

Turbulence considerations for comparing ecosystem exchange over old-growth and clear-cut stands for limited fetch and complex canopy flow conditions

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ABSTRACT

Carbon dioxide, water vapor, and energy fluxes were measured using eddy covariance (EC) methodology over three adjacent evergreen forests in southern Washington State to identify stand-level age-effects on ecosystem exchange. The sites represent Douglas-fir forest ecosystems at two contrasting successional stages: old-growth (OG) and early seral (ES). Here we present eddy flux and meteorological data from two early seral stands and the Wind River AmeriFlux old-growth forest during the growing season (March–October) in 2006 and 2007. We show an alternative approach to the usual friction velocity (u_*) method for determining periods of adequate atmospheric boundary layer mixing based on the ratio of mean horizontal (U) or vertical (W) wind flow to a modified turbulent kinetic energy scale (U_{TKE}). This new parameter in addition to footprint modeling showed that daytime CO_2 fluxes (F_{NEE}) in small clear-cuts (<10 ha) can be measured accurately with EC if micrometeorological conditions are carefully evaluated.

Peak midday CO_2 fluxes ($F_{NEE} = -14.0$ to $-12.3 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$) at OG were measured in April in both 2006 and 2007 before bud break when air and soil temperatures and vapor pressure deficit were relatively low, and soil moisture and light levels were favorable for photosynthesis. At the early seral stands, peak midday CO_2 fluxes ($F_{NEE} = -11.0$ to $-8.7 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$) were measured in June and July while spring-time CO_2 fluxes were much smaller ($F_{NEE} = -3.8$ to $-3.6 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$). Overall, we measured lower evapotranspiration (OG = 230 mm, ES = 297 mm), higher midday F_{NEE} (OG $F_{NEE} = -9.0 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$, ES $F_{NEE} = -7.3 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$) and higher Bowen ratios (OG $B = 2.0$, ES $B = 1.2$) at the old-growth forest than at the ES sites during the summer months (May–August). Eddy covariance studies such as ours add critical land-atmosphere exchange data for an abundant, but rarely studied Douglas-fir age class.

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1. Introduction

The Pacific Northwest region of the U.S. is one of the most productive forested areas in the world and its future role in the terrestrial carbon cycle will be dependent on how silviculture practices alter the age structure of these forests (Song and Woodcock, 2002). Over the past 50 years, staggered-set clear-cutting on local Federal lands has created a fragmented landscape of different age Douglas-fir forests ranging from early seral (ES) (0–15 years), young (15–80 years), intermediate (80–200 years), mature (200–400 years), to old-growth (OG) (approximately greater than 400 years old). While early seral stands can compromise up to 40% of total forest coverage in the Western Cascade Mountains (Cohen

et al., 1996) and are an essential component of the regional assessment of CO_2 fluxes, ecosystem exchange within this youngest age class has not been thoroughly studied with eddy covariance (EC).

Ecosystem responses to seasonal climate (e.g., summer drought), timing of extreme weather events (e.g., summer rain pulses), and phenological changes (e.g., bud break) likely vary with stand age and affect biosphere-atmosphere exchange. Yet, our understanding of stand-level age-effects remains limited for several reasons. One difficulty that often restricts chronosequence flux studies is the presence of vastly different species distributions making it hard to compare mature and young forest sites for age-effects. All of our study sites at Wind River are dominated or co-dominated by Douglas-fir, an extremely long-lived (up to ~1000 years) pioneering species. Second, the placement of study sites must be carefully considered in order to reduce regional or terrain-induced weather differences from misinterpreting stand-level comparisons. This means that the forests of interest may need to be within a couple of kilometers of each other in a complex terrain environment. And last, since early seral stands are often the result

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of a size-restricted harvest on Federal lands, they are limited by the size of fetch. This creates a unique set of micrometeorological concerns for the eddy covariance technique which will be discussed next.

