# FOR/FES-599

# 3-PG FOREST GROWTH MODEL


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# Lecture 5

**Water**
**&**
**Energy Balance**

# Energy Exchanges

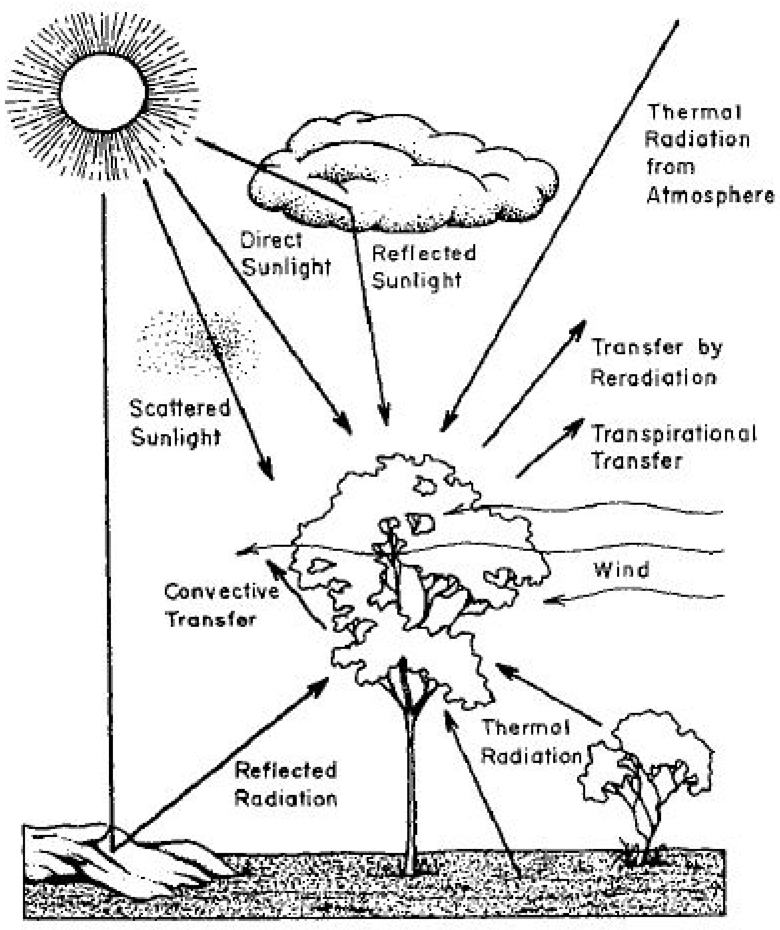


**FIGURE 2.2.** Energy exchange between vegetation and the environment involves a number of processes. Solar radiation reaches plant canopies as direct, scattered, and reflected sunlight, all of which contain some short-wave components important for photosynthesis. On partly cloudy days, reflection from clouds can increase incident short-wave radiation at the ground surface by as much as 30%. On clear days, less than 10% of the short-wave radiation is scattered by the atmosphere; on overcast days, incident short-wave radiation is reduced and diffuse, casting no shadows. Plant and other surfaces absorb and reflect short-wave and long-wave radiation, and they emit thermal radiation as a function of their absolute (Kelvin) temperature. The bulk of the heat load on plants is reradiated; evaporative cooling by transpiration and heat transfer by convection and wind (advection) remove the rest. Some heat is stored temporarily in the soil and plant tissue , which is later reradiated. (After Gates, 1980.)

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# Energy Exchange Balance For a Douglas-Fir Stand in B.C.

**TABLE 2.1**
**Reflectivity (Albedo) of Various Surfaces**[a]

| Surface | Albedo |
|---|---|
| Forests | 0.05–0.18 |
| Grass | 0.22–0.28 |
| Crops | 0.15–0.26 |
| Snow (old–new) | 0.75–0.95 |
| Wet soil | 0.09 ± 0.04 |
| Dry soil | 0.19 ± 0.06 |
| Water | 0.05 to >0.20 |

[a]After Jones (1992) and Lowry (1969).

