Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Agricultural and Forest Meteorology 130 (2005) 39–58
AGRICULTURAL AND FOREST METEOROLOGY
www.elsevier.com/locate/agrformet

Vertical stratification of soil water storage and release dynamics in Pacific Northwest coniferous forests

J.M. Warren [a,*], F.C. Meinzer [a], J.R. Brooks [b], J.C. Domec [c]

[a] *USDA Forest Service, PNW Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331, USA*
[b] *Western Ecology Division, US EPA/NHEERL, Corvallis, OR 97333 USA*
[c] *Department of Wood Science and Engineering, Oregon State University, Corvallis, OR 97331, USA*

Received 21 July 2004; accepted 31 January 2005

Abstract

We characterized vertical variation in the seasonal release of stored soil moisture in old-growth ponderosa pine (OG-PP, xeric), and young and old-growth Douglas-fir (Y-DF, OG-DF, mesic) forests to evaluate changes in water availability for root uptake. Soil water potential (ψ) and volumetric water content (θ) were measured concurrently at 10 cm intervals to 1 m depth to create in situ soil water retention curves (SWRC) under drying conditions. Non-linear regression was used to fit SWRC specific to each depth and site. We also quantified root biomass, soil texture, and hydraulic redistribution (HR) of soil water by roots to identify factors affecting the seasonal dynamics of root water uptake and depletion from the soil profile. Soil θ measured at a particular ψ increased with soil depth, and was strongly dependent upon soil texture. For example, when ψ was -0.1 MPa, θ ranged from 13% at 20 cm to 35% at 100 cm for the OG-DF forest. Soil texture and bulk density accounted for 60–90% of the variation in the SWRC. As the summer drought progressed, water extraction shifted to the deeper layers, and recharge from HR approached 0.15 mm day^{-1} in the upper 60 cm for all sites. Total water use from the upper 2 m at all sites peaked between 1.5–2.5 mm day^{-1} in mid-July and then declined to 0.5–1.0 mm day^{-1} by the end of the dry season. Total fine root biomass in the upper 1 m was 0.77 kg m^{-2} (OG-PP), 1.08 kg m^{-2} (OG-DF) and 1.15 kg m^{-2} (Y-DF), with 40% (PP) to 60% (DF) of fine roots located in the upper 20 cm. However, the upper 20 cm only accounted for 20% of total water depletion from the upper 2 m at peak water uptake, declining to 4–6% later in the season, illustrating the contribution of deeper roots to water uptake. Nevertheless, daily water uptake from the entire 2 m profile was strongly dependent on water potential at 20 cm, indicating that fine roots in the upper soil may play an important role in regulating water uptake through hydraulic effects on stomatal conductance.

Keywords: Root water uptake; Soil water modeling; Water retention curve; Hydraulic redistribution; Water potential; Volumetric water content; Douglas-fir; Ponderosa pine

1. Introduction

Plant communities that experience low precipitation inputs during the growing season must rely on

* Corresponding author. Tel.: +1 541 758 8766; fax: +1 541 750 7329.
E-mail address: jeffwarren@fs.fed.us (J.M. Warren).

0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2005.01.004

plant or soil water storage to provide adequate water for growth processes. The uptake of stored soil water by roots depends on soil physical and chemical characteristics and is driven by water potential gradients within the soil-plant-atmosphere continuum. The dynamics of soil water storage and release (uptake) from the unsaturated vadose zone govern various aspects of ecosystem functioning. A good understanding of soil water dynamics is therefore, critical for modeling water and heat flux, plant productivity and stand development. However, belowground processes are technically more difficult to quantify than aboveground processes due to the much denser and arguably more heterogeneous soil medium. As such, in situ physical and physiological data from belowground observations for use in modeling water and carbon dynamics through ecosystems are relatively scarce, which often necessitates a simplified 'black box' style treatment of some processes.

Soil water release under drying conditions is site- and depth-specific, and is non-linearly related to soil water potential (Brooks and Corey, 1964; van Genuchten, 1980). Measurement of soil water content (θ) and soil water potential (ψ) in the field is expensive, time consuming and technically difficult and thus datasets containing concurrent in situ measurements of θ and ψ are scarce (e.g., Bréda et al., 1995; Katul et al., 1997). Soil water retention curves (SWRC) relating θ and ψ are more frequently generated by progressively drying soil cores in the lab where θ and ψ are easily measured gravimetrically (θ) or with pressure plates (ψ) (e.g., Abrahamson et al., 1998; Heiskanen and Mäkitalo, 2002). Another alternative is to measure soil physical characteristics, such as soil texture, bulk density (BD) or organic matter, which affect the release of stored water under drying conditions in a predictable manner. Soil particle size distribution (sand, silt, and clay (%)) and/or other soil characteristics can be substituted into pedotransfer functions (Saxton et al., 1986; Wösten et al., 2001) to generate SWRC that relate water content to water potential (Brooks and Corey, 1964; van Genuchten, 1980). Related equations can also be used to estimate unsaturated soil hydraulic conductivity if saturated conductivity is known (Mualem, 1976; van Genuchten, 1980). Thus, in principle, the general dynamics of soil water movement and release can be estimated using only a few simple equations. However, comparisons with empirical in situ data to test the validity of this approach are rare.

It has been widely reported that water uptake and growth of shallowly-rooted herbaceous crops and grasses falls precipitously as ψ declines (e.g., Yang and de Jong, 1971; Childs and Hanks, 1975; Schleiff and Schaffer, 1984; Zhang and Davies, 1989; Dean-Knox et al., 1998). However, few field studies have described the dependence of water uptake by woody roots on ψ in forest vegetation that experiences prolonged seasonal drought (e.g., Bréda et al., 1995). In coniferous forests of the Pacific Northwest, for example, water potential in the upper soil horizons commonly falls below -1.5 MPa during the dry summer months (Meinzer et al., 2004; Domec et al., 2004), yet forest transpiration is sustained at relatively high rates (Irvine et al., 2002). This implies that shallow roots of coniferous trees are able to continue extracting soil water at very low water potentials or that a substantial fraction of transpired water is taken up by deep roots located in horizons where ψ is closer to zero. Predawn leaf water potential has routinely been used as a surrogate for ψ (e.g., Law et al., 2000b), but several recent reports indicate that substantial predawn disequilibrium between plant and ψ can exist owing to factors such as nocturnal transpiration and hydraulic redistribution, especially for ecosystems that experience extended dry seasons (e.g., Donovan et al., 2003; Bucci et al., 2004). Thus, the most reliable way to evaluate ψ and its impact on root water uptake is to either measure it directly, or to validate models that predict ψ from soil physical characteristics and the more easily measured θ.

In the present study, we characterized vertical gradients in θ, ψ, and the underlying soil physical and biological characteristics for three contrasting coniferous forest ecosystems in Oregon and Washington, USA during a seasonal dry period. These measurements allowed us to evaluate the range of physiologically available soil water storage, the effect of hydraulic redistribution on θ, ψ, and vertical gradients in soil water release characteristics. The semiarid ponderosa pine ecosystem and two mesic Douglas-fir ecosystems studied have been extensively investigated and some of their key processes modeled over the past several years (Law et al., 2000a,b; Phillips et al., 2002; Licata, 2003; Unsworth et al., 2004; Chen et al., 2004). Our goals were to create site-specific in situ SWRC