full Text

Environmental Response and Simulation of Stomatal Conductance in Apple Tree Leaves on the Loess Plateau

MIAO Yu[1], **GAO Guanlong**[1],[2],[3], **LI Wei**[1] [1]College of Environment and Resource, Shanxi University, Taiyuan 030006, Shanxi, China [2]Shaanxi Key Laboratory of Land Consolidation, Chang' an University, Xi' an 710064, Shaanxi, China [3]Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, Gansu, China

Abstract

Stomatal conductance (gs) is a critical parameter that measures the exchange rate of water, CO_2, and other substances between plants and the external environment. The observation and simulation of gs can effectively indicate material exchange processes and various physiological parameters. Using a portable photosynthesis system, we observed the physiological parameters of apple trees on the Loess Plateau, analyzed the diurnal variation characteristics of gs and its response relationships with environmental factors, and simulated gs using the Jarvis model and the Ball-Woodrow-Berry (BWB) model. The results show that: (1) The diurnal variation of gs in apple trees on the Loess Plateau exhibited a bimodal curve during the observation days in August and September when temperatures were high and radiation was strong. In the morning (8:00-12:00), as solar radiation gradually increased, stomata opened and gs reached its first peak between 11:00 and 13:00. At midday (12:00-14:00), to avoid excessive water loss from cells as temperature (Ta) increased, stomata closed, resulting in a temporary "midday depression of photosynthesis." In the afternoon (14:00-18:00), as Ta and photosynthetically active radiation (PAR) decreased, gs gradually increased and a second peak appeared between 15:00 and 17:00. (2) Through grey relational degree analysis, the correlation between gs and various environmental factors was found to be, in descending order: PAR (0.731) > CO_2 concentration (Ca, 0.712) > vapor pressure deficit (VPD, 0.702) > Ta (0.689) > relative humidity (hs, 0.673). The response relationships between gs and environmental factors showed that gs increased with increasing PAR, Ta, Ca, and hs, but decreased with increasing VPD. (3) The simulation results for gs indicated that the Jarvis model performed well, with higher values for the determination coefficient (0.678), modified coefficient of efficiency (0.335), and modified index of agreement (0.803) compared to the BWB model (0.329, -1.630, and 0.138, respectively), while its mean absolute error (0.103) was smaller than that of the BWB model (0.143). Through systematic analysis of the environmental response and simulation of gs in apple tree leaves on the Loess Plateau, this study provides important insights for understanding the temporal changes in water demand by apple tree leaves throughout the day and for improving water use efficiency in apple cultivation in this region.

Keywords: stomatal conductance; grey relational degree; apple tree; Loess Plateau

1. Study Area Overview

The experimental plot was located at the Dongyang Experimental Research Base of the Institute of Plant Protection, Shanxi Academy of Agricultural Sciences, situated in the central terrain region of Shanxi Province. The area belongs to a temperate monsoon climate zone, with concentrated precipitation in summer and autumn, and relatively dry conditions in winter and spring. The average annual precipitation is 450 mm, the average annual temperature is 9.5 °C, and the average annual wind speed is 2.4 $\mathrm{m \cdot s^{-1}}$. The experimental plot contained apple trees with an average crown width of 316 cm × 318 cm and an average ground diameter of 10.9 cm.

2.1 Experimental Design and Methods

Observations were conducted during the main growing season of apple trees from June to September. In the experimental plot, three apple trees with good growth conditions were selected as sample trees. A LI-6400 portable photosynthesis system (LI-COR, USA) was used to observe physiological parameters including net photosynthetic rate (Pn, $\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$), transpiration rate (Tr, $\mathrm{mmol \cdot m^{-2} \cdot s^{-1}}$), intercellular CO_2 concentration (Ca, $\mathrm{mol \cdot mol^{-1}}$), and leaf surface CO_2 concentration (Cs, $\mathrm{mol \cdot mol^{-1}}$). During the observation process, three sun-exposed leaves were selected on each sample tree, and each parameter was recorded repeatedly three times. Observations were made from 8:00 to 18:00 at 2-hour intervals, with adjustments made on different observation dates according to weather conditions and sunrise/sunset times. Additionally, to obtain meteorological parameters such as vapor pressure deficit (VPD), air temperature (Ta), relative humidity (hs), and wind speed (u, $\mathrm{m \cdot s^{-1}}$) within the sample plot, a small weather station was set up for observations. After data collection and processing, SPSS 24.0 was used for data preprocessing to facilitate subsequent model simulation.