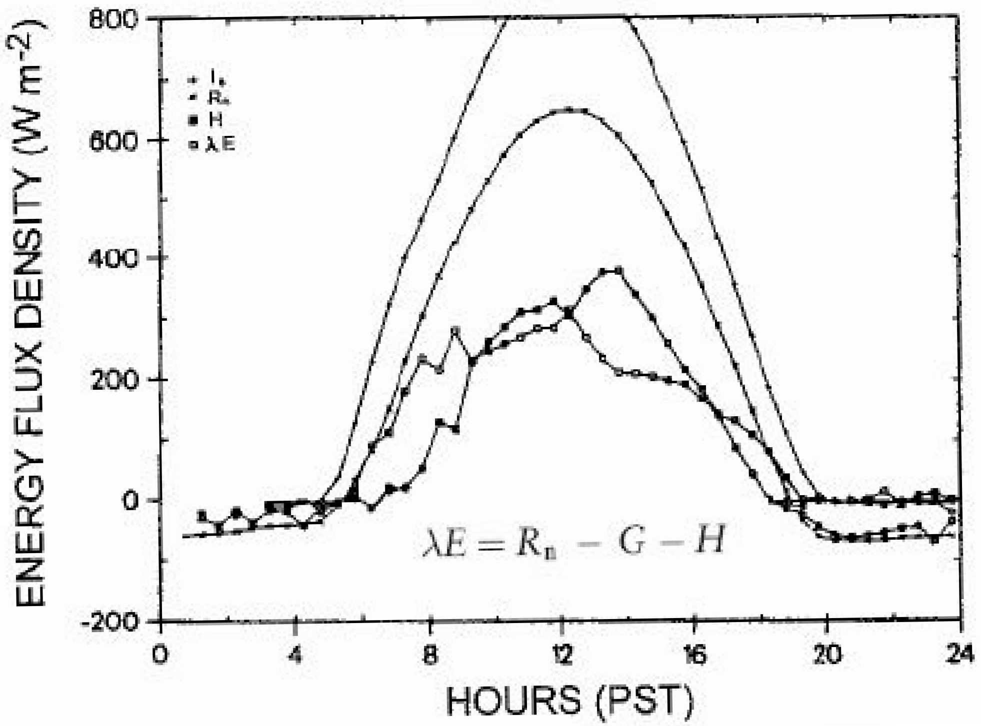
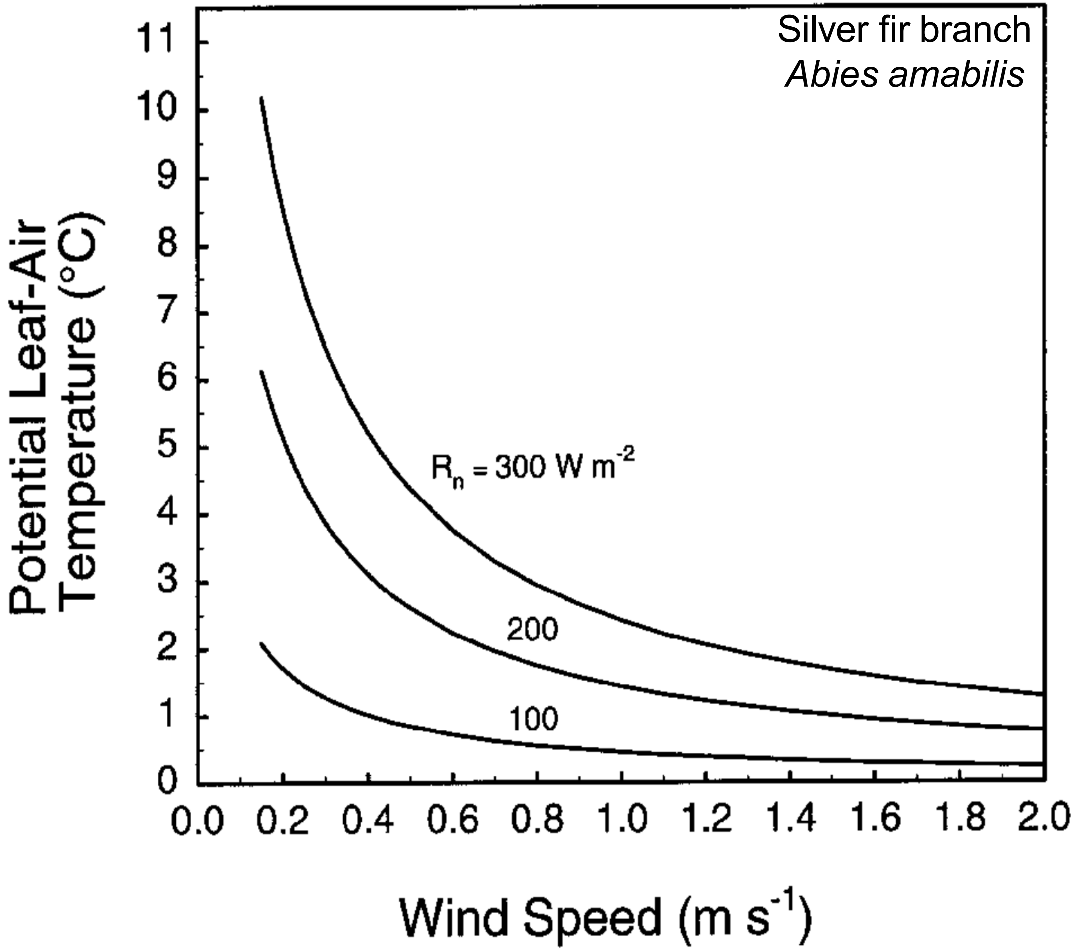



