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Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands

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ABSTRACT

We used the eddy-covariance technique to measure evapotranspiration (E) and gross primary production (GPP) in a chronosequence of three coastal Douglas-fir (*Pseudotsuga menziesii*) stands (7, 19 and 58 years old in 2007, hereafter referred to as HDF00, HDF88 and DF49, respectively) since 1998. Here, we focus on the controls on canopy conductance (g_c), E, GPP and water use efficiency (WUE) and the effect of interannual climate variability at the intermediate-aged stand (DF49) and then analyze the effects of stand age following clearcut harvesting on these characteristics. Daytime dry-foliage Priestley–Taylor α and g_c at DF49 were 0.4–0.8 and 2–6 mm s^{-1}, respectively, and were linearly correlated (R^2 = 0.65). Low values of α and g_c at DF49 as well at the other two stands suggested stomatal limitation to transpiration. Monthly E, however, showed strong positive linear correlations to monthly net radiation (R^2 = 0.94), air temperature (R^2 = 0.77), and daytime vapour pressure deficit (R^2 = 0.76). During July–September, monthly E (mm) was linearly correlated to monthly mean soil water content (θ, $m^3\ m^{-3}$) in the 0–60 cm layer ($E = 453\theta - 21$, R^2 = 0.69), and GPP was similarly affected. Annual E and GPP of DF49 for the period 1998–2007 varied from 370 to 430 mm and from 1950 to 2390 g C m^{-2}, respectively. After clearcut harvesting, E dropped to about 70% of that for DF49 while ecosystem evapotranspiration was fully recovered when stand age was ~12 years. This contrasted to GPP, which varied hyperbolically with stand age. Monthly GPP showed a strong positive linear relationship with E irrespective of the stand age. While annual WUE of HDF00 and HDF88 varied with age from 0.5 to 4.1 g C m^{-2} kg^{-1} and from 2.8 to 4.4 g C m^{-2} kg^{-1}, respectively, it was quite conservative at ~5.3 g C m^{-2} kg^{-1} for DF49. N-fertilization had little first-year response on E and WUE. This study not only provides important results for a more detailed validation of process-based models but also helps in predicting the influences of climate change and forest management on water vapour and CO_2 fluxes in Douglas-fir forests.

1. Introduction

Water is an important factor influencing forest growth and thereby potential carbon (C) uptake by photosynthesis (Baldocchi, 1997; Arneth et al., 1998). The study of evapotranspiration is fundamental to understanding terrestrial ecosystems. Evapotranspiration (E) is a major component of the earth's surface energy balance that determines behaviour of the planetary boundary layer. Studying E from forests is also important in relation to regional climate through surface–atmosphere interactions (Garratt, 1993; Bonan, 2008). This can affect mesoscale circulation patterns and thus the weather (e.g., Andre et al., 1989). E can also be a large term in the water balance of catchments supplying water for domestic and industrial purposes. Since plants need to take-up carbon dioxide (CO_2) for C assimilation, they need to open their stomata as much as possible. On the other hand, this strategy risks wasting much water, which is required to maintain hydration and physiological functioning. It has been determined that plants control the opening of stomata to optimally satisfy the trade-off between the amount of C assimilated and the amount of water transpired (Cowan and Farquhar, 1977). Stomatal conductance determines both diffusion of CO_2 into and diffusion of water out of the leaf with the diffusion coefficient of H_2O being 1.6 times greater than for the lighter CO_2 molecules. Besides the leaf-level response to environmental change, understanding the response of the whole ecosystem is critical to evaluating the potential impacts of climate change.

Douglas-fir, an important timber species, occupies a large area in the Pacific Northwest (PNW) and is an important part of the economy. The climate of this area is characterized by wet, mild winters and dry, warm summers. Low summer precipitation can cause summer droughts, which contrasts this region with most

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other temperate regions in Europe and Asia where precipitation is relatively constant throughout the year (Waring and Franklin, 1979). The climate of the PNW is changing and according to the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2007) the change will continue at an even faster rate. The PNW will have greater warming and changes in precipitation than the global average (Mote, 2003; Spittlehouse, 2008). Summers will be drier and winters will be wetter. Past research on coastal Douglas-fir stands through the summer months has found transpiration to be strongly limited by canopy conductance (Humphreys et al., 2003), which in turn depended on soil water potential and the water vapour saturation deficit of the air (Black, 1979; Tan and Black, 1976). Summer soil water deficit has been found to significantly decrease ecosystem photosynthesis (GPP), respiration (*R*) and *E* in coastal Douglas-fir stands (Jassal et al., 2007, 2008a).

To predict changes in water use and productivity of coastal Douglas-fir under changing climate, it is essential to understand the environmental controls of *E* and CO_2 uptake (i.e., GPP) at stand and ecosystem scales. Water use efficiency (WUE), defined as GPP/*E* (i.e., inverse of transpiration ratio (TR) (Briggs and Shantz, 1913)), indicates water-use strategy at different life stages of plants (Donovan and Ehleringer, 1991), and can be used for evaluating the effects of water resources on the functioning of an ecosystem as a C sink or a source. Seasonal and interannual climate variability and interactive effects of plant nutrients and soil water supply may influence GPP and *E* differently, and hence WUE through their effects on energy partitioning and canopy conductance. Since part of *E* is due to evaporation from the soil and wet leaf surfaces (due to precipitation interception), stand structure and age are expected to strongly influence WUE. To predict the associated changes in productivity, it is essential to understand how WUE changes with climate (Xu and Hsiao, 2004). The eddy-covariance (EC) technique, which provides direct measurements of carbon and water exchanges between atmosphere and ecosystem, can be used in studying the characteristics of *E*, GPP and WUE, and their responses and adaptations to global climate change at the ecosystem scale (Law et al., 2002; Baldocchi, 2003; Barr et al., 2006).

