

Sap Flow Characteristics of Zaosu Pear Trees in Different Tree Shapes and Their Effects on Meteorological Factors

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Abstract. The lack of water resources in the arid northwest of China has seriously restricted the growth and efficient production of fruit trees. Zaosu pear (*Pyrus ssp. Va.*, Zaosu) is the main variety of pear cultivation in Gansu Province and one of the pillar industries for local economic development. This study compared the changes in sap flow of Zaosu pear trees in different tree shapes (Y-shaped, single-armed, and spindle-shaped trees) in different months, weather conditions, and developmental stages, as well as the relationship between sap flow and meteorological factors, to provide a theoretical basis for the selection of Zaosu pear tree shapes in arid areas. The results showed that the daily variation of sap flow was affected by tree shape and weather conditions. The start time of sap flow of the single-arm tree was later than that of the Y-shaped and spindle-shaped trees in spring, but the average daily sap flow in the growth and development period (June, July, and August) on sunny days was 73.05, 51.41, and 76.33 g·h⁻¹, respectively, and the daily cumulative sap flow could reach 3503.4, 2467.4, and 3664 g·h⁻¹, which were significantly higher than those of the Y-shaped and spindle-shaped trees. Different growth stages had a significant effect on sap flow, and the peak sap flow was the highest during the fruit expansion and maturity stages. This stage was the critical period for water demand. The sap flow of the three tree shapes started at 8:00 AM, reached a peak at 1:00 PM, and stopped at 7:00 PM in the first fruit expansion, the second fruit expansion, and the maturity stage. The sap flow of the single-arm tree was the largest. Correlation analysis showed that sap flow was significantly positively correlated with temperature and solar radiation. The higher the temperature, the stronger the transpiration, the greater the sap flow, and it was significantly negatively correlated with humidity. In summary, the single-arm tree shape is more suitable for cultivation in arid areas and has good water use efficiency and environmental adaptability.

China has rich pear resources and a long history of cultivation. Its cultivated area and yield are among the highest in the world (Teng 2011). Zaosu pear is an important fruit resource in Gansu Province (Huang et al. 2022). It has the characteristics of high fruit yield, thin and crisp fruit skin, sweet juice, rich in amino acids, vitamins and phenols, and high nutritional and economic value (Jiang et al. 2023; Sun et al. 2021; Topuz and Bakkalbasi 2022). Jingtai County is located in the transition zone from the southern edge of the Tengger Desert and the Qilian Mountains to the Loess Plateau. In the critical period of fruit tree growth in summer, there are high temperatures and droughts, which poses a severe challenge to the growth and yield of Zaosu pear. Water is essential for plant growth and development and is the main environmental factor affecting plant growth. Therefore, how to improve the water use efficiency of pear trees has become one of the

key issues in fruit tree cultivation and management (Behzad et al. 2023; He et al. 2023; Li et al. 2024).

Sap flow is an indicator that quantitatively describes the water status in plants and characterizes the drought tolerance and water movement patterns of plants. This study examines the sap flow dynamics (xylem sap flow) of Zaosu pear trees and their response to meteorological factors. Sap flow can reflect the water utilization status of the xylem, characterize the dynamic changes in water movement in plants, indicate the response of plant physiological and ecological characteristics to changes in the surrounding environment, and reflect the water utilization strategy of plants (Dai et al. 2024). It is one of the important ways for plants to redistribute water. Studies have shown that sap flow not only affects the water acquisition of plants but also has a significant impact on soil moisture status and microbial environment (He et al. 2023). In

addition, sap flow characteristics are affected by many factors, including tree species, tree structure, precipitation intensity, and meteorological conditions (Crockford and Richardson 2000; Dupont et al. 2015). It is generally believed that meteorological factors such as solar radiation and air temperature are the main environmental factors that control changes in plant sap flow, and the atmosphere and soil are the main environmental factors that drive water transport (Manzoni et al. 2013). Sap flow, as a direct reflection of plant water transport, is a key indicator for understanding plant water relations and their response to the environment (Gonzalez-Ollauri et al. 2020). The sap flow characteristics of fruit trees are affected by both tree structure and environmental factors. Among them, differences in tree shape directly affect the distribution and flow pattern of water inside the tree, which in turn affects the transpiration and water use efficiency of the tree. Meteorological factors such as temperature, humidity, wind speed, and solar radiation also have a significant correlation with sap flow characteristics.

As an important factor in fruit tree cultivation and management, tree structure not only affects light distribution and ventilation and light transmittance but may also affect sap flow characteristics, affecting light interception and stomatal conductance by changing the canopy structure, thereby regulating the water transfer path (Kim et al. 2004). However, there are relatively few studies on the effects of different tree structures on sap flow characteristics of pear trees, especially on the Zaosu pear variety.

Therefore, this study aims to explore the changes in sap flow of different Zaosu pear tree shapes in different months, weather conditions, and growing seasons, as well as the relationship between sap flow and meteorological factors. By comparing and analyzing the sap flow dynamics under different tree structures, the influence mechanism of tree structure on sap flow process is revealed, providing a scientific basis for optimizing fruit tree cultivation management, water conservation, and efficient water use.

Materials and Methods

Overview of the test site. The experimental orchard is located in Gansu Province, in Silver City, Jingtai County, at Strip Hill Farm. The test site is situated at the southern edge of the Tengger Desert, at an elevation of 1619.5 m. It belongs to a temperate arid climate, with an average annual temperature of 8.2 °C, annual precipitation of 184.8 mm, 2725 h of sunshine annually, and a frost-free period of 141 d. The orchard soil is sandy gray calcium soil, with a soil pH value of 8.2 and an organic matter content of 1.2% at a depth of the soil layer. The terrain of the orchard is flat. The irrigation method is drip irrigation, routine management, and consistent fertilization. The tree planting direction is north–south row direction, and the tree shape cultivation is neat and standard.

Test materials. The experiment was carried out in 2021 in the experimental demonstration garden of National Pear Industry Technology System Lanzhou Experiment Station in Jingtai County, Baiyin City, Gansu Province, China. As illustrated in Table 1, the test material was Zaosu pear, with trees aged 7 years. Three kinds of tree shapes were selected: Y shape, single-arm shape, and spindle shape. Three trees of each shape were chosen with consistent growth throughout the garden as the test trees. Each tree was treated individually, with the treatment repeated three times.

Measurement of liquid flow rate. During the continuous growth period of the pear trees from March to the end of August, the sap flow (xylem sap flow) rate (g/h) was measured by heat dissipation probe method, according to Granier's method (Granier 1987), using the FLAGS-TDP system (Dynamax, Inc., Houston, TX, USA). Sensors with a length of 30 mm were installed on the north side of each treatment tree at a height of 45 cm from the ground. The exposed part of the sensor was sealed to prevent direct contact with the atmosphere. All probes were wrapped with several layers of insulating foam and shielded with aluminum foil to minimize the amplitude of temperature changes. The entire cross-sectional area of the tree was considered to be sapwood in this study. The temperature difference between the heated probe and the reference probe was measured every 60 s, and the average value was recorded every 10 min using a data logger. These data were used to calculate the tree sap flow density according to the formula derived by Granier (1987).

Environmental factor data collection. Meteorological factor data were continuously monitored by an Em50/G data logger (METER Group Inc., Pullman, WA, USA) installed in

the test area. The data mainly measured air temperature, humidity, solar radiation, precipitation, and wind speed and were automatically recorded and stored at intervals of 0.5 h.

Data analysis. Excel 2021 (Microsoft, Redmond, WA, USA) was used for data processing and charting, Origin 2024 (Origin Inc., San Francisco, CA, USA) software was used for bar charts and line graphs, and the data were analyzed for significance using SPSS 26.0 (SPSS Inc., Chicago, IL, USA) for analysis of variance (ANOVA) and multiple comparisons using one-way ANOVA, with a significance level of $P < 0.05$.

