Xylem cavitation in Scots pine and Sitka spruce saplings during water stress

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Summary  Xylem cavitation and sap flow rates, stomatal conductance and shoot water potential were observed in irrigated and drought-treated saplings of Sitka spruce (Picea sitchensis (Bong.) Carr.), a drought-susceptible species, and Scots pine (Pinus sylvestris L.), a drought-resistant species. In Scots pine, cavitation rates increased as shoot water potential decreased below a threshold of around −0.55 MPa. In Sitka spruce, cavitation rates were inversely related to shoot water potential in irrigated saplings but not in drought-treated saplings. Sap flow rates declined sharply in both species as shoot water potential fell during the drought treatment. Thus sap flow rate was positively associated with cavitation rate in Scots pine but not in Sitka spruce. Three days after the drought treatment ended, shoot water potentials, stomatal conductances and sap flow rates in both species regained values observed before the drought treatment. In Sitka spruce, stem relative water content also returned to a value close to that observed before the drought treatment. Even 2 weeks after the end of the drought treatment, shoot water potentials, stomatal conductances and sap flow rates in both species regained values observed before the drought treatment. Even 2 weeks after the end of the drought treatment, shoot water potentials, stomatal conductances and sap flow rates in both species regained values observed before the drought treatment.

Keywords: drought, Picea sitchensis, Pinus sylvestris, sap flow rates, stem relative water content, stomatal conductance, threshold water potential, ultrasonic acoustic emissions.

Introduction

When water is withheld from vascular plants, the tension within xylem water columns increases until cavitation occurs (Milburn 1979). Cavitation is widely believed to result when air from intercellular spaces or from other embolized conduits enters water-filled vessels and tracheids through the interconduit pit membranes (Edwards and Jarvis 1982, Sperry and Tyree 1988). The tension at which cavitation occurs may determine a species’ drought tolerance, the least cavitation-prone species being the most drought tolerant (Tyree and Sperry 1989).

Cavitations can be detected by their ultrasonic acoustic emissions (Tyree and Dixon 1983). This paper reports a study of cavitation and plant water relations during the slow development of and subsequent recovery from water stress in Scots pine (Pinus sylvestris L.) and Sitka spruce (Picea sitchensis (Bong.) Carr.). Scots pine, a native to Britain, grows best in well-drained soils on sites with moderate rainfall. Sitka spruce is native to the northwest coast of North America and is largely confined to areas of heavy precipitation. We postulated that Scots pine is better adapted to drought and that it recovers from drought more swiftly and completely than Sitka spruce.

Materials and methods

Plant material

Two-year-old Scots pine and Sitka spruce saplings were obtained from a Forestry Commission nursery in January 1992. Each sapling was transplanted to a black plastic tube (60 cm tall, 15 cm in diameter) containing a 7/3/2 (v/v) mixture of loam, peat and sand plus 5 kg m⁻³ of slow release N,P,K fertilizer (ENMAG fertilizers, ICI, Fernhurst, Surrey, U.K.), 1 kg m⁻³ of calcium bicarbonate and 400 g m⁻³ fritted trace elements. The saplings were grown outside for 18 months at the University of Edinburgh, Scotland, at the end of which time four saplings of each species were harvested for the determination of morphological characteristics (Table 1). At the end of June 1993, 38 Scots pine and 34 Sitka spruce saplings were paired on the basis of height, foliage area and vigor, and transferred to an unheated greenhouse. All saplings were watered to field capacity at 2- to 3-day intervals for 5 weeks (until July 28). During the next 5 weeks, water was withheld from one randomly selected sapling of each pair, while the other sapling continued to receive regular irrigation. Following the drought treatment, all saplings were watered regularly to field capacity for 2 weeks. Water relations parameters and stomatal conductance were measured on four saplings of each treatment every 2 to 4 days. Measurements were made only on days that were relatively cloud-free. After 10 and 30 days of drought, measurements on at least three saplings were made at 3 h intervals between 0400 and 1930 h, whereas sap flow and xylem cavitation rates were measured continuously.
Table 1. Mean values for morphological characteristics of 3-year-old Scots pine and Sitka spruce. SLA = leaf area per leaf dry weight, LAR = leaf area per total plant dry weight, and LWR = leaf dry weight per total plant dry weight. Standard errors are shown in brackets.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Scots pine</th>
<th>Sitka spruce</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific leaf area (SLA) (cm² g⁻¹)</td>
<td>49.9 (1.6)</td>
<td>46.3 (2.6)</td>
<td>0.88</td>
</tr>
<tr>
<td>Leaf area ratio (LAR) (cm² g⁻¹)</td>
<td>16.8 (0.6)</td>
<td>10.3 (2.3)</td>
<td>0.04</td>
</tr>
<tr>
<td>Leaf weight ratio (LWR) (g g⁻¹)</td>
<td>0.35 (0.02)</td>
<td>0.22 (0.04)</td>
<td>0.03</td>
</tr>
<tr>
<td>Total leaf area (cm²)</td>
<td>1324 (240)</td>
<td>1453 (244)</td>
<td>0.80</td>
</tr>
<tr>
<td>Total root dry weight (g)</td>
<td>37.6 (2.3)</td>
<td>70.4 (10.8)</td>
<td>0.06</td>
</tr>
<tr>
<td>Sapwood area (cm²)</td>
<td>1.81 (0.1)</td>
<td>1.49 (0.1)</td>
<td>0.20</td>
</tr>
<tr>
<td>Leaf area/sapwood area ratio (cm² cm⁻²)</td>
<td>750 (76)</td>
<td>1330 (135)</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Soil water content**