A desirable fetch-to-instrument height ratio in micrometeorological applications is dependent on atmospheric boundary layer (ABL) stability and surface-canopy roughness but has generally been accepted at ~40:1 (e.g., Kruijt, 1994; Schmid, 1994; Irvine et al., 1997). Fetch requirements in small, individual forest stands (e.g., clear-cuts) within a heterogeneous vegetative area are less certain and may be more site-specific. In one study done by van Breugel et al. (1999), a fetch:instrument height ratio of 36:1 ensured that the EC instruments were measuring turbulent fluxes within the equilibrium layer (part of the atmosphere where the local stress is largely in equilibrium with the underlying vegetative surface) under most atmospheric conditions over a patchy Netherlands forest landscape. A similar, but broader fetch:instrument height range was estimated at 25 to 50:1 by Kolari et al. (2004) who looked at turbulent fluxes over a 7 ha, 12-year-old clear-cut in Southern Finland. Equilibrium layer depth, in addition to being sensitive to site-specific canopy roughness, also varies dramatically during the course of a day. The ABL tends towards stable conditions at night and moderately stable-to-convective conditions during the day depending on the production and dissipation of buoyancy-driven turbulence and production of Shear-generated turbulence. Atmospheric mixing near the surface is further complicated by variable topography which creates complex wind flows including strong, along-valley-axis flows (wind direction shifts) and gravity-driven, mountain-valley flows that are particularly strong at night.

Prior chronosequence flux studies in very young (re-established after a clear-cut disturbance) and mature conifer forests have not shown universal results in regards to stand age-effects on ecosystem exchange. Most of the site variability has occurred in the growing season energy and water vapor fluxes, while CO₂ exchange tends to have greater age-specific trends. Some research suggests that rates of evapotranspiration (E_T) in early seral and mature forests are nearly equal (Amiro et al., 2006) while other studies have found significant age-related differences (Anthoni et al., 2002). Nearly all age-effect studies have shown that net carbon uptake is greater in mature conifer stands than in the 0–20-year-age class (e.g., Anthoni et al., 2002; Irvine et al., 2002; Law et al., 2003; Thomas and Winner, 2002; Amiro et al., 2006; Humphreys et al., 2006). At Wind River, four Douglas fir age classes have been studied for age-effects on CO₂ or H₂O exchange: early seral (this study, Bauerle et al., 1999; Thomas and Winner, 2002), 20-year-old (Chen et al., 2002, 2004; Phillips et al., 2002; McDowell et al., 2005), 40-year-old (Chen et al., 2002, 2004; Phillips et al., 2002), and old-growth (this study, Bauerle et al., 1999; Chen et al., 2002, 2004; Phillips et al., 2002; Thomas and Winner, 2002; Paw U et al., 2004; Unsworth et al., 2004; Winner et al., 2004; Falk et al., 2005, 2008). Even across the Wind River chronosequence the studies have not shown similar age-related results. For example, measurements by Chen et al. (2004) and Thomas and Winner (2002) indicated higher photosynthetic rates in the old-growth trees than in the youngest stands while McDowell et al. (2005) and Bauerle et al. (1999) found no significant age-related differences.

Our study represents the longest, continuous record of flux exchange at Wind River for the early seral age class. Presented are data from two early seral stands of nearly identical age and species composition. Our goals were to (1) determine whether fluxes can be accurately measured in typical Douglas-fir early seral stands of the Pacific Northwest and (2) identify any growing season or drought season flux differences between the old-growth and early seral stands. For a in-depth analysis of ecophysiological response' to age-effects see Wharton et al. (2009).

2. Site description and instrumentation

2.1. Overview

Despite the surrounding complex terrain of the Western Cascade Mountains, the three forest sites are located in a relatively flat valley (slope is 3.5%) in southern Washington State. The predominant wind direction is from the west although valley flow (northwest-southeast) wind shifts are also common. The climate at Wind River is dominated by two distinct seasons: a cool, wet winter and a warm, dry summer. Very little rain (<10% of 2233 mm annual average) typically falls from July through August and consistent precipitation usually does not return to the area until the end of October. This study uses daily precipitation (P) data collected 5 km north of Wind River at the Carson Fish Hatchery (CFH) NOAA Meteorological Station (45°31'12"N, 121°34'48"W; 345.6 m above sea level) and acquired from the National Climatic Data Center (<http://cdo.ncdc.noaa.gov/CDO/cdo>). EC and micrometeorological data were measured continuously at the old-growth forest from January to December 2006 (OG06) and January to December 2007 (OG07) although winter data (November–February) are not presented here. Data were collected at early seral north (ESN06) during the 2006 growing season and at early seral south (ESS07) during the 2007 growing season. Growing season is defined here as March–October; drought season as July–October. Detailed data availability periods and gap-filled data percentages are listed in Table 1.

