

Comparing Cold and Drought Tolerance in *Sequoia sempervirens* and *Sequoiadendron giganteum* at The Butchart Gardens and University of Victoria

by

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## Abstract

Drought and cold are important limiting factors for plant growth that can impact health and visual appeal. For show gardens that often plant non-native species, it is important to understand a species' tolerance of the conditions in a foreign range. The Butchart Gardens (TBG) in Victoria, B.C. is a National Historic Site of Canada that features many prominent, non-native species. The two Californian *Sequoia sempervirens* (D. Don) Endl. planted on the property are important focal points within the Gardens, but this species is known to have poor cold and drought tolerance. Comparatively, the *Sequoiadendron giganteum* (Lindl.) Buchh. is a related Californian species that is commonly planted as an ornamental tree. Due to its cold and dry native range, the *S. giganteum* is considered to have greater drought and cold tolerance. Drought and cold tolerance of individuals of both species at TBG and the University of Victoria (UVic) were compared from late summer to early winter in the context of irrigation regimes to understand what differences in care may improve stress tolerance and growth of these trees. Drought tolerance was assessed biweekly from July to November with a Scholander pressure chamber using shoot samples of *S. sempervirens* and *S. giganteum* individuals at UVic and TBG. The cold tolerance of shoot samples from the same individuals were assessed from September to January using a freeze-induced electrolyte leakage test. The *S. giganteum* individuals developed cold tolerance more rapidly than *S. sempervirens* in autumn, likely a result of the *S. giganteum* adaptation to colder native ranges. The *S. giganteum* showed greater variability in drought stress through the sample period, but responded rapidly to changing water availability, unlike the *S. sempervirens*. The *S. sempervirens* individuals at UVic that received high amounts of irrigation were less drought stressed, indicating a reliance on irrigation to minimize drought stress and that individuals at TBG would benefit from increased irrigation. The sampled *S. giganteum* individuals were more drought and cold tolerant than the *S. sempervirens*, indicating that *S. giganteum* is more tolerant of the climate and weather in Victoria, B.C.

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## **Introduction**

Drought and cold are two important abiotic factors that can limit plant growth, and impact overall plant health and aesthetics (Da Sois et al., 2024; Zhang et al., 2021). A plant's ability to withstand stress caused by these factors can be directly related to the species' native range, and the conditions it may experience there (Kreyling et al., 2015). When moved outside of their native range, and exposed to different climates, individuals may show signs of damage or stress if they are not adapted to such conditions. As many horticulturally significant species are not native, and may come from regions that have vastly different climates from where they are planted, it is important to understand how these non-native species are tolerating potential stressors in a foreign environment. This can provide a better understanding of what can be done to best support these species, and identify what conditions pose the greatest risk for them.

### **Impacts and Tolerance of Drought in Plants**

Drought occurs when water is unavailable to a plant for extended periods of time. This can be a result of high temperatures and no precipitation, or conditions that may physically prevent water uptake. This includes high salinity or freezing temperatures, which can alter water transport and lead to drought stress (Zhang et al., 2021). The severity of drought the plant experiences will depend on potential morphological and physiological adaptations that the plant may have for dry environments (Pivovarovoff et al., 2016). Periods of drought are often accompanied by conditions of high evaporative demand, which lead to increased xylem tensions within the plant. As the tension in the xylem increases, so does the risk of cavitation in the water column. This will occur when the cohesion and adhesion effects that maintain the water column in the xylem fail, and the column of water breaks, allowing for air bubbles to form (Hacke et al., 2015). High tension leads to cavitation by disrupting normal cohesion and adhesion effects, or by the high-tension conditions forcing water into the gaseous state (Hacke et al., 2015). Serious cavitation results in embolism, which is a full blockage of the xylem, and can further decrease the ability of the plant to transport water (Hacke et al., 2015). Plant species adapted to drier environments may alter their xylem anatomy to improve their tolerance of high tensions, thus decreasing cavitation risk, or to allow for better recovery after cavitation has occurred (Pivovarovoff et al., 2016). Many species increase xylem cell wall thickness to allow for better tolerance of high tensions, or have divisions within the xylem to isolate and block off damaged

segments (Hacke et al., 2015; Pivovarovoff et al., 2016). Blocking the embolized tissue prevents air bubbles from spreading and can allow for recovery in certain species (Hacke et al., 2015; Klein et al., 2017). As the tension in the xylem decreases, and the plant water status becomes more favourable, some species may reopen the xylem divisions and allow for the tissues to be recovered (Klein et al., 2017).

Ultimately, increased xylem tensions from drought can lead to decreases in nutrient transport and photosynthesis, and a loss of turgor within the entire plant (Sevanto et al., 2013). This can lead to wilting, localized tissue death, or whole plant mortality in severe instances (Sevanto et al., 2013).

The tension in the xylem is represented by water potential; the higher the tension is in the xylem, the more negative the water potential becomes (Irvine & Grace, 1997). Water potential in plants is normally assigned a negative value due to the tension transpiration creates, which allows the water to be pulled upward from the soils into the plants leaves (Irvine & Grace, 1997). Therefore, water potential decreases in a gradient with increasing plant height, and the soil water potential is normally less negative than in the plant's roots. This gradient drives the flow of water into the plant, and can be impacted when water potential becomes extremely negative due to increased transpiration or declining water potential in the roots (Irvine & Grace, 1997; Martínez-Vilalta & Garcia-Forner, 2016).

To tolerate increasingly negative water potentials, plants utilize a variety of different morphological and physiological adaptations. Morphological changes include alteration of leaf shape, thickness, and structure, as well as a higher investment in root biomass (Lo Gullo & Salleo, 1988; Qin et al., 2019; Pivovarovoff et al., 2016). Physiological adaptations consist of Crassulacean acid metabolism or C4 photosynthesis, and acclimation includes stomatal closure, and controlled leaf abscission (Karami et al., 2023; Males & Griffiths, 2017; Brodrribb et al., 2014; Stephenson et al., 2018). Leaf adaptations or acclimation to drought include a lower overall surface area, and leaves that have scaled appearances and thick waxy cuticles (Lo Gullo & Salleo, 1988; Qin et al., 2019). These traits decrease water loss due to evapotranspiration, which can improve the plant's overall water use efficiency and allows for continued photosynthesis during dry periods (Qin et al., 2019). Species growing in regions with limited precipitation also tend to invest more energy in belowground biomass, allowing them to develop large root systems with tap roots and increased numbers of root hairs. This improves deep soil

water uptake and limits potential water stress during extended dry periods (Pivovarov et al., 2016; Ambrose et al., 2015).

Stomatal closure is a common response during sustained water stress, as it reduces water loss from transpiration and can allow the plant to regain a favourable water status (Brodribb et al., 2014). In most species, stomatal closure is triggered by an accumulation of abscisic acid within the foliar tissue, although some species may simply rely on negative water potentials to decrease guard cell turgor pressure (Brodribb et al., 2014). However, this strategy can lead to carbon starvation as there is a greater stomatal resistance to gas exchange (Lopes et al., 2022). Therefore, this is a short-term attempt to regain a more favourable water status. Some species may also abscise older or less photosynthetically active tissues to prevent widespread mortality (Ambrose et al., 2018). By abscising older tissues, the plant decreases its overall leaf area, lowering the demand for foliar water, and decreasing transpiration from less productive tissues (Jump et al., 2017; Stephenson et al., 2018).

If a plant lacks these adaptations, or is unable to tolerate the level of drought, mortality may occur. This will be triggered when there is a loss of water transport capacity in the xylem, also known as complete hydraulic failure. Under persistent drought conditions, this may lead to a large mass of tissue drying out and total plant death (Da Sois et al., 2024).

### **Cold Tolerance in Woody Plants**

Cold damage and drought share many similarities, as freezing temperatures may result in similar conditions of low water availability within the plant. The drought-like conditions that result from freezing damage are typically a direct product of cold damage, but can also be an important signal in the induction of cold hardiness (Tyree et al, 1978; Anísco & Lindstrom, 1996; Close, 1996).

Plants achieve cold acclimation by two main strategies: freezing avoidance and freezing tolerance (Levitt, 1980). Both strategies use similar cues to induce acclimation, which commonly include decreasing photoperiods, mild drought, and declining, but not sub-zero, temperatures (Williams et al., 1972; Anísco & Lindstrom, 1996; Li et al., 2004). All of these signals together will induce acclimation. However, photoperiod is typically the first signal perceived (Williams et al, 1972). Declining fall temperatures and mild drought trigger the plant to continue cold hardening and can be important signals for species in colder climates (Repo et al., 2000; Li et al., 2002).

Aside from morphological adaptations, plants avoid freezing by supercooling cellular contents and accumulating solutes (Levitt, 1980). Depending on the species, plants are able to supercool cellular water and have it remain in a liquid state at temperatures as low as  $-47^{\circ}\text{C}$  (Levitt, 1980). Supercooling can occur in tissue cells or within the xylem (Wisniewski & Davis, 1995; Levitt, 1980); this process can occur so long as there is a sufficient barrier between the supercooled water and the extracellular ice (Wisniewski & Davis, 1995). The concentration of solutes in a cell can increase due to freezing as the water exits the cell, leaving a relatively higher concentration of solutes inside (Ruelland et al., 2009). Some species may also accumulate sugars such as fructose, glucose, and sucrose in vulnerable tissue like buds, stems, and leaves to increase the solute concentration (Walker et al., 2008). The accumulation of sugars lowers the freezing point of the remaining water in the plant cell and prevents cellular water from exiting the cell, helping protect from the spread of ice crystals (Levitt, 1980; Walker et al., 2008). Both strategies allow the plant to have cellular water in a liquid state without extracellular ice spreading within the cells.

Freezing tolerance can be achieved by inducing a period of winter dormancy and by altering gene expression. Through gene expression, plants are able to produce a multitude of proteins that can act as antifreezes, cryoprotectants, or that are relatively cold stable (Wisniewski et al., 2014; Levitt, 1980). These various compounds prevent cellular water from freezing, even at sub-zero temperatures, and can act as molecular chaperones by stabilizing other proteins and the cell membranes as the temperature decreases (Wisniewski et al., 2014; Close, 1996). A key example is the protein dehydrin, which is associated with dehydration stress (Li et al., 2004; Close, 1996). The production of the protein is strongly correlated to the development of cold tolerance and is a prominent cryoprotectant in many species (Close, 1996; Wisniewski et al., 1999).

Cold hardiness is a complex trait that can be influenced by a multitude of factors, including environmental, morphological, and physiological traits (Wisniewski et al., 2003). While a plant's acclimation strategy mainly influences its tolerance of cold temperatures, morphological features may also contribute to the plant's cold tolerance. Features such as bark or wood hardiness, retention or shedding of leaves, and the cold tolerance of buds may influence the level of damage the plant sustains (Wisniewski et al., 2003). The development of cold hardiness may be split into five important steps; the date of induction of cold acclimation, the

rate of acclimation, the degree of cold tolerance reached, maintenance of cold tolerance throughout the season, and the rate of de-hardening in the spring (Wisniewski et al., 2003). The dates of these developmental stages are related to the native environment of the species, and the native conditions will influence the maximum cold hardiness the species may attain (Kreyling et al., 2015).

For there to be any freezing damage to plant tissues, ice must first nucleate either on the surface of the plant or within surface tissues (Lindow et al., 1982; Gross et al., 1988). If ice nucleates on the outer surface of the plant, the ice crystals may be able to propagate into the plant through cracks in the cuticle, the lenticels, or open stomata (Levitt, 1980). The movement of ice crystals may be limited if the plant has morphological adaptations such as thick waxy cuticles or thick bark (Wisniewski et al., 1997; Levitt, 1980). Once ice crystals are in the plant they will grow through extracellular spaces or the xylem. However, the growth of internal ice crystals may be limited by the level of cold hardiness the plant has achieved (Levitt, 1980; Workmaster et al., 1999).

Freezing damage commonly occurs from the formation of extracellular ice, which can lead to severe cellular dehydration due to rapid reduction in water potential (Wisniewski et al., 2003). This results in further cellular damage including changes in membrane folding, protein denaturation, changes in solute concentration, and cytorrhysis if enough water is lost or intracellular ice forms (Wisniewski et al., 2003). Freezing damage may also occur from freeze-thaw cycles, as expansion of cellular water may damage cell walls or embolisms may form in vessels during thawing (Ruelland et al., 2009; Sperry & Sullivan, 1992; Wisniewski et al., 2003). If large amounts of intracellular ice forms, this will be lethal to the cell (Levitt, 1980; Muldrew & McGann, 1990).