At 2- to 3-day intervals throughout the experiment, volumetric soil water (VSW) content was determined by time domain reflectometry with a Tektronix cable tester 1502C, interfaced with a datalogger (CR 21X, Campbell Scientific Ltd., Leicestershire, U.K.). Before the start of the experiment, four pairs of probes (3-mm diameter stainless steel rods of lengths 15, 30, 45 and 55 cm) were inserted into each container for the duration of the experiment. This gave an integrated VSW value to these depths.

**Microclimate**

Throughout the drought and rewatering cycle, photosynthetically active radiation (PAR), temperature and relative humidity were measured every 15 s, and means were recorded with a data logger (CR 21X) at 5-min intervals. Vapor pressure deficit (VPD) was calculated from the saturation vapor pressure at the measured temperature minus the water vapor partial pressure at that temperature.

**Stomatal conductance**

Stomatal conductance of current-year shoots was measured with a steady state porometer (LI-1600, Li-Cor Inc., Lincoln, NE). Shoots were measured repeatedly on approximately three occasions before they were removed for determination of projected needle area with a leaf area meter (LI 3250, Li-Cor Inc.).

**Shoot water potential**

Current-year shoots, approximately 5 cm long, were excised and their water potential measured with a pressure chamber (Scholander et al. 1965).

**Sap flow**

The rate of water movement through stems was monitored by the heat balance method (Sakuratani 1981, 1984, Baker and van Bavel 1987). Eight gauges were constructed according to the design of Dynagauge™ (model SGA13, Houston, TX) and modified by incorporating an additional thermocouple to measure the heat storage component. Gauges were installed on four Scots pine and four Sitka spruce saplings, and measurements were made every day from dawn until dusk throughout the experiment. Readings were taken automatically every 15 s and averaged every 10 min. Gauges were subsequently calibrated by forcing water through stem segments at known rates. Sap fluxes were determined using individual calibrations, and any highly inaccurate flow rates were excluded (Sakuratani 1981). Sap flow rates were calculated on a leaf area basis.

**Cavitation**

A drought stress monitor (model 4615 DSM, Physical Acoustic Corp., Princeton, NJ) was used to detect ultrasonic acoustic emissions from the xylem. Three transducers (I15I, Physical Acoustic Corp.) were placed on each of three Scots pine and three Sitka spruce saplings. A rectangular window (12 × 3 mm) was made in the bark, and the exposed xylem smeared with petroleum jelly. The transducers were clamped with a force of 30 N onto the exposed xylem. Sapplings were measured consecutively at 1-min intervals throughout the drought and rewatering phases of the experiment. The amplification gain of the drought stress monitor was adjusted to 74 dB. At this setting, unattached sensors recorded less than one spurious cavitation event per minute. Each Scots pine sapling was fitted with a sap flow meter, and the transducer was positioned approximately 30 mm above the insulation shielding. Two Sitka spruce saplings were fitted with both sap flow meters and cavitation transducers, but the third transducer was clamped to a sapling with no sap flow meter to determine interference between sensors. No interference was detected.

