Mist Level Influences Vapor Pressure Deficit and Gas Exchange During Rooting of Juvenile Stem Cuttings of Loblolly Pine

Anthony V. LeBude,1 Barry Goldfarb,2 Frank A. Blazich,3 John Frampton,4 and Farrell C. Wise5

Department of Forestry, North Carolina State University, Raleigh, NC 27695-8002

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Abstract. Two experiments were conducted during which juvenile hardwood or softwood stem cuttings of loblolly pine (Pinus taeda L.) were rooted under six mist regimes in a polyethylene-covered greenhouse to investigate the effect of mist level on vapor pressure deficit (VPD) and cutting water potential (Ψc), and to determine the relationships between these variables and rooting percentage. In addition, net photosynthesis at ambient conditions (Aambient) and stomatal conductance (gs) were measured in stem cuttings during adventitious root formation to determine their relationship to rooting percentage. Hardwood stem cuttings rooted ≥80% when mean daily VPD between 1000 and 1800 HR ranged from 0.60 to 0.85 kPa. Although rooting percentage was related to Ψc, rooting percentage of softwood stem cuttings was not related to Aambient of stem cuttings. Using VPD as a control mechanism for mist application during adventitious rooting of stem cuttings of loblolly pine might increase rooting percentages across a variety of rooting environments.

Loblolly pine (Pinus taeda) is the most important timber species in the southeastern United States. Adventitious rooting of stem cuttings of loblolly pine collected from stock plants in the juvenile growth phase can be used to multiply superior genotypes (clones) within families for progeny testing in breeding programs (Isik et al., 2004), or for use directly in reforestation (Frampton et al., 2000, 2002). Loblolly pine has been considered recalcitrant to propagation by stem cuttings (Zobel and Talbert, 1984) and somatic embryogenesis (Pullman et al., 2003), posing an obstacle to large-scale use in clonal forestry. For vegetative propagation of stem cuttings of loblolly pine to attain operational levels, successful rooting must be accomplished in low-cost environments. Several propagation environments, including greenhouses, shadehouses, and nursery beds are being tested (Gocke, 2001). Abiotic factors, such as rooting substrate, mist application, air temperature, wind, relative humidity (RH), and irradiance can vary among these environments and affect rooting percentage. Thus, irrigation schedules that are optimized for one rooting environment may not be successful in others. Understanding how environmental factors induce the physiological responses associated with increased rooting could enable propagators to reproduce those conditions utilizing a variety of production systems.

LeBude et al. (2004) determined previously that, provided substrate water potential was –2.4 ± 0.2 kPa, mist level was the most important factor influencing rooting percentage of juvenile stem cuttings of loblolly pine. Mist level was strongly related to cutting water potential (Ψc), a physiological indicator of water deficit, and Ψc was related to rooting percentage. They hypothesized that stem cuttings of loblolly pine need to experience a moderate, mean daily water deficit to stimulate adventitious root formation and development. Using Ψc as an indicator of rooting percentage, however, would be cumbersome in an operational system because measurements are labor intensive.

Vapor pressure deficit (VPD) has been used successfully to control mist frequency dynamically on stem cuttings of ‘Freedom Dark Red’ poinsettia (Euphorbia pulcherrima Willd. ex Klotzsch ‘Freedom Dark Red’) during the transition period between root emergence and subsequent root growth (Olofsson et al., 2001a; 2003). Although VPD has been monitored during rooting of stem cuttings in other species, correlations between VPD, rooting percentage, and Ψc were not intended as objectives of various studies (Aminah et al., 1997; Grossnickle and Russell, 1993; Newton et al., 1992). An initial step in using an environmental factor to control mist application or predict rooting success is to define the response of stem cuttings to that factor (Zolnier et al., 2001b). Such research has not been reported for stem cuttings of loblolly pine.