2.2. Old-growth forest

The Wind River Canopy Crane (45°49'13.76"N, 121°57'06.88"W; 371 m a.s.l.) is located in a 500-ha old-growth, coniferous forest in the T.T. Munger Research Natural Area, a protected section of the Gifford Pinelot National Forest (Fig. 1). The site has been unmanaged for centuries since originating from a natural fire disturbance. A detailed site description for the Wind River old-growth forest is given by Shaw et al. (2004). In brief, the two dominant tree species are Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Trees within the stand range in age from 0 to approximately 500 years old and reach maximum heights of 60 m. Leaf area index (LAI) is between 8.2 and 9.2 m² m⁻² (Parker et al., 2004) and does not change significantly from year to year or season to season (Thomas and Winner, 2000). Despite a co-dominance of western hemlock, Douglas-fir likely exert significant control over carbon uptake in the stand since their crowns are located in the highest light environment of all canopy species (Thomas and Winner, 2000). The soils are classified as medial, mesic, Entic Vitrandis and are 2–3 m deep. These soils are homogeneous rock-free and have a low bulk density and high organic matter content. The water table generally ranges from 0.4 m in the winter rainy season to 2 m in late summer (Shaw et al., 2004). Most tree roots are found within the first 0.5 m although roots of mature Douglas-fir can extend depths of one to two meters. Table 1 lists additional stand characteristics.

We provide a short description of the eddy covariance set-up here while more detailed descriptions of the methodology are given by Paw U et al. (2004), Falk (2005), and Falk et al. (2008). The EC system consisted of a sonic anemometer (Solent HS, Gill Instruments, Lymington, England, UK) and a closed-path infrared gas analyzer (IRGA) (LI-7000, LI-COR Inc., Lincoln, Nebraska, USA) which measured the wind velocity vectors and sonic temperature, and concentrations (mixing ratios) of H₂O and CO₂, respectively, at 10 Hz. The IRGA and sonic anemometer were mounted at the end of a 5-m long boom at a height of 67 m above ground level on the crane tower. The anemometer faced west towards the maximum

Table 1
Stand characteristics and flux tower descriptions.

	Early seral north	Early seral south	Old-growth stand
Measurement period			
2006	27 March–25 October		1 March–31 October
2007		14 April–31 August	1 March–31 October
Gap-filled data			
EC flux*	36%	25%	16% (2006), 11% (2007)
Micro-meteorological	29%	4%	1% (2006), 1% (2007)
Stand properties			
Maximum tree age (years)	10	14	~450–500
Stand area (ha)	7	10	478
Slope (%)	<10	<5	3.5
Site preparation	Minimal: abundant coarse woody debris (CWD): snags, logs	Extensive: no CWD, mechanically homogenized soil to 1 m	None: natural fire recovery
Mean h_c (m)	4.4	3.6	50
LAI ($m^2 m^{-2}$)	1.1–1.8	0.6–1.1	8.2–9.2 (Parker et al., 2004)
Foliar N%; Foliar C:N	1.2; 44:1 $\pm$ 3	1.4; 37:1 $\pm$ 3	1.2; 41:1 (Klopatek et al., 2006)
Soil properties			
sand:silt:clay	66:28:6	62:29:9	60:31:9 (Shaw et al., 2004)
C:N	27:1 $\pm$ 6	26:1 $\pm$ 3	25:1 $\pm$ 1 (Klopatek, 2002)
Tree bulk density ($g cm^{-3}$)	0.94	1.07	0.83

* Percentage of daylight hours.

area of homogeneous vegetation (1–2 km). Footprint modeling (following analytical solutions given by Wilson and Swaters, 1991) was done by Paw U et al. (2004) and Falk (2005). Their results showed that the source area affecting the vertical flux at the canopy crane is within the old-growth stand boundaries for nearly all wind directions under unstable atmospheric conditions but extends outside the stand under very stable conditions.