2.2 Introduction to gs Models

The Jarvis model comprehensively considers the effects of PAR, Ta, and Ca on plant leaf gs, with the following expression:

$$g_s = g_{smax} \cdot f_1(PAR) \cdot f_2(VPD) \cdot f_3(Ta) \cdot f_4(Ca)$$

where $f_1(PAR)$, $f_2(VPD)$, $f_3(Ta)$, and $f_4(Ca)$ are response functions of gs to each environmental factor. In previous studies, scholars have proposed different expressions for the single-factor response models. The commonly used forms are:

$$f_1(PAR) = \frac{a_1 + PAR}{a_2 + PAR}$$
$$f_2(VPD) = 1 - a_3 \cdot VPD$$
$$f_3(Ta) = a_4 \cdot Ta + a_5 \cdot Ta^2$$
$$f_4(Ca) = 1 - a_6 \cdot Ca$$

where a_1, a_2, a_3, a_4, a_5, and a_6 are parameters to be determined.

The BWB model assumes a linear relationship between gs and net photosynthesis rate (A), which largely describes the mechanism of stomatal opening and closing. The calculation formula is:

$$g_s = g_0 + m \cdot \frac{A \cdot hs}{Cs}$$

where m and g_0 are parameters to be determined; A is the photosynthetic rate; hs is relative humidity; and Cs is leaf surface CO_2 concentration.

2.3 Model Simulation Accuracy Evaluation Indicators

By comparing measured leaf stomatal conductance with simulated results from each model, the simulation accuracy of the models can be determined. Following the indicators selected by Legates and McCabe (1999), this study used the determination coefficient (R^2), modified coefficient of efficiency (E), modified index of agreement (d), and mean absolute error (MAE) to evaluate model simulation accuracy:

$$R^2 = \left[\frac{\sum_{i=1}^{N}(O_i - \bar{O})(M_i - \bar{M})}{\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{N}(M_i - \bar{M})^2}} \right]^2$$

$$E = 1 - \frac{\sum_{i=1}^{N} |O_i - M_i|}{\sum_{i=1}^{N} |O_i - \bar{O}|}$$

$$d = 1 - \frac{\sum_{i=1}^{N} |O_i - M_i|}{\sum_{i=1}^{N}(|M_i - \bar{O}| + |O_i - \bar{O}|)}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |O_i - M_i|$$

where O_i is the measured leaf stomatal conductance ($\mathrm{mol} \cdot \mathrm{H_2O} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$); M_i is the simulated stomatal conductance ($\mathrm{mol} \cdot \mathrm{H_2O} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$); $\bar{O}$ is the mean measured stomatal conductance ($\mathrm{mol} \cdot \mathrm{H_2O} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$); and N is the total number of samples. A model is considered to have high simulation accuracy if it has larger R^2, E, and d values, smaller MAE values, and a slope close to 1.

2.4 Grey Relational Degree Analysis

Grey relational degree analysis primarily reflects the degree of association between variables based on the similarity or consistency of their development trends. Before conducting grey relational degree analysis on gs, a grey system must first be established. Using 1-2 typical days with clear weather and good data records as the data source, gs was set as the reference sequence, and the five environmental factors of PAR, Ta, Ca, VPD, and hs were set as comparative sequences to determine the correlation coefficients (xi) and relational degrees (ri).

