Postprint: Frost Damage Characteristics of Wild Walnut at Different Slope Positions in the West Tianshan Canyon, Xinjiang

Authors: Liu Huaqing, Wang Bo, Jia Yanyan, Xie Xinran, Zhang Wei

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Abstract

Severe frost damage affects walnut growth and development and even leads to plant mortality. Using the quadrat method, we investigated the frost damage conditions of wild walnuts at different slope positions in the Wild Walnut Nature Reserve of the West Tianshan Canyon, Xinjiang, and analyzed the distribution characteristics of wild walnut frost damage, as well as the effects of tree height, crown width, and slope position on wild walnut frost damage. The results showed that: (1) The total frost damage rate of wild walnuts was 87.1%, among which the proportion of grade 2 frost-damaged trees was the highest (43.4%), followed by grade 1 (22.5%) and grade 3 (17.5%), with grade 4 being the lowest (3.7%). (2) The proportion of frost-damaged trees was highest on the middle slope (46.5%), followed by the bottom slope (35.9%), and lowest on the top slope (4.7%); the proportion of undamaged trees was highest on the top slope (7.4%), followed by the bottom slope (3.3%), and lowest on the middle slope (2.2%). (3) The proportions of frost-damaged trees in six tree height classes (H) were in the following order: H1 (43.4%) > H4 (19.5%) > H6 (17.0%) > H5 (15.7%) > H3 (4.3%) > H2 (0.1%). (4) The proportions of frost-damaged trees in six crown width classes (CW) were in the following order: CW1 (43.4%) > CW4 (22.1%) > CW3 (20.3%) > CW5 (9.5%) > CW2 (2.9%) > CW6 (1.8%). (5) The proportions of frost-damaged trees differed significantly among different tree height classes and crown width classes at the same slope position ($P<0.05$); grade 1 and grade 2 frost-damaged trees mainly occurred on the middle and bottom slopes, while grade 3 and grade 4 frost-damaged trees mainly occurred on the middle slope. (6) Frost-damaged trees were significantly correlated with DBH ($P<0.05$) and highly significantly negatively correlated with crown width ($P<0.01$). Most wild walnut plants in the reserve suffered frost damage, and the proportions of frost damage grades varied substantially among different slope positions, tree height classes, and crown width classes. The results of this

study provide a scientific reference for reserve management and frost damage prevention in wild walnuts.

Full Text

Characteristics of Freezing Injury to *Juglans regia* at Different Slope Positions in the West Tianshan Valley of Xinjiang, China

LIU Huaqing[1], WANG Bo[2], JIA Yanyan[1], XIE Xinran[1], ZHANG Wei[1,3]

(1. College of Biological Science and Technology, Yili Normal University, Yining, Xinjiang 835000, China;
2. College of Resources and Environment, Yili Normal University, Yining, Xinjiang 835000, China;
3. Key Laboratory of Plant Resources Protection and Utilization in Xinjiang Yili Valley, Yining, Xinjiang 835000, China)

Abstract: Severe freezing injury has a significant impact on the growth and development of walnuts (*Juglans regia*), even leading to plant death in some cases. This study employed the sample method to examine the freezing injury to *J. regia* in the Wild Walnut Nature Reserve located in the West Tianshan valley in Xinjiang. The distribution characteristics of freezing injury among *J. regia* were analyzed, and the influence of tree height, crown width, and slope position on the extent of freezing injury was investigated. The results indicated that (1) the total freezing injury rate of *J. regia* was 87.1%. Among these, the proportion of plants with grade 2 freezing injury was the largest (43.4%), followed by grade 1 (22.5%), grade 3 (17.5%), and grade 4 (3.7%). (2) the proportion of freezing injury in *J. regia* plants was the largest in the middle of slope (46.5%), followed by the bottom (35.9%), and the top (4.7%); the proportion of uninjured plants was the maximum at the top of slope (7.4%), followed by the bottom (3.3%), and the middle (2.2%). (3) the proportion of freezing injured plants in the six height classes (H) was most prominent in H1 (43.4%), followed by H4 (19.5%), H6 (17.0%), H5 (15.7%), H3 (4.3%), and H2 (0.1%). (4) the proportion of freezing injured plants in the six crown width classes (CW) was most extensive in CW1 (43.4%), followed by CW4 (22.1%), CW3 (20.3%), CW5 (9.5%), CW2 (2.9%), and CW6 (1.8%). (5) the proportion of freezing injured plants in different H and CW classes at the same slope position differed significantly ($P<0.05$). Plants with grade 1 and 2 freezing injuries were mainly restricted to the middle and bottom of the slope, and those with grade 3 and 4 injuries to the middle. (6) freezing injury in plants was markedly correlated with diameter at breast height ($P<0.05$) and extremely negatively correlated with CW ($P<0.01$). Most *J. regia* plants in the Reserve suffered from freezing injury, and the proportions of freezing injury grades varied conspicuously among the different slope positions and different H and CW classes. The results of this study provide a scientific reference for the management of the Wild Walnut

Nature Reserve and the prevention of freezing injury in *J. regia*.