Air temperature and relative humidity (sheltered HMP-35C, Vaisala Oyj, Helsinki, Finland) and photosynthetically active radiation (PAR) (190-SB, LI-COR Inc.) were measured at heights

of 2 m (below canopy) and 70 m (above canopy) along the canopy crane tower. Vapor pressure deficit (VPD) was calculated from air temperature and relative humidity measurements. Volumetric soil water content was measured at an integrated depth of 0–30 cm in 2006 with a time-domain reflectometry (TDR) system (TDR100, Campbell Scientific Inc., Logan, Utah, USA). In 2007, soil water content was measured with four Sentek soil moisture probes at incremental depths from 20 to 200 cm (Sentek EnviroSMART, Sentek Sensor Technologies, Stepney, Australia). The ground heat flux was measured with a HFT-3.1 (REBS, Seattle, Washington,

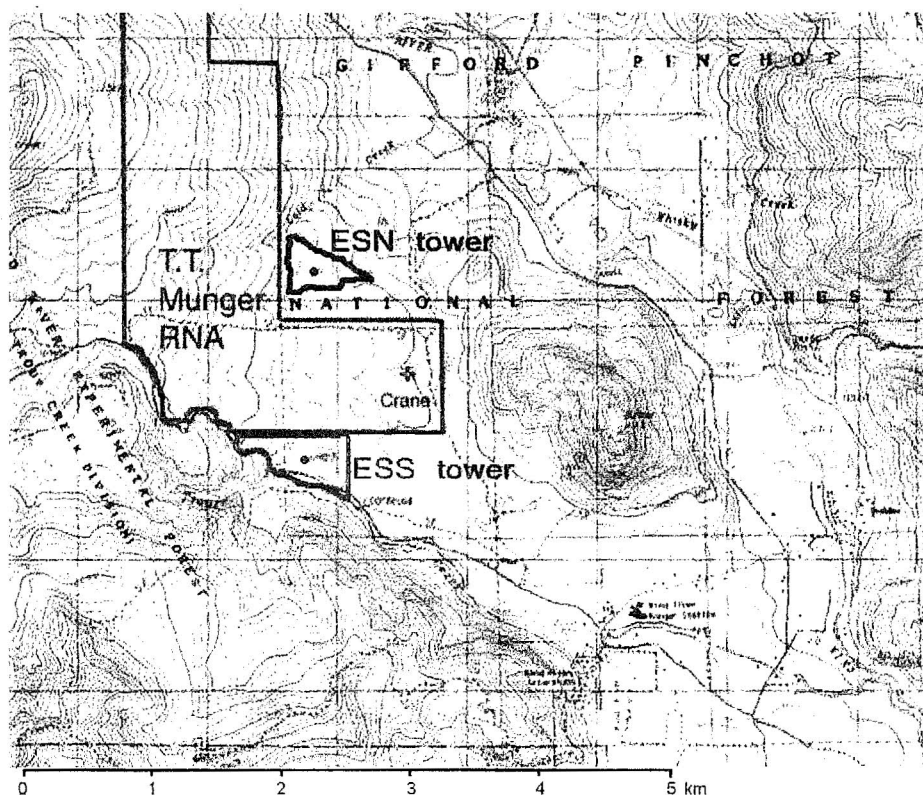


Fig. 1. Location of the old-growth canopy crane, two early seral flux towers, and stand boundaries within the surrounding terrain of the Gifford Pinchot National Forest, Southern Washington. Bunker Hill is directly east-southeast of the Canopy Crane and Trout Creek Hill is located on the northwest corner of the map.

USA) soil heat flux plate buried 7.5 cm below the surface. The meteorological measurements were collected as 30-min averages.

2.3. Early seral north

The early seral north (ESN06, measured in 2006) flux tower (45°49'37.2"N, 121°57'39.6"W; 361 m a.s.l.) was located in a 7 ha clear-cut on the southeastern foot of Trout Creek Hill and was 1.25 km northwest of the Wind River Canopy Crane (Fig. 1). Topographic slope is from west to east and is less than 10%. This is a third generation Douglas-fir forest: the original old-growth trees were logged in 1920 and a clear-cut harvest was done in 1994 on 80-year-old Douglas-fir. The harvested stand is surrounded by 40 m tall, 80-year-old trees. In 1997, five plots were planted with Douglas-fir (*P. menziesii*) and red alder (*Alnus rubra*) saplings as part of a Hardwood Silviculture Cooperative Type 3 project. Each plot was planted with 741 trees per hectare in various species proportions and no fertilization treatments were applied. In September 2005 we erected a 6-m tall flux tower in the 100% Douglas-fir planted plot. At that time standing biomass measurements were taken ($n=45$): mean tree height was 4.4 m, height range was 1.2–5.3 m, and mean diameter at breast height (d.b.h.) was 5.7 cm. The five planted blocks covered roughly half of the stand; the remainder was dominated by naturally seeded Douglas-fir. Western hemlock (*T. heterophylla*) and western white pine (*Pinus monticola*) seedlings were also present in insignificant amounts. Dominant ground cover species included salal (*Gaultheria shallon*), Oregon grape (*Berberis nervosa*), bracken fern (*Pteridium aquilinum*), sword fern (*Polystichum munitum*) and blackberry (*Rubus ursinus*).