Results

Daily variation characteristics of sap flow rate of different tree shapes in different months and weather conditions

The weather conditions on Mar 20, 23, 27, and 29 were cloudy, foggy, sunny, and cloudy, respectively (Fig. 1).

Y-shaped trees in March. On hazy days, the sap flow reaches a peak at night, especially around 2:00 AM, and then drops rapidly to zero after 3:00 AM. Large sap flow fluctuations were also observed during cloudy and overcast evening hours. On cloudy days, the sap flow was higher at early time points, then dropped rapidly after 3:00 AM, and recovered slightly around 5:00 AM; on clear and cloudy days, the sap flow was zero for a period of time after 12:00 AM and then only showed changes in sap flow at certain specific time points. Under cloudy and overcast weather conditions, the fluctuations in sap flow were not as dramatic as on hazy days, and the overall sap flow was lower than on hazy days but higher than on clear days (Fig. 1A).

Single-arm shaped trees in March. Cloudy and overcast weather has higher sap flow in the early morning and evening, which may be related to the physiological activities of plants during these time periods. Sap flow in sunny and foggy days takes place during the day, and sap flow activity begins to increase in the morning and continues in the evening. In overcast and overcast weather, there will be sap flow activity in the morning and evening, and the sap flow is more uniform, and the amount is smaller. In hazy weather, the sap flow is higher from midnight to early morning and close to zero at other times. In clear weather, the sap flow has a higher peak in the evening (Fig. 1B).

Spindle-shaped trees in March. In hazy weather, sap flow increases significantly at night, especially between 8:00 and 11:00 PM. Sap flow in sunny weather also increases at night, but the increase is not as large as in hazy days. Sap flow in cloudy and overcast days changes relatively smoothly throughout

the day. In the morning and afternoon of the day, sap flow is generally low in all weather conditions (Fig. 1C).

In summary, the spindle-shaped tree shape can maintain the stability of sap flow in changeable weather and may be a reasonable choice. The Y-shaped tree shape has a stronger ability to absorb water in hazy weather and may be more suitable. For trees with obvious changes in light and need to absorb water for sap flow at different times of the day, the single-arm tree shape may be a better choice.

Y-shaped trees in April. On cloudy days, the sap flow mostly increased at night (9:00 PM to 12:00 AM), reaching a maximum at 11:30 PM with a peak value of $31.59 \text{ g}\cdot\text{h}^{-1}$, while remaining unchanged during the day. The change trend of sap flow in cloudy weather was similar to that of cloudy days. The sap flow increased significantly during the period from 10:00 PM to 12:00 AM, and there was a slight increase from 4:00 to 5:00 AM. In clear weather, the sap flow increased slightly in the early morning and reached a peak of $4.59 \text{ g}\cdot\text{h}^{-1}$ at 2:00 AM, but did not change during the day. In light rainy weather, the sap flow increased significantly in the early morning, reaching a maximum at 1:00 and 1:30 AM, with the same peak value of $23.87 \text{ g}\cdot\text{h}^{-1}$, then dropped rapidly to zero, and did not change during the day (Fig. 2A).

Single-arm shaped trees in April. The sap flow rate on cloudy days fluctuates greatly, with a peak at 8:00 PM to 12:00 AM, indicating that the sap flow rate increases significantly during this period. The sap flow rate in cloudy weather increases more steadily, but there is still a clear peak in the evening. Under sunny conditions, the sap flow rate is relatively low, but there is a slight increase in the morning and afternoon. In light rain weather, the sap flow rate is very high in the early morning, but it remains at a low level from the morning to the night, with only a slight increase in the evening. In short, in overcast, cloudy, and sunny weather, the sap flow rate is mainly concentrated at 8:00 to 11:30 PM, indicating that under these weather conditions, plants mainly transpire at night; in light rain, the sap flow rate is relatively high at multiple times of the day, especially in the early morning and at night, which may be because the rain provides sufficient water to make the plant transpire more actively (Fig. 2B).

Spindle-shaped trees in April. In light rainy weather, the stemflow activity is very high in the early morning hours and then remains at a low level until it rises again in the evening. In sunny weather, there is a significant peak of stemflow activity between 7:00 and 11:30 PM. In cloudy and overcast weather, the stemflow activity is also relatively high at night, and the stemflow volume

Table 1. Tree species and plantings.

Cultivar	Tree shape	Plant spacing (m)	Row spacing (m)	Acres of trees (plants)
Zaosu pear	Y shape	2	4	83
	Single arm	2	4	83
	Spindle shape	2	4	83

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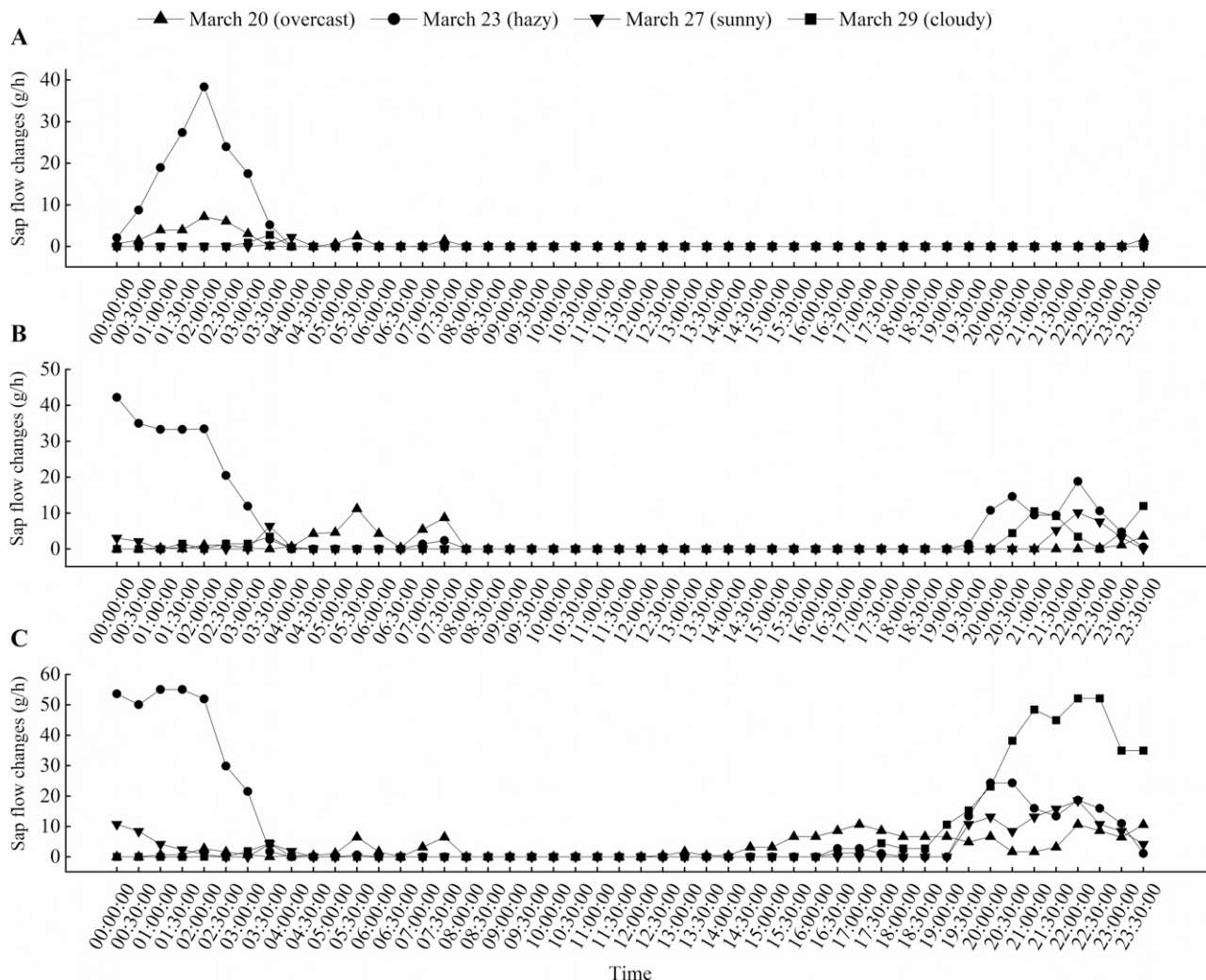


Fig. 1. Daily changes of sap flow in different tree shapes under different weather conditions in March. (A) Y-shaped tree. (B) Single-arm tree. (C) Spindle-shaped tree.

increases significantly from 10:00 to 11:30 PM. Through the analysis of daily stemflow activity under four different weather conditions, it can be concluded that night and early morning are periods of high stemflow activity. In the case of rainfall, the stemflow activity is particularly high in the early morning, which may be related to the change in soil moisture caused by rainfall. On sunny days, the stemflow activity is also high in the evening, which may be related to the lower temperature at night, and the plant adopts a strategy of absorbing water for storage (Fig. 2C).