Current photosynthesis (photosynthetic rate of stem cuttings during the period of adventitious root formation and development) and stomatal conductance to water vapor (gs) are two physiological variables that may influence adventitious root formation in stem cuttings (Davis, 1988). Photosynthetic rate in stem cuttings is dependent upon a complex interaction among the level of photosynthetically active radiation (PAR), RH, stomatal opening, and water potential (Davis, 1988). Because Ψc is associated with rooting percentage (Hartmann et al., 2002; LeBude et al., 2004; LeBude et al., 2004; Loach and Whalley, 1978), its effect on current photosynthesis might explain the relationship between Ψc and rooting percentage. Moreover, the relationship between these processes might aid design of rooting environments to induce photosynthetic responses in stem cuttings associated with increased rooting percentages.

The experiments in this report were conducted concurrently with the experiments of LeBude et al. (2004) using the same stem cuttings, rooting environments, and mist treatments. The goal of this report is to first broaden the impact of LeBude et al. (2004) by developing quantitative information for controlling rooting environments, and secondly, to describe the nature of the relationship between Ψc and rooting percentage by studying gas exchange in stem cuttings. Therefore, the following two experiments were conducted to determine 1) the relationships between VPD and Ψc, and VPD and rooting percentage, and to determine 2) the relationship between gas exchange and adventitious rooting of juvenile stem cuttings of loblolly pine.

Materials and Methods

Plant material. The provenance, propagation and culture of stock plants, and subsequent collection of stem cuttings for these experiments, were described previously (LeBude et al., 2004). Methods described for Expts. 3 and 4 in LeBude et al. (2004) are the same for Expts. 1 and 2 in the present study. Briefly, either juvenile hardwood (Expt. 1) or juvenile softwood (Expt. 2) terminal stem cuttings were collected and bulked from recently sheared (hedged) stock plants of two full-sib families of loblolly pine, and then placed in insulated coolers. For Expt. 1, the coolers were placed in a cold room and maintained at 4 °C for 8 weeks until setting the cuttings (insertion into the rooting substrate) on 5 Apr. 2002, whereas in Expt. 2, the coolers were placed under a greenhouse bench overnight until the cuttings were set the following day, 29 June 2002. Before setting cuttings to a depth of 1 cm, cuttings were recut from the proximal ends to a final length of 9 cm, and the basal 1 cm was dipped for 3 s in either 10 mM 1-naphthaleneacetic acid (NAA; 1.86 g L–1 in 30% ethanol v/v) for Expt. 1, or 2.5 mM NAA (0.46 g L–1 in 20% ethanol v/v) for Expt. 2. Needles were not removed from the basal portions of the cuttings that were inserted into the rooting medium.
Rooting environment. Both experiments were conducted under natural photoperiod and irradiance in a clear polyethylene-covered greenhouse; however, irradiance in Expt. 2 was decreased 60% by placing shade cloth on the greenhouse exterior. Heating and cooling systems were adjusted to maintain the daily air temperature between 23 and 26 °C and the night temperature between 20 and 23 °C. Cuttings were misted intermittently at a variable frequency related inversely to the RH (50–Y Temp/RH Probe, QCQ Corp., Irvine, Calif.) surrounding stem cuttings being rooted on an adjacent bench within the greenhouse. The Temp/RH probe was also misted with 12 L/min of water at each boom pass. Variable frequencies were defined by designating minimum (60% RH) and maximum (99% RH) off-times between mist applications. Off-times for intermediate humidity values were calculated using a linear function. The minimum and maximum off-times varied according to the time of day. For the period from 0600 to 0900 hr, the minimum and maximum off-times were 10 and 35 min, respectively. For the periods from 0900 to 1800 hr, 1800 to 2100 hr, and 2100 to 0600 hr, minimum and maximum off-times were 8 and 24 min, 10 and 40 min, and 60 and 240 min, respectively. A greenhouse environmental management software program (GEM3; QCQ Corp., Irvine, Calif.) calculated mist frequency and triggered a traveling gantry (boom) (Solaris; McConkey Co., Mt. Puyallup, Wash.) to apply mist. Misting frequency (number of boom passes) was similar for all cuttings within each experiment; however, boom traveling speeds were altered to create different mist application treatments. For each boom speed, mist application was calculated by dividing the total output for all nozzles (258 mL min⁻¹ per nozzle × 26 nozzles) (TeecJet nozzle #800667; Spraying Systems, Co., Neuvo, Calif.) by the area covered by the boom in 1 min, expressed as milliliters per square meter. The experimental design was a randomized complete block with two replications of mist. The mist treatments were 45, 61, 75, 102, 147, or 310 mL·m⁻² of mist per boom pass. Each plot was divided by clear polyethylene plastic barriers (91.4 cm tall) to minimize environmental gradients within the greenhouse and to separate treatments. Experimental stem cuttings were surrounded by two rows of border cuttings of the same genetic origin.