2.4.1 Dimensionless Processing Since the environmental factors affecting apple tree leaf gs have different physiological meanings and value ranges, the data require dimensionless standardization. Common dimensionless processing methods include mean normalization, initial value normalization, and range transformation. This study primarily used range transformation for data processing.

2.4.2 Correlation Coefficients and Relational Degree Grey relational degree analysis was performed on the dimensionless data to obtain xi and ri between gs and each environmental factor. The correlation degree essentially refers to the similarity of curve trend development. In this study, gs was selected as the reference sequence, and PAR, Ca, VPD, Ta, and hs were selected as comparative sequences to calculate xi and ri between the reference sequence and comparative sequences at each time point (i.e., each point on the curve). The calculation methods are as follows:

$$\xi_{xi}(k) = \frac{\Delta_{min} + \rho \cdot \Delta_{max}}{\Delta_{xi}(k) + \rho \cdot \Delta_{max}}$$

$$r_i = \frac{1}{N} \sum_{k=1}^{N} \xi_{xi}(k)$$

where ρ is the resolution coefficient, generally between 0 and 1, typically taken as 0.5; Δ_{min} is the minimum difference between the reference sequence and comparative sequences; Δ_{max} is the maximum difference; $\Delta_{xi}(k)$ is the absolute difference between the reference sequence and comparative sequences at each point; x_i represents the five comparative sequences of PAR, Ca, VPD, Ta, and hs; k represents the observation points of environmental factors ($k = 1, 2, ...$); and N is the total number of observations for each environmental factor.

3.1 Diurnal Variation of Apple Tree gs

Based on measured gs data from the main growing season (June–September) of apple trees, clear weather conditions were selected each month to analyze leaf gs variation [Figure 1: see original paper]. The results show that the diurnal variation of apple tree leaf gs exhibited a bimodal curve on observation days in August and September when temperatures were high and radiation was strong. In the morning, as light intensity continuously increased, stomatal aperture gradually expanded, and gs reached its first peak between 11:00 and 13:00. At midday, high temperature and radiation conditions increased the water vapor pressure gradient between the leaf interior and exterior (midday temperature generally around 36.8 °C), and transpiration gradually intensified. To reduce excessive water loss, stomata closed and gs decreased. In the afternoon (14:00–18:00), as transpiration rate decreased, leaf water potential recovered to some extent, gs gradually increased and exhibited a brief upward trend with a second peak, after which gs tended to decline. The afternoon gs peak was consistently lower than the morning peak.

3.2.1 Grey Relational Degree Analysis

Based on dimensionless standardized data, the correlation coefficients xi and relational degrees ri between gs and each environmental factor were calculated . The results show that the correlation between gs and environmental factors was, in descending order: PAR (0.731) > Ca (0.712) > VPD (0.702) > Ta (0.689) > hs (0.673). PAR and Ca showed relatively close relationships with gs and had greater influence on stomatal aperture, while hs had the lowest correlation with gs.

3.2.2 Response of gs to Environmental Factors

Sunlight is an important condition for plant photosynthesis and transpiration and a significant factor affecting leaf gs. As shown in [Figure 3: see original paper], gs gradually increased with increasing PAR. In the morning (8:00–12:00), PAR gradually increased, and gs reached its first peak between 11:00 and 13:00. After 12:00–14:00 (midday), PAR continued to strengthen, and when it exceeded 1200 $\mathrm{W \cdot m^{-2}}$ (midday PAR generally around 1385 $\mathrm{W \cdot m^{-2}}$), to reduce excessive water loss, stomata closed and gs consequently decreased. In the afternoon (14:00–18:00), as PAR and Tr decreased, leaf water potential recovered to some extent, gs showed a brief upward trend and reached a second peak, after which gs tended to decline.

CO_2 is an important raw material for plant photosynthesis. It is generally believed that low Ca can promote stomatal opening, while high Ca causes rapid stomatal closure. The response relationship between gs and Ca shows that when Ca was low, gs gradually increased with increasing Ca; when Ca increased beyond 375 mol · mol^{-1}, gs showed a more obvious decreasing trend with Ca. The Ca range for maintaining relatively high gs was approximately 350–375 mol · mol^{-1}; too high or too low Ca would have an inhibitory effect on plant gs.