EC estimates of vertical H_2O and CO_2 fluxes were made using a CSAT-3 sonic anemometer (Campbell Scientific Inc.) and an open-path fast response LI-7500 IRGA (LI-COR Inc.) which measured the wind velocity vectors, air temperature, and densities of CO_2 and H_2O vapor above the canopy. The sonic anemometer was mounted facing west-southwest and pointed in the direction of greatest homogenous fetch (200 m of even-aged Douglas-fir). Both the LI-7500 and CSAT-3 were mounted at 5.5 m a.g.l., 1.1 m above the canopy, on a boom extending from a 6-m tall triangular-frame steel tower. The EC data were measured at 10 Hz and 30-min averages were archived in the field using a CR1000 data logger (Campbell Scientific Inc.). Meteorological data included half-hour measurements of air temperature and relative humidity (sheltered HMP-35C, Vaisala Oyj), net radiation (Q7.1, REBS), soil temperature (5, 10 and 15 cm) (CS106B, Campbell Scientific Inc.), and volumetric soil moisture (two replicates of 0–30 and 30–60 cm integrated depths) (TDR100, Campbell Scientific Inc.).

2.4. Early seral south

The early seral south (ESS07, measured in 2007) flux tower (45°48'47.4"N, 121°57'32.9"W; 371 m a.s.l.) was located in a 10 ha abandoned clear-cut (1985), 910 m southwest of the canopy crane (Fig. 1) and was naturally seeded with Douglas-fir from surrounding cone crops. Tree measurements were taken three times at 4-month intervals in 2007. Average tree height ($n=95$) was 3.3 ± 0.8 m in April, 3.9 ± 0.9 m in July, and 4.0 ± 1.0 m in October. Tree diameter was additionally measured in July (d.b.h. = 4.6 ± 1.6 cm) and October (d.b.h. = 4.7 ± 1.4 cm). Estimated tree density was 1063 trees per hectare (eight sampled plots of 100 m² each). Above-ground biomass (stem wood + stem bark + live branch + total foliage) was estimated at 14.5 Mg C ha⁻¹ using allometric equations derived from regional Douglas-fir data (Grier and Logan, 1977). The average Douglas-fir tree was 9–14 years of age in July 2007 (tree cores, $n=10$). Other tree species included western white pine, red alder, and planted Pacific silver fir (*Abies amabilis*) and

Pacific yew (*Taxus brevifolia*) saplings in insignificant amounts. Bracken fern was the dominant ground species. Grass species and scotch broom (*Cytisus scoparius*) were also common in the more open areas. The EC system was identical to the setup used at ESN except that the sonic anemometer was mounted facing south and the instruments were placed at a height of 5 m, 1.4 m above the canopy. The meteorological instrumentation was also identical to ESN, and in addition we added up- and down-facing PAR sensors (190-SB, LI-COR Inc.) and two TDR soil moisture probes at 60–90 cm depth. All early seral instruments were powered using a 110 W solar panel and bank of batteries. Soil samples (three replicates at two measurement depths) were dug up at ESN06 and ESS07 and brought to the ANR Analytical Laboratory at UC Davis for analysis in September 2007.