Dependent variables. A pressure chamber (Scholander et al., 1965) (SoilMoisture Equipment Corp., Santa Barbara, Calif.) was used to measure Ψₛₑₑ destructively every 3 h beginning at 0500 until 2300 hr (seven measurements) on two cuttings per plot 7, 14, 21, 28, or 35 (Expt. 2 only) d after setting (DAS). Data for both cuttings were subsequently averaged to provide a mean for each plot per measurement time. Substrate water potential (Ψₛₑₑ) was also measured in each plot using a tensiometer (Irrometer Co., Riverside, Calif.) at 0500 and 1400 hr on the same days that Ψₛₑₑ was measured; however, Ψₛₑₑ was not significantly different among plots [data not presented, see LeBude et al. (2004) for construction and maintenance of Ψₛₑₑ]. Cuttings selected randomly for Ψₛₑₑ measurements were replaced to maintain canopy dynamics, but were excluded from subsequent measurements. Adventitious roots began to emerge about 28 to 42 DAS; however, the percentage of cuttings producing at least one root ≥1 mm was recorded for each plot 70 DAS.

Effect of mist level on VPD, and VPD on Ψₛₑₑ and rooting percentage (Expt. 1). Leaf temperatures were recorded in all plots continuously using thermocouples (Type-T; Omega Engineering, Stamford, Conn.) connected to a micrologger (23X; Campbell Scientific, Logan, Utah). RH at the stem cutting level was recorded in each mist plot in the second replication only by six separate HOBO data loggers (Onset Computer Corp., Bourne, Mass.). Data for leaf temperature and RH were averaged continuously from both data loggers over 15-min intervals. VPD based on the leaf temperature and RH was calculated using equations of Buck (1981) and Prenger and Ling (2001). Leaf temperature was used as a substitute for air temperature because leaf temperature was measured in both replications and air temperature and humidity in one replication only. Because VPD was calculated for each plot using this method, data for VPD were averaged over both replications before analyses to account for this limitation. In some cases, HOBO data loggers malfunctioned while data were being recorded due to either saturated conditions or battery failure. As a result, data were being recorded due to either saturated conditions or battery failure. Although VPD was recorded in Expt. 2, data logger malfunction prevented data from being retrieved for use. Therefore, data for VPD in Expt. 2 are not presented.

Mean VPD between 1000 and 1800 hr was used in analyses, because the greatest variation among mist levels occurred during this period and, subsequently, was found to contribute most meaningfully to the statistical relationships between variables. Likewise, mean Ψₛₑₑ for cuttings measured at 1100, 1400, or 1700 hr were used to coincide with this time frame. Previously, rooting percentage was found to be related to mean daily Ψₛₑₑ averaged from 0500 to 2300 hr, and related to the single daily minimum Ψₛₑₑ (most negative) measured (LeBude et al., 2004). The present paper differs by reporting the relationship between the environmental conditions during rooting that contribute to the mean midmorning to late afternoon Ψₛₑₑ.