Using EC, we have been measuring *E* and GPP, and climatic variables in a chronosequence of three coastal Douglas-fir stands since 1998. There is need to synthesize this long-term dataset to understand how, compared to GPP, *E* and its response to environmental controls, especially summer drought, as well as management, depend on stand structure. This is also necessary for assessing the impact of climate change as well as vegetation feedback on climate over the course of stand development. El Niño-Southern Oscillations (ENSO) cause significant interannual climate variation in this region with the landscape undergoing annual soil water deficit in July–September due to low rainfall in these months. As soil (e.g., water and nutrients) and atmospheric (e.g., radiation) resources vary with interannual variation in climate, the resultant variations in above- and belowground translocation (Brower, 1997) will likely influence WUE. Gessel et al. (1990) showed that soil nitrogen availability strongly effects growth of coastal Douglas-fir. The three stands were fertilized with urea at 200 kg N ha^{-1} in January 2007 to evaluate the response of *E* and GPP. Specifically, the objectives of this paper are (i) to evaluate the variations in canopy conductance (g_c) and its impact on *E* and GPP on seasonal and annual time scales in the three stands, with a special emphasis on DF49 due to its long record of measurements, and (ii) to describe the effects of stand age following clearcut harvesting and seasonal and interannual climate variability on *E* and WUE in west coast Douglas-fir. We also report the change in these entities in the three stands in the first year after N-fertilization.

2. Materials and methods

2.1. Site descriptions

The measurements were made in three coastal Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) stands on the east coast of Vancouver Island, BC, Canada. This area is classed as seasonally dry temperate rainforest (Meidinger and Pojar, 1991). The three stands that spanned the typical ages of forests found in this region, were 7, 19 and 58 years old in 2007, and are henceforth referred to as HDF00, HDF88 and DF49, respectively. The soils at the three stands are humo-ferric podzols with similar concentrations of C and N measured in the surface organic horizons and mineral soil layers. However, the depth of the surface organic horizons varied between and within stands with the deepest average depth at HDF88. The active growing season extends from March to October. Notwithstanding slight differences in soil characteristics and elevation, the three stands are located within similar biogeoclimatic units of the dry maritime Coastal Western Hemlock subzone, CWHxm (Meidinger and Pojar, 1991). Overall, differences in *E* among stands can be treated as being mainly related to stand age and corresponding differences in stand structural characteristics.

The intermediate-aged stand, DF49 (~130 ha) is located about 10 km southwest of Campbell River (49°52′7.8″N, 125°20′6.3″W, 300 m above mean sea level (amsl), flux-tower location), The site naturally regenerated after a forest fire. Stand density in 2007 was about 1100 stems ha^{-1}, tree height was about 33 m, mean tree diameter at the 1.3 m height was 31 cm, and leaf area index (LAI) was 7.3 (Chen et al., 2006). The stand consists primarily of Douglas-fir (*Pseudotsuga menezeisii* (Mirbel) Franco) (77%), with lesser proportions of western red cedar (*Thuja plicata* Donn) (18%) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (4.6%). Understory at the site is sparse, mainly consisting of salal (*Gaultheria shallon* Pursh.), Oregon grape (*Berberis nervosa* Pursh.), vanilla-leaf deer foot (*Achlys triphylla* DC) and a shallow layer of ferns and mosses. The soil, a Quimper sandy loam with a variable surface LFH organic layer of 0–6 cm thick, is underlain with a dense compacted till at a depth of 1 m (Jungen, 1986). Below the organic layer, soil texture gradually changes to gravelly loamy sand in the upper 40 cm and to gravelly sand with increasing depth. The mean annual temperature and precipitation at the site are 8.6 °C and 1470 mm, respectively, and the site is occasionally subjected to a soil water deficit in August, September and October. Further details on soil and vegetation characteristics of the three stands can be found in Humphreys et al. (2006).

The second stand (49°31′11.0″N, 124°54′6.0″W, 170 m amsl, flux-tower location), HDF88 (~110 ha) is situated 30 km southwest of DF49 and 4 km northwest of Buckley Bay. The site, on 2–5% sloping terrain, was harvested in 1987; broadcast burned and planted in 1988 with 75% Douglas-fir, 21% western red cedar and 4% grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.). Stand density in 2007 was 1200 stems ha^{-1}, mean tree height was 7.5 m, mean tree diameter at the 1.3 m height was 8 cm, and mean annual LAI was 5.0. The stand has a dense understory of deciduous and evergreen species such as fireweed (*Epilobium angustifolium* L. s.l.), sword fern (*Polystichum munitum* (Kaulf.) C. Presl) and bracken fern (*Pteridium aquilinum* (L.) Kuhn), salal, Rubus spp., and red huckleberry (*Vaccinium* parvifolium Sm.). The soil is a deep (>1 m) gravelly loam with a 24% coarse (>2 mm diameter) fraction. The mean annual temperature and rainfall at the site are 9.6 °C and 1610 mm, respectively.

The youngest stand, HDF00 (49°52′20.0″N, 125°17′32.0″W, 175 m amsl, flux-tower location) is located about 2 km southeast of DF49 at an elevation of 175 m. Prior to planting in the early