Keywords: *Juglans regia*; freezing injury; tree height; crown width; slope position; Xinjiang

Introduction

In forest ecosystems, freezing injury is a critical abiotic disturbance factor that hinders forest regeneration and establishment, exacerbates the risk of secondary disasters, and severely impacts forestry production and development. Tree height represents one of the most important architectural compensatory mechanisms for light acquisition, while the crown converts solar energy into productivity and serves as the energy conversion site for heat, water, and other material exchanges between the tree and the soil and atmosphere. Together, they determine tree vitality and productivity levels, while also reflecting competition intensity throughout the tree's growth process. When trees suffer freezing injury, both tree height and crown directly influence their ability to resist such damage. Slope position is an important topographic factor; differences in slope position within the same region create variations in light intensity, water, and soil nutrient distribution, leading to differential freezing injury severity and consequently affecting plant growth and development. Walnut is an important economic tree species, and freezing injury constitutes a major meteorological disaster affecting its survival and growth. The degree of freezing injury is related to walnut variety, individual growth characteristics, and site conditions. Investigating the effects of tree height, crown width, and slope position on freezing injury to wild walnut will provide a scientific reference for its prevention.

Juglans regia, belonging to the Juglandaceae family, is a deciduous tree and a precious relict component of Tertiary temperate broad-leaved forests. It is a priority conservation species of international biodiversity significance in China. In Asia, it only occurs in large patches within the Wild Walnut Nature Reserve in the West Tianshan valley of Xinjiang. Its natural population holds special scientific value for studying the origin and evolution of cultivated walnut, changes in paleofloristic regions, and Tertiary and Quaternary climate changes, while playing an important role in protecting biodiversity and maintaining and improving ecosystem functions in the Yili River Valley. Current research on Xinjiang wild walnut has primarily focused on resource distribution, biological and ecological characteristics, community features, population structure and dynamics, and molecular genetics. Studies on freezing injury to Xinjiang wild walnut are rarely reported. Winter low temperatures and cold wave invasions, particularly when extreme minimum temperatures fall below -25°C, can cause freezing injury to walnut branches (seedling shoots), and below -30°C, can result in severe damage to branches and trunks. Research on the effects of tree height, crown width, and slope position on freezing injury to Xinjiang wild walnut is even rarer. This study investigated the freezing injury status of the wild walnut population in the West Tianshan valley, analyzing the proportional distribution of freezing injury across different slope positions, tree height classes, and

crown width classes, as well as the correlation between freezing injury/grades and individual growth characteristics (diameter at breast height, tree height, crown width) and slope position, to provide a scientific reference for reserve management and freezing injury prevention.

1. Materials and Methods

1.1 Study Area

The Wild Walnut Nature Reserve is located in the gullies and slopes of the Kaiteming Mountain deep valley, south of Gongliu County in the Yili Prefecture of the West Tianshan canyon (13 km from Gongliu County town). The reserve covers an area of 1,180 hm^2, with wild walnut distributed across approximately 45 hm^2, primarily in gullies and slopes at elevations of 1,200–1,670 m. The area has a mean annual precipitation of 580 mm, mean annual evaporation of 1,200 mm, mean annual relative humidity of 70.0%–80.0%, mean annual temperature of 7.6°C, $ $10°C accumulated temperature of 1,865.4–2,338.9°C, and mean January temperature of -3.3°C. According to Gongliu County Meteorological Bureau data, the daily minimum temperature in Gongliu County urban area (elevation 800 m) during December 2020 and January 2021 ranged from -24 to -28°C. The reserve's location has higher elevation and lower temperatures than the county town, making prolonged extreme low temperatures inevitable and causing freezing injury to Xinjiang wild walnut. The reserve's soil has high humus content, is moist and deep, rich in organic matter and nutrients, with relatively high fertility and pH of 6.4–8.9.