The response relationship between gs and VPD shows that gs gradually decreased with increasing VPD. Throughout the day, VPD began to continuously increase from 8:00–12:00, with a small decrease in gs; at midday (12:00–14:00), VPD increased significantly, with a peak reaching 3.784 kPa and a maximum of 7.107 kPa. Stomata closed to avoid excessive water loss, and gs values rapidly decreased.

It is generally believed that the effect of Ta on plant leaf gs is that gs tends to increase with rising Ta, but when Ta exceeds a certain limit, gs rapidly decreases. The results show that gs gradually increased with rising Ta, reaching a maximum around 30 °C–35 °C, after which gs gradually decreased with further Ta increase.

The response relationship between gs and hs shows that gs increased with increasing hs. Throughout the day, hs was relatively high in the early morning (average about 52.191%), and gs increased with hs; in the afternoon (14:00–18:00), as Ta and VPD increased, hs rapidly decreased, and gs also showed a downward trend due to high temperature effects.

3.3.1 Determination of Jarvis and BWB Model Expressions

Based on the single-factor response models for gs in the Jarvis model, different combinations of factor calculation formulas can determine various forms of Jarvis model expressions. This study compared the simulation results of different Jarvis model expressions based on observed apple tree leaf gs data, and determined the optimal model expression by comparing R^2 values. Additionally, SPSS 24.0 was used to fit the observed data and determine the parameter values, ultimately establishing the Jarvis model expressions. The specific results are shown in and .

3.3.2 Comparison of gs Model Accuracy

The comparison between measured gs and Jarvis model-simulated gs during the main growing season of apple trees is shown in [Figure 4: see original paper]. The evaluation metrics for model simulation accuracy are presented in . The results show that the simulated gs values for apple trees calculated by the Jarvis model were more concentrated in the scatter plot, with a linear fitting equation slope (0.678) and R^2 (0.335) that were higher than the corresponding values for the BWB model (0.329 and -1.630, respectively). The Jarvis model also showed higher E and d values and lower MAE compared to the BWB model. Therefore, in this study, the Jarvis model demonstrated higher simulation accuracy for apple tree leaf gs.

4. Discussion

The diurnal variation of gs reached its first peak between 11:00 and 13:00; at midday, due to increased Ta, stomata closed under intense transpiration, and gs decreased; in the afternoon, as Tr weakened, gs recovered and reached a second peak between 15:00 and 17:00, with the afternoon peak consistently lower than the morning peak.

In the response relationships with environmental factors, leaf gs showed an upward trend with increasing PAR, Ca, hs, and Ta, but decreased after exceeding certain thresholds for each factor. This conclusion is consistent with the results of Chai Mengying on apple tree leaf gs response to PAR, Wang Haizhen et al. on Populus euphratica gs response to Ca and Ta, and Si Jianhua et al. on Populus pruinosa gs response to hs. However, it differs from the results of Ruan Chengjiang et al. on seabuckthorn gs response to Ca in the Loess Hilly Region and Tang Fengde et al. on broadleaved Korean pine forest leaf gs response to Ca and hs in Changbai Mountain, which may be related to differences in regional geography and plant species.

Regarding the response of gs to VPD, the results show that gs decreased with increasing VPD, consistent with the findings of Wang Haizhen et al. on Populus euphratica and Zhou Lina et al. on understory ginseng leaf gs. The different response relationships between gs and environmental factors are due to variations in plant physiological characteristics and environmental adaptation mechanisms.