3. Materials and methods

3.1. Flux calculations and corrections

3.1.1. Old-growth stand

Fluxes of carbon dioxide (F_c , $\mu\text{mol } CO_2 \text{ m}^{-2} \text{ s}^{-1}$), water vapor (F_{H_2O} , $\text{mmol } H_2O \text{ m}^{-2} \text{ s}^{-1}$), sensible heat (H , $W \text{ m}^{-2}$) and latent heat ($*E$, $W \text{ m}^{-2}$) were computed from 10 Hz eddy covariance data using an in-house FORTRAN90 code with a time averaging period of 30 min and a horizontal coordinate rotation (mean cross-wind velocities were forced to zero). The rate of change in CO_2 concentration (storage flux, S_c , $\mu\text{mol } CO_2 \text{ m}^{-2} \text{ s}^{-1}$) within the canopy volume was estimated on a half-hourly basis using time changes in the mean CO_2 mixing ratio measured at the top of the canopy (Falk et al., 2008). To account for CO_2 stored within the canopy and below the detection height of the instruments, S_e was added to F_c to estimate net ecosystem exchange of carbon (F_{NEE} , $\mu\text{mol } CO_2 \text{ m}^{-2} \text{ s}^{-1}$) on a half-hourly basis. F_{NEE} and $*E$ were further screened for incomplete half-hours, general instrument failure (e.g., pressure problems in the closed-path EC system), non-preferred wind directions (45–180°), major rain or snow events, or significant outliers (above or below the 95th confidence intervals). For complete details on old-growth flux post-processing see Paw U et al. (2004), Falk (2005), and Falk et al. (2008).

3.1.2. Early seral stands

At the two early seral stands F_c , F_{H_2O} , H , and $*E$ were calculated in real-time from 10 Hz covariance data using the CR1000 eddy covariance program (Campbell Scientific Inc.). The flux program used a 30-min averaging period and included WPL80 (Webb et al., 1980) density corrections to eliminate air density fluctuation effects on CO_2 and H_2O fluxes. During post-processing all scalar and energy fluxes were re-calculated after the mean cross-wind (following the natural wind coordinate system) and mean vertical wind velocities were forced to zero. Calculated sonic anemometer tilt was 2.50° at ESN06 and 4° at ESS07. Prior to coordinate rotation, average w was -0.02 m s^{-1} at ESN06 and -0.05 m s^{-1} at ESS07. The rate of change of CO_2 concentration (S_c) within the canopy was estimated using the half-hourly changes in the CO_2 mixing ratio measured at the top of the canopy and was added to F_c to estimate F_{NEE} .

3.2. Data screening Criteria at ESN and ESS

The early seral flux data necessitated a different screening protocol than the old-growth data for various reasons. First, continuous raw data (10 Hz) were not archived at the ES stands which meant that some of the standard EC corrections could not be applied to the time series data (e.g., spectral corrections for frequency loss, optimization of the time lag between wand CO_2 to correct for the separation distance between the IRGA and CSAT-3). Second, fetch availability and turbulence-induced edge effects

(from an abrupt rough-to-smooth canopy roughness transition) were a much higher concern at the early seral stands and warranted the creation of data criteria 5 and 6 as described below.

Half-hour F_{NEE} , F_{H2O} , and energy fluxes were excluded from the time series if one or more of the following criteria were met: (1) instrument malfunction or incomplete half-hour, (2) "tower shadowing" or flow distortion around the CSAT-3, (3) heavy precipitation, (4) spike filter = 1 (F_c only), (5) ratio of mean vertical or horizontal wind flow to turbulent velocity scale was greater than the critical threshold, (6) insufficient fetch, or (7) half-hourly variance was greater than the 95th and less than the 5th confidence intervals. We used a spike filter methodology in criterion 4 to detect significant half-hour CO_2 anomalies or outliers in the time series as described in Papale et al. (2006). The spike filter algorithm is based on a double-differenced time series and uses the median of absolute deviation about the mean (Sachs, 1996) to detect unusually large deviations or "spikes" in the CO_2 flux record. Each 30-min F_c was flagged if the spike filter equaled one and was replaced with a gap-filled flux value. The spike filter methodology removed 5% of available F_c data at ESN06 and 7% at ESS07.

Criterion 5 was used to identify half-hour fluxes measured during conditions when transport by mean flow could no longer be neglected compared to turbulent flow in the wind field. This concern is shown by studying the Reynolds-averaged mass balance equation for biosphere-atmosphere exchange of CO_2 :

$$\frac{\partial \bar{\rho}_c}{\partial t} + \frac{\partial(\bar{u}_i \bar{\rho}_c)}{\partial x_i} + \frac{\partial(\bar{u}_i' \rho_c')}{\partial x_i} = \bar{S}_c \quad (1)$$

Eq. (1) shows that the CO_2 source or sink magnitude (net ecosystem exchange when integrated over the height of the canopy), $\bar{S}_c$, equals the sum of three terms: the rate of change in CO_2 storage (first term on LHS, estimated from measurement data in our study), the collective horizontal and vertical advection terms (second term, not measured or directly estimated in our study) and the collective eddy covariance terms (third term, vertical flux measured in our study, flux divergences not measured or directly estimated in our study). Note that the contribution of CO_2 exchange from the advective terms is often ignored or considered negligible during daytime, and at many sites, during nighttime hours as well.