**FIGURE 2.3.** Ecosyst e m energy exchange balance for a Douglas-fir stand in British Columbia for a clear day in July. Variation in incoming short-wave radiation *U,),* net radiation (R.), heal storage (G), and fluxes of sensible heat (HJ and latent heat(}.£) are presented for a 24-hr period. The Bowen ratio *(HIAE)* was small in early morning as dew evaporated freely from leaf surfaces. From 0800 to 1200 transpiration dissipated nearly as much ene rgy as was lost through sensible heat transfer (Bowen ratio approximately 1.0). During midafternoon, partial closure of leaf stomata reduced A£ and increased the Bowen ratio to nearly 2.0. (Modified from *Agric11{ tural a11d Forest Meteorology,* Volume 50, D. T. Price and T. A. Black, "Effects of short-term variation in weather on diurnal canopy *COl* flux and evaporation of a juvenile Douglas-fir stand," pp. 139-158, 1990, wi1h kind permission of Elsevier Science- NL, Sara Burgerhart straat 25, 1055 KY Amsterdam, The Ne1herlands.)

# Potential Leaf-Air Temperature in Function of the Wind Speed




$$\lambda E = \frac{\rho c_p (e_o - e_a)}{\gamma (r_{av} + r_s)}$$

$$H = \frac{\rho c_p (T_o - T_a)}{r_{ah}}$$

# Boundary-Layer Conductance in Function of the Wind Speed

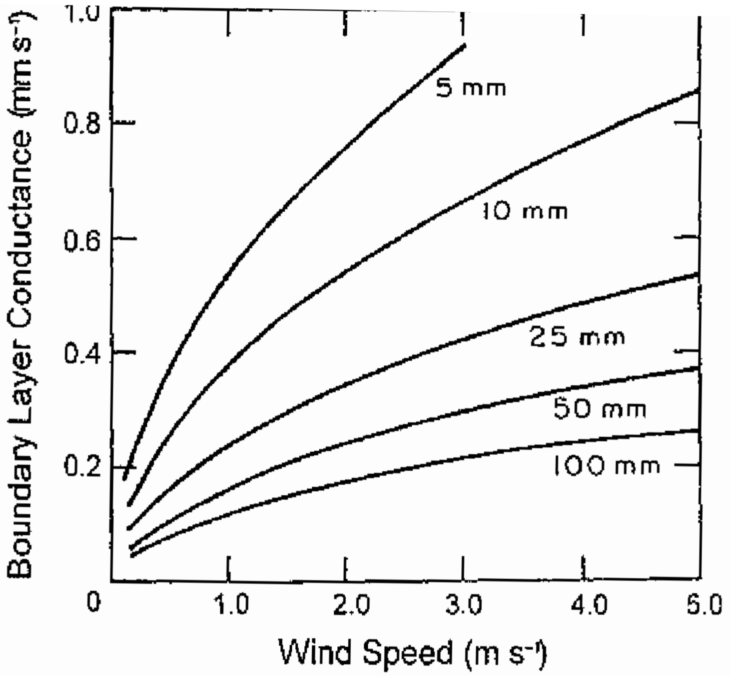