### **Introduction to *Sequoia sempervirens* and *Sequoiadendron giganteum***

*Sequoia sempervirens* (D. Don) Endl. (Coast redwood) is native to the central and northern coastlines of California. The range extends from the southwestern coast of Oregon down to the Santa Lucia Mountains in California, occupying a strip of forests roughly 720 km long and 10 – 60 km wide at varying points (Appendix A; Olson et al., 1990). This region experiences annual mean temperatures of 10 – 15 °C, and temperatures rarely go below 0 °C or above 30 °C. There is heavy rainfall along the entire coastal region from November to March of each year, and the summers experience light, infrequent rainfall, with July being the driest month

(National Park Service [NPS], 2022; Olson et al., 1990). Yearly rainfall ranges between 1500 to 3200 mm, with minimal snow only on the highest points of the eastern range. Within this range, Coast redwoods may grow in pure stands, or alongside species such as: *Pseudotsuga menziesii* (Mirb.) Franco, *Abies grandis* (Douglas ex D. Don) Lindl., *Tsuga heterophylla* (Raf.) Sarg., *Lithocarpus densiflorus* (Hook. & Arn.) Rehder, and *Arbutus menziesii* Pursh.

The Coast redwood only experiences a low level of soil drought during the dry season due to heavy winter rainfall, mild temperatures, and frequent summer fog banks. The fog banks can reduce water loss due to evapotranspiration from the tree by decreasing the ambient air temperature and increasing humidity, which in turn reduces the vapour pressure deficit (Petreshen et al., 2025). Fog banks can also relieve water stress within the tree by increasing soil moisture from fog drip and by supplying water through foliar uptake (Petreshen et al., 2025; Ewing et al., 2009). Water droplets from the fog bank can precipitate out of the air when in contact with a leaf and be transported into the tree's vascular system (Limm et al., 2009). This water allows the tree to regain a favourable water status and maintain growth during the summer season (Petreshen et al., 2025). During heavy fog events, the amount of water taken up can reverse sap-flow in the tree for a period (overnight, or up to 24 hours), which allows for the water status in the entire tree, not just the crown, to be improved. Sap-flow reversal allows the entire tree to replenish water stores and repair cavitated structures (Burgess & Dawson, 2004; Petreshen et al., 2025).

To aid in foliar water uptake, Coast redwoods have unique dimorphic shoots, which allow them to balance water uptake with photosynthesis (Chin et al., 2022). Since continual leaf wetting can decrease photosynthetic rates by inhibiting gas exchange (Aparecido et al., 2017), the majority of their shoots have leaves that are broad, flat needled, and slightly waxy (Chin et al., 2022). These peripheral shoots are found on the outermost points of the tree's crown and make up most of the leaf area and active photosynthetic tissue. However, the wax on the peripheral shoots decreases foliar water uptake (Chin et al., 2022). This is advantageous for photosynthesis during the seasonally wet periods, but limits their water uptake abilities from fog banks during the dry season (Chin et al., 2022). Foliar uptake is primarily done by the Coast redwood's axial shoots, which are scaled, decurrent shoots within the crown of the tree. These shoots support the clusters of peripheral shoots and can take up water at three times the rate of peripheral shoots (Chin et al., 2022). Along the eastern most points of the Coast redwood range,

where summer precipitation is lower, these shoots are found in a higher abundance and are common on trees experiencing more hydraulic stress (Chin et al., 2022).

Upon maturity, the Coast redwood reaches a mean height of 60 m, or 100 m if grown in rich soil. These trees have a mean diameter at breast height (DBH) of 1.0 - 1.5 m, but individuals with a DBH of 3.0 – 4.0 m are common in older stands (Olson et al., 1990). While these trees do grow to impressive heights, they can be considered a shallow rooting species, and have large, wide spreading lateral roots (Olson et al., 1990). Due to having such a shallow root system, Coast redwoods rely heavily on consistent rainfall to dampen the top soil layers, and are unable to benefit from deep groundwater resources (Burgess & Dawson, 2004).

The closest living relative of the Coast redwood is the *Sequoiadendron giganteum* (Lindl.) Buchh. (Giant sequoia), due to both being in the subfamily Sequoioideae and the family Cupressaceae (Keeley & Pausas, 2025). Native to the western slopes of the Sierra-Nevada mountains, Giant sequoias occupy a limited range totalling approximately 14,000 hectares. Most groves are located towards the southern end of this range and can vary in size from less than 1 ha to 1500 ha (Appendix B; Weatherspoon, 1990; Nydick et al., 2018). The climate within this range varies with elevation, as these trees typically grow between elevations of 1400 to 2150 m (Weatherspoon, 1990). Annual precipitation varies, but is usually less than 1000 mm, with no more than 30 mm annually during the dry season (June to October). At elevation, most precipitation falls as snow, with annual snowfall around 350 – 500 cm, and a snowpack of 2.0 m (Weatherspoon, 1990). Again, yearly temperature varies with elevation, but ranges between monthly lows of – 6 °C and highs of 25 °C. Temperatures rarely go below – 20 °C or above 36 °C (NPS, 2025; Weatherspoon, 1990). Giant sequoias are tolerant of frost and freezing temperatures; however, they will show signs of damage when exposed to temperatures consistently below –12 °C (Wilson et al., 2016). Within this range, Giant sequoias grow alongside species such as: *Abies concolor* var. *lowiana* (Gordon & Glend.) Lemmon, *Pinus lambertiana* Douglas, *Calocedrus decurrens* (Torr.) Florin, *Abies magnifica* A. Murray, and *Pinus ponderosa* Douglas ex P. Lawson & C. Lawson.

Due to the lack of precipitation during summer months, the Giant sequoia relies mostly on deep soil water formed from winter snow. To access this water, they grow a large taproot that commonly extends 30 m down into the soil and may occupy an area approximately 0.3 ha in size (Weatherspoon, 1990). Generally, Giant sequoias produce 2.0 – 2.5x more underground biomass

than shoot biomass to support their massive size during the dry season (Weatherspoon, 1990; Ambrose et al., 2015). To decrease water loss due to transpiration, Giant sequoias have scaled, waxy shoots, with a small surface area to volume ratio (Ambrose et al., 2015). During periods of declining soil moisture, Giant sequoias will close their stomata to recover a more favourable water status and to help prevent trunk xylem embolism (Ambrose et al., 2015). Leaf morphology and stomatal control allows them to tolerate the mild to moderate drought conditions that they may experience during the growing season. During seasons that are severely dry, Giant sequoias may practice controlled senescence to limit branch or entire tree mortality (Stephenson et al., 2018). Shoots and small branches that are not photosynthetically favoured or contain older tissue will be abscised to limit water loss (Stephenson et al., 2018; Jump et al., 2017).

A mature Giant sequoia may reach a mean diameter (above any buttressing roots) of 3 – 6 m and a height of 76 m. Individuals tend to grow quickly, putting on 0.5 – 0.7 m of height and 1.0 – 2.0 cm of diameter yearly (Weatherspoon, 1990).

Due to the seasonally cold and hot climate they experience, and their morphological and physiological adaptations, Giant sequoias are generally considered to have higher cold and drought tolerance than Coast redwoods (Ambrose et al., 2015; Kreyling et al., 2015; Wilson et al., 2016). Coast redwoods are limited to their coastal range due to a reliance on summer fog and mild temperatures, while sub-zero winter temperatures and dry, hot summer conditions limit them from growing inland or at elevation (Wilson et al., 2016).

Compared to Giant sequoias, Coast redwoods display more negative shoot water potentials under the same growing conditions and have been shown to be more sensitive to declining moisture (Ambrose et al., 2015). When grown under drought conditions, Coast redwoods experienced a substantial decline in basal diameter and height growth compared to Giant sequoias of the same age (Ambrose et al., 2015). Due to their sensitivity to drought, Coast redwoods have higher embolism rates compared to Giant sequoias. However, native embolism rates are high in Coast redwoods, and they are able to recover embolized tissue more efficiently than Giant sequoias (Ambrose et al., 2015). While Giant sequoias have responsive stomatal control, Coast redwoods have limited ability to close their stomata (Ambrose et al., 2015). High transpiration rates, asymmetrical guard cells, and foliar endophytes that may prevent full stomatal closure impact their ability to limit water loss by transpiration during dry periods (Ambrose et al., 2015; Burgess & Dawson, 2004). Under similar water conditions, Giant

sequoias will close their stomata to limit their shoot water potential from falling below  $-2.5$  MPa, while Coast redwood individuals may reach shoot water potentials of  $-5.3$  MPa due to their lack of stomatal control (Ambrose et al., 2015). Giant sequoias are more drought tolerant, but hot and dry conditions spanning multiple seasons and declining winter snowpacks may increase their vulnerability to drought-induced damage that can impact their productivity in the next season (Ambrose et al., 2018).

While both species have been successfully grown outside of their natural range, they are both limited to temperate, mild climates (Wilson et al., 2016). Coast redwoods tend to be more limited in where they can be grown outside of their native habitat but have been planted successfully in both urban and forestry settings in Europe and Canada (Guinon et al., 1981; Wilson et al., 2016). Coast redwoods are limited to regions that are similar to their native range, since they require temperate environments for successful growth (Olson et al., 1990; Wilson et al., 2016). Giant sequoias can tolerate regions that are seasonally hot or cold, but they are still limited by the conditions they experience in their native range (Weatherspoon, 1990; Kreyling et al., 2015).

### **Study Location and Research Objectives**

Sampling for this study was conducted in Victoria, British Columbia (B.C.) at both the University of Victoria (UVic) and The Butchart Gardens (TBG). Both locations are in the Coastal Douglas fir (CDFmm) biogeoclimatic zone (Nuszdorfer et al., 1991). This region experiences around 1000 mm of annual rainfall and has mild year-round temperatures that very rarely fall below  $-10$  °C or rise above 35 °C (Nuszdorfer et al., 1991; Environment and Climate Change Canada [ECCC], 2026). The summers tend to be long, warm, and dry with limited precipitation, while snowfall is infrequent during winter months, and usually only lasts for one to two weeks of the entire season (Nuszdorfer et al., 1991; ECCC, 2026).

TBG is located on the south-eastern tip of Vancouver Island, planted on land bordering the ocean and surrounded by a maintained second growth forest (Clarke, 2006). Officially opened in 1904, the Gardens were established by Jennie Butchart and built on the land of her family's limestone quarry (Clarke, 2006). The Gardens currently occupy 22.25 ha of the 60.7 ha property, which include garden beds planted on the converted quarry, old farmland, and grounds of the original estate (The Butchart Gardens, 2026). TBG is classified as a show garden, meaning that the majority of the garden beds are being constantly replanted, and that many plants will not

remain in the Gardens longer than one to two months of the year. However, many trees and shrubs will remain planted for years acting as backdrops, screens, or focal points within and around the Gardens. These plants are usually native species, or unique introduced species that can tolerate the climate without showing signs of physiological stress that may impact their aesthetic appeal.

Planted in 1934, TBG hosts two champion Coast redwood trees (Appendix C). Towering above the rest of the native tree species, these trees are a key focal point in this sector of the Gardens. Preventing morphological signs of stress is not only crucial for maintaining plant health, but is also important aesthetically. Since these trees are of significance to the Gardens and their visitors alike, it is integral for TBG to understand what conditions may put these trees at risk of damage and stress. As the climate changes, and these trees continue to mature, this will allow gardeners to understand when the trees may be at risk and make changes to their care before the trees show signs of stress.

Since Coast redwoods are native to a moist, temperate environment, cold and drought stress are the two most significant risks to these individuals. While the climate is temperate in western B.C., on eastern Vancouver Island, it is still significantly drier than the Coast redwoods' native range, with warmer summers and colder winters (NPS, 2022; Olson et al., 1990; Nuszdorfer et al., 1991). Climate change may also begin to alter regular weather trends and increase variability, potentially leading to hotter summers with more frequent drought, and less predictable winter storms that could bring snowfall and freezing temperatures (IPCC, 2023). Therefore, understanding how TBG's Coast redwoods are currently tolerating drought conditions in summer and autumn, and how well they are acclimating to winter temperatures will provide valuable information for seasons to come.

To understand the drought and cold tolerance of the Coast redwoods at TBG, these individuals were compared to Coast redwoods at UVic (Appendix C), and to another species at both locations. The Giant sequoia was selected as the comparison species, as they are the closest living relative of Coast redwoods and are generally considered to have greater cold and drought tolerance (Keeley & Pausas, 2025; Ambrose et al., 2015). Both Coast redwood and Giant sequoia individuals at UVic (Appendix C) are regularly maintained and watered by UVic gardening staff, and are planted alongside buildings, walking paths, and roadways.

The main objective of this study is to understand the differences in cold and drought tolerance between Coast redwood and Giant sequoia individuals planted at TBG and UVic. Any differences between individuals will be compared to the watering and care regimes each tree experiences to understand what differences in care may improve the tolerance and growth of TBG's Coast redwood trees. More specifically, the drought vulnerability of the TBG Coast redwoods was tracked throughout the dry season to understand when they were the most drought stressed, and what conditions precede their drought stress. The cold tolerance of TBG's Coast redwoods was assessed by identifying when they induced cold hardiness, when they were the most hardy, and how well they maintain hardiness throughout the season. The TBG Coast redwoods were compared to the UVic Coast redwoods, and the Giant sequoias at both locations, to understand how they tolerate cold and drought, comparatively. This information will allow TBG to design watering and care to better support the growth of their Coast redwood trees.