The LI-6400 portable photosynthesis system was used to observe apple tree gs and analyze its diurnal variation characteristics under clear weather conditions. The results show that apple tree gs exhibited a bimodal curve on observation days with high temperature and strong radiation in August and September, consistent with the findings of Gao Zhaoquan et al. on apple trees under different water conditions and Li Mingxia et al. on apple trees at the end of the fruiting period. The reason is that in the morning, as PAR, Ta, and Ca gradually increased, stomatal aperture expanded, leading to accelerated Pn and increased gs; when environmental factors exceeded certain thresholds, leaves closed stomata under high temperature and VPD to reduce excessive water loss, causing gs to decrease.

5. Conclusions

This study systematically examined apple tree gs on the Loess Plateau, first analyzing the diurnal variation characteristics of leaf gs and explaining the response relationships between gs and environmental factors, then conducting simulation analysis using the Jarvis model. The main conclusions are as follows:

(1) The diurnal variation of gs in apple trees on the Loess Plateau exhibited a bimodal curve on observation days with high temperature and strong radiation in August and September, with the morning peak consistently higher than the afternoon peak. The reasons are: in the morning, in-

fluenced by PAR, stomata opened and gs rapidly increased, reaching its first peak between 11:00 and 13:00; at midday, as Ta increased, stomata closed under intense transpiration and gs decreased; in the afternoon, as Tr weakened, gs recovered and reached a second peak between 15:00 and 17:00, with the afternoon peak consistently lower than the morning peak.

(2) The correlation between gs and environmental factors was, in descending order: PAR > Ca > VPD > Ta > hs. The response relationships showed that gs increased with increasing PAR, Ta, Ca, and hs, but decreased with increasing VPD. The different response relationships are due to: throughout the day, as PAR, Ta, and Ca gradually increased, stomatal aperture expanded, accelerating Pn and increasing gs; when environmental factors exceeded certain thresholds, leaves closed stomata under high temperature and VPD stimulation to reduce excessive water loss, causing gs to decrease. Higher hs values corresponded to early morning, evening, or cloudy conditions with weak light, where gs values were lower compared to clear weather conditions.

(3) The simulation results for gs showed that the Jarvis model had good simulation performance. In the future, simulation studies of gs for various crops under arid and semi-arid climate conditions, as well as estimation and simulation of evapotranspiration and ecological water requirements for natural vegetation in arid regions, should be strengthened to further explore the applicability of the Jarvis model.

References

[1] Shi Jianhong, Zhou Suoquan, Yu Hua, et al. Stomatal conductance models of typical tree species in the basin of Poyang Lake in summer and comparison of their influencing factors[J]. Research of Environmental Sciences, 2010, 23(1): 33-40.

[2] Zhang Zhongdian, Zhang Dalong, Li Jianming, et al. Environmental response of stomatal and hydraulic conductances and their effects on regulating transpiration of cucumber[J]. Transactions of the Chinese Society for Agricultural Machinery, 2016, 47(6): 139-147.

[3] Gao Guanlong, Zhang Xiaoyou, Yu Tengfei, et al. Simulation of leaf stomatal conductance of Populus euphratica Oliv under extremely dry conditions[J]. Arid Land Geography, 2016, 39(3): 607-612.

[4] Zhang Min. The analysis of apple photosynthetic characteristic and relationship with impact factors under water storage pit irrigation[D]. Taiyuan: Taiyuan University of Technology, 2015.

[5] Ma Wenyun. Effects of irrigation upper and lower limits on transpiration characteristics of apple trees at different scales under water storage pit irrigation[D]. Taiyuan: Taiyuan University of Technology, 2019.

[6] Qiu Qunyi. Research on characteristics of evaporation and transpiration of apple trees under water storage pit irrigation[D]. Taiyuan: Taiyuan University of Technology, 2014.

[7] Li Bo, Guo Xianghong, Sun Xihuan, et al. A study on leaf photosynthesis properties of young apple trees at different lower limit of irrigation under water storage pit irrigation conditions[J]. Water Saving Irrigation, 2016, 6(5): 51-56.

[8] Li Rui. Effect of pit depths and irrigation under water storage pit irrigation on growth of dwarf stock young apple trees[D]. Taiyuan: Taiyuan University of Technology, 2017.