Effect of mist level on photosynthesis at ambient conditions (A₅₀ and stomatal conductance to water vapor (gₛ) and their effect on rooting percentage (Expt. 2). A₅₀ and gₛ were measured on nonrooted stem cuttings 14, 28, 42, 56, or 70 DAS using a LI-6400 infrared gas analyzer (IRGA) (Software version Open 3.4, LI-COR, Lincoln, Nebr.) equipped with a 6-cm² cuvette and a 6400-02B red–blue LED light source. The same measurements during rooting that contribute to the mean midmorning to late afternoon Ψₛₑₑ.
Table 1. Analysis of variance summary for potential effects of mist level (M), days after setting (DAS), and time of day (TOD) on photosynthetic rate (A<sub>ambient</sub>) and stomatal conductance (g<sub>s</g>) of nonrooted, juvenile, softwood stem cuttings of loblolly pine in Expt. 2 (conducted June 2002) 14, 28, 42, 56, or 70 DAS, and of intact, rooted control plants evaluated 28 or 70 DAS. Values are the probability of a greater F statistic. Bold values are statistically significant at P < 0.05.

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Fig. 1. Effect of mist level on mean vapor-pressure deficit (VPD) by hours over 20 (75 mL·m<sup>–2</sup>) or 30 d after setting (DAS) for Expt. 1 (April 2002). Mist level of 61 mL·m<sup>–2</sup> was not included due to instrument error while data were recorded. Symbols are means of two replications.

Fig. 2. Rooting percentage [70 d after setting (DAS)] as a function of Ψ<sub>cut</sub> averaged over both replications for measurements recorded at 1100, 1400, or 1700 hst 7, 14, 20 (75 mL·m<sup>–2</sup> only) or 30 DAS for juvenile, hardwood stem cuttings rooted in Expt. 1 (April 2002). Mist level of 61 mL·m<sup>–2</sup> was not included due to instrument error while data were recorded. The regression equation is as follows: rooting (%) = 4.15 – 224.62(Ψ<sub>cut</sub>)<sup>2</sup> + 115.90(Ψ<sub>cut</sub>) – 0.03, r<sup>2</sup> = 0.97. Data for the quadratic term (Ψ<sub>cut</sub> <sup>2</sup>) were generated by squaring the linear term and then averaging over measurement times and DAS.
Results

Effect of mist level on VPD, and VPD on $\Psi_{cut}$ (Expt. 1). Mean VPD ranged from 0 to 1.2 kPa, depending on time of day and mist application (Fig. 1). For example, between 1300 and 1700 hr, VPD was highest for the mist level of 75 mL · m$^{-2}$ (1.2 kPa) and lowest for the mist level of 310 mL · m$^{-2}$ (0.6 kPa). Between 2100 and 0700 hr, VPD was near 0 kPa for all mist levels (Fig. 1). Averaged between 1000 and 1800 hr, VPD was strongly related to the log of mist application $[\text{VPD} = 1.81 - 0.22\ln(\text{mL} \cdot \text{m}^{-2})], P = 0.01, r^2 = 0.82$]. Mean $\Psi_{cut}$ for measurements recorded at 1100, 1400, or 1700 hr, decreased (became more negative) as the log of VPD increased (averaged between 1000 and 1800 hr) $[\Psi_{cut} = -1.94 + 1.96\ln(\text{VPD})], P = 0.02, r^2 = 0.89$.

Relationship between rooting percentage, $\Psi_{cut}$ and VPD (Expt. 1). Rooting percentage was strongly related to the linear and quadratic terms of $\Psi_{cut}$ (Fig. 2). The regression equation predicted ≥80% rooting with mean $\Psi_{cut}$ between −0.55 and −1.2 MPa (averaged over 1100, 1400, and 1700 hr). Rooting percentage was also related strongly to the linear and quadratic terms of mean daily VPD (Fig. 3A). Rooting percentages ≥80% occurred when mean daily VPD ranged from 0.6 to 0.85 kPa between 1000 and 1800 hr.

The maximum daily VPD value for a single 15-min interval was recorded for each mist level and averaged 20 DAS (75 mL · m$^{-2}$ only) or 30 DAS. Rooting percentage was related strongly with the linear and quadratic terms of mean maximum daily VPD (Fig. 3B). Rooting percentage was predicted ≥80% when daily maximum VPD ranged from 0.85 to 1.3 kPa.