**FIGURE 2.5.** The aerodynamic or boundary-layer conductance ($g_b$) is generally high for tall vegetation because of turbulence. With shorter vegetation, however, less turbulence is present, and the width of leaves (shown from 5 to 100 mm) and wind speed become increasingly important in determining $g_b$. (After Grace, 1981.)

| Variable | pasture | crop | forest |
|---|---|---|---|
| Height, m | 0.05 | 0.5 | 20 |
| $g_{b}$, m/s | 0.01 | 0.02 | 0.2 |
| $E_{max}$, mm/hr | 0.05 | 0.065 | 0.3 |

# Stomatal Conductance

Canopy stomata conductance: response to radiation, temperature, and vapor pressure deficit

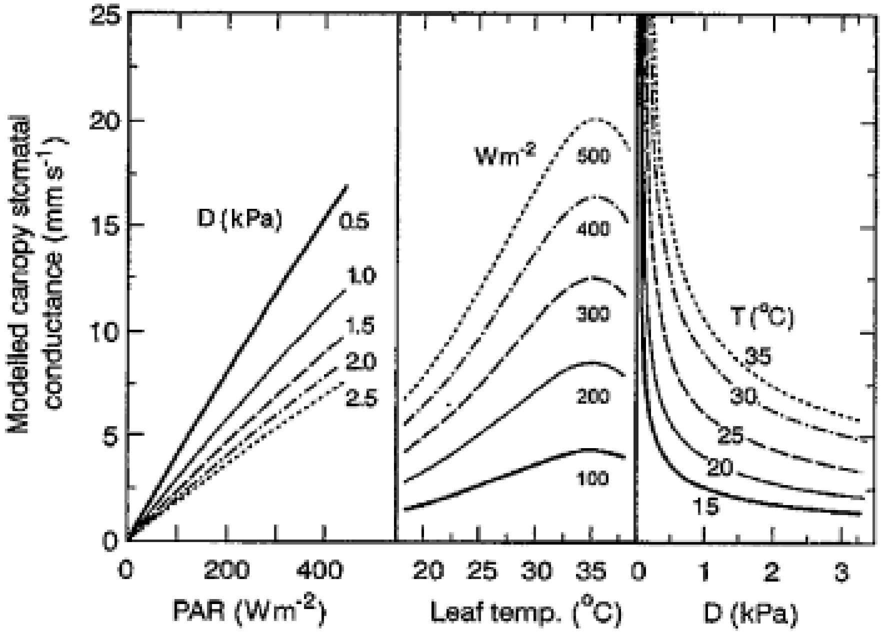



**Figure 1:** modeled data based on measurements of stomatal conductance made at an Amazonia rain forest site illustrate that canopy conductance (*G*) varies with meteorological conditions. *G* increases with photosynthetically active radiation (PAR), but less rapidly at higher values of *D*; the increase with temperature (*T*) is much greater at high than at (relatively) low temperatures; decreases with vapor pressure gradient between the foliage and the air (*D*) are very rapid at all air temperatures, but note the differences in the rate of decline, and the lowest values reached, at different air temperatures. © 1995 by John Wiley and Sons, reprinted with permission, taken from Lloyd *et al.* (1995).