In summary, under cloudy and light rainy weather, the Y-shaped tree has a higher peak value of sap flow at night. Under cloudy and overcast conditions, the sap flow growth of the single-arm tree is relatively stable. The spindle-shaped tree has high sap flow activity in the early morning after light rain.

Y-shaped trees in May. In cloudy weather, there are two obvious peaks in the sap flow of the tree that appear at 10:00 AM and 6:00 PM. In cloudy weather, the sap flow is low in the morning, and the sap flow shows a single peak change, reaching the peak of sap flow at 10:00 AM, then gradually decreases,

and shows a certain upward trend in the evening. The sap flow changes the most in hazy weather, with the highest sap flow peak, and the sap flow changes greatly within a day; the change of sap flow on sunny days is similar to that on cloudy days, but the overall sap flow is less than that on cloudy days; the sap flow of the tree changes more slowly in light rain weather. From the analysis results, it can be seen that plants may absorb and transport more water in the morning but relatively less at night, which may be related to the photosynthesis and transpiration of plants. The increase in Y-shaped sap flow on sunny and light rainy days can promote the absorption and utilization of water (Fig. 3A).

Single-arm shaped trees in May. In clear weather, stemflow shows a very obvious increasing trend during the day, especially between 8:00 AM and 3:00 PM. A similar trend is seen in cloudy and hazy weather, with relatively high stemflow values around 11:30 AM. In light rain, stemflow peaks at 8:30 AM and then changes relatively slowly. In cloudy weather, stemflow activity is evident during the day, with an obvious peak at 10:00 AM, followed by a gradual decline. This tree shape has

higher stemflow activity during the day on sunny days, indicating that photosynthesis and transpiration can be carried out more efficiently under high light conditions (Fig. 3B).

Spindle-shaped trees in May. The sap flow rate in cloudy weather gradually decreases from the early morning and then gradually decreases after reaching a peak at 11:00 AM; the changes in sap flow in cloudy and hazy weather are similar to the trend in cloudy weather, while the changes in sap flow in sunny and light rainy weather show obvious differences. On sunny days, the sap flow starts at 8:00 AM and starts to decrease at 18:30 PM, showing obvious daily changes; the sap flow changes relatively slowly in light rain weather, and the sap flow rate is relatively low. On sunny and hazy days, the sap flow rate reaches a peak during the day and is relatively low at night and on cloudy days. The spindle-shaped tree shape shows obvious peaks of sap flow activity in cloudy, sunny, and light rainy weather, indicating that it can effectively manage water under changing weather conditions (Fig. 3C).

Y-shaped trees in June. The sap flow of plants tends to be higher on sunny days, while

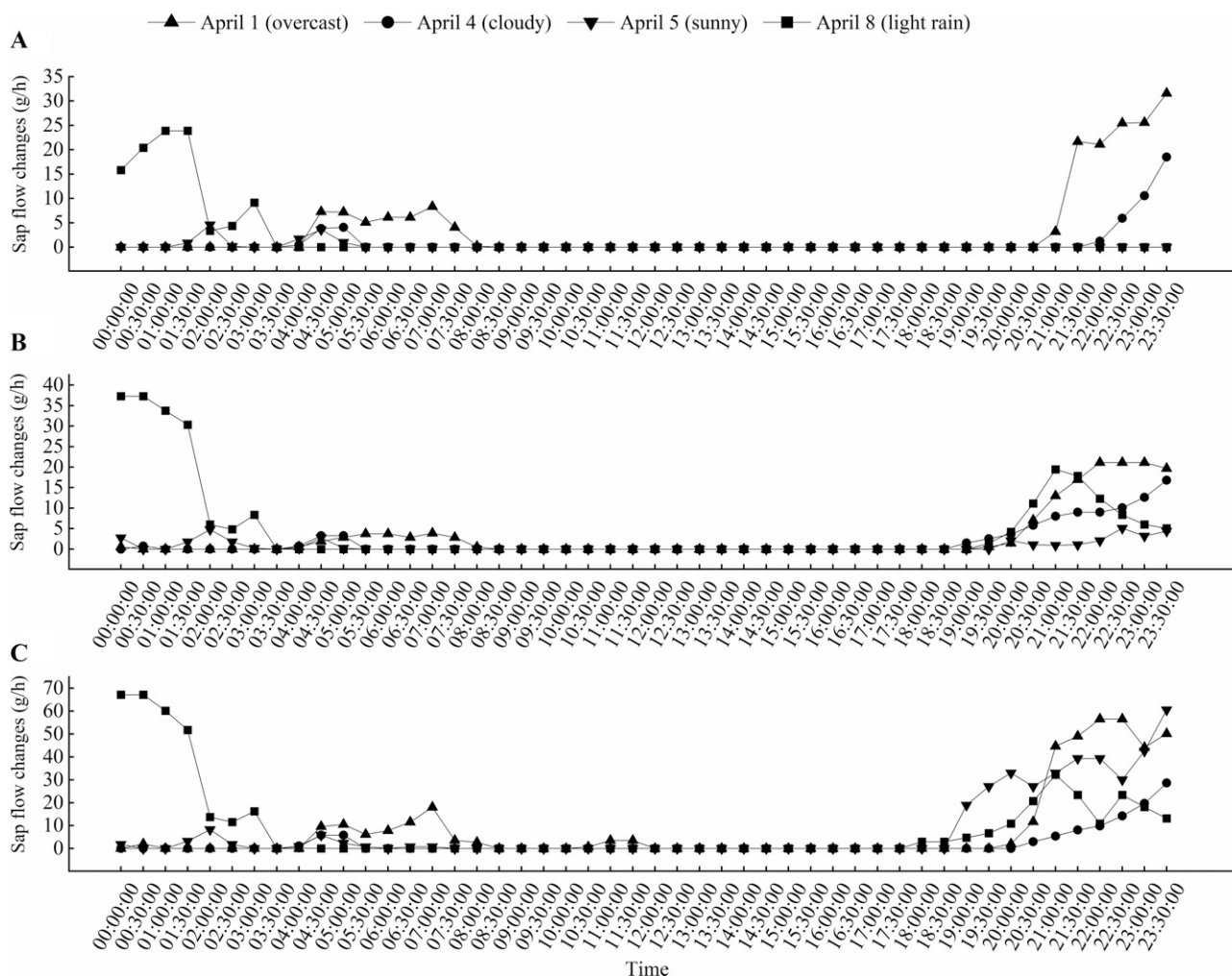


Fig. 2. Daily changes of sap flow in different tree shapes under different weather conditions in April. (A) Y-shaped tree. (B) Single-arm tree. (C) Spindle-shaped tree.

the sap flow decreases on rainy days or at night. The peak sap flow on cloudy days occurs at 9:00 AM, with a sap flow of $74.45 \text{ g} \cdot \text{h}^{-1}$; the peak sap flow on cloudy days occurs at 8:30 AM, with a sap flow of $60.40 \text{ g} \cdot \text{h}^{-1}$; the peak on 8 Jun (heavy rain) occurs at 10:00 AM, with a sap flow of $101.93 \text{ g} \cdot \text{h}^{-1}$, and the sap flow changes have obvious fluctuations; the peak sap flow on light rainy days occurs at 11:00 AM, with a sap flow of $102.54 \text{ g} \cdot \text{h}^{-1}$; the peak sap flow on sunny days occurs at 11:30 AM, with a sap flow of $81.88 \text{ g} \cdot \text{h}^{-1}$ (Fig. 4A).