**Stem relative water content**

Two weeks after termination of the drought treatment, the saplings used for sap flow measurements were harvested. The stem was debarked and cut into 20-mm sections. Relative water content (RWC) was determined according to the method of Sobrado et al. (1992):

\[
\text{RWC} = 100(\frac{W_f - W_d}{r_w V_f[1 - (W_d/r_f V_d)]}),
\]

where \(W_f\) and \(W_d\) are fresh and dry weights, respectively, measured to the nearest 0.1 mg, \(V_f\) is the wood volume determined by Archimedes’ principle (Borghetti et al. 1991), and \(r_w\) and \(r_f\) are the density of water and wood solids, respectively. The value of \(r_f\) was assumed to be a constant of 1530 kg m⁻³ (Siau 1971).
Results

Changes in volumetric soil water content (VSW) during the drought treatment and subsequent rewatering are shown in Figure 1. During the drought treatment, VSW declined further and faster in containers with Scots pine than in containers with Sitka spruce; however, the difference was not statistically significant. We have, therefore, presented sap flow and cavitation rate data on the basis of treatment time, not VSW.

Between the tenth and last day of the drought treatment, cavitation rates of drought-treated Scots pine saplings exceeded those of irrigated control saplings (Figure 2). During the drought treatment, differences in cavitation rates between watered and drought-treated saplings became evident earlier in Sitka spruce than in Scots pine, but tended to diminish toward the end of the drought treatment (Figure 2). There were large day to day differences in cavitation rates, which reflected day to day differences in weather conditions. Following termination of the drought treatment, cavitation rates in drought-treated and control Scots pines saplings were the same at 1 to 2 events per minute (EPM). In Sitka spruce, however, cavitation rates of saplings rewatered after the drought treatment remained considerably higher than those of control saplings.

Among control saplings, sap flow rates in Scots pine were approximately twice those in Sitka spruce. However, among drought-treated saplings, sap flow rates declined earlier and faster in Scots pine than in Sitka spruce (Figure 3). On watering after the drought treatment, both species maintained low

![Figure 1](image1.png)  
Figure 1. Volumetric soil water content throughout the drought and rewatering cycle. Observations were made at four soil depths: ■ = 15 cm, □ = 30 cm, ○ = 45 cm, and ● = 55 cm. Data are presented for drying soil only.

![Figure 2](image2.png)  
Figure 2. Mean daily cavitation rates throughout the drought and rewatering cycle for each 24-h period (■ = watered, □ = drought-treated).

![Figure 3](image3.png)  
Figure 3. Mean daily sap flow rates throughout the drought and rewatering cycle, measured between 1200 and 1500 h (■ = watered, □ = drought-treated).
rates of sap flow for 1 day, but rates recovered to values observed before the drought by the second day. Thereafter, sap flow rates in drought-treated Scots pine were similar to those of control saplings, whereas in drought-treated Sitka spruce, sap flow rate rose until the fourth day when it was approximately twice that of the control saplings. Large day to day differences in sap flow rates reflected day to day differences in weather conditions.

Figures 4 and 5 show the daily course of PAR, VPD, cavitation, sap flow, stomatal conductance and shoot water potential on the 10th and 30th days of drought treatment, respectively. On Day 10, PAR and VPD declined steeply after 1000 h, with the formation of complete cloud cover, which was broken only briefly at approximately 1500 h (Figure 4). Declines in PAR and VPD were mirrored by a decline in sap flow rates, with only a brief recovery corresponding with the break in cloud cover. Stomatal conductance fell steeply throughout the day. There was little difference in stomatal conductance between the drought-treated Sitka spruce and the controls, but stomatal conductance was significantly lower in drought-treated Scots

Figure 4. Diurnal variation after 10 days of drought for Scots pine (a–f) and Sitka spruce (g–l). Values for the drought treatment are represented by open symbols and broken lines, and values for the irrigated control treatment are represented by solid symbols and unbroken lines. Bars indicate the magnitudes of standard errors. The two peaks in cavitation rate were recorded before dawn.
pine than in the controls. Shoot water potential in drought-
treated Scots pine saplings was significantly lower than in the
control saplings. In Sitka spruce, there was a similar but
smaller difference in shoot water potential between the treat-
ments. The daily mean cavitation rate in Scots pine was 1.6
EPM in drought-treated saplings versus 0.4 EPM in the con-
trols. The corresponding values for Sitka spruce were 9.1 and
8.2 EPM, respectively. A higher overall cavitation rate in Sitka
spruce compared with Scots pine was observed throughout the
experiment (Figure 2). Peaks in cavitation rate in drought-
treated saplings coincided with peaks in sap flow rate, which
in turn coincided with peaks in PAR and VPD.