## Methods

Sampling took place in two locations, at TBG and UVic. At each location, two Coast redwood and three Giant sequoias were selected for sampling

At TBG, two mature Coast redwoods are located north of the Garden's concert venue, along the edge of the maintained gardens. The Coast redwood individuals are located at 48°33'55.9"N, 123°28'11.7"W, at an elevation of 20 m and slope of 10%. All samples were taken from an aspect of 237° SW. On the east, west, and south sides, the trees are surrounded by low lying vegetation, including *Polystichum munitum* (Kaulf.) C. Presl and *Rhododendron macrophyllum* D. Don, and maintained seasonal flower beds. On the north side, within 5 m of the Coast redwood's canopy, there is a small stand of *Pseudotsuga menziesii* and *Thuja plicata* Donn ex. D. Don. The Coast redwoods are located upslope of the surrounding garden beds and concert venue. The Giant sequoias are planted west of the main entrance to the Gardens, behind the upper parking lot. These individuals are located at 48°33'45.0"N, 123°28'02.3"W, at an elevation of 30 m and a slope of 0%. All samples were taken from the aspect of 296° NW. They are planted in a row of 20 trees, with a gravel road on the north side, and a maintained stand of *Pseudotsuga menziesii*, *Thuja plicata*, *Acer macrophyllum* Pursh, and *Abies grandis* immediately next to the Giant sequoia canopy on the southern side. The area around all the Giant sequoias is clear of any understory plants, and they are planted upslope from TBG's sunken garden, which is on the southern side of the trees.

At UVic, the two Coast redwood trees are planted at two different locations. The first tree is planted in Finnerty Gardens and is surrounded by *Abies grandis* and low-lying vegetation on all four sides. This site is located at 48°27'37.8"N, 123°18'56.0"W at an elevation of 38 m. All samples were taken from the side of the tree facing 263°W. This tree is planted on a flat surface, along a gravel walkway. The second tree is planted alone by the south side of the Jaime Cassels Centre, upslope of the surrounding lawn and building. This individual is located at 48°27'52.8"N, 123°18'43.8"W at an elevation of 40m. This site has an aspect of 270°W and has a 10% slope. The three Giant sequoia trees at UVic are located on the southeast side of campus at 48°27'37.1"N, 123°18'50.6"W, by the Henderson Road entrance. All three trees are planted on an open, flat, grassy area, along the edge of Cunningham Woods. This site has an elevation of 38m, and an aspect of 248°W. They are bordered by *Quercus rubra* L. and *Betula papyrifera* Marshall on the western and eastern sides, which grow within 10 m of the Giant sequoia's

canopy. There is limited undergrowth, which includes some maintained lawn and *Polystichum munitum*.

For this study, four Coast redwoods were sampled; two from TBG and two from UVic. There were six Giant sequoias sampled, three from TBG and three from UVic, totalling ten different trees, five at each location.

Prior to any sampling, the height, diameter at breast height (DBH), and age of each tree was recorded. The height was obtained using a clinometer at a measured distance from the base of the tree (Martin, 2022). The angle from the clinometer and the distance to the base of the tree were used to calculate the height (Appendix D). The DBH was taken 1.37 m above the base of the tree using a DBH tape. The age of each tree was obtained from gardening records at both TBG and UVic. The weekly irrigation rates for all trees were obtained from gardening records at both TBG and UVic. For the TBG individuals, weekly irrigation was estimated based on sprinkler type and watering duration.

For the entire sample period, the temperature and precipitation were obtained from an Environment and Climate Change Canada weather station at the Saanichton CFIA (located in North Saanich). The mean weekly (Sunday to Saturday) temperature was calculated from the daily mean temperatures reported by this station. Precipitation was summed every week (Sunday to Saturday) from daily rainfall totals. No snowfall was recorded during the sample period, so total precipitation was only calculated from rainfall records.

The water potential of each tree was sampled every two weeks from August 8, 2025 to November 14, 2025. Shoot samples were harvested every Friday, between 7:00 a.m. and 10:00 a.m., from lower branches on the west side of each tree. From each tree, three 15-20 cm shoots were harvested from the tips of main branches. For mature trees that lacked accessible branches, a Barnel B188Z4-6 pruning pole was used to sample from the lowest available branches. All other samples were taken from the lowest, mature branches with a Corona classic cut hand pruner. Samples were transported to UVic on ice, and remained on ice until they could be tested.

A Scholander pressure chamber (Soil Moisture Corp., Goleta, CA; Scholander et al., 1964) at UVic was used to determine the water potential of each shoot sample. This method was chosen as it is a simple, reliable method for measuring shoot water potential in mature, woody plants (Cochard et al., 2001). This provides an indirect measure of water potential, while still

producing comparable results to other more complex, methods of measuring water potential (Cochard et al., 2001).

Each shoot was prepared by cutting the top 0.5 cm of stem from the cut end of the shoot off, then stripping the outer bark from the top 3 cm back from the cut end of the shoot. This shoot was inserted into the chamber lid with the stripped length protruding upwards, and the gasket surrounding the shoot was tightened sufficiently to hold the sample in place. The lid was placed on the pressure chamber with the shoot inside the chamber, and nitrogen gas was released into the chamber until a slick of water was visible on the cut surface of the shoot (Scholander et al., 1964; Boyer, 1967). The pressure inside the chamber was recorded in bars, then converted to MPa and multiplied by -1 to convert to the equivalent tension in the xylem. This process was repeated for three shoot samples per tree, for each of the ten trees. For each tree, the mean water potential of the three samples was calculated.

Every four weeks, from September 5, 2025 to January 9, 2026, the cold hardiness of each tree was measured by a freeze-thaw electrolyte leakage test (Dexter et al., 1930). This method was chosen as it is sensitive to damage at mild temperatures and is most effective in determining relative cold tolerance in trimmed shoots and leaves of mature, woody plants (Odium and Blake, 1995).

Shoot samples were harvested once every four weeks by the same method used for water potential samples. All samples were transported to UVic on ice, then refrigerated for two days before they were prepared.

Samples were prepared by cutting a 10 cm length of each shoot into 0.5 cm pieces with a razor blade. These 20 shoot sections were then divided equally among four 20 mL vials each containing 180  $\mu$ L of distilled water. For the Coast redwood trees, the needles were trimmed from the stems before the stem was cut into 20 pieces. This process was repeated for three shoots per tree, for all ten trees. The four vials from each shoot sample were then placed at random on four identical trays.

All trays were refrigerated overnight, then three trays were placed in a programmable freezer (Caltec Scientific Ltd., Hayward, CA) at 9:30 a.m. the following day. One tray remained in the refrigerator as a control group. The freezer was then programmed to cool from 0 °C down to - 8 °C over 1 hr 36 min, then hold this temperature for 1 hr. After this hour, the first tray was removed and placed back in the refrigerator. This process was repeated with 1 hr of cooling to

–13 °C and –18 °C, with 1 hr held at each temperature, after which one tray was removed. All samples were refrigerated overnight.

The following morning, 10 mL of distilled water was added to each vial in all four trays using a Brinkmann dispensette. All trays were then put on a shaker plate for 24 hr at 100 rpm. After shaking, the conductivity ( $\mu\text{S}/\text{m}$ ) of each vial was measured with a Jenway 4020 conductivity meter. All trays were then placed in an oven for 3 hr at 100 °C. Once removed from the oven, all trays were placed back on the shaker plate overnight, at 100 rpm. The following day, the conductivity ( $\mu\text{S}/\text{m}$ ) of each vial was measured again, and samples were disposed of.

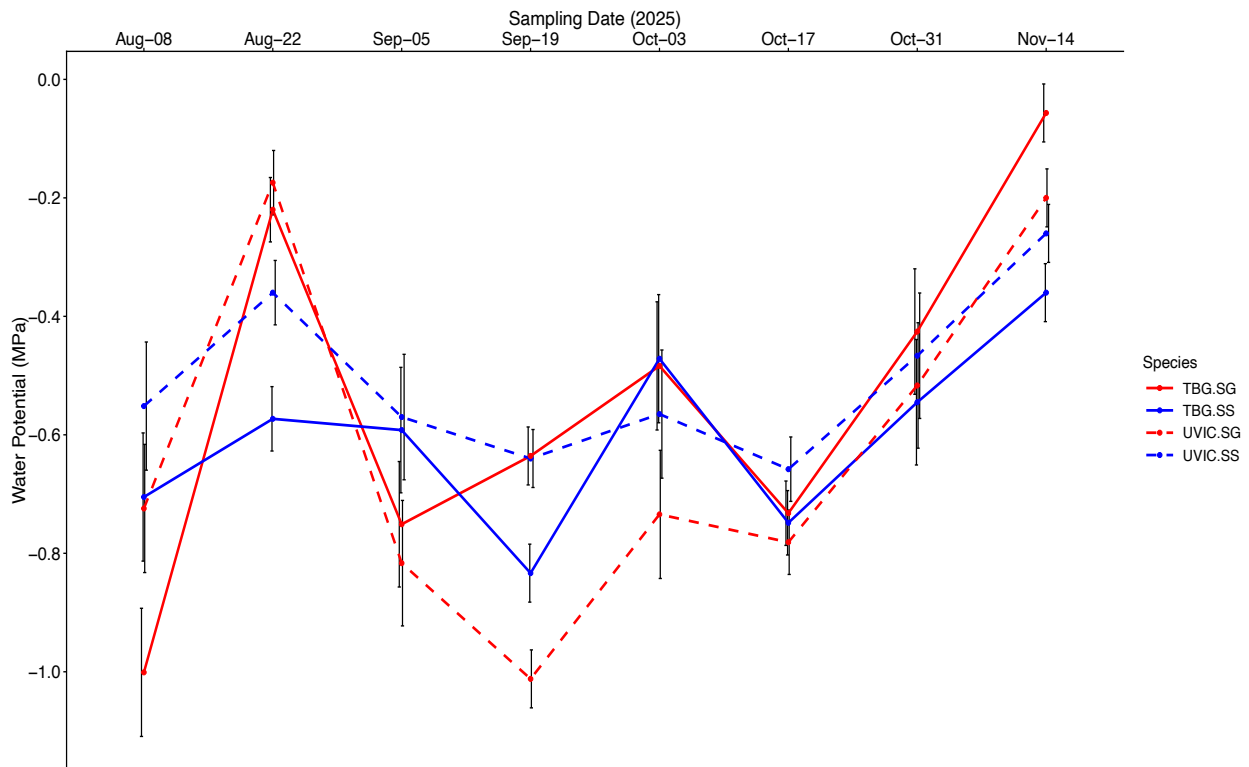
The index of injury (%) was calculated for each sample, at each freezing temperature, using the conductivity after freezing, after cooking, and from the control samples (Flint et al., 1967; Appendix D). For each tree, the mean index of injury was calculated from the three branch samples at each of the freezing temperatures.

To analyze results, repeated measures two-way ANOVA was used to test for significant effects of species, their locations, and the interaction of species and location, on mean water potential and index of injury. The water potential was initially analyzed as an entire dataset, using repeated measures two-way ANOVA, to determine if there was a significant interaction of species x location. Since there was not a significant interaction between the species and locations throughout the entire sample period (Appendix E), the data were reanalyzed for each sample date. The cold hardiness data were analyzed as an entire dataset, for each temperature, using the repeated measures two-way ANOVA. This ANOVA showed that there was a significant interaction between species and locations (Appendix E). However, since all three temperatures showed similar graphical trends and analyzing each date separately could reveal important information, the data were averaged across the temperatures, and analyzed separately for each date. Normality assumptions were made for each data set by assessing residual plots from the repeated measures two-way ANOVA.

Two-way ANOVAs were conducted for each drought and cold tolerance sampling date to test for the date-specific interactions between species and locations, and their impact on mean water potential and freezing tolerance. All statistical analyses were completed with R statistical software version 4.4.2 using the tidyverse 2.0 package (R Core Team, 2026; Wickham et al., 2019).

## Results

The mean water potentials in both species and locations were highly variable throughout the sample period (Figure 1). However, the Giant sequoias at both locations showed greater variation in mean water potential during the four-month period, compared to the Coast redwoods (Figure 1). On the first sampling date (August 8), there was a significant difference in mean water potential between species and location (Table 1).



**Figure 1.** Mean ( $\pm$  S.E.) water potential (MPa) of Coast redwoods (blue) and Giant sequoias (red) at TBG (solid lines) and UVic (dashed lines) as measured by a Scholander pressure chamber over a four-month period (August 8<sup>th</sup>- November 14<sup>th</sup>, 2025). The mean water potential was obtained from measurements of three branches from each of two Coast redwood trees each location, and three Giant sequoia trees at each location.