Single-arm shaped trees in June. On cloudy days, the stemflow of the tree body began to increase significantly at 8:00 AM, and the changes in stemflow were relatively consistent between 9:00 AM and 2:30 PM. The peak of stemflow appeared at 3:00 PM and then slowly decreased. On cloudy days, the stemflow began to increase from 7:30 AM, and the peak of stemflow appeared around 9:00 AM. The subsequent trend of change was consistent with that on cloudy days. On rainy days, the stemflow began to increase at 8:30 AM, reached the peak of stemflow at 12:30 PM, maintained until 3:30 PM in the afternoon, and then began to decrease. The peak of stemflow was significantly higher

than that on cloudy and cloudy days. On sunny days, the stemflow started at 8:30 AM, and the changes in stemflow showed a bimodal change, but the amplitude of change was weaker than that on light rainy days. Under various weather conditions, the stemflow activity gradually increased from 7:30 to 9:30 AM and remained at a relatively peak state between 9:00 AM and 12:30 PM. The results showed that this time period was the most active period for plant stemflow activity (Fig. 4B).

Spindle-shaped trees in June. The sap flow rate on 1 Jun reached a peak of $117.21 \text{ g} \cdot \text{h}^{-1}$ at 11:30 AM; the sap flow rate on 3 Jun with cloudy weather and 8 Jun with heavy rain both reached a peak at 10:00 AM: $131.77 \text{ g} \cdot \text{h}^{-1}$ and $152.02 \text{ g} \cdot \text{h}^{-1}$ respectively; the sap flow rate on Jun 10, light rain, reached a peak of $107.66 \text{ g} \cdot \text{h}^{-1}$ at 8:30 AM; the sap flow rate on 25 Jun 25 with sunny weather reached a peak of $124.77 \text{ g} \cdot \text{h}^{-1}$ at 9:00 AM, and the sap flow rate gradually decreased over time. In the early morning and evening, all sap flow variables were close to zero, indicating that the sap flow activity was very low during these time periods. Starting at 8:00 AM, the sap flow rate began to increase, indicating that the plant began to absorb and transport water (Fig. 4C). In summary, the stable sap

flow peak and sap flow rate of the single-arm tree shape indicate that it is more effective in water transport in the morning and is more suitable for areas with sufficient sunlight.

Y-shaped trees in July. In light rainy weather, the sap flow peak is reached at 9:00 AM, with a sap flow rate of $50.66 \text{ g} \cdot \text{h}^{-1}$. In cloudy weather, the sap flow peak is reached at 10:00 AM, with a sap flow rate of $46.78 \text{ g} \cdot \text{h}^{-1}$. In sunny weather, the sap flow peak occurs at 10:30 AM, with a sap flow rate of $70.61 \text{ g} \cdot \text{h}^{-1}$. In cloudy weather, the sap flow peak occurs at 9:00 AM, with a sap flow rate of $31.43 \text{ g} \cdot \text{h}^{-1}$ (Fig. 5A).

Single-arm shaped trees in July. In light rain weather, it starts at 7:30 AM, then gradually rises, reaches the sap flow peak at 12:00 noon, drops at 3:00 PM, rises again, reaches the minimum at 6:30 PM, and then stabilizes. The sap flow start time in cloudy weather is consistent with light rain weather; the sap flow rises and then stabilizes, reaches the peak at 12:00 noon, and starts to decline after 6:30 PM. In sunny weather, the sap flow rises earlier, rises rapidly after 4:00 PM, and reaches the peak at 11:00 PM. In cloudy weather, the fluctuation of sap flow is similar to that of light rain and cloudy weather, but the overall sap flow is relatively low. The sap flow change on

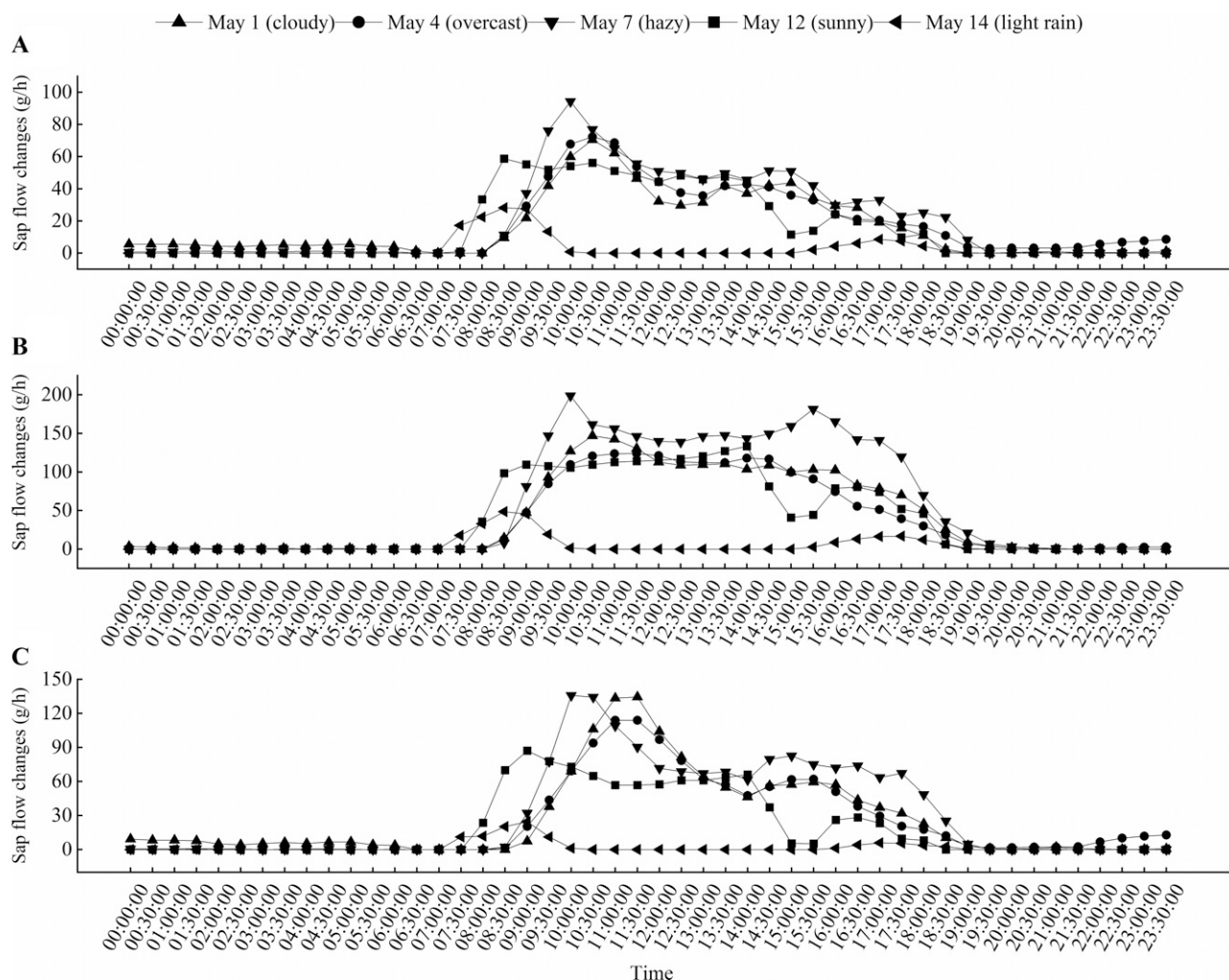


Fig. 3. Daily changes of sap flow in different tree shapes under different weather conditions in May. (A) Y-shaped tree. (B) Single-arm tree. (C) Spindle-shaped tree.

sunny days shows a bimodal change, with the sap flow starting at 7:00 AM, then rising rapidly, reaching the sap flow peak at 11:30 AM, dropping to a low point at 4:00 PM and then rising, reaching the second peak at 5:30 PM, and then falling rapidly (Fig. 5B).