$$g_s = g_{max}\, f_1(L)\, f_2(T)\, f_3(D)\, f_4(H_2O)\, f_5(CO_2).$$

# Stomatal Conductance

Stomatal conductance constrained by soil drought too

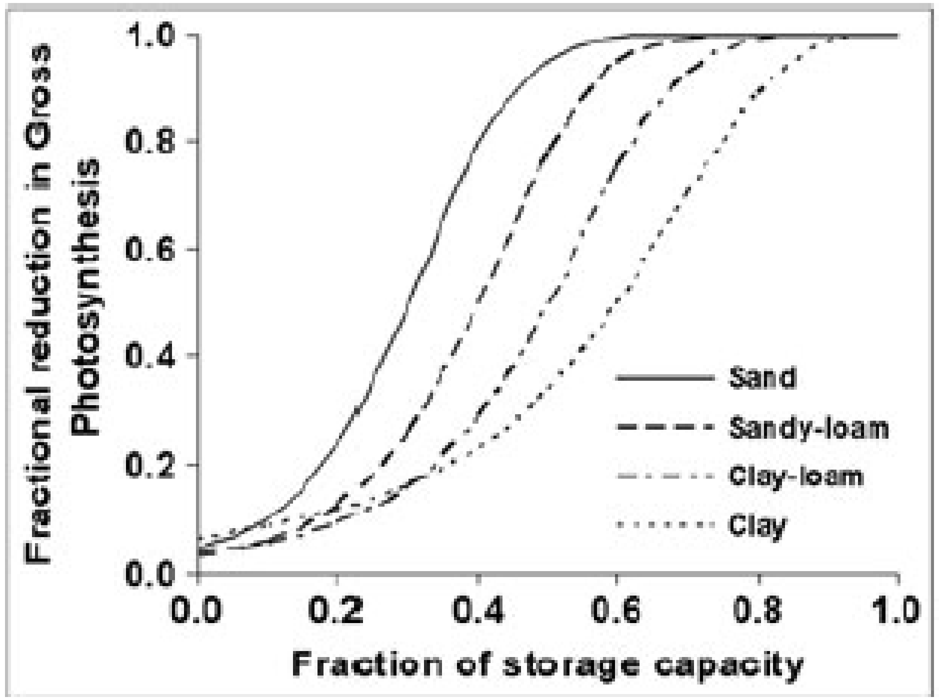



Figure 5. Coarse-textured soils hold water in a more readily available form than finer textured soils. As a result, the latter impose progressively more constraints on photosynthesis and transpiration as water is withdrawn from the soil profile (Landsberg and Waring, 1997).