By Day 30 of the drought treatment (Figure 5), saplings
were severely water stressed, and stomatal conductance was
practically zero throughout the day. Vapor pressure deficit
exceeded 1.5 kPa for most of the day, and PAR varied between
0.4 and 1 mmol m$^{-2}$ s$^{-1}$. Sap flow rates declined throughout
the day and reached negligible values in the afternoon. The

Figure 5. Diurnal variation after 30 days
of drought for Scots pine (a–f) and Sitka
spruce (g–l). Values for the drought treat-
ment are represented by open symbols and
broken lines, and values for the irrigated
control treatment are represented by solid
symbols and unbroken lines. Bars indicate
the magnitudes of standard errors. The
two peaks in cavitation rate were recorded
before dawn.
mean daily cavitation rate in drought-treated Scots pine saplings was much higher (27.5 EPM) than in the controls (1.4 EPM). In Sitka spruce, however, there was little difference in cavitation rate between the drought-treated and control saplings (9.6 versus 7.1 EPM). The small difference in cavitation rate between treatments was typical of Sitka spruce after Day 17 (Figure 2), when complete stomatal closure occurred for the first time.

In both species and treatments, sap flow rate followed VPD on Days 10 and 30 (Figures 4 and 5, respectively), with five peaks in sap flow rate and VPD on Day 10 and four peaks in sap flow rate and VPD on Day 30. On Day 30, cavitation rates in Scots pine showed three peaks corresponding with peaks in sap flow. After the third peak, there was a large peak in cavitation rate (at 1400 h) in the drought-treated saplings, coinciding with a release of xylem tension (as indicated by a rise in shoot water potential). In Sitka spruce, there was a conspicuous peak in cavitation at noon, after which shoot water potential rose. In Scots pine, the correlation between sap flow and cavitation rate was positive for most days. An increase in PAR or VPD or both frequently led to a rapid increase in rates of sap flow and cavitation. However, no such relationship was evident in drought-treated Sitka spruce, which is not surprising because there was no increase in cavitation rate with decrease in shoot water potential (Figure 6). In Scots pine, cavitation rates were inversely related to shoot water potential below a threshold of −0.55 MPa.

In the Sitka spruce controls, there was an inverse relationship between cavitation rate and shoot water potential (Figure 6). In drought-treated saplings, which showed a wider range of water potentials, no such relationship was evident (Figure 6). A relationship between shoot water potential and cavitation rate was apparent in both drought-treated and control Scots pine saplings (Figure 6). Shoot water potentials declined to similar values in both species, indicating that differences between the species in cavitation rate were due to differences in vulnerability. Low sap flow rates before dawn and at dusk were associated with high shoot water potentials (Figures 4 and 5).

Two weeks after rewatering, stem relative water content in drought-treated Scots pine was significantly lower \( (P < 0.02) \) than in the controls, which had been irrigated throughout (Figure 7), but the difference in Sitka spruce was smaller and not statistically significant \( (P < 0.31) \).

Hydraulic conductance per unit leaf area (leaf specific hydraulic conductance) was calculated from the slope of the relationship between shoot water potential and sap flow rate (Cohen et al. 1987) for Days 10 and 30 of the drought treatment and during the first 2 weeks after rewatering. Comparison could not be made between the watered and drought-treated saplings because the relationship for the drought-treated saplings was nonlinear. However, in the irrigated controls, leaf specific hydraulic conductance was significantly lower in Sitka spruce than in Scots pine (Table 2).

![Figure 6](image1.png)

**Figure 6.** Relationship between the logarithm of cavitation rate and shoot water potential \( (\bullet = \text{watered}, \square = \text{drought-treated}) \). The broken horizontal line corresponds to one cavitation event per minute, the detection threshold.