Wild walnut is the constructive species in the reserve. Associated tree species include *Prunus armeniaca*, *Malus sieversii*, *Betula tianschanica*, *Populus tremula*, and *Salix pseudotangii*. Shrubs mainly consist of *Lonicera humilis*, *Spiraea hypericifolia*, *Rubus caesius*, *Berberis heteropoda*, and *Juniperus pseudosabina*. Herbaceous plants are primarily *Trollius altaicus*, *Crocus alatavicus*, *Sophora alopecuroides*, *Bromus benekenii*, and *Impatiens brachycentra*.

1.2 Field Survey

Referencing the slope aspect classification method of Xu Shaojun et al., and combining it with the reserve's topographic factors, we used a compass to determine geographic slope aspect. Taking true north as 0°, slope aspects were divided into sunny slope (157.5°–247.5°), semi-sunny slope (112.5°–157.5°, 247.5°–292.5°), shady slope (0°–67.5°, 337.5°–360°), and semi-shady slope (67.5°–112.5°, 292.5°–337.5°).

In mid-January 2021, we selected typical wild walnut distribution areas on sunny, semi-sunny, shady, and semi-shady slopes within the Wild Walnut Nature Reserve, establishing two 20 m × 20 m sample plots in each slope aspect. Slope positions were demarcated based on the vertical elevation lower and upper limits of wild walnut distribution in each plot. For sunny slope plots, the

vertical elevation range of wild walnut distribution was 1,280–1,640 m, with 1,280–1,390 m as slope bottom, 1,390–1,500 m as slope middle, and 1,500–1,640 m as slope top. For semi-sunny slope plots, the range was 1,300–1,600 m, with 1,300–1,400 m as bottom, 1,400–1,500 m as middle, and 1,500–1,600 m as top. For shady slope plots, the range was 1,240–1,660 m, with 1,240–1,380 m as bottom, 1,380–1,520 m as middle, and 1,520–1,660 m as top. For semi-shady slope plots, the range was 1,280–1,660 m, with 1,280–1,400 m as bottom, 1,400–1,520 m as middle, and 1,520–1,660 m as top.

For convenient surveying, each plot was divided into 5 m × 5 m subplots, which were further divided into 1 m × 1 m small quadrats using the adjacent grid method. Every wild walnut plant in each small quadrat was investigated individually, recording diameter at breast height (DBH; base diameter for seedlings), tree height (plant height for seedlings), crown width, freezing injury grade, slope position, slope aspect, and other indicators. DBH was measured at 1.2 m above ground using a steel tape to determine trunk circumference, which was then converted to diameter (seedling base diameter was measured at 0.1 m using vernier calipers). Tree height was measured using a laser rangefinder (Deli DL331050L) (seedling height was measured with a steel tape). Crown width was calculated as the average of east-west and north-south vertical projection widths of the canopy, measured with a tape measure.

1.3 Tree Height Classification

Following the tree height classification method for arbor species by Lieberman et al., the wild walnut population at slope top was divided into six height classes, while those at slope middle and bottom were divided into five height classes. Height class 1 (H1) was 0–1.4 m (DBH $<$ 2.0 cm), H2 was 1.4–3.0 m (DBH $<$ 2.0 cm), H3 was 3.0–6.0 m (DBH $\geq$ 2.0 cm), and subsequent classes were divided at 3.0 m intervals.

1.4 Crown Width Classification

Referencing the crown width classification method for arbor species by Zhang Zhixiang et al., the wild walnut population at slope top was divided into six crown width classes, while those at slope middle and bottom were divided into five classes. Crown width class 1 (CW1) was 0–1.0 m (DBH $<$ 2.0 cm), CW2 was 1.0–2.0 m (DBH $<$ 2.0 cm), CW3 was 2.0–4.0 m (DBH $\geq$ 2.0 cm), and subsequent classes were divided at 2.0 m intervals.

1.5 Freezing Injury Grade Classification

Referencing the methods of Fan Jiangbin et al. and Xue Hengxin et al., we used visual observation combined with wild walnut growth characteristics. Each plant was examined at three positions (lower, middle, upper) and in four directions (east, west, south, north). Based on observations, freezing injury was classified into five grades: Grade 0: no freezing injury; Grade 1: mild injury, with $ $1/10

of buds frozen and dried, no trunk damage; Grade 2: moderate injury, with $ $3/10 of buds frozen and dried, $ $1/10 of one-year-old branches killed, and $ $1/10 of trunk area damaged; Grade 3: severe injury, with >3/10 of buds frozen and dried, 1/10–3/10 of one-year-old branches killed, and >1/10 of trunk area damaged; Grade 4: very severe injury, with >3/10 of buds frozen and dried, >3/10 of one-year-old branches killed, and >3/10 of trunk area damaged.