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# Available Soil Water

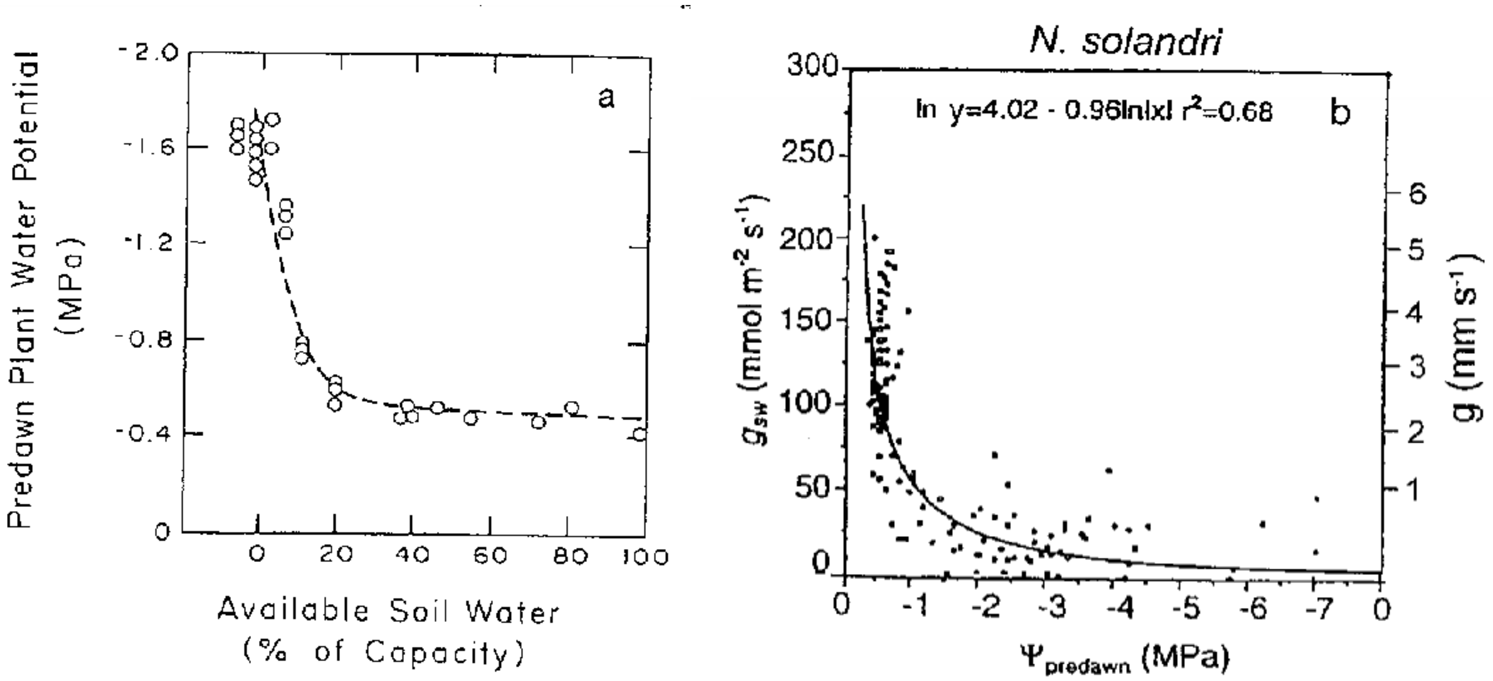


**FIGURE 2.13.** (a) Until more than three-quarters of the available water held between −0.01 and −1.5 MPa is depleted from the rooting zone, a pine stand exhibits a constant predawn water potential of −0.5 MPa. As the remaining available water is withdrawn from the soil, predawn Ψ falls rapidly to below −1.5 MPa. (After "Water potential in red pine: Soil moisture, evapotranspiration, crown position" by E. Sucoff, *Ecology*, 1972, 53, 681–686. Copyright © 1972 by the Ecological Society of America. Reprinted by permission.) (b) Maximum daily leaf stomatal conductance (*g*, in two alternative units) for *Nothofagus solandri*, native to New Zealand, shows an exponential decrease as predawn water potential ($\Psi_{predawn}$) falls. (After Sun *et al.*, 1995.)

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# Combining Drought and VPD Effects on Stomatal Conductance