**Table 1.** *P*-values for the main and interaction effects of species and location for analysis of mean water potential on each sampling date (August 8 – November 14, 2025). All *P*-values were obtained by two-way ANOVA,  $\alpha = 0.05$ .

Sampling Date (2025)	Source of Variation	<i>P</i> -value
August 8	Location	<b>0.03</b>
	Species	<b>0.029</b>
	Species x Location	0.481
August 22	Location	0.19
	Species	<b>0.013</b>
	Species x Location	0.324
September 5	Location	0.842
	Species	0.225
	Species x Location	0.78
September 19	Location	0.287
	Species	0.527
	Species x Location	0.07
October 3	Location	0.068
	Species	0.333
	Species x Location	0.397
October 17	Location	0.855
	Species	0.192
	Species x Location	0.104
October 31	Location	0.105
	Species	<b>0.032</b>
	Species x Location	<b>0.0005</b>
November 14	Location	0.3
	Species	<b>0.005</b>
	Species x Location	<b>0.026</b>

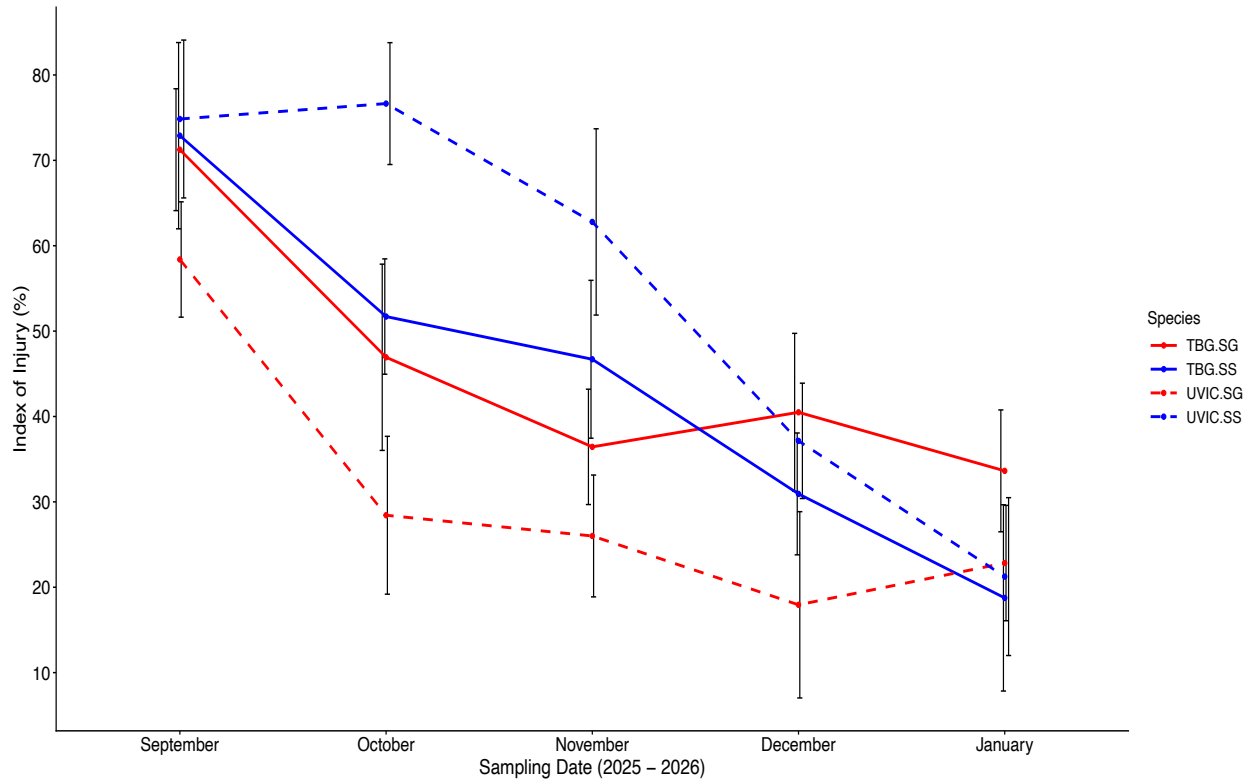
The TBG Giant sequoias had the most negative mean water potential on August 8, indicating they were more drought stressed than the UVic Giant sequoias and the Coast redwoods at both locations (Figure 1). On this date, the TBG Coast redwoods and Giant sequoias were significantly more drought stressed than the Giant sequoia and Coast redwood individuals at UVic (Figure 1; Table 1).

On August 22, there was a significant difference in mean water potential between both species (Table 1). The Giant sequoias at both locations had the least negative mean water potentials, compared to the Coast redwoods at TBG and UVic, which were more drought stressed. The Coast redwoods at TBG had the most negative mean water potential on August 22 (Figure 1).

Sampling dates from September 5 to October 17 did not show a significant difference in mean water potentials between species or location, or a significant interaction between species and location (Table 1). There was a significant difference in mean water potential between species, and a significant interaction between species and location on October 31 (Table 1; Figure 1). The Giant sequoias at TBG had the least negative mean water potential, while the TBG Coast redwoods had the most negative mean water potential and therefore were more drought stressed (Figure 1).

On the last sampling date (November 14) there was a significant difference in mean water potential between species, and a significant interaction between species and location (Table 1; Figure 1). On this date, the Giant sequoias at TBG had the least negative mean water potentials, while the TBG Coast redwoods showed the most negative mean water potential on this date (Figure 1).

Over the cold tolerance sampling period, the mean index of injury, resulting from controlled freezing, decreased in both species and at both locations (Figure 2).



**Figure 2.** Mean ( $\pm$  S.E.) index of injury (%) for *S. sempervirens* (blue) and *S. giganteum* (red) at TBG (solid lines) and UVic (dashed lines) as measured by the freeze-thaw electrolyte leakage test over a five-month sample period (September 2025 – January 2026). The mean index of injury was calculated from indices of injury measured at  $-8^{\circ}\text{C}$ ,  $-13^{\circ}\text{C}$ , and  $-18^{\circ}\text{C}$ . The mean index of injury was obtained from measurements of three branches from two *S. sempervirens* trees at each location, and three *S. giganteum* trees at each location.

In September, on the first sampling date, there was not a significant difference in the mean index of injury between species or location (Figure 2; Table 2).

**Table 2.** *P*-values for the main and interaction effects of the species x location interaction term for the analysis of mean index of injury on each sampling date (September 2025 – January 2026). All *P*-values obtained by two-way ANOVA,  $\alpha = 0.05$ .

Month (2025-2026)	Source of Variation	<i>P</i> -value
September	Location	0.142
	Species	0.074
	Species x Location	0.127
October	Location	0.876
	Species	<b>0.009</b>
	Species x Location	0.022
November	Location	0.979
	Species	<b>0.011</b>
	Species x Location	0.087
December	Location	<b>0.031</b>
	Species	0.274
	Species x Location	<b>0.012</b>
January	Location	0.427
	Species	0.257
	Species x Location	0.351

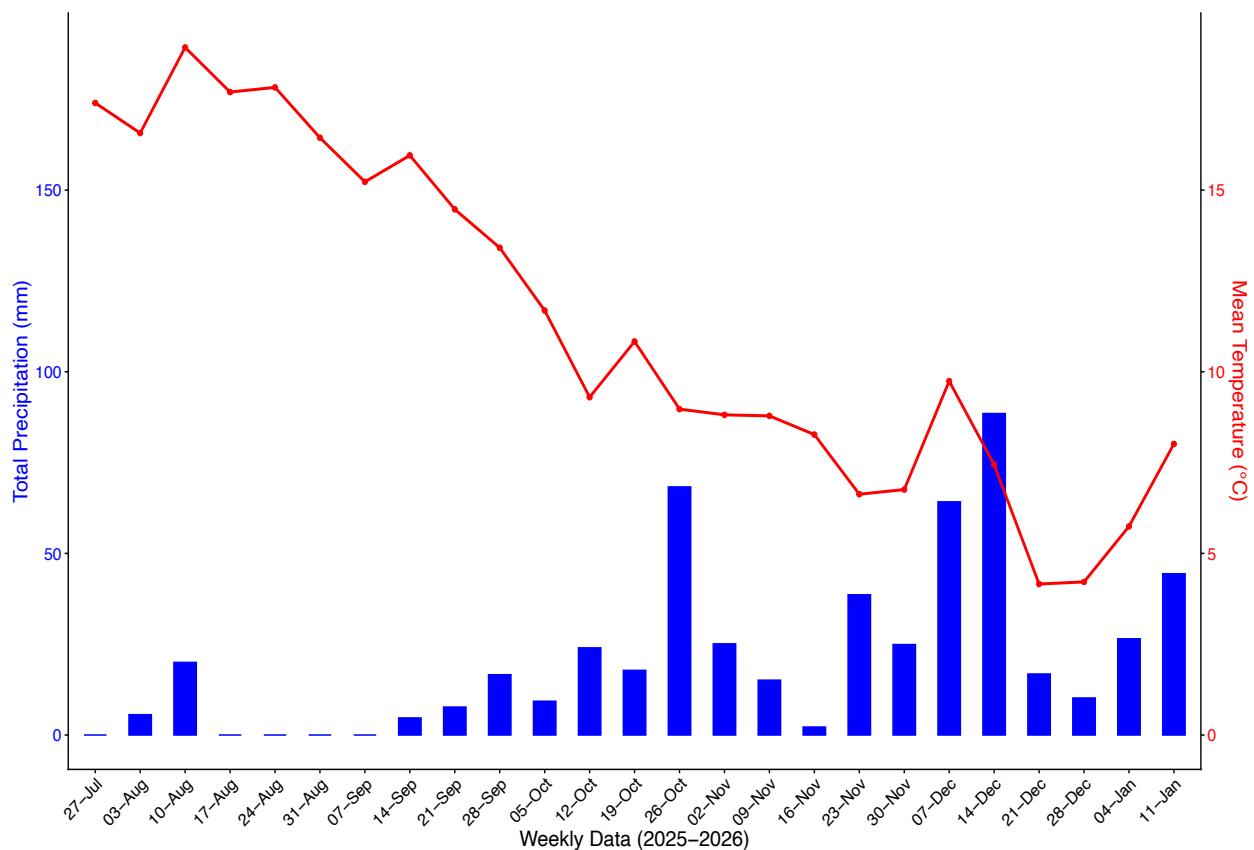
In October and November there was a significant difference in mean index of injury between species (Table 2; Figure 2). During these two months, the mean index of injury decreased in both species and at both locations (Figure 2). The Giant sequoias at UVic continued to be more cold tolerant, on average, while the UVic Coast redwoods had the highest mean index of injury again during both months (Figure 2), and, during October, this interaction was significant (Table 2). During this month, the UVic Coast redwoods showed a small increase in mean index of injury compared to the September injury score, before declining again in November (Figure 2).

In December, there was a significant difference between mean index of injury at both locations and a significant interaction between species and location (Table 2). During this

sample, the mean index of injury for both TBG and UVic Coast redwoods, and the UVic Giant sequoias, continued to decline (Figure 2). However, the mean index of injury in the TBG Giant sequoias appeared to plateau (Figure 2).

On the last sampling date (January), the lowest mean index of injury values were recorded for the entire sample period (Figure 2). On this date, there was no significant difference in mean index of injury between species or location (Table 2). However, the mean index of injury for the Coast redwoods at both locations continued to decline (Figure 2). On this date, the Coast redwoods at both locations had the lowest mean index of injury, while the mean index of injury in the TBG and UVic Giant sequoias appeared to plateau (Figure 2).

The mean weekly air temperature during the sample period was highest during the week of August 10, 2025, and was lowest during the week of December 21, 2025 (Figure 3).



**Figure 3.** Weekly total precipitation (blue - mm) and mean temperature (red - °C) for Victoria, B.C from July 27, 2025 to January 17, 2026. Data collected by Environment Canada from the Saanichton CFIA weather station (ECCC, 2026).

Weekly total precipitation was highest in late October and November and in early December. The highest total precipitation was recorded during the week of December 14, 2025. Summer precipitation was low during July, August, and early September, with the only substantial rainfall occurring during the weeks of August 3 and 10, 2025.

The estimated weekly irrigation was highest for the UVic Coast redwood planted in Finnerty Gardens (Table 3).

**Table 3.** Approximate weekly irrigation (cm) for *S. sempervirens* and *S. giganteum* at TBG and UVic. Irrigation schedules were obtained from the gardeners at UVic, and TBG irrigation was estimated based on sprinkler type and watering duration.