![Figure 7](image2.png)

**Figure 7.** Relative water content (RWC) of drought-treated (PD) and control (AW) Scots pine and Sitka spruce stems 14 days after termination of the drought treatment. Bars indicate the magnitudes of standard errors.

**Table 2.** Hydraulic conductance calculated from the slope of the relationship between sap flow rate and shoot water potential. All values are for irrigated control trees measured throughout the day on Days 10 and 30, and at midday only during the rewatering period. The \( r^2 \) value is the fit of the relationship between sap flow rate and water potential.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Species</th>
<th>Hydraulic conductance ( (\text{g} \text{ m}^{-2} \text{s}^{-1} \text{MPa}^{-1}) )</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diurnal measurements on Day 10</td>
<td>Scots pine</td>
<td>0.063</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Sitka spruce</td>
<td>0.021</td>
<td>0.95</td>
</tr>
<tr>
<td>Diurnal measurements on Day 30</td>
<td>Scots pine</td>
<td>0.089</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Sitka spruce</td>
<td>0.017</td>
<td>0.94</td>
</tr>
<tr>
<td>Midday measurements taken following rewatering</td>
<td>Scots pine</td>
<td>0.137</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Sitka spruce</td>
<td>0.017</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Discussion

In coniferous and other microphyllous foliage the aerodynamic resistance is low and transpiration rates are often closely proportional to VPD and stomatal conductance, $g_s$ (Jarvis and Stewart 1979). According to the cohesion theory of water transport, an increase in transpiration rate should cause a decline in leaf water potential and a corresponding increase in sap flow. In the present study, this is exemplified by the high correlation between transpiration rate (estimated from VPD and $g_s$, the Penman-Monteith equation) and sap flow rate ($r^2 = 0.81$ and $0.67$ for Scots pine and Sitka spruce, respectively). It is more difficult to follow the relationship between sap flow and shoot water potential because the stem psychrometer (Dixon and Tyree 1984) is damaged by resin production, and the pressure probe (Zimmermann and Balling 1989) is not reliable when inserted into woody tissue. Three-hourly readings of shoot water potential made with the pressure chamber show a general relationship with sap flow, but the technique lacks the temporal resolution to evaluate correlations between VPD, sap flow, and shoot water potential. It may be supposed, however, that as VPD (or $g_s$) increases, transpiration, leaf to soil water potential gradient, sap flow rate and (above a threshold) cavitation rate all increase. These relationships will be subject to both positive and negative feedbacks: (i) hydraulic conductance may decline significantly as a result of cavitation, thus steepening the relationship between sap flow rate and leaf to soil water potential gradient, unless new tracheid formation occurs at a sufficient rate to compensate; (ii) $g_s$ may decline, either in response to root signals (Khalil and Grace 1993) or as a direct response to declining leaf water content; and (iii) cavitation releases water, and so may cause leaf water potential to increase, as shown by Dixon et al. (1984). Both species studied here showed the latter phenomenon, with increases in shoot water potential following the large bursts of cavitation shown in Figures 5c and 5i.

As expected from its maritime distribution, generally higher rates of cavitation were found in Sitka spruce than in Scots pine, but surprisingly, low shoot water potentials during the severe drought did not induce high rates of cavitation in the drought-treated Sitka spruce. The high rate of cavitation in watered Sitka spruce is hard to explain. The shoot water potentials of the watered saplings ranged over similar values each day. Thus if tracheids cavitate at a fixed cavitation pressure, then after 1 day, all elements vulnerable within the daily water potential range should have cavitated and the acoustic emissions should thereafter have been at the background rate; however, this was not the case. One explanation could be that tracheids increase in vulnerability over time, so that at a particular water potential threshold, a different group of tracheids cavitate each day. Alternatively, cavitated tracheids may refill overnight. Refilling is more likely in well-watered saplings than in drought-treated saplings. Perhaps, therefore, in drought-treated saplings, cavitation on successive days occurred in populations of progressively less vulnerable tracheids in response to the day to day decline in shoot water potential.