Effect of mist level on $A_{ambient}$ and $g_s$ (Expt. 2). Mist level and DAS significantly affected $A_{ambient}$ and $g_s$ of nonrooted stem cuttings (Table 1). Greater mist volumes generally increased $A_{ambient}$ in all five measurement periods (Fig. 4A). When $A_{ambient}$ was averaged for all mist levels at each measurement period, the response declined initially between 14 and 28 DAS, and then remained relatively steady through 70 DAS (see mean Fig. 4A). Stomatal conductance of nonrooted stem cuttings responded similarly to mist level and DAS (Fig. 4B). In contrast to nonrooted stem cuttings, $A_{ambient}$ and $g_s$ of rooted controls was affected by DAS, but not mist (Table 1). Mean $A_{ambient}$ was 2.19 and 8.49 µmol · m$^{-2}$ · s$^{-1}$ at 28 and 70 DAS, respectively, and $g_s$ was 59 and 328 mmol · m$^{-2}$ · s$^{-1}$ at 28 and 70 DAS, respectively, averaged across mist levels.

Photosynthesis and $g_s$ of juvenile, nonrooted, succulent stem cuttings were related strongly to the log of mist level when data for 14, 28, or 42 DAS were averaged together to represent the period during adventitious root formation (Fig. 5A and B). Both responses increased as mist level increased. It was reported previously that daily mean $\Psi_{cut}$ was also related strongly to mist level in juvenile stem cuttings of loblolly pine (LeBude et al., 2004). In the present study, $A_{ambient}$ increased linearly as $\Psi_{cut}$ increased (became less negative) (Fig. 6A). Stomatal conductance, however, had a different response to $\Psi_{cut}$ increasing gradually (35 mmol · m$^{-2}$ · s$^{-1}$).
between –1.3 and –0.9 MPa, and then sharply (150 mmol·m⁻²·s⁻¹) thereafter until reaching –0.5 MPa (Fig. 6B).

Stomatal conductance affected A_ambient in nonrooted stem cuttings similarly at 28 and 70 DAS (Fig. 7A). In rooted controls 28 DAS, the response was similar to nonrooted stem cuttings measured at the same time (compare solid symbols between Fig. 7A and B). At 70 DAS, however, overall rates of A_ambient and gₛ were greater for the controls (Fig. 7A and B, compare open symbols). When data for both 28 and 70 DAS were included in the model for the controls, there was a strong overall relationship between A_ambient and gₛ (Fig. 7B, both open and solid symbols).

Relationships between rooting percentage and A_ambient and gₛ (Expt. 2). Rooting percentage was not related to A_ambient of nonrooted, juvenile, succulent, stem cuttings of loblolly pine (Fig. 8A). Rooting percentage was related to the linear and quadratic terms of gₛ (Fig. 8B). The equation predicted ≥70% rooting when gₛ ranged from 40 to 150 mmol·m⁻²·s⁻¹.

Discussion

Effect of mist level on VPD and VPD on Ψ_cut and rooting percentage (Expt. 1). Mist level contributed to both the VPD surrounding the stem cuttings and Ψ_cut when data for both variables were averaged between 1000 and 1800 hr. Mist application decreases VPD by lowering leaf temperatures and increasing the RH surrounding stem cuttings (Tukey, 1978). Thus, there is less of a transpirational demand on stem cuttings and/or increased absorption of water through the foliage; both of which aid in maintaining or increasing Ψ_cut during the rooting period (LeBude et al., 2004).

Rooting ≥80% occurred for juvenile hardwood stem cuttings of loblolly pine when mean Ψ_cut was maintained between –0.6 and –1.2 MPa. This corresponded to a mean daily VPD between 0.60 and 0.85 kPa. Values of mean VPD associated with increased rooting are similar to those of Newton et al. (1992) when stem cuttings of terminalia (Terminalia spinosa Engl.) rooted at 80%. In light red meranti (Shorea leprosula Miq.), rooting was 60% within this range of VPD; however, higher maximum VPDs were recorded during rooting, which could have corresponded to increased water stress (Aminah et al., 1997).