Location	Species	Total weekly irrigation depth (cm)
TBG	<i>S. sempervirens</i>	6
TBG	<i>S. giganteum</i>	3
UVic (Finnerty)	<i>S. sempervirens</i>	11.5
UVic (Cassels)	<i>S. sempervirens</i>	5
UVic	<i>S. giganteum</i>	5

All of the Giant sequoias at UVic and the UVic Cassels Coast redwood received a similar amount of weekly irrigation (Figure 3). The TBG Coast redwoods received slightly more weekly irrigation than the Coast redwood at UVic Cassels, but were watered less each week than the UVic Finnerty Coast redwood. The TBG Giant sequoias received the least water weekly.

## Discussion

### **Drought Tolerance of *Sequoia sempervirens* and *Sequoiadendron giganteum***

At the beginning of the sample period, the TBG and UVic Giant sequoias had very negative mean water potentials, likely due to the lack of rainfall during July and early August. However, on the second sampling date (August 22) the Giant sequoias at both locations recovered to less negative mean water potentials. During the two weeks between the August 8 and 22 samples, there were three days of minimal rainfall, totalling 5.6 mm. These conditions appear to have resulted in all species, at both TBG and UVic, recovering to more favourable mean water potentials. However, the TBG and UVic Giant sequoias appeared to react more strongly to the change in conditions and were able to recover to a greater extent than the Coast redwoods. Therefore, the UVic and TBG Giant sequoias appeared to be more responsive to small changes in water availability. This likely allowed them to recover quickly to more favourable water potentials, unlike the Coast redwoods which appeared to show limited recovery in response to water availability.

After the period of drought in July and early August, the Giant sequoia at TBG had the lowest mean water potential, while the Coast redwood at UVic appeared to be the least drought stressed. This may be related to differences in irrigation, and the surface water available to the individuals at each location during drought. The UVic Coast redwoods had the most frequent irrigation, with the greatest amount of water delivered, while the Giant sequoias at TBG were irrigated infrequently and received minimal water. Both the TBG Coast redwoods and UVic Giant sequoias receive a moderate amount of irrigation, compared to the other individuals at both locations. These differences in water availability during the extended period of drought are likely to have resulted in the significant differences in water potential. This shows the benefit of consistent irrigation.

The significant difference in mean water potentials between species on the August 8 and 22 sampling dates supports the conclusion that the Giant sequoias reacted favourably to minor increases in water availability. Unlike the Giant sequoias at both locations, the TBG and UVic Coast redwoods appeared to not react as quickly or strongly to the increased available water. On the first sampling date, the significant difference in water potential between species after a 5-week period of no rainfall suggests there may be a difference in response to long periods of

drought between both species. During September and early October, there was very limited, sporadic rainfall, which resulted in nonsignificant variations in mean water potential between both species and locations.

Starting in mid-October there was an increase in recorded rainfall, which led to recovery of water potential in both species at TBG and UVic. On the last sampling date (November 14), the Giant sequoias at both locations recovered to less negative mean water potentials compared to the Coast redwoods. The Giant sequoia individuals at both locations appear to have a significantly better ability to recover from drought stress, and a greater response to changes in water availability. This is shown by their response to mild or moderate rainfall throughout the sample period and is likely a result of their adaptation to drought in their native range.

While the Coast redwood individuals did show minor variations in mean water potential as a response to changing weather conditions, they did not exhibit as strong a response as the Giant sequoias. At the end of the sample period, both the UVic and TBG Coast redwoods were able to recover to less negative mean water potentials but were both still significantly more negative than the Giant sequoias at both locations. This shows that these Coast redwoods individuals do not respond as quickly to changes in water availability or temperature, which is likely due to their lack of drought adaptations and reliance on a naturally wet environment (Olson et al., 1990).

The Coast redwoods at UVic were less drought stressed throughout the sample period compared to the TBG Coast redwoods. Since the UVic Coast redwoods received more frequent and greater irrigation than the TBG Coast redwoods, it is very likely that the TBG individuals would benefit from more frequent irrigation in the summer and autumn. The increased irrigation would help to improve the TBG Coast redwoods' water potential throughout the summer and help the individuals to recover more quickly to a favourable water status in autumn. Since the Coast redwoods and Giant sequoias mean water potentials continued to improve until November, it is likely that the Coast redwoods would benefit from continued irrigation into late autumn, as this would best support their recovery from summer drought conditions.

### **Potential Explanations for Observed Drought Tolerance Trends**

The Giant sequoias at both locations showed overall better drought tolerance throughout the sample period, compared to the Coast redwoods. This is likely explained by the Giant sequoia's adaptations to drought conditions within their native range (Weatherspoon, 1990), and

the Coast redwoods' reliance on mild, rainy year-round weather (Olson et al., 1990; NPS, 2022). The Giant sequoias were not only able to tolerate drought conditions but were able to respond quickly to changes in water availability and temperature. This is likely a result of their physiological and morphological adaptations to drought, including a deep and wide spreading root system, waxy, scaled leaves, and the ability to control their stomata (Ambrose et al., 2015; Weatherspoon, 1990; Stephenson et al., 2018). The Giant sequoia's expansive root system, with a large taproot and numerous lateral branches, allows them to better access deep water reserves and take up surface water quickly (Ambrose et al., 2015; Weatherspoon, 1990). Their root system allows them to take advantage of the limited precipitation or irrigation that they may receive during the dry season, and provides individuals with a source of water during periods of no rainfall. This would explain the Giant sequoias' rapid recovery to less negative mean water potentials after minimal precipitation in early August.

Stomatal closure and waxy, scaled leaves will limit water loss from transpiration and prevent further decreases in water potential during extended periods of drought (Ambrose et al., 2015). Aside from their leaf morphology, the Giant sequoias are able to control their stomata to balance gas exchange and water loss during drier periods. When there is abundant soil water, Giant sequoias will have high levels of gas exchange, and keep their stomata open for long periods (Ambrose et al., 2015). However, when the available soil water declines, and their water potential becomes more negative, Giant sequoias will close their stomata to limit further water loss and potential damage such as cavitation (Ambrose et al., 2015). These traits make Giant sequoias more tolerant of high temperature and drought conditions, potentially contributing to their increased rate of recovery after dry periods.

In comparison, the Coast redwoods are adapted for a milder environment with frequent precipitation (Olson et al., 1990; NPS, 2022). Therefore, unlike the Giant sequoias, they lack the adaptations to tolerate drier conditions (Olson et al., 1990; Ambrose et al., 2015). Coast redwoods have very shallow rooting systems, with a limited number of root hairs, making soil water uptake more difficult for this species (Ambrose et al., 2015; Burgess & Dawson, 2004). Due to the limitations of the Coast redwoods' root system, they are more sensitive to drought and are unable to respond quickly to minor increases in soil water from irrigation or precipitation (Burgess & Dawson, 2004). Coast redwoods are not as effective at limiting water loss by transpiration. This is due to poor stomatal control, and dimorphic shoots adapted to high amounts

of rainfall, not dry conditions (Chin et al., 2022). Therefore, during drought, the Coast redwood is unable to prevent their water potentials from becoming more negative, due to continued water loss from transpiration (Ambrose et al., 2015; Burgess & Dawson, 2004). The Coast redwoods' lack of adaptations to dry environments may explain their limited response to changes in precipitation, and the length of time it took them to recover after drought.

Coast redwoods rely on long wet seasons in their native range, low temperatures, and summer fog banks to decrease transpiration and maintain soil wetness at all times (Burgess & Dawson, 2004; Olson et al., 1990). During the dry season, regular fog banks may also prevent drought stress in Coast redwoods by providing water directly to the tree through foliar uptake or fog drip (Petreshen et al., 2025; Simonin et al., 2009). In the absence of summer fog and high precipitation, the Coast redwood may be vulnerable to drought stress (Burgess & Dawson, 2004; Petreshen et al., 2025). These dry conditions could lead to very negative water potentials that may result in cavitation and visible signs of stress (Hacke et al., 2015). Recent literature suggests there is a significant impact on the Coast redwood's growth when they are under water stress, and their water potential becomes very negative (Ambrose et al., 2015). Under drought conditions, Coast redwoods may have up to 41% less height and 56% less lateral growth compared to non-drought conditions (Ambrose et al., 2015). Therefore, when grown in regions that lack frequent rainfall and fog events, Coast redwoods would require high amounts of irrigation in the summer and autumn to prevent water stress and the resulting impacts on growth. This is shown by the Coast redwoods at UVic and TBG that experience frequent irrigation, but still show poor recovery after drought compared to the Giant sequoias that receive less irrigation.

At the start of the sample period, and in early September, the Giant sequoias at one or both locations had more negative water potentials than the Coast redwoods. Since both instances followed a period of mild drought, these trends could be explained by irrigation, as the Giant sequoias at both locations receive slightly less consistent irrigation, compared to the Coast redwoods. The effect of irrigation would be most apparent during periods of time with no precipitation, so the regularity of the irrigation and the amount of water delivered each time could explain the Giant sequoia's more negative water potentials.

During late August and early September, the Giant sequoias at UVic and TBG showed signs of controlled senescence (Appendix H). This was most apparent at TBG and was seen

throughout the entire crown of all the sampled individuals. Controlled senescence is an established response to drought (Jump et al., 2017), but has only recently been observed in Giant sequoias during moderate-to-severe drought (Stephenson et al., 2018). Controlled senescence would occur in an effort to decrease water loss and prevent water potentials from becoming more negative (Stephenson et al., 2018). The presence of mild controlled senescence in the Giant sequoia's foliage at TBG and UVic indicates the individuals were experiencing some level of drought stress throughout the sample period (Stephenson et al., 2018). This supports the observed drought stress and indicates that during the sample period, the Giant sequoias were experiencing a moderate degree of drought stress (Stephenson et al., 2018).

While controlled senescence has not been documented in Coast redwoods, it is likely that they would also shed non-photosynthetically favoured tissue when water potentials become very negative. During the sample period, there was mild controlled senescence observed in the Coast redwoods at TBG and one of the UVic individuals. Since the one Coast redwood individual at UVic that showed no controlled senescence received the most irrigation, it is likely that the foliage dieback was related to negative water potentials and drought conditions.

Drought tolerance results show that Giant sequoias are typically more drought tolerant than Coast redwoods, and that they respond better to changes in water availability. Coast redwoods are more sensitive to drought conditions and would require frequent irrigation throughout the summer and autumn to maintain proper growth, health, and aesthetics. This study produced similar results to other recent literature, which also showed that Giant sequoias are typically more drought tolerant than Coast redwoods (Ambrose et al., 2015), and that Coast redwoods rely on frequent irrigation when planted outside their native range (Litvak et al., 2011). The urban Coast redwoods analyzed by Litvak et al. (2011) had more negative water potentials compared to the individuals in this study. While the water potential results do differ, the urban trees did receive regular irrigation and still showed signs of stress, including controlled senescence (Litvak et al., 2011). The exact cause of the controlled senescence in Litvak et al. (2011) was not fully understood, but was attributed to either water stress or nutrient deficiency within the sample trees.

## **Observed Cold Tolerance Trends in *Sequoia sempervirens* and *Sequoiadendron giganteum***

The Giant sequoias at both TBG and UVic had a significantly lower mean index of injury during the first three months of the sample period, compared to the Coast redwoods at both locations. The TBG and UVic Giant sequoia's low index of injury in September, and the rapid induction of cold tolerance in early autumn, is most likely an adaptive response to the cold conditions of their native range. These adaptations would cause them to induce cold tolerance earlier in the season to avoid early winter cold damage, and ensure they reach maximum cold hardiness before any snowfall occurs. The Coast redwoods at both locations induced cold tolerance significantly slower in early autumn, and hardened at a relatively stable rate into November and December. It is likely that the Coast redwoods induced cold tolerance more slowly since they are not adapted to a seasonally cold environment and are only exposed to cool, but not sub-zero, temperatures in December and January in their native range (Kreyling et al., 2015; Olson et al., 1990). This would make the TBG and UVic Coast redwoods more at risk of frost and cold damage during extreme events in autumn or early winter, compared to the Giant sequoias.

Since cold tolerance is closely related to a species' native range, the Giant sequoia is expected to be more cold tolerant than the Coast redwood (Kreyling et al., 2015; Weatherspoon, 1990). Unlike the Coast redwoods, the Giant sequoia's native range has frequent snowfall and sub-zero temperatures (Weatherspoon, 1990; NPS, 2025). These climatic conditions contribute to the Giant sequoias' cold tolerance, making them relatively tolerant of temperatures as low as  $-25\text{ }^{\circ}\text{C}$  (Kreyling et al., 2015). While Giant sequoias display a moderate level of cold tolerance, low temperatures are still a limiting factor for their growth (Weatherspoon, 1990), and they may show visible signs of damage when exposed to temperatures consistently below  $-10\text{ }^{\circ}\text{C}$  (Kreyling et al., 2015; Wilson et al., 2016).