Spindle-shaped trees in July. In light rain weather, sap flow began to rise at 7:30 AM, reached the peak sap flow at 10:30 in the morning, then decreased slightly, decreased again at 2:00 PM, and quickly dropped to zero after 4:00 PM. This shows that light rain can promote a certain amount of sap flow, but when the rain weakens, the sap flow also decreases. In cloudy weather, the change pattern of sap flow is similar to that of light rain weather, but the sap flow is higher in the morning, decreases more slowly in the afternoon, and does not drop to zero until after 6:00 PM. Sunny weather increases sap flow and reaches the peak sap flow of the day. Sap flow begins to rise rapidly at 9:00 AM, remains at a relatively high level from 10:00 AM to 12:00 PM, and does not begin to decline significantly until after 3:00 PM. Sunny days cause a lot of evaporation and plant transpiration, resulting in an increase in sap flow. Under cloudy conditions, the overall trend of sap flow was

similar to that of cloudy days, but the peak occurred earlier and decreased in the early afternoon. The overall trend was that the sap flow was the smallest under cloudy days, indicating that cloudy days reduced solar radiation and slowed down the transpiration rate, thus affecting the sap flow (Fig. 5C).

Y-shaped trees in August. On a rainy day, the sap flow changes relatively slowly in the morning. The sap flow starts at 12:00 PM and reaches the peak at 2:00 PM, with a sap flow of 109.48 g h^{-1} . On a cloudy day, the sap flow starts at 8:30 AM and reaches the peak at 10:30 AM, with a sap flow of 93.58 g h^{-1} . Then it gradually decreases, reaching the minimum at 5:30 PM and remains unchanged. On a cloudy day, the sap flow starts at 8:30 in the morning, reaches the peak at 3:30 PM with a sap flow of 102.87 g h^{-1} , and drops to the minimum at 7:30 PM. On a sunny day, the sap flow starts at 7:30 AM, reaches the peak at 10:30 AM with a sap flow of 119.88 g h^{-1} , and drops to the minimum at 6:00 PM. Under the four weather conditions, the average sap flow rate changes the most on sunny days, followed by cloudy days, and slightly lower on overcast days, while the average sap flow rate changes the

least under light rain conditions, indicating that the strong evaporation on sunny days leads to large changes in sap flow rate, while in weather with little rainfall, the changes in sap flow rate are relatively small. The sap flow rate is zero before 5:00 AM and after 8:00 PM, indicating that the plants mainly hibernate at night (Fig. 6A).

Single-arm shaped trees in August. On rainy days, the stemflow value is very high from morning to afternoon, reaching the peak at 2:30 PM, which is significantly higher than the other two tree shapes. On cloudy days, there is also high stemflow activity from morning to afternoon, reaching the peak at 2:00 PM. The highest peak of stemflow on cloudy days occurs at 2:30 PM. Under sunny conditions, the plant stemflow also varies greatly throughout the day and reaches the maximum peak at 2:30 PM (Fig. 6B).

Spindle-shaped trees in August. In light rainy weather, the sap flow rate began to increase from 5:00 AM, reached a peak at 2:00 PM, and then gradually decreased until it was close to zero at 9:00 PM. In cloudy weather, the sap flow rate began to increase from 8:00 AM, reached a peak at around 3:30 PM, and then rapidly decreased to near zero. The

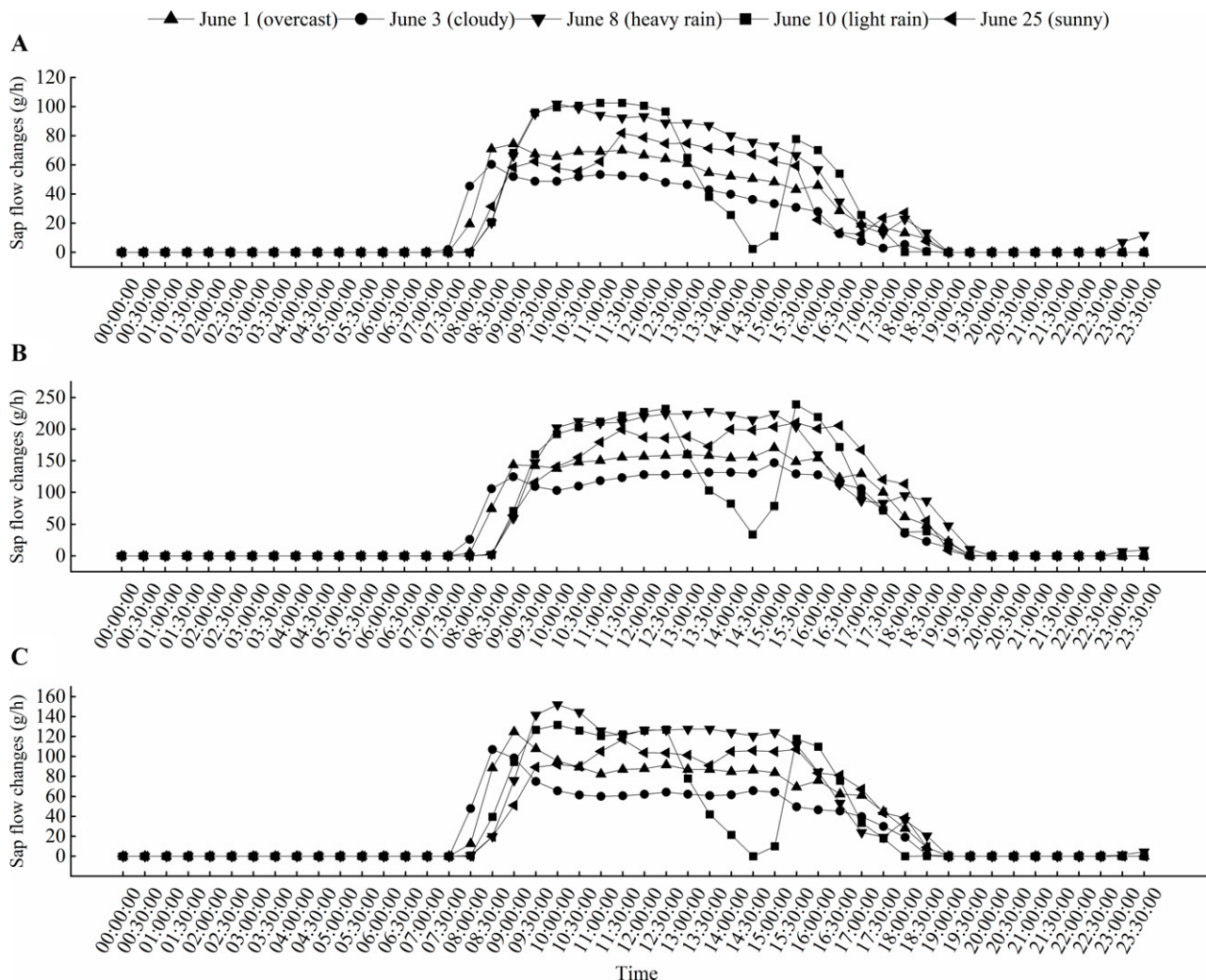


Fig. 4. Daily changes of sap flow in different tree shapes under different weather conditions in June. (A) Y-shaped tree. (B) Single-arm tree. (C) Spindle-shaped tree.

trend on cloudy days was similar to that on the cloudy day of 1 Aug, but the overall sap flow rate decreased slightly. The sap flow rate in sunny weather changed more dramatically. The sap flow rate began to increase rapidly at 8:30 AM, reached a very high level before 10:00 AM, then stabilized, and maintained a relatively high sap flow rate in the afternoon. This shows that plants absorb and transport a large amount of water in sunny weather, especially under strong light conditions. The total sap flow rate of the three tree shapes in different weather conditions was single-arm shape > spindle shape > Y shape (Fig. 6C).