1.6 Data Processing

Microsoft Excel 2019 and SPSS 26.0 software were used for statistical analysis and graphing. All data were tested for normality and homogeneity of variance before analysis. One-sample t-tests and one-way ANOVA were employed to compare differences in freezing injury proportions ($\alpha = 0.05$), and Spearman correlation coefficients were used to analyze correlations between freezing injury and individual growth characteristics and slope position. For the reserve's wild walnut population overall, and for freezing injury and uninjured proportions across different slope positions, statistics were based on the total number of wild walnut plants surveyed. For grades 1–4 freezing injury distribution across different tree height and crown width classes, statistics were based on the number of freezing-injured plants (87.1%). For grade 0 (uninjured) distribution across different tree height and crown width classes, statistics were based on the number of uninjured plants (12.9%).

2. Results and Analysis

2.1 Population Freezing Injury Grade Distribution

A total of 1,000 individual wild walnut plants were surveyed across three slope positions in the Wild Walnut Nature Reserve. Among these, 871 plants suffered varying degrees of freezing injury, accounting for 87.1%, while 129 plants (12.9%) remained uninjured. Across different freezing injury grades, grade 2 was the most common, representing 43.4% of the total individuals, followed by grade 1 (22.5%), grade 3 (17.5%), and grade 4 (3.7%). One-sample t-tests revealed significant differences in proportions among different freezing injury grades ($P < 0.05$). These results indicate that the extreme low temperature events during the winter of 2020–2021 caused freezing injury to most wild walnut plants in the reserve, with moderate injury (grade 2) predominating at 43.4%, while very severe injury (grade 4) was relatively rare.

2.2 Freezing Injury Distribution at Different Slope Positions

The distribution of freezing-injured and uninjured wild walnut plants varied across the three slope positions. Injured plants were most numerous in the slope middle with 465 individuals (46.5%), followed by slope bottom with 359 individuals (35.9%), and fewest at slope top with 47 individuals (4.7%). Uninjured plants were most numerous at slope top with 74 individuals (7.4%), followed by slope bottom with 33 individuals (3.3%), and fewest in slope middle

with 22 individuals (2.2%). One-way ANOVA revealed significant differences in freezing injury proportions among different slope positions ($P < 0.05$). These results demonstrate that wild walnut plants in slope middle and bottom were relatively susceptible to freezing injury, while those at slope top were relatively resistant.

2.3 Freezing Injury Distribution in Different Tree Height Classes

Among the six tree height classes (H), freezing-injured plants ranked from most to least numerous as: H1 > H4 > H6 > H5 > H3 > H2. Uninjured plants ranked as: H2 > H3 > H4 > H5 > H6 > H1. Across the three slope positions, freezing-injured plants in slope top, middle, and bottom all showed the highest proportion in H1. Slope top and bottom had the lowest proportion in H2, while slope middle had the lowest in H3. Uninjured plants across all three slope positions showed the highest proportion in H2; however, no uninjured plants were found in H1 at slope top or in H2 at slope middle.

Grade 1 freezing injury was most prevalent in H1 across all positions. Grade 2 injury also peaked in H1, with no grade 2 injuries in H2 at slope bottom. Grade 3 injury was most common in H4, while grade 4 injury occurred primarily in H1 and H4. Among different slope positions, the proportion of injured plants in H1 differed significantly between slope middle and top ($P < 0.05$), and H4 proportions differed significantly between slope middle and top, and between slope top and bottom ($P < 0.05$). Within the same slope position, significant differences in injury proportions among height classes were observed: H2–H5 at slope top ($P < 0.05$), H1–H4 at slope middle ($P < 0.05$), and H1–H4 at slope bottom ($P < 0.05$). These results indicate that wild walnut plants in H2 and H3 were generally resistant to freezing injury, while mild, moderate, and severe injury (grades 1, 2, and 4) occurred mainly in H1, and severe injury (grade 3) predominantly in H4.