[9] Zhao Wenyuan, Sun Xihuan, Ma Juanjuan, et al. Study on the diurnal variation of canopy conductance of apple trees under water storage pit irrigation and its influencing factors[J]. Water Saving Irrigation, 2020(9): 64-68, 74.

[10] Chai Mengying. Photosynthetic efficiency of apple leaves under water storage pit irrigation[D]. Taiyuan: Taiyuan University of Technology, 2018.

[11] Gao Juan. Effects of nitrogen application on growth and photosynthetic characteristics of apple trees under water storage pit irrigation[D]. Taiyuan: Taiyuan University of Technology, 2019.

[12] Zheng Lijian. Moisture migration mechanism of dwarfing apple tree under water storage pit irrigation based on stable isotope technology[D]. Taiyuan: Taiyuan University of Technology, 2019.

[13] Wang Haizhen, Han Lu, Xu Yali, et al. Characteristics of stomatal conductance of Populus pruinosa and the quantitative simulation[J]. Scientia Silvae Sinicae, 2016, 52(1): 136-142.

[14] Ruan Chengjiang, Li Daiqiong. Stomatal conductance and influence factors of seabuckthorn in Loess Hilly Region[J]. Acta Botanica Boreali Occidentalia Sinica, 2001, 21(6): 30-36.

[15] Tang Fengde, Wu Yaoxiang, Han Shijie, et al. Relationship of stomatal conductance of leaf with environmental factors in broadleaved Korean pine forest at Changbai Mountain[J]. Acta Ecologica Sinica, 2008, 28(11): 5649-5655.

[16] Zhou Lina, Liu Yan, Zhang Lei, et al. Research on the relationship between the stomatal conductance and environmental factors of ginseng under forest[J]. Journal of Anhui Agricultural Sciences, 2009, 37(33): 16616-16618.

[17] Gao Guanlong, Feng Qi, Liu Xiande, et al. Simulating the leaf stomatal conductance of the desert riparian Tamarix ramosissima Ledeb based on three empirical models[J]. Acta Ecologica Sinica, 2020, 40(10): 1-9.

[18] Ma Rong, Mamattursun Eziz, Hamid Yimit, et al. Characteristics and quantitatives simulation of stomotal conductance of phragmites communis leaves in north shore of Bosten Lake in Xinjiang[J]. Acta Agriculturae Boreali occidentalis Sinica, 2016, 25(1): 123-128.

[19] Liu Yanbo, Sun Hongrong, Xiang Yang, et al. Germplasm selection of drought resistance maize seedlings by grey relational grade analysis[J]. Seed, 2014, 33(10): 74-77.

[20] Si Jianhua, Chang Zongqiang, Su Yonghong, et al. Stomatal conductance characteristics of Populus euphratica leaves and response to environmental factors in the extreme arid region[J]. Acta Botanica Boreali Occidentalia Sinica, 2008, 28(1): 125-130.

[21] Li Mingxia, Geng Guijun, Bai Gangshuan, et al. Effect of renewal pruning on apple photosynthetic ability and fruit quality in final full productive stage[J]. Journal of Northwest A & F University (Natural Science Edition), 2011, 39(1): 179-185.

[22] Liu Shubao, Chen Yaning, Li Weihong, et al. Application of D and O stable isotopes in analyzing the water sources of different ages of Populus euphratica in the lower reaches of the Heihe River[J]. Arid Land Geography, 2014, 37(5): 988-995.

[23] Jarvis P G. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field[J]. Philosophical Transactions of the Royal Society B: Biological Sciences, 1976, 273(927): 593-610.

[24] Ball J T, Woodrow I E, Berry J A. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions[C]//Progress in Photosynthesis Research. Springer, 1987: 221-224.

[25] Legates D R, Mccabe G J. Evaluating the use of goodness measures in hydrologic and hydroclimatic model validation[J]. Water Resources Research, 1999, 35(1): 233-241.

Note: Figure translations are in progress. See original paper for figures.