Changes of sap flow in different tree shapes at different developmental stages

Sap flow of Y-shaped trees. The time of sap flow in different growth stages is different. During the flower bud germination period, the tree sap flow occurs and reaches its peak between 3:30 and 4:00 AM; the sap flow increases rapidly between 1:30 and 2:00 AM during the inflorescence elongation period. During the initial flowering period, the tree sap flow has a relatively high sap

flow value from the evening to 6:30 AM and then drops rapidly. After 7:30 AM during the physiological fruit drop period and fruit ripening period, the sap flow begins to increase significantly. The first fruit expansion period and the second fruit expansion period mainly show an increase at 8:30 AM, but the sap flow in the first fruit expansion period has a large range of change, with a sharp drop at 2:30 PM to $2.425 \text{ g} \cdot \text{h}^{-1}$, and then gradually increases, with a double peak change trend (Fig. 7A).

Sap flow of single-arm shape trees. The overall trend of each phenological period is the same as the Y shape. The total sap flow during the physiological fruit drop period, the first fruit expansion period and the maturity period is much higher than that of other periods, indicating that the plant has a greater demand for water during these periods. The physiological fruit drop period, the first fruit expansion period, the second fruit expansion period, and the maturity period show a significant intraday variation pattern, especially in the morning and at noon. There are small peaks in the early morning and evening during the flower bud germination period and

the inflorescence elongation period. A peak appears in the first half of the night during the initial flowering period, and the tree sap flow during the fruit development period is significantly higher than that of the spindle shape and Y shape (Fig. 7B).

Sap flow of Spindle-shaped trees. In the budding period, inflorescence elongation period and initial flowering period, the sap flow of trees is generally higher than that of single-arm and Y-shaped trees. In the physiological fruit drop period, the first fruit expansion period, the second fruit expansion period and the maturity period, the average daily net flow of trees is higher than that of Y-shaped trees and lower than that of single-arm trees. This may be related to the canopy structure of the tree, leading to changes in the sap flow of the tree (Fig. 7C).

In summary, the trends of sap flow changes on sunny days in different growth periods of the three tree shapes are basically consistent: that is, in the budding period (March), inflorescence elongation period (April), and initial flowering period (April), the tree sap flow changes slightly and fluctuates at night and in the early morning. In the fruit ripening period,

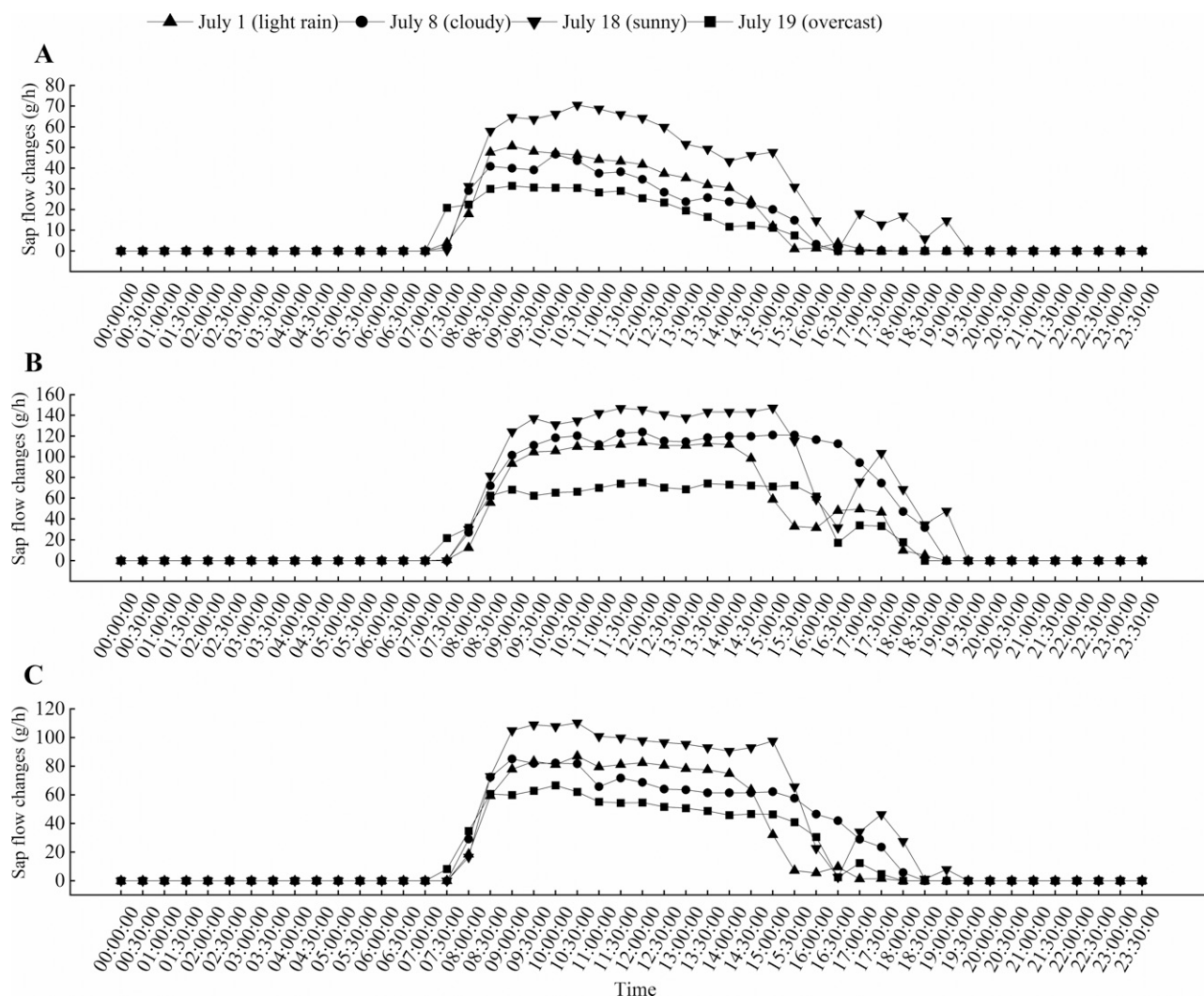


Fig. 5. Daily changes of sap flow in different tree shapes under different weather conditions in July. (A) Y-shaped tree. (B) Single-arm tree. (C) Spindle-shaped tree.

the sap flow changes the most, followed by the first fruit expansion period and then the physiological fruit drop period, indicating that the evaporation and water demand of the Zaosu pear of different tree shapes are relatively large at these stages.

Changes of meteorological factors in different growth stages

As shown in Fig. 8A, the wind speed varies greatly in different growth stages. The wind speed is relatively high from morning to afternoon during the inflorescence elongation period. The average wind speed is the highest during the flower bud budding period, which is 1.38 m/s. The average wind speed during the inflorescence elongation period is 1.12 m/s, is 0.38 m/s during the initial flowering period, is 0.59 m/s during the physiological fruit drop period, is 0.48 m/s during the first fruit expansion period, is 0.39 m/s during the second fruit expansion period, and is 0.79 m/s during the maturity period. The higher the wind speed, the greater the air flow rate, thereby accelerating the transpiration of the leaves, but too high a wind speed

will lead to the closure of the stomata and a decrease in the sap flow rate.