Due to the conditions in their native range, Giant sequoias typically induce cold tolerance in early autumn, and reach their maximum tolerance in the mid-winter (December/January) (Kretling et al., 2015). This makes individuals more tolerant of the early snowfalls and frost that they may experience during autumn (Weatherspoon, 1990; NPS, 2025), while still aligning their maximum tolerance levels with the coldest conditions in mid-winter. The conditions that the Giant sequoias experience in their native range are likely an explanation for the cold tolerance trends observed in this study.

The Giant sequoias are also drought tolerant, and from a fairly dry environment (Weatherspoon, 1990). Aside from temperature and snowfall in a species native range, precipitation levels can be connected to a species' ability to tolerate cold (Kreyling et al., 2015). Not only can exposure to drought improve cold tolerance, but species in ranges with limited precipitation may have better cold tolerance compared to species in wetter regions (Kreyling et al., 2015). Since the Giant sequoia is from a significantly drier range, compared to the Coast redwood, this may also contribute to the higher levels of cold tolerance that the Giant sequoia displayed throughout the sample period (Kreyling et al., 2015).

The TBG and UVic Giant sequoias' index of injury plateaued at different times in mid-winter. At TBG the increase was observed in December, while at UVic the index of injury increased in January. Mid-winter is when these trees should be most cold tolerant, since this would be the coldest time of year in their native range (Weatherspoon, 1990; Kreyling et al., 2015). The plateau of mean index of injury in mid-winter could be due to the Giant sequoias not receiving the appropriate signals to fully induce cold tolerance or be a result of acclimation to the climate in Victoria (Knight & Knight, 2012; Li et al., 2004). Giant sequoias are adapted for consistent exposure to sub-zero temperatures in mid-winter, and therefore require low temperatures as a signal to reach their maximum cold tolerance (Kozłowski & Pallardy, 2002; Knight & Knight, 2012; Li et al., 2004). They likely require temperatures consistently below 3 °C for up to a week to induce maximum cold tolerance (Kozłowski & Pallardy, 2002). During the sample period, temperatures never fell below -1 °C, and were rarely below 4 °C for longer than a few days at a time (ECCC, 2026). In addition to the lack of low temperatures, there was no recorded snowfall during the sample period. Mean weekly temperatures during December and January instead varied between 10 °C and 4 °C and were accompanied by high levels of rainfall in early December. Thus, the weather recorded during the sample period was very mild, and may have resulted in the Giant sequoia individuals not receiving the low temperature signals they require to attain maximum cold tolerance (Kozłowski & Pallardy, 2002; Li et al., 2004). This could explain why the Giant sequoias index of injury plateaued.

Unlike the Giant sequoias, Coast redwoods are not considered to be cold tolerant (Olson et al., 1990; Kreyling et al., 2015). Their native range is very mild, with temperatures rarely falling below 0 °C and minimal snowfall only occurring at higher elevations (Olson et al., 1990; Wilson et al., 2016). Due to mild autumn and spring temperatures in their native range, Coast

redwoods induce cold tolerance later in the season and will begin to de-harden rapidly in the spring (Olson et al., 1990; NPS, 2022; Kreyling et al., 2015). However, freeze-induced electrolyte tests by Kreyling et al. (2015) found that Coast redwoods shoot samples were tolerant of temperatures as low as -25 °C during mid-winter. The individuals sampled in the Kreyling et al. (2015) experiment did however show visible signs of freezing in January and February, potentially indicating that they cannot tolerate low temperatures for extended periods of time. Even though foliage damage was observed, this does indicate that Coast redwoods develop a moderate level of cold tolerance in mid-winter (Kreyling et al., 2015).

### **Implications and Future Directions**

Due to the Coast redwoods' lack of drought tolerance, and their poor response to an increase in water availability, the TBG trees would benefit greatly from a consistent increase in irrigation during the summer and autumn. For TBG, this means that irrigation for their two Coast redwoods should either be increased to three times a week or increased in the amount of water that is delivered with each watering. Since the UVic Coast redwoods appeared to be less drought stressed during the sample period and since they received more water, I recommend that the TBG Coast redwood should receive water in amounts similar to that of the UVic Coast redwood (i.e., increase to 11.5 cm per week). This would be roughly two times more water than the TBG Coast redwoods are receiving currently, and should be enough to better support TBG's Coast redwoods. An increase in irrigation should make the water potentials of TBG's Coast redwoods less negative during the summer months, which could decrease the amount of controlled senescence that the trees experience during summertime.

The Giant sequoias at TBG were generally less drought stressed than the UVic individuals; however, they did show signs of controlled senescence during the summer and fall (Appendix H). Therefore, this could indicate that they require more irrigation during the hottest and driest months (July – September). Since the TBG Giant sequoias are watered once a week currently, they could likely benefit from another watering each week (i.e., increase to 5 cm per week).

For TBG, it would be beneficial to revisit their Coast redwoods and Giant sequoias after they have experienced an increase in irrigation. Water potentials could again be compared to those of the UVic Coast redwoods and Giant sequoias to track the improvements in drought tolerance during summer and autumn. This would ensure that the increase in irrigation is making

a difference in drought tolerance for TBG's trees and understand if the irrigation needs to be increased further.

The Coast redwoods were also less cold tolerant in the early autumn, compared to the Giant sequoias. This could put them at risk of frost or freezing damage in October and November from early snowfall or negative temperatures. This may result in foliar damage during autumn and could impact the aesthetics of the TBG trees.

Due to the amount of water that Coast redwoods require to support their growth and appearance in this environment, when compared to the Giant sequoia they would not be the best choice for planting in a horticultural context. While Coast redwoods are beautiful trees, they do have a similar appearance to Giant sequoias, which are more cold and drought tolerant. Between the two, Giant sequoias would be a better choice for planting due to lower irrigation requirements and better cold tolerance. As the climate continues to change, and potentially becomes warmer and drier in the summer, the Giant sequoia will be better able to tolerate these conditions, compared to the Coast redwoods. Since water for irrigation is a finite resource for any garden, Giant sequoias would be a better planting choice since they do not require as much water, leaving more for the irrigation of lawns and smaller flowering plants. If climate change leads to more variable winters and unexpected storms, the Giant sequoia would be better able to tolerate changes in temperature, and unexpected snowfall, without showing foliar damage. The Coast redwood is a valuable horticultural tree, but will require more irrigation and care compared to the similar Giant sequoia.

The sample size for this study was limited ( $n=10$ ), with six Giant sequoias and four Coast redwoods. Access to individuals was limited by the number of Coast redwoods grown at TBG and UVic, and the minimal numbers of Coast redwoods grown throughout Victoria. There were numerous Giant sequoias at both study sites, but only six were sampled in an attempt to keep the sample sizes balanced. The small sample size may have impacted the error associated with the drought and cold tolerance samples and would explain the large standard error bars reported for each sampling date. All data were presented as the means, which would also be impacted by the small sample size, as some individuals sampled may display unique behaviour that could have a strong impact on the mean.

The Coast redwood and Giant sequoia individuals sampled at TBG and UVic were different heights and ages (Appendix I, J), which could have impacted the observed differences

between location and species. The Giant sequoias and Coast redwoods at UVic were all of a similar age and height, but Coast redwoods at TBG were significantly taller and older, while the Giant sequoias were shorter and younger (Appendix I, J). The height and age differences among sampled individuals could potentially alter the observed trends in mean water potential and index of injury, as the more mature trees could be better acclimated to the local conditions and their height may alter water relations (Koch et al., 2004). In future research, it would be best to control for height and age, as these factors could impact the observed differences between sampling groups.

Since the Coast redwood and Giant sequoia individuals were all of different heights, the shoot samples used for the cold and drought tolerance testing were simply taken from the lowest available branches on each tree. However, the lowest available branches on both Coast redwoods at TBG were roughly three meters off the ground and only accessible by pruning poles. In comparison, the Giant sequoias at TBG were relatively short (Appendix I) and had branches less than a meter off the ground. Similarly, the Coast redwood at UVic required a pruning pole, while the Giant sequoias had lower branches within two meters of the ground. All samples were taken at a height within 1-3 m of the ground, but this variation could have affected the water potential observed for each individual. Water potential becomes more negative at a gradient of approximately 0.1 MPa for each meter of tree height, therefore making samples taken from a greater height under more tension (Koch et al., 2004). However, samples were taken consistently from the same height on each individual tree, making the potential impact of the different sampling height the same across all sampling dates.

All of the Coast redwood and Giant sequoia individuals received slightly different amounts of irrigation. While the amount of irrigation did differ between TBG and UVic, with the TBG individuals receiving slightly less water, there were no individuals in the study that received no irrigation. Irrigation levels also varied for the Coast redwood individuals sampled at UVic, with the individual in Finnerty Gardens receiving over two times more water than the individual outside the Jamie Cassels Centre. The irrigation levels for the other Coast redwood and Giant sequoia individuals were consistent at each location. Therefore, in future research, it would be best to compare individuals of both species that receive no irrigation and irrigated individuals that receive a standard amount of water. In the absence of irrigation, drought and

cold tolerance results could look very different and may reveal more about the adaptations of Coast redwoods and Giant sequoias.

In future research, it would be beneficial to increase the number of Giant sequoia and Coast redwood individuals sampled. This would allow for a better understanding of the drought and cold trends observed in the study, and show if they are a reflection of the individuals sampled, or the differences in responses between out-of-range Coast redwoods and Giant sequoias. A larger sample size, with individuals that are not planted in maintained gardens, would give a better idea of the Giant sequoia's and Coast redwood's response to the drought and cold conditions here in Victoria. This would better assess both species' suitability for planting in this region.

This study showed that the Coast redwoods at TBG would benefit from increased irrigation during summer and autumn, which would limit drought stress and improve recovery after an extended period of drought. Increased irrigation would likely limit the controlled senescence that the TBG Coast redwoods showed during summer and may improve the visual appeal of the trees. Compared to the UVic Coast redwoods, the TBG individuals induced cold tolerance earlier in the season, which may be a result of acclimation to the local climate in Victoria, B.C. However, compared to the Giant sequoias, the Coast redwoods were slower to induce cold tolerance and may be at risk of damage from early frost and snowfall in autumn or early winter. These results indicate that the Coast redwoods are more at risk of damage from cold or drought and must be closely monitored to avoid health and visual impacts. Due to the Coast redwoods requiring such high amounts of irrigation to limit drought stress, they may not be the best choice for planting in a show garden. Instead, the Giant sequoia is visually similar but more drought and cold tolerant, as shown by the results in this study. The Giant sequoia may be a better choice for future plantings in a show garden, due to lower irrigation requirements and the potential to better tolerate future changes in the climate.

## References

- Ambrose, A.R., Baxter, W.L., Martin, R.E., Francis, E., Asner, G.P., Nydick, K.R., & Dawson, T.E. (2018). Leaf and crown-level adjustments help giant sequoias maintain favourable water status during severe drought. *Forest Ecology and Management*, 419-420, 257-267. doi: 10.1016/j.foreco.2018.01.012
- Ambrose, A.R., Baxter, W.L., Wong, C.S., Næsborg, R.R., Williams, C.B., & Dawson, T.E. (2015). Contrasting drought-response strategies in California redwoods. *Tree Physiology*, 35(5), 453-469. doi: 10.1093/treephys/tpv016
- Anísco, T., & Lindstrom, O.M. (1996). Cold hardiness and water relations parameters in Rhododendron cv. Catawbiense Boursault subjected to drought episodes. *Physiologia Plantarum*, 98, 147-155. doi: 10.1111/j.1399-3054.1996.tb00686.x
- Aparecido, L.M.T., Miller, G.R., Cahill, A.T., & Moore, G.W. (2017). Leaf surface traits and water storage retention affect photosynthetic responses to leaf surface wetness among wet tropical forest and semiarid savanna plants. *Tree Physiology*, 37(10), 1285-1300. doi: 10.1093/treephys/tpx092
- Burgess, S.S.O., & Dawson, T.E. (2004). The contribution of fog to the water relations of *Sequoia sempervirens* (D.Don): Foliar uptake and prevention of dehydration. *Plant, Cell & Environment*, 27(8), 1023-1034. <https://online> doi: 10.1111/j.1365-3040.2004.01207.x
- Chin, A.R.O., Guzmán-Delgado, P., Sillett, S.C., Orozco, J., Kramer, R.D., Kerhoulas, L.P., Moore, Z.J., Reed, M., & Zwieniecki, M.A. (2022). Shoot dimorphism enables *S. sempervirens* to separate requirements for foliar water uptake and photosynthesis. *American Journal of Botany*, 109(4), 564-579. doi: 1002/ajb2.1841
- Clarke, D. (2006). *The Butchart Gardens: A Family Legacy*. The Butchart Gardens Ltd., Victoria, BC.
- Close, T.J. (1996). Dehydrins: Emergence of a biochemical role of a family of plant dehydration proteins. *Physiologia Plantarum*, 97, 795-803. doi: 10.1111/j.1399-3054.1996.tb00546.x
- Cochard, H., Forestier, S., & Améglio, T. (2001). A new validation of the Scholander pressure chamber technique based on stem diameter variations. *Journal of Experimental Botany*, 52(359), 1361-1365. doi: 1093/jexbot/52.359.1361
- Da Sois, L., Mencuccini, M., Castells, E., Sanchez-Martinez, P., & Martínez-Vilalta, J. (2024). How are physiological responses to drought modulated by water relations and leaf economics' traits in woody plants? *Agricultural Water Management*, 291. doi: 10.1016/j.agwat.2023.108613
- Ewing, H.A., Weathers, K.C., Templer, P.H., Dawson, P.H., Dawson, T.E., Firestone, M.K.,