2.4 Freezing Injury Distribution in Different Crown Width Classes

Among the six crown width classes (CW), freezing-injured plants ranked from most to least numerous as: CW1 > CW4 > CW3 > CW5 > CW2 > CW6. Uninjured plants ranked as: CW2 > CW3 > CW4 > CW5 > CW6 > CW1. Across the three slope positions, injured plants in slope top, middle, and bottom all showed the highest proportion in CW1, with no CW6 injured plants at slope top. Uninjured plants across all positions showed the highest proportion in CW2; however, no uninjured plants were found in CW1 at slope top or in CW6 at slope middle.

Grade 1 freezing injury was most prevalent in CW1 across all positions. Grade 2 injury also peaked in CW1, with no grade 2 injuries in CW6 at slope top or bottom. Grade 3 injury was most common in CW4, while grade 4 injury occurred primarily in CW1 and CW4. Among different slope positions, the proportion of injured plants in CW1 differed significantly between slope middle

and top ($P < 0.05$). Within the same slope position, significant differences in injury proportions among crown width classes were observed: CW1–CW5 at slope middle ($P < 0.05$) and CW1–CW4 at slope bottom ($P < 0.05$). These results indicate that wild walnut plants in CW2 were resistant to freezing injury, while those in CW1 were susceptible to all injury grades (mild, moderate, severe, and very severe), and CW4 plants were also relatively susceptible to severe injury.

Correlation analysis revealed that overall freezing injury was significantly correlated with diameter at breast height ($P < 0.05$) and extremely negatively correlated with crown width ($P < 0.01$). Grade 1 injury was significantly correlated with DBH, tree height, and crown width ($P < 0.01$), while grade 2 injury was extremely negatively correlated with crown width ($P < 0.01$). Grade 3 injury was significantly negatively correlated with slope position ($P < 0.05$), and grade 4 injury was significantly negatively correlated with tree height ($P < 0.05$). These findings demonstrate that freezing injury, both overall and by grade, was significantly associated with most individual growth characteristics and slope position.

3. Discussion

3.1 Overall Freezing Injury and Cold Resistance Analysis

Low-temperature freezing injury is a critical factor affecting walnut growth, development, and industry development. In Gongliu County, minimum temperatures dropped below -25°C during December 2020–January 2021, with two cold wave and blizzard events occurring in January (Gongliu County Meteorological Bureau data). The reserve's higher elevation and lower temperatures than the county town inevitably exposed Xinjiang wild walnut to freezing injury, resulting in a total injury rate of 87.1%. In injured plants, buds become dehydrated and shriveled, one-year-old branches suffer physiological drought, and trunk cortex cells die during freeze-thaw cycles, weakening overall tree vigor and increasing susceptibility to secondary disasters such as pests and diseases, potentially leading to plant death. Therefore, the Xinjiang Wild Walnut Nature Reserve should establish permanent observation and research plots and implement effective measures to prevent freezing injury and protect this precious wild plant resource.

Plant cold resistance is an ability to adapt to low temperatures acquired through long-term environmental adaptation, self-variation, and natural selection. Plants regulate their life cycles through active growth or dormancy during warm seasons or winter to reduce freezing injury risk. Although the reserve experienced prolonged extreme low temperatures, the wild walnut population predominantly suffered mild and moderate injury (65.9%), with severe injury accounting for only 3.7%. Studies have shown that Xinjiang wild walnut possesses stronger cold resistance than cultivated Xinjiang and Shaanxi walnuts, and the reserve is located in the middle of the winter temperature

inversion layer on the northern Tianshan slope. Consequently, Xinjiang wild walnut has robust inherent cold resistance and has developed mechanisms to withstand extreme low temperatures through long-term evolution.

3.2 Effect of Slope Position on Freezing Injury

Slope position is a crucial topographic factor influencing solar radiation and precipitation distribution. Through redistribution of light, temperature, and water at local scales, it creates different plant response mechanisms to freezing injury. Generally, in a given region, freezing injury severity decreases from slope top to bottom as elevation decreases. However, in the Wild Walnut Nature Reserve, injured plants were most numerous in slope middle, followed by bottom, and fewest at top—a pattern differing from Chen Botao et al.'s findings on *Jatropha curcas*, where upper slopes suffered greater low-temperature damage than lower slopes. This discrepancy arises from habitat condition differences among slope positions. Slope top has less water resources but better air circulation and light, resulting in relatively dry soil, slower autumn growth, but better branch maturity. Slope middle and bottom have richer water resources but poorer circulation, higher soil moisture, delayed autumn senescence, and poorer branch maturity. Consequently, despite lower temperatures at slope top, freezing injury was lighter, while higher temperatures at middle and bottom slopes resulted in more severe injury.