Mean daily maximum VPD recorded in the present study was between 0.85 and 1.25 kPa when rooting percentage was ≥80%. Because individual species may respond differently to VPD, an initial step in designing suitable rooting environments would be to define the physiological response and rooting of stem cuttings to such environmental factors. After rooting percentage was 100% in stem cuttings of poinsettia, VPD was used as a dynamic control for mist application during subsequent root growth and development (Zolnier et al., 2003). Our data indicate the potential use of VPD to control mist application during the period of adventitious root formation in dormant, hardwood stem cuttings of loblolly pine to produce a range of Ψ_cut necessary for optimal rooting.

Fig. 4. (A) Photosynthetic rate (A_ambient) and (B) stomatal conductance (gₛ) of nonrooted, juvenile, softwood stem cuttings of loblolly pine in Expt. 2 (June 2002) 14, 28, 42, 56, or 70 d after setting (DAS) for each mist level. Symbols are means of measurements recorded in the AM or PM for two replications of each mist level.

Mist per application (mL m⁻²)

![Graph showing mist per application](image)

![Graph showing CO₂ assimilation rate](image)

![Graph showing Stomatal conductance](image)

![Graph showing Days after setting](image)
are decreased when our results are compared to those of 1- to 2-year-old intact seedlings of loblolly pine grown in the field in other experiments (Kramer and Clark, 1947; Seiler and Johnson, 1985). Both processes increased, however, with increasing mist volume (Fig. 5A and B). This was probably due to the strong affect of mist level on $\Psi_{cut}$ (Fig. 5, LeBude et al., 2004), and the subsequent effect of $\Psi_{cut}$ on the relationship between $A_{ambient}$ and $g_s$ (Figs. 6A and B and 7A and B). In stem cuttings of other species, variation among treatments or decreases in photosynthetic rate were attributed generally to water deficit (Svenson et al., 1995), to water deficit induced by high irradiance (Mesén et al., 1997), or to water deficit induced by various leaf area treatments (Newton et al., 1992). This is not surprising since the dual roles of stomata are to regulate water loss while assimilating CO$_2$. In some species, stomatal regulation is a response to water deficit (Sperry, 2000).

Photosynthetic rate of juvenile, nonrooted, succulent stem cuttings of loblolly pine was not related to rooting percentage. Some previous reports have also noted no relationship between photosynthetic rates during the rooting period and rooting percentage (Mesén et al., 1997; Okoroon and Grace, 1976; Smalley et al., 1991; Svenson et al., 1995). Moreover, efforts to increase rooting of stem cuttings of loblolly pine by increasing levels of CO$_2$ artificially in polyethylene greenhouses were not successful in the 1970s (Michael Greenwood, Dept. of Forest Ecosystem Sci., Univ. of Maine, Orono (personal communication)). In studies where photosynthetic rates among treatments were not related to percent rooting, such factors as the phase change of the stock plants (Grossnickle and Russell, 1993), clonal differences in rooting (von Schaeberg et al., 1993), or poor environmental conditions were inferred to be contributing causes (Yue and Margolis, 1993). It has been proposed that photosynthesis does not occur in nonrooted stem cuttings because of minimal leaf conductance (Yue and Loach, 1977). In contrast, other researchers have found that the photosynthetic rate in stem cuttings of tropical tree species affected rooting percentage (Aminah et al., 1997; Hoad and Leakey, 1996; Newton et al., 1992). Additional support for this hypothesis comes from Leakey and Coutts (1989) who measured levels of carbohydrates and correlated them with rooting percentage. Rooting percentages in that study, however, also could have been explained by differences in water deficits among treatments rather than as a direct result of photosynthetic activity.