- Elliott., A.M., & Boukili, V.K.S. (2009). Fog water and ecosystem function: Heterogeneity in a California Redwood forest. *Ecosystems*, *12*, 417-433. doi: 10.1007/s10021-009-9232-x
- Environment and Climate Change Canada [ECCC]. (2026). *Historical climate change data*. Government of Canada. [https://climate.weather.gc.ca/index\\_e.html](https://climate.weather.gc.ca/index_e.html)
- Gross, D.C., Proebsting, E.L., & Maccrindle-Zimmerman, H. (1988). Development, distribution, and characteristics of intrinsic, nonbacterial ice nuclei in *Prunus* wood. *Plant Physiology*, *88*(3), 915-922. doi: 10.1104/pp.88.3.915
- Guinon, M., Larsen, J.B., & Spethmann, W. (1981). Frost resistance and early growth of *Sequoiadendron giganteum* seedlings of different origins. *Silvae Genetica*, *31*, 5-6. [https://www.thuenen.de/media/institute/fg/PDF/Silvae\\_Genetica/1982/Vol.\\_31\\_Heft\\_5-6/31\\_5-6\\_173.pdf](https://www.thuenen.de/media/institute/fg/PDF/Silvae_Genetica/1982/Vol._31_Heft_5-6/31_5-6_173.pdf)
- Hacke, U. (2015). *Functional and Ecological Xylem Anatomy*. Springer International Publishing, Switzerland. doi: 10.1007/978-3-319-15783-2
- IPCC. (2023). *Summary for Policymakers*. In Core Writing Team, H. Lee and J. Romero (Eds.), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR69789291691647.001
- Irvine, J., & Grace, J. (1997). Continuous measurements of water tensions in the xylem of trees based on the elastic properties of wood. *Planta*, *202*, 455-461. doi: 10.1007/s004250050149
- Jump, A.S., Ruiz-Benito, P., Greenwood, S., Allen, C.D., Kitzberger, T., Fensham, R., Martínez-Vilalta, J., & Lloret, F. (2017). Structural overshoot of tree growth with climate variability and the global spectrum of drought-induced forest dieback. *Global Change Biology*, *23*(9), 3742-3757. doi: 10.1111/gcb.13636
- Karami, S., Shiran, B., Ravash, R., & Fallahi, H. (2023). A comprehensive analysis of transcriptomic data for comparison of plants with different photosynthetic pathways in response to drought stress. *PLOS ONE*, *18*(6). doi: 10.1371/journal.pone.0287761
- Keeley, J.E., & Pausas, J.P. (2025) *Sequoia and Sequoiadendron: Two paleoendemic megatrees with markedly different adaptive responses to recent high-severity fires*. *American Journal of Botany*, *112*(10). doi: 10.1002/ajb2.70089
- Klein, T., Zeppel, M.J.B., Anderegg, W.R.L., Bloemen, J., De Kauwe, M.G., Hudson, P., Ruehr, N.K., Powell, T.L., von Arx, G., & Nardini, A. (2018). Xylem embolism refilling and resilience against drought-induced mortality in woody plants: Processes and trade-offs. *Ecological Research*, *33*, 839-855. doi: 10.1007/s11284-018-1588-y

- Knight, M.R., & Knight, H. (2012). Low-temperature perception leading to gene expression and cold tolerance in higher plants. *New Phytologist*, 195(4), 737-751. doi: 10.1111/j.1469-8137.2012.04239.x
- Koch, G.W., Sillett, S.C., Jennings, G.M., & Davis, S.D. (2004). The limits to tree height. *Nature*, 428, 851-854. doi: 10.1038/nature02417
- Kozłowski, T.T., & Pallardy, S.G. (2002). Acclimation and adaptive responses of woody plants to environmental stresses. *The Botanical Review*, 68, 270-334. doi: 10.1663/0006-8101(2002)068[0270:AAAROW]2.0.CO;2
- Kreyling, J., Schmid, S., & Aas, G. (2015). Cold tolerance of tree species is related to the climate of their native ranges. *Journal of Biogeography*, 42(1), 156-166. <https://www.jstor.org/stable/44001923>
- Levitt, J. (1980). *Responses of plants to environmental stresses: Volume 1. Chilling, freezing and high temperature stresses* [eBook edition]. Elsevier Science & Technology. <https://ebookcentral.proquest.com/lib/uvic/detail.action?docID=1178488#>
- Li, C., Junttila, O., & Palva, E.T. (2004). Environmental regulation and physiological basis of freezing tolerance in woody plants. *Acta Physiologiae Plantarum*, 26, 213-222. doi: 10.1007/s11738-004-0010-2
- Li, C., Puhakainen, T., Welling, A., Viherä-Aarnio, A., Ernstsén, A., Junttila, O., Heino, P., & Palva, E.T. (2002). Cold acclimation in silver birch (*Betula pendula*). Development of freezing tolerance in different tissues and climatic ecotypes. *Physiologia Plantarum*, 116(4), 478-488. doi: 10.1034/j.1399-3054.2002.1160406.x
- Limm, E.B., Simonin, K.A., Bothman, A.G., & Dawson, T.E. (2009). Foliar water uptake: A common water acquisition strategy for plants of redwood forest. *Oecologia*, 161, 449-459. doi: 10.1007/s00442-009-1400-3
- Lindow, S.E., Army, D.C., & Upper, C.D. (1982). Bacterial ice nucleation: A factor in frost injury to plants. *Plant Physiology*, 70(4), 1084-1089. doi: 10.1104/pp.70.4.1084
- Little, E.L. (1971). *Atlas of United States trees. Volume 1. Conifers and important hardwoods*. Misc. Publ. 1146. Washington, DC: U.S. Department of Agriculture, Forest Service 320 p. [1462]
- Lo Gullo, M.A., & Salleo, S. (1988). Different strategies of drought resistance in three Mediterranean sclerophyllous trees growing in the same environmental conditions. *New Phytology*, 108, 267-276. doi: 10.1111/j.1469-8137.1988.tb04162.x
- Lopes, R.F., Melo, A.S., & Santos, M.G. (2022). Drought tolerance mechanisms of a woody evergreen in a tropical dry forest. *Theoretical and Experimental Plant Physiology*, 34,

433-445. [https://link-springer-com.ezproxy.library.uvic.ca/content/pdf/10.1007/s40626-022-00256-y.pdf?utm\\_source=clarivate&getft\\_integrator=clarivate](https://link-springer-com.ezproxy.library.uvic.ca/content/pdf/10.1007/s40626-022-00256-y.pdf?utm_source=clarivate&getft_integrator=clarivate)

- Litvak, E., McCarthy, H.R., & Pataki, D.E. (2011). Water relations of Coast redwood planted in the semi-arid climate of southern California. *Plant, Cell & Environment*, 34(8), 1384 – 1400. doi: 10.1111/j.1365-3040.2011.02339.x
- Males, J., & Griffiths, H. (2017). Stomatal biology of CAM plants. *Plant Physiology*, 174, 2, 550-560. doi: 10.1104/pp.17.00114
- Martínez-Vilalta, J. & Garcia-Forner, N. (2016). Water potential regulation, stomatal behaviour and hydraulic transport under drought: Deconstructing the iso/anisohydric concept. *Plant, Cell & Environment*, 40(6), 962-976. doi: 10.1111/pce.12846
- Martin, A.J.F. (2022). Accuracy and precision in urban forestry tools for estimating total tree height. *Arboriculture & Urban Forestry*, 48(6), 319-332. doi: 10.48044/jauf.2022.024
- Muldrew, K., & McGann, L.E. (1990). Mechanisms of intracellular ice formation. *Biophysical Journal*, 57(3), 525-532. [https://www.cell.com/fulltext/S0006-3495\(90\)82568-6](https://www.cell.com/fulltext/S0006-3495(90)82568-6)
- National Park Service [NPS]. (2022). *Redwood Weather*. National Park Service. <https://www.nps.gov/redw/planyourvisit/weather.htm>
- National Park Service [NPS]. (2025). *Sequoia & Kings Canyon Weather*. National Park Service. <https://www.nps.gov/seki/planyourvisit/weather.htm>
- Nydick, K.R., Stephenson, N.L., Ambrose, A.R., Asner, G.P., Baxter, W.L., Das, A.J., Dawson, T., Martin, R.E., & Paz-Kagan, T. (2018). Leaf to landscape responses of Giant sequoia to hotter drought: An introduction and synthesis for the special section. *Forest Ecology and Management*, 419-420, 249-256. doi: 10.1016/j.foreco.2018.03.028
- Nuszdorfer, F.C., Klinka, K., & Demarchi, D.A. (1991). Chapter 5: Coastal Douglas-fir Zone. In D. Meidinger and J. Pojar (Eds.), *Ecosystems of British Columbia*. BC Ministry of Forests, Victoria, B.C., Canada, pp. 81-94. <https://sherwoodsforests.com/Downloads/BGC-zones-of-British-Columbia.pdf>
- Odium, K.D., & Blake, T.J. (1996). A comparison of analytical approaches for assessing freezing damage in black spruce using electrolyte leakage methods. *Canadian Journal of Botany*, 74(6). doi: 10.1139/b96-118
- Olson, D.F., Roy, D.F., & Walters, G.A. (1990). *Sequoia sempervirens* (D. Don) Endl. Redwood. In R.M Burns & B.H. Honkala (Eds.), *Silvics of North America: Volume 1. Conifers*. Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington DC. <https://dendro.cnre.vt.edu/DENDROLOGY/USDAFSSilvics/180.pdf>

- Petreshen, J., Dymond, S.F., Keppeler, E.T., Allen, S.T., & Wagenbrenner, J.W. (2025) Fog presence and ecosystem responses in a managed coast redwood forest. *Agricultural and Forest Meteorology*, 368(1). doi: 10.1016/j.agrformet.2025.110525
- Pivovarovoff, A.L., Pasquini, S.C., De Guzman, M.E., Alstad, K.P., Stenke, J.S., & Santiago, L.S. (2016). Multiple strategies for drought survival among woody plant species. *Functional Ecology*, 30, 517-526. doi: 10.1111/1365-2435.12518
- Qin, J., Shangguan, Z., & Xi, W. (2019). Seasonal variations of leaf traits and drought adaptation strategies of four common woody species in South Texas, USA. *Journal Forest Research*, 30(5), 1715-1725. [https://link-springer.com.ezproxy.library.uvic.ca/content/pdf/10.1007/s11676-018-0742-2.pdf?utm\\_source=clarivate&getft\\_integrator=clarivate](https://link-springer.com.ezproxy.library.uvic.ca/content/pdf/10.1007/s11676-018-0742-2.pdf?utm_source=clarivate&getft_integrator=clarivate)
- R Core Team (2024). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>
- Repo, T., Zhang, G., Ryypö, A., Rikala, R., & Vuorinen, M. (2000). The relation between growth cessation and frost hardening in Scots pines of different origins. *Trees*, 14, 456-464. doi: 10.1007/s004680000059
- Ruelland, E., Vaulier, M., Zachowski, A., & Hurry, V., (2009). Cold signalling and cold acclimation in plants. *Advances in Botanical Research*, 49(8). doi: 10.1016/S0065-2296(08)00602-2
- Scholander, P.F., Hammel, H.T., Hemmingsen, E.A., & Brardstreet, E.D. (1964). Hydrostatic pressure and osmotic potential in leaves of Mangroves and some other plants. *Botany*, 52. doi: 10.1073/pnas.52.1.119
- Sevanto, S., McDowell, N.G., Dickman, L.T., Pangle, R., & Pockman, W.T. (2013). How do trees die? A test of the hydraulic failure and carbon starvation hypothesis. *Plant, Cell & Environment*, 37(1), 153-161. doi: 10.1111/pce.12141
- Simonin, K.A., Santiago, L.S., & Dawson, T.E. (2009). Fog interception by *Sequoia sempervirens* (D. Don) crowns decouples physiology from soil water deficit. *Plant, Cell & Environment*, 32(7), 882-892. doi: 10.1111/j.1365-3040.2009.01967.x
- Sperry, J.S., & Sullivan, J.E.M. (1992). Xylem embolism in response to freeze-thaw cycles and water stress in ring-porous, diffuse-porous, and conifer species. *Plant Physiology*, 100(2), 605-613. doi: 10.1104/pp.100.2.605
- Stephenson, N.L., Das, A.J., Amperssee, N.J., Cahill, K.G., Caprio, A.C., Sanders, J.E., & Williams, A.P. (2018). Patterns and correlates of Giant sequoia foliage dieback during California's 2012-2016 hotter drought. *Forest Ecology and Management*, 419-420, 268-278. doi: 10.1016/j.foreco.2017.10.053