The numbers of uninjured wild walnut plants were: 74 at slope top (7.4%), 33 at slope bottom (3.3%), and 22 at slope middle (2.2%), confirming that slope middle and bottom are more vulnerable to freezing injury than slope top, and verifying slope position as an important factor influencing wild walnut cold resistance. Therefore, reserve managers should promptly drain low-lying water accumulation at slope middle and bottom to reduce tissue freezing potential and enhance cold resistance. Statistics show that proportions of mild, severe, and very severe injury (grades 1, 3, and 4) were highest at slope bottom, while moderate injury (grade 2) peaked at slope middle. This suggests that injury severity is influenced not only by temperature but also by multiple factors including light and soil moisture, warranting multi-year continuous monitoring in fixed plots across different slope positions and physiological control experiments for further verification.

3.3 Effect of Tree Height on Freezing Injury

Tree height is a crucial factor influencing the freezing injury resistance of arbor species. Chen Jie's research on eucalyptus showed that damage proportion decreased with increasing tree height after freezing injury. In contrast, the Wild Walnut Nature Reserve exhibited the highest freezing injury in height class 1 (H1) and the lowest in H2, while uninjured plants were most numerous in H2 and fewest in H1. This occurs because wild walnuts in H1 are in the juvenile stage, with slender stems, low lignification, and limited light resources due to dense canopy cover from mature wild walnuts and associated trees (e.g.,

Populus tremula, *Prunus armeniaca*). Consequently, their freezing resistance is weak. When wild walnuts develop to H2, they have strong vitality, vigorous growth, produce fewer fruits, and have sufficient nutrients to resist freezing injury, resulting in lower injury rates.

Different height classes experienced varying injury severities: mild, moderate, and very severe injuries (grades 1, 2, and 4) were most common in H1, while severe injury (grade 3) peaked in H4. These findings parallel research on *Pinus taiwanensis* populations, where low-temperature injury severity did not increase with tree height. This reveals that wild walnut's freezing resistance varies across developmental stages. Future research should continue investigating the mechanisms of freezing resistance to support the long-term healthy development of the reserve's wild walnut population.

The canopy is the most direct part of arbor species for photosynthesis, and crown width determines its contact area with natural resources. Crown width directly affects the ability to absorb light, water, and other nutrients, while also significantly influencing freezing injury severity. Zhu Hongwei's research indicates that larger crown width correlates with greater low-temperature damage. However, in the Wild Walnut Nature Reserve, the highest freezing injury occurred in CW1 and CW4, while the lowest was in CW2; uninjured plants were most numerous in CW2 and fewest in CW1. Plants in CW1 (juvenile stage) have low lignification and weak freezing resistance, suffering severe damage to cells, tissues, and organs under prolonged low temperatures due to inadequate light and heat. Plants in CW4 (almost non-fruiting) have vigorous growth, strong vitality, and strong freezing resistance due to less reproductive allocation and abundant nutrients. The low injury rate in CW6 occurs because wild walnut is a warmth-loving plant; larger crown width provides greater light exposure and stronger photosynthesis, and at CW6, the freezing resistance mechanism is well-developed and balanced, providing strong low-temperature resistance.

4. Conclusion

During the severe freezing climate event in the winter of 2020–2021, most wild walnut plants in the West Tianshan valley reserve suffered varying degrees of freezing injury, with a total injury rate of 87.1%. However, only 3.7% of plants experienced severe injury (grade 4), with mild (grade 1) and moderate (grade 2) injuries predominating (65.9%). Wild walnuts in slope middle and bottom were relatively susceptible, with injury rates of 46.5% and 35.9%, respectively, whereas those at slope top were relatively resistant, with an injury rate of only 17.6%. Mild (grade 1) and moderate (grade 2) injuries occurred mainly in slope middle and bottom, while severe (grade 3) and very severe (grade 4) injuries were concentrated in slope middle.

Height class H1 and crown width class CW1 were both susceptible to injury, with injury rates of 43.4% each, while H2 and CW2 were resistant, with injury rates of 0.1% and 2.9%, respectively. Significant differences in injury proportions

among different height and crown width classes were observed within the same slope position ($P < 0.05$). Overall freezing injury showed significant correlations with both diameter at breast height and crown width ($P < 0.05$), and freezing injury grades were significantly correlated with individual growth characteristics (DBH, tree height, crown width) and slope position ($P < 0.05$).

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