The generally high rates of cavitation in Sitka spruce compared to those in Scots pine suggest greater vulnerability of Sitka spruce to cavitation. High rates of cavitation have been ascribed to large vessel or tracheid size (e.g., Carlquist 1977, Zimmermann 1983), with larger tracheids or vessels reported to cavitate at lower tensions than smaller conduits. This has been shown to be true within certain species (Tyree and Sperry 1989), but it is not true for interspecies comparisons (Cochard and Tyree 1990). Moreover, tracheid size appears to vary little in conifers (Cochard 1992, Sperry and Sullivan 1992), and even within species there appears to be no relationship between conducting element size and vulnerability to cavitation (Sperry and Sullivan 1992).

Recently, the morphology of the interconduit pit membrane has been suggested as an important factor accounting for variation in vulnerability to cavitation. The tendency of the torus to be displaced from its central position over the bordered pit appears to determine cavitation pressure. Sitka spruce may have a more flexible pit membrane than Scots pine, permitting cavitation to occur at more moderate shoot water potentials. Sperry and Tyree (1990) conclude that there must be a trade off between the safety required to prevent xylem embolism and the efficiency of water conduction. In particular, they assumed that a more rigid membrane has smaller water conducting pores. Consequently, lower vulnerability to cavitation reduces xylem conductivity. According to this interpretation, Sitka spruce, with its relatively high vulnerability to cavitation, is adapted to a relatively drought-free environment, whereas Scots pine is better adapted to drier areas.

Jones and Sutherland (1991) modeled optimal stomatal behavior as soil water potential declined on the assumption that complete stomatal closure should prevent cavitation. They concluded that complete stomatal closure is not always the optimal response to drought and that some embolism can be tolerated in order to allow a species to maximize photosynthetic production.

In our study, after 3 weeks of drought treatment, extremely low stomatal conductances occurred in both Scots pine and Sitka spruce. Nevertheless, cavitation rates in Scots pine continued to increase. However, our conductance measurements were carried out mainly at midday, and stomatal opening may have occurred at times of lower evaporative demand (Jackson et al. 1995). Alternatively, cavitation in drought-treated Scots pine may have occurred without stomatal opening. Bréda et al. (1993) found that stomatal regulation restricted embolism in Quercus petraea L. ex Liebl. but only over a limited range of soil water potentials.

The absence of a statistically significant difference in stem relative water content between control and drought-treated Sitka spruce saplings 2 weeks after the termination of the drought treatment lends further support to the idea that refilling of tracheids after cavitation occurs in this species. If this interpretation is correct, the higher cavitation rate in drought-treated saplings after rewatering than in control saplings may be indicative of a lower water stress threshold for cavitation in refilled tracheids.

The persistence in Scots pine of a reduced stem relative water content 2 weeks after the termination of drought sug-
suggests that refilling of cavitated tracheids did not occur in this species. This is contrary to the conclusions of others studies. For example, Borghetti et al. (1991) conducted two experiments with Scots pine: one with 3-year-old seedlings and another with 7-year-old saplings. Drought was progressively imposed over 20 days on the seedlings, and rapidly imposed on the saplings by uprooting. In both cases, tracheid refilling occurred within 24 h of rewatering. Peña and Grace (1986) withheld water from 5- to 6-year-old Scots pine for 25 days, and 14 days after rewatering, they found a complete recovery of xylem density to the predrought value, indicating complete refilling of water conducting elements. Sobrado et al. (1992) also found that refilling occurred in 8-year-old Scots pine branches dehydrated on the laboratory bench; however, they imposed drought much more rapidly than in our study, and this may have prevented irreversible sealing of bordered pits (Sperry and Tyree 1990). Sperry and Tyree (1990) suggest that conifers lack the ability to refill cavitated tracheids because they cannot generate positive xylem pressures.

The threshold water potential for cavitation in Scots pine has been estimated in several different ways. Peña and Grace (1986) used the acoustic emission technique and obtained a threshold value of −0.5 MPa in 5- to 6-year-old trees, which compares well with the threshold value of −0.55 MPa in our study. However, Cochard (1992), using the hydraulic conductivity technique (Sperry et al. 1988) in a comparative study of seven conifers, obtained a threshold value of −2.5 MPa and concluded that Scots pine was the most vulnerable of the seven species studied. The reason for such discrepancies does not seem apparent, indicating the need to interpret cavitation vulnerability curves with caution.

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References