The gusts showed a gradually decreasing trend in different growth stages (Fig. 8B). The average intensity in the budding stage was about 4.07, the average intensity of the gusts in the inflorescence elongation stage was 2.19, the average intensity of the gusts in the initial flowering stage was 1.01, and the average intensity of the gusts in the physiological fruit drop stage was 2.07, which was similar to the inflorescence elongation stage, but the maximum value reached 4.4. The average intensity of the gusts in the first fruit expansion stage was 1.46, which was higher than that in the initial flowering stage. The average intensity of the gusts in the second fruit expansion stage was 0.97, with a small range of change. The average intensity of the gusts in the maturity stage was the smallest at 0.76, and the range of change was relatively small compared with other stages.

The temperature fluctuations show a pattern of rising during the day and falling at night (Fig. 8C). As the growth period progresses, the temperature gradually rises, but

the overall trend of change is consistent. The average temperature is the highest during the second fruit expansion period, followed by the maturity period. This is inconsistent with the trend of sap flow changes in the tree. During the maturity period, the first and second fruit expansion periods, the temperature fluctuates greatly.

The changes in relative humidity during different growth periods show a phenomenon of high at both ends and low in the middle (Fig. 8D). After 9:00 AM, the relative humidity gradually decreases to 7:00 PM, and the relative humidity gradually increases. During the budding period, the initial flowering period, the physiological fruit drop period, and the second fruit expansion period, the relative humidity of the air is relatively small, and the variation range is wide; during the inflorescence elongation period, the first fruit expansion period, and the maturity period, the relative humidity of the air is high.

The changes in solar radiation in each growth period are basically the same (Fig. 8E). Except for the first fruit drop period and inflorescence elongation period, which show a

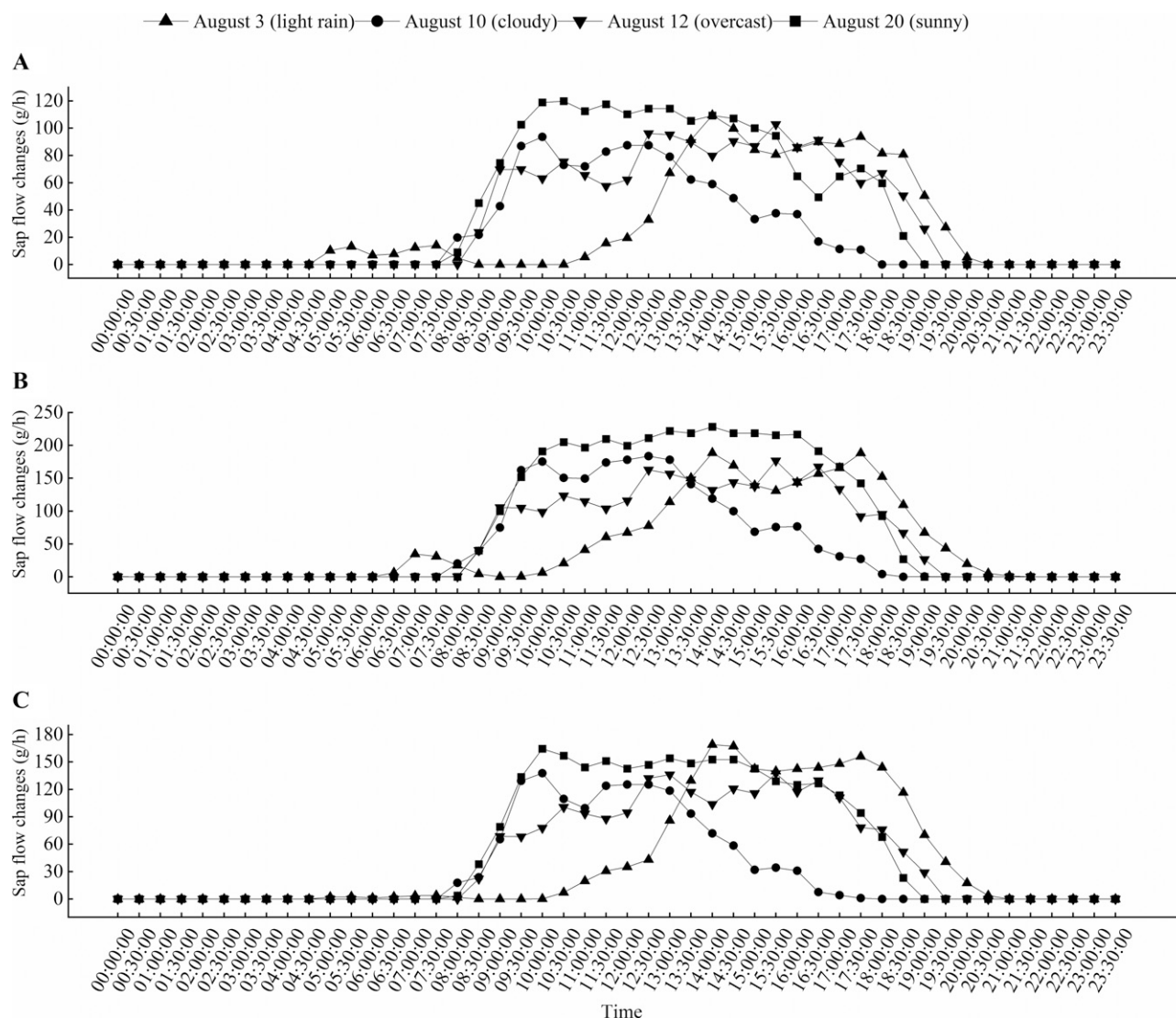


Fig. 6. Daily changes of sap flow in different tree shapes under different weather conditions in August. (A) Y-shaped tree. (B) Single-arm tree. (C) Spindle-shaped tree.

significant decrease and fluctuation at 10:00 AM and 15:00 PM, the changes at other times are not large. The cumulative amount of solar radiation in all growth periods starts from 12:00 AM. After sunrise, as the intensity of solar radiation increases, the cumulative amount begins to rise. The time when solar radiation reaches its peak is roughly at noon, after which the intensity of solar radiation begins to decrease.

Relationship between stemflow and meteorological factors

As can be seen from Fig. 9A, the correlation between sap flow and wind speed, gusts, humidity, and temperature. There is a very significant positive correlation between sap flow and temperature, indicating that plants may have higher water absorption and transpiration in a hotter environment. It is negatively correlated with humidity, indicating that increased humidity reduces the transpiration of the tree and reduces sap flow. Sap flow also shows a positive correlation with

wind speed and gusts, which may be because the increase in wind speed helps the evaporation of water from plant leaves, thereby increasing sap flow.

There is a very significant positive correlation between solar radiation and sap flow (Fig. 9B). As solar radiation increases, sap flow also increases accordingly. This shows that at different times of the day, as solar radiation changes, the sap flow of plants also shows corresponding regularity.

Discussion

The effect of tree shape on sap flow is mainly reflected in its impact on water transpiration and transport pathways. Larger or more open crowns are generally associated with higher water losses because more leaf area is exposed to the atmosphere, thereby increasing transpiration (Granier et al. 1996). In addition, the shape and size of the crown determine the effectiveness of photosynthesis, which further affects water use and demand. There is a certain proportional relationship

between leaf and branch biomass and stem biomass, which also involves the growth regulatory network, including the role of plant hormones and signaling molecules (Zhou et al. 2021). In this study, it was found that the stemflow activities of different tree shapes varied in different months and weather conditions. In the hazy weather in March, the Y-shaped tree had the highest stemflow and strong adaptability. In areas with large changes in light, the single-arm tree performed better. In April, the Y-shaped tree had a high peak stemflow at night and in rainy weather; on cloudy and overcast days, the stemflow growth of the single-arm tree was relatively stable. In May, the single-arm tree had the highest stemflow rate in all climates. After June, the tree entered a rapid growth stage. The stemflow of the single-arm tree in different weather conditions was significantly higher than that of the other two tree shapes, indicating that the single-arm tree performed well in water efficiency and nutrient transport. The results of this study show that different tree structures have a significant effect on the