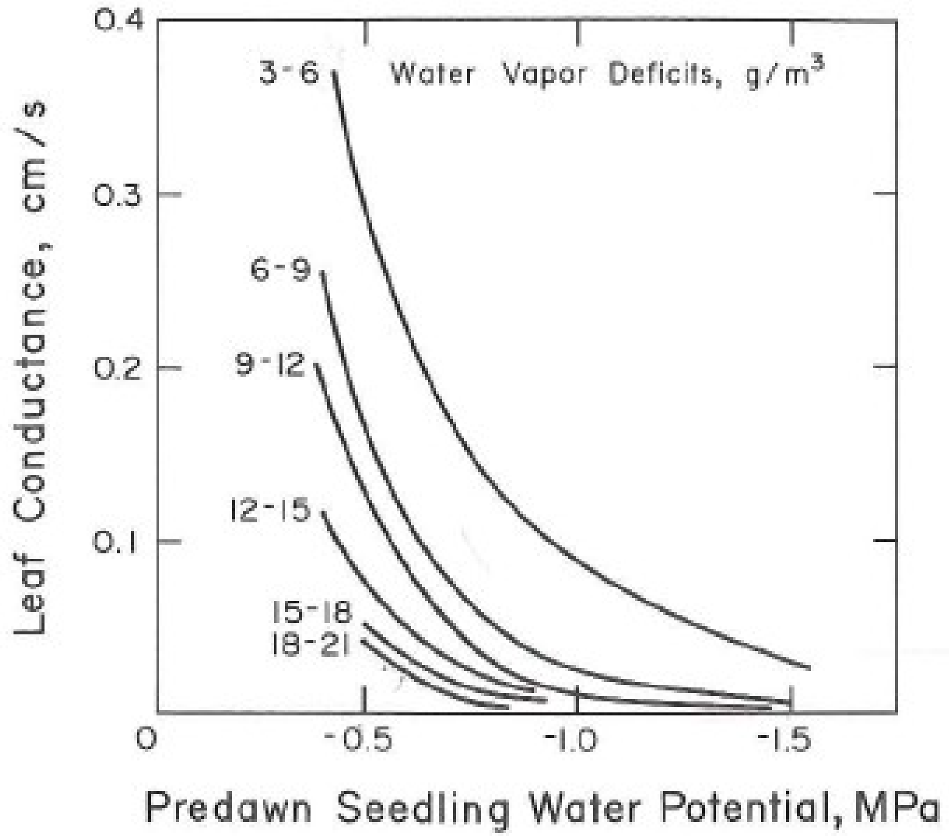


**Fig. 4.10.** As predawn water potentials decrease, young seedlings of Douglas fir close stomata more at a given water vapor deficit, here expressed in grams of water per cubic centimeter of air. (After Lassoie, 1982.)

$$\overbrace{\lambda_v E = \frac{\Delta(R_n - G) + \rho_a c_p (\delta e) g_a}{\Delta + \gamma(1 + g_a/g_s)}}^{\text{Energy flux rate}} \iff \overbrace{ET_o = \frac{\Delta(R_n - G) + \rho_a c_p (\delta e) g_a}{(\Delta + \gamma(1 + g_a/g_s)) L_v}}^{\text{Volume flux rate}}$$

# Penman-Monteith Equation

| | |
|---|---|
| *(Lambda)* $\lambda_v$ | = Latent heat of vaporization. Energy required per unit mass of water vaporized. (J $g^{-1}$) |
| $L_v$ | = Volumetric latent heat of vaporization. Energy required per water volume vaporized. (Lv = 2453 MJ $m^{-3}$) |
| $E$ | = Mass water evapotranspiration rate (g $s^{-1}$ $m^{-2}$) |
| $ET_o$ | = Water volume evapotranspired (mm $s^{-1}$) |
| *(Delta)* $\Delta$ | = Rate of change of saturation specific humidity with air temperature. (Pa $K^{-1}$) |
| $R_n$ | = Net irradiance (W $m^{-2}$), the external source of energy flux |
| $c_p$ | = Specific heat capacity of air (J $kg^{-1}$ $K^{-1}$) |
| *(rho)* $\rho_a$ | = dry air density (kg $m^{-3}$) |
| *(delta)* $\delta e$ | = vapor pressure deficit, or specific humidity (Pa) |
| $g_a$ | = Conductivity of air, atmospheric conductance (m $s^{-1}$) |
| $g_s$ | = Conductivity of stoma, surface conductance (m $s^{-1}$) |
| (gamma) $\gamma$ | = Psychrometric constant ($\gamma \approx 66$ Pa $K^{-1}$) |

**Monteith, J.L. 1965. Evaporation and the environment. Symp. Society Exp. Biol. 19:205-236**
**Derivation of PM equation**:
www.bsyse.wsu.edu/joan/teaching/bsyse556/W7/L7Joan.pdf

# Conclusions

1) **Evaporative Demand** is a function of net radiation, and the water vapor deficit between a surface and the air, and the momentum of wind.
2) **Surface temperature** varies with dimension of the surface, net radiation and wind speed, as they affect thickness of boundary layer
3) **Constraints on Evaporation** are imposed by the % wetness of the surface, canopy boundary layer and stomatal conductance
4) **Penman-Monteith Equation** combines demand and constraints of ET. When all foliage is wet, the canopy stomatal conductance is infinite.
5) **Drought** also affects stomatal conductance as best measured
   in reference to predawn plant water potential when plants are not transpiring.
6) **Atmospheric $CO_2$** increase allows reduction in stomatal conductance, increasing water-use efficiency.