- The Butchart Gardens. (2026). *Our story*. The Butchart Gardens Ltd. <https://butchartgardens.com>
- Tyree, M.T., Cheung, Y.N.S., MacGregor, M.E., & Talbot, A.J.B. (1978). The characteristics of seasonal and ontogenetic changes in the tissue - water relations of *Acer*, *Populus*, *Tsuga*, and *Picea*. *Canadian Journal of Botany*, 56. doi: 10.1139/b78-071
- Walker, D.J., Romero, P., de Hoyos, A., & Correal, E. (2008). Seasonal changes in cold tolerance, water relations and accumulation of cations and compatible solutes in *Atriplex halimus* L. *Environmental and Experimental Biology*, 64(3), 217-224. doi: 10.1016/j.envexpbot.2008.05.012
- Weatherspoon, C.P. (1990). *Sequoiadendron giganteum* (Lindl.) Buchholz. Giant Sequoia. In R.M Burns & B.H. Honkala (Eds.), *Silvics of North America: Volume 1. Conifers*. Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington DC. <https://dendro.cnre.vt.edu/dendrology/USDAFSSilvics/136.pdf>
- Wilson, S.M., Mason, B., Jinks, R., Gil-Moreno, D., & Savill, P. (2016). The Redwoods and Red Cedar. Coast redwood (*Sequoia sempervirens*), giant redwood (*Sequoiadendron giganteum*) and western red cedar (*Thuja plicata*) – species, silviculture and utilisation potential. *Quarterly Journal of Forestry*, 110, 244-256.
- Williams, B.J., Pellett, N.E., & Klein, R.M. (1972). Phytochrome control of growth cessation and initiation of cold acclimation in selected woody plants. *Plant Physiology*, 50(2), 262-265. doi: 10.1104/pp.50.2.262
- Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., & Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, 4(43), 1686. doi:10.21105/joss.01686
- Wisniewski, M., & Davis, G. (1995) Immunogold localization of pectins and glycoproteins in tissues of peach with reference to deep supercooling. *Trees* 9, 253-260. doi: 10.1007/BF00202015
- Wisniewski, M., Bassett, C., & Gusta, L. (2003). An overview of cold hardiness in woody plants: Seeing the forest through the trees. *HortScience*, 38(5), 952-959. doi: 10.21273/HORTSCI.38.5.952
- Wisniewski, M., Lindow, S.E., & Ashworth, E.N. (1997). Observations of ice nucleation and propagation in plants using infrared video thermography. *Plant Physiology*, 113(2), 327-334. doi: 10.1104/pp.113.2.327
- Wisniewski, M., Nassuth, A., Teulières, C., Marque, C., Rowland, J., Cao, P.B., & Brown, A. (2014). Genomics of cold hardiness in woody plants. *Critical Reviews in Plant Science*,

33(2-3), 92-124. doi: 10.1080/07352689.2014.870408

Wisniewski, M., Webb, R., Balsamo, R., Close, T.J., Yu, X., & Griffith, M. (1999). Purification, immunolocalization, cryoprotective, and antifreeze activity of PCA60: A dehydrin from peach (*Prunus persica*). *Physiologia Plantarum*, *105*, 600-608. doi: 10.1034/j.1399-3054.1999.105402.x

Workmaster, B.A.A., Palta, J.P., & Wisniewski, M. (1999). Ice nucleation and propagation in cranberry uprights and fruit using infrared video thermography. *Journal of the American Society for Horticultural Science*, *124*(6), 619-624. doi: 20/2014/03/58

Zhang, H., Zhu, J., Gong, Z., & Zhu, J. (2021). Abiotic stress responses in plants. *Nature Reviews Genetics*, *23*. doi: 10.1038/s41576-021-00413-0

Appendix A

*S. sempervirens* Range Map



**Image A1.** Distribution map of *S. sempervirens* (range indicated in green) with Victoria B.C. marked by a red star (Little, 1971).

Appendix B  
*S. giganteum* Range Map



**Image B1.** Distribution map for *S. giganteum* (fragmented ranges located inside the black circle) with Victoria B.C. marked by a red star (Little, 1971).

**Appendix C**  
**Photographs of Study Trees**



**Image C1.** *S. sempervirens* individuals located at TBG (July 2025).



**Image C2.** Row of *S. giganteum* individuals at TBG (July 2025).



**Image C3.** *S. giganteum* individuals at UVic (September 2025).



**C4.** *S. sempervirens* individuals at UVic (September 2025), they are planted in Finnerty Gardens (left) and outside the Jamie Cassels Centre (right).

## Appendix D Calculations

### D1: Tree Height

$$\tan(\theta) = \frac{opp}{adj}$$

$$Tree\ height\ (opp) = \tan(\theta) \times measured\ distance\ to\ tree\ base\ (adj)$$

### D2: Index of Injury (Flint et al., 1966)

$$Index\ of\ Injury = 100 \times \frac{R_t - R_o}{1 - R_o}$$

$$R_t = \frac{L_t}{L_k}$$

$$R_o = \frac{L_o}{L_d}$$

where:

$R_t$  = Fractional release of electrolytes from sample exposed to temperature ( $t$ )

$R_o$  = Fractional release of electrolytes from unfrozen sample

$L_t$  = Conductivity of sample after freezing at temperature ( $t$ )

$L_k$  = Conductivity of sample after freezing at temperature ( $t$ ) and heat-killed

$L_o$  = Conductivity of unfrozen sample

$L_d$  = Conductivity of unfrozen sample, heat killed

**Appendix E**  
**Repeated Measures Two-way ANOVA Tables**

**Table E1.** Summary table from a repeated measures two-way ANOVA,  $\alpha = 0.05$  for the analysis of index of injury throughout the entire sample period, assuming repeated sampling from the same individuals.

	Source of Variation	Df	Sum Sq	Mean Sq	F-value	<i>P</i> -value
Error: Individuals	Location					
	Species	1	297.9	297.9	3.166	0.125
	Location x Species	1	1486.8	1486.8	15.800	<b>0.007</b>
	Residuals	1	1930.5	1930.5	20.517	<b>0.004</b>
	Error: Within	6	564.6	94.1		
Error: Within	Residuals	40	15834	94.1		

**Table E2.** Summary table from a repeated measures two-way ANOVA,  $\alpha = 0.05$  for the analysis of water potential throughout the entire sample period, assuming repeated sampling from the same individuals.

	Source of Variation	Df	Sum Sq	Mean Sq	F-value	<i>P</i> -value
Error: Individual	Location					
	Species	1	0.0025	0.0025	0.036	0.855
	Location x Species	1	0.0101	0.0101	0.146	0.715
	Residuals	1	0.1494	0.1494	2.175	0.191
Error: Within	Residuals	6	0.4120	0.0687		

## Appendix F

### Two-way ANOVA Tables for Drought Tolerance Testing

**Table F1.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on August 8, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.129	0.129	7.999	<b>0.030</b>
Species	1	0.132	0.132	8.160	<b>0.029</b>
Location x Species	1	0.009	0.009	0.563	0.481
Residuals	6	0.067	0.016		

**Table F2.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on August 22, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.032	0.032	2.181	0.190
Species	1	0.174	0.174	11.981	<b>0.013</b>
Location x Species	1	0.017	0.017	1.156	0.324
Residuals	6	0.087	0.015		

**Table F3.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on September 5, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.002	0.002	0.043	0.842
Species	1	0.099	0.099	1.830	0.225
Location x Species	1	0.005	0.005	0.085	0.780
Residuals	6	0.087	0.015		

**Table F4.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on September 19, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.055	0.055	1.364	0.287
Species	1	0.018	0.018	0.451	0.527
Location x Species	1	0.195	0.195	4.828	0.070
Residuals	6	0.242	0.040		

**Table F5.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on October 3, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.088	0.088	4.954	0.068
Species	1	0.020	0.020	1.110	0.333
Location x Species	1	0.015	0.015	0.833	0.397
Residuals	6	0.107	0.018		

**Table F6.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on October 17, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.0001	0.0001	0.036	0.855
Species	1	0.007	0.007	2.160	0.192
Location x Species	1	0.012	0.012	3.660	0.104
Residuals	6	0.025	0.003		

**Table F7.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on October 31, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.001	0.0001	3.650	0.105
Species	1	0.003	0.003	7.787	<b>0.032</b>
Location x Species	1	0.017	0.017	46.762	<b>0.0005</b>
Residuals	6	0.002	0.004		

**Table F8.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential on November 14, 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.005	0.005	2.287	0.300
Species	1	0.079	0.079	19.266	<b>0.005</b>
Location x Species	1	0.036	0.036	8.462	<b>0.026</b>
Residuals	6	0.025	0.004		

## Appendix G

### Two-way ANOVA Tables for Cold Tolerance Testing

**Table G1.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential in September 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	120.2	120.2	2.857	0.142
Species	1	196.5	196.5	4.670	0.074
Location x Species	1	131.7	131.7	3.129	0.127
Residuals	6	252.4	42.07		

**Table G2.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential in October 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	3.2	3.2	2.857	0.876
Species	1	1684.5	1684.5	4.670	<b>0.009</b>
Location x Species	1	1132.5	1132.5	3.129	<b>0.022</b>
Residuals	6	716.2	119.4		

**Table G3.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential in November 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	0.1	0.1	0.001	0.979
Species	1	1327.9	1327.9	13.162	<b>0.011</b>
Location x Species	1	422.1	422.1	4.184	0.087
Residuals	6	605.3	100.9		

**Table G4.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential in December 2025. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	304.9	304.9	7.929	<b>0.031</b>
Species	1	55.8	55.8	1.452	0.274
Location x Species	1	496.4	496.4	12.907	<b>0.012</b>
Residuals	6	230.7	38.5		

**Table G5.** Two-way ANOVA table,  $\alpha = 0.05$  for the analysis of water potential in January 2026. ANOVA conducted with R statistical software.

Source of Variation	Df	Sum Sq	Mean Sq	F-value	P-value
Location	1	75.1	75.1	0.725	0.427
Species	1	162.6	162.6	1.570	0.257
Location x Species	1	106	106	1.024	0.351
Residuals	6	621.5	103.59		

## Appendix H

### Controlled Senescence Photos



**Image H1.** Controlled senescence in the *S. giganteum* at TBG. Righthand photo taken on July 10, 2025 and lefthand photo taken September 18, 2025. Both photos were taken of the same individual, which was sampled for both drought and cold tolerance testing. This individual, and others at the same location, began showing controlled senescence in up to 20% of the crown during August and September.

**Appendix I**  
**Tree Heights and Diameters**

**Table II.** The measured heights (m) and diameters (m) of *S. sempervirens* and *S. giganteum* at TBG and UVic. The diameter at breast height was measured 1.34 m from the ground with a diameter tape and height was measured using a clinometer.

Location	Species	Diameter at breast height (m)	Height (m)
TBG	<i>S. sempervirens</i>	2.30	51.5
TBG	<i>S. sempervirens</i>	2.05	66.3
UVic (Cassels)	<i>S. sempervirens</i>	1.48	22.1
UVic (Finnerty)	<i>S. sempervirens</i>	0.99	20.6
TBG	<i>S. giganteum</i>	0.56	19.5
TBG	<i>S. giganteum</i>	0.60	16.5
TBG	<i>S. giganteum</i>	0.39	15.3
UVic	<i>S. giganteum</i>	1.83	34.9
UVic	<i>S. giganteum</i>	1.92	37.3
UVic	<i>S. giganteum</i>	1.69	32.7

**Appendix J**  
**Tree Ages**

**Table J1.** Ages (years) of *S. sempervirens* and *S. giganteum* individuals at TBG and UVic. All ages acquired from gardening records at both sites.

Location	Species	Age (years)
TBG	<i>S. sempervirens</i>	92
TBG	<i>S. sempervirens</i>	92
UVic (Cassels)	<i>S. sempervirens</i>	56
UVic (Finnerty)	<i>S. sempervirens</i>	56
TBG	<i>S. giganteum</i>	31
TBG	<i>S. giganteum</i>	31
TBG	<i>S. giganteum</i>	31
UVic	<i>S. giganteum</i>	56
UVic	<i>S. giganteum</i>	56
UVic	<i>S. giganteum</i>	56