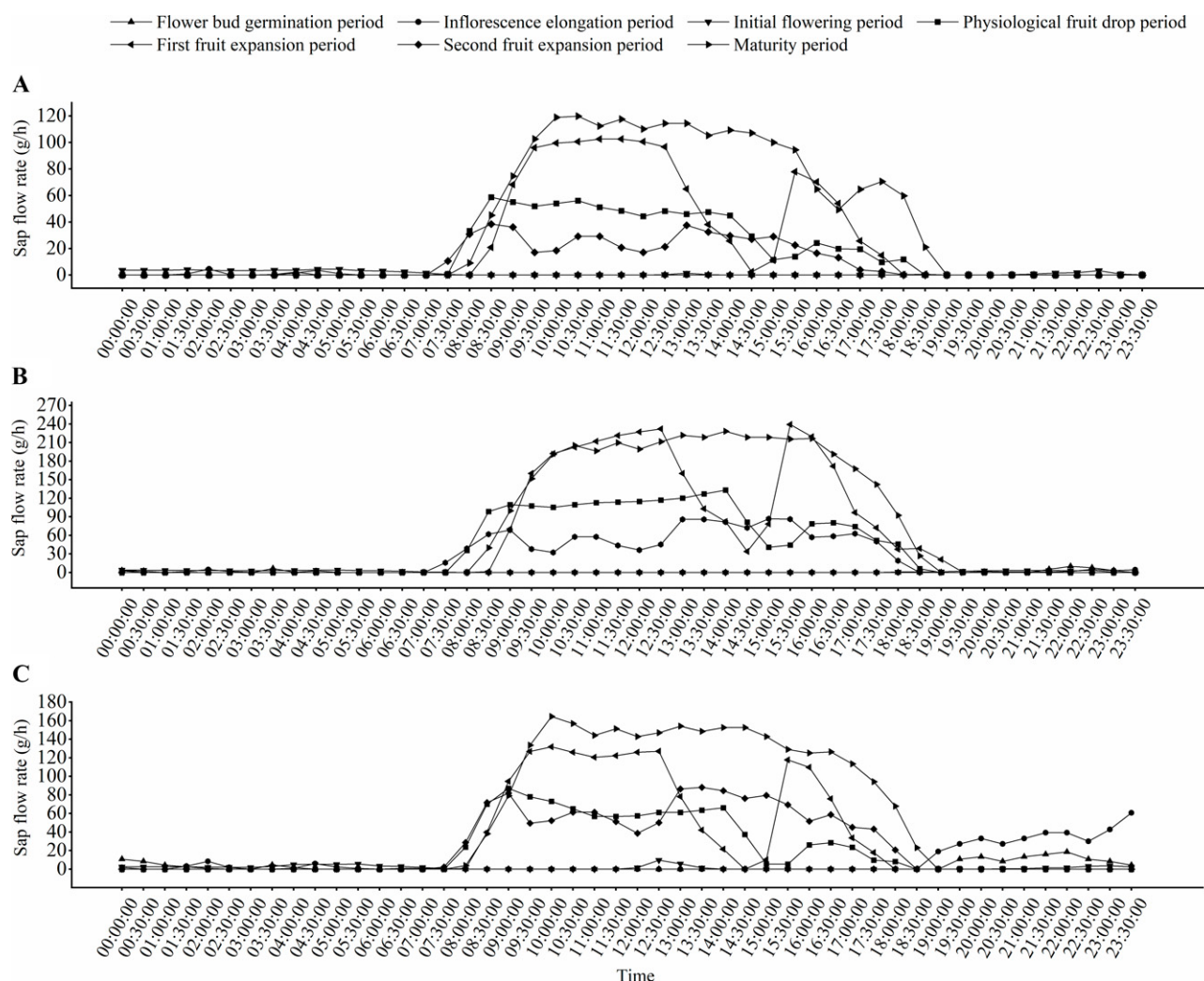


Fig. 7. Diurnal variation of sap flow rate in different tree shapes and growth stages. (A) Y-shaped tree. (B) Single-arm tree. (C) Spindle-shaped tree.

sap flow of Zaosu pear trees, and its changes are jointly regulated by meteorological factors and weather conditions. This finding is consistent with the research results of Yuan et al. (2017); that is, the sap flow of trees is affected not only by rainfall but also by the combined effects of multiple factors such as tree structure, branch angle, and weather conditions. In addition, through simulated rainfall experiments, Zhang et al. (2021) clarified the regulatory effects of rainfall intensity and raindrop size on sap flow, and pointed out that there is a “critical point” for maximum sap flow production. This suggests that the impact of different rainfall types on the response of tree structure is nonlinear. In the future, we can further start from different rainfall types to establish a more complete structure–rainfall–sap flow change mechanism.

In different tree shapes, the proportion of branches is also an important factor affecting sap flow. Fruit trees with more open tree shapes may have larger transpiration areas, which in turn affects sap flow (Zhang et al. 2025). Dwarfing cultivation technology affects the water status and sap flow of trees by restricting tree growth and changing nutrient distribution. This shows that different tree

shapes lead to differences in water and nutrient transport pathways, which in turn affect the dynamic changes of sap flow. Honda et al. (2015) pointed out that tree structure (such as trunk uprightness and branch distribution angle) is an important morphological basis for determining differences in sap flow. The single-arm tree shape has an open structure and good ventilation, which can effectively collect and guide rainwater to flow along the main trunk, thus showing higher sap flow activity and stability in this study.

The demand for water and the efficiency of its use vary at different growth stages of trees. In the early growing season, trees may need more water to support new growth; in maturity, water demand may decrease. Zhou et al. (2023) found in his study that stem growth mainly occurs in the early morning and at night and is significantly affected by temperature and vapor pressure difference, while sap flow has a clear seasonal peak when the soil is moist. The adaptability of tree shape can explain the changes in sap flow at different growth stages to some extent, because some tree shapes or crown characteristics may be more efficient in obtaining or conserving water at specific times (Schäfer et al. 2000). The

time of the peak of sap flow in the Y-shaped tree varies at different growth stages, especially in the morning and early morning. The water demand of the single-arm shape is particularly significant during the physiological fruit drop period and fruit expansion period, and the sap flow rate in these stages is much higher than in other periods. Studies have found that tree structure has a significant effect on sap flow and its redistribution of water and nutrients in the rhizosphere (Levia and Frost 2003). Crockford and Richardson (2000) also pointed out that different tree structures will significantly affect the distribution of rainfall in the canopy, thereby affecting sap flow efficiency, which is consistent with the differences shown by different tree shapes of Zaosu pear in this study. The influence of tree structure on sap flow is a complex process, involving the distribution of tree biomass, hormone regulation, and signal transduction of branching mechanism, and the growth dynamics of xylem formation and its regulatory mechanism. The next step of research can deepen our understanding of the influence of sap flow by further analyzing the molecular mechanisms in these biological processes and promote a comprehensive understanding of the

spindle-shaped) under different meteorological conditions and growth periods and revealed the correlation between sap flow and major meteorological factors. The results showed that tree shape significantly affected the sap flow dynamics of pear trees, among which single-armed trees showed higher daily average sap flow rates and total sap flow on sunny days, in different seasons, and during fruit expansion and maturity, indicating that they have obvious advantages in water absorption and transportation efficiency. The single-armed structure is open and has good ventilation and light transmittance, which is conducive to enhancing the tree's utilization of light and heat resources and water conduction. Correlation analysis showed that sap flow was significantly positively correlated with temperature and solar radiation and significantly negatively correlated with air humidity. Meteorological factors such as wind speed and gust also showed significant correlations with sap flow at different stages.

In summary, the single-arm tree shape has outstanding advantages in water absorption efficiency, environmental adaptability and suitability for cultivation in arid areas. It is recommended that this type of tree shape be used for pear tree pruning and cultivation in the arid areas of northwest China. At the same time, future research should further explore the intrinsic relationship between tree sap flow and plant water regulation mechanism and combine physiological and molecular data to build a more systematic theoretical system for efficient water utilization of fruit trees.

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