The hypothesis that current photosynthetic rate affects rooting percentage has neither been proven nor refuted, as it is supported in some cases but not in others. This might be due to the inherent obstacle of independently controlling the photosynthetic rates of stem cuttings (Davis, 1988), in addition to the difficulty of replicating experiments over time, the use of various angiosperms vs. gymnosperms, as well as the use of different genetic experimental units within species (i.e., number of different cultivars, clones, or the use of seedlings). Moreover, in the present study, gas exchange was measured on succulent rather than dormant stem cuttings because it was thought
that succulent stem cuttings would be more photosynthetically active than dormant stem cuttings. We suggest that photosynthesis in juvenile, succulent, stem cuttings of loblolly pine, at least at a minimal level, might be an indication of the relative ability of cuttings to function under conditions of high stress. In this case, it is an indication of the ability of the stem cutting to assimilate carbon while experiencing repeated severe water deficit coupled with high leaf temperatures and irradiance. Above that minimal level, water deficit, photosynthesis and, therefore, carbohydrate supply are not limiting to rooting percentage.

In the present investigation, rooting percentage was more closely related to moderate rates of $g_s$ than to $A_{ambient}$ in softwood, juvenile stem cuttings of loblolly pine. Rooting percentage and $g_s$ could be related indirectly as indicated by the inability of the linear and quadratic equation to predict more than about 50% of the variation in rooting percentage (Fig. 8B). Stomatal conductance could be related indirectly to rooting percentage by moderating $\Psi_{cut}$. The mechanism(s) by which $\Psi_{cut}$ influence rooting percentage is largely unknown (LeBude et al., 2004; Sinclair and Ludlow, 1985), but this effect could be independent of any effect $g_s$ has on rooting percentage.

Summary. This study measured various environmental variables and physiological processes to learn how to better design and control rooting environments for stem cuttings of loblolly pine. Although $A_{ambient}$, $g_s$, $\Psi_{cut}$, and VPD were affected by varying mist levels, the relationships between $A_{ambient}$ and $g_s$ with rooting percentage were not as strong as between $\Psi_{cut}$ and VPD with rooting percentage. Moreover, $A_{ambient}$, $g_s$, and $\Psi_{cut}$ are time consuming measurements, limiting the number of measurements that can be taken and their subsequent simultaneous use in dynamic control of mist application. On the other hand, VPD was related strongly to rooting percentage, and VPD can be measured rapidly, calculated automatically, and integrated into a system to control mist application dynamically. Our results suggest that VPD could be used as a dynamic control for mist application when managing $\Psi_{cut}$ in stem cuttings of loblolly pine.

A mean daily range of VPD between 1000 and 1800 hr of 0.6 to 0.85 kPa should produce beneficial levels of $\Psi_{cut}$ that improve rooting percentages in stem cuttings of loblolly pine. Further research is necessary to validate the VPD-based model as a control system for mist application, as well as establish appropriate levels of VPD for a wider range of species in different rooting environments.

Literature Cited

Fig. 7. Relationship between photosynthetic rate ($A_{ambient}$) and stomatal conductance ($g_s$) for (A) nonrooted, juvenile, softwood stemcuttings of loblolly pine 28 (solid symbols) and 70 (open symbols) d after setting (DAS) and (B) rooted controls at 28 (solid symbols) and 70 (open symbols) DAS in Exp. 2 (June 2002). The regression equations are ($A_{ambient}$) $= –0.27 + 0.05(g_s) – 0.0002 (g_s^2), P = 0.01, r^2 = 0.92,$ and $A_{ambient}(70\text{ DAS}) = –0.43 + 0.08(g_s) – 0.0003 (g_s^2), P = 0.01, r^2 = 0.92$ for nonrooted stem cuttings and (B) $A_{ambient}(28$ and 70 DAS) $= –7.9 + 2.91 \ln(g_s), P = 0.01, r^2 = 0.80$ for rooted controls.
Fig. 8. Rooting percentage and (A) photosynthetic rate ($A_{\text{net}}$) and (B) stomatal conductance ($g_s$) of nonrooted, juvenile, softwood stem cuttings averaged for AM or PM measurements recorded 14, 28, or 42 d after setting (DAS) in Expt. 2 (June 2002). Rooting percentage (70 DAS) was not significantly related to photosynthetic rate. The regression equation in B is rooting (%) = 34.48 + 1.55$g_s$ – 0.007$g_s^2$, $P = 0.04$, $r^2 = 0.52$.