To assess the contribution of turbulent transport to net ecosystem exchange, we first assumed that the efficiency of turbulence to transport mass and energy could be represented by the magnitude of turbulent kinetic energy (TKE). We then defined two turbulence intensity parameters I_w and I_u based on the ratio of mean vertical (w , $m s^{-1}$) or horizontal (U , $m s^{-1}$) wind velocity to a modified turbulent velocity scale (U_{TKE} , $m s^{-1}$), where U_{TKE} is defined as.

$$U_{TKE} = \sqrt{(u'^2 + v'^2 + w'^2)} \quad (2)$$

and $\frac{u'^2}{2}$, $\frac{v'^2}{2}$ and $\frac{w'^2}{2}$ are the mean variances in the stream-wise, cross-wise and vertical velocity directions, respectively. Note that U_{TKE} now has the same dimensions as the original velocity variables. We used a vertical turbulence intensity ratio,

$$I_w = \frac{\bar{w}}{U_{TKE}} \quad (3)$$

to determine conditions when transport by mean vertical wind flow (measured w) $I_w = w/U_{TKE}$ could no longer be neglected compared to turbulent eddy flow. This value was called critical I_w , threshold (I_{wcrit}). Since vertical velocity is hard to measure with high accuracy and is subject to errors associated with the mis-leveling of the sonic anemometer, we made tower-specific I_w thresholds and assumed that no significant changes in the

precision of measurements occurred during the study period for any given anemometer. A horizontal turbulence intensity ratio,

$$I_u = \frac{U}{U_{TKE}} \quad (4)$$

was used to determine the contributions of transport by mean horizontal wind flow to turbulent eddy flow. If $I_u > I_{ucrit}$ or $I_w > I_{wcrit}$, advective transport of energy, mass and momentum was considered non-negligible compared to the turbulent transport and the eddy fluxes were gap-filled.

We chose to use a modified turbulent velocity scale (U_{TKE}) instead of the commonly used surface friction velocity (u_*) to infer ABL turbulence conditions. Friction velocity is routinely used in EC studies as a filter for identifying (and removing) CO_2 flux measurements taken during inadequate nighttime turbulence (called the "u-star correction method," Goulden et al., 1996; see also Aubinet et al., 2000; Massman and Lee, 2002; Gu et al., 2005; Papale et al., 2006). We argue that using U_* is not the most ideal way of determining turbulence in clear-cut stands because (1) intermittent, buoyancy-driven turbulence can occur at night over landscapes with canopy roughness changes and complex terrain, and non-shear turbulence will not be captured by the u_* parameter, (2) under certain ABL conditions (e.g., mesoscale exchange) turbulent fluxes are small but U_* indicates highly turbulent conditions, and vice versa, there are times when turbulent fluxes are nonzero but u_* suggests no turbulence (Acevedo et al., 2009), and (3) under certain ABL conditions (e.g., unstable with low wind speeds) the momentum sink is absent and U_* is zero but scalar sources are present and the turbulent exchange is nonzero. On a theoretical basis, U_* is not an independent state variable when used to filter CO_2 fluxes. U-star is defined from the stream-wise and cross-wise momentum fluxes, Eq. (5)

$$u_*^2 = \sqrt{(u'w'^2 + v'w'^2)} = \frac{|\tau_{Reynolds}|}{\bar{\rho}} \quad (5)$$

where the Reynolds stress ($\tau_{Reynolds}$) is calculated from the sum of the individual surface stresses, τ_{uw} and τ_{vw} (Eq. (6)),

$$|\tau_{Reynolds}| = \sqrt{(\tau_{uw}^2 + \tau_{vw}^2)} \quad (6)$$

Therefore, friction velocity is really a flux and is the result of the momentum sink, while U_{TKE} is instead conceptually linked to the independent ability of turbulence to transfer mass and energy through the ABL. The U_{TKE} -derived variables in Eqs. (2–4) are all direct measures of turbulence.

3.3. Footprint and advection estimates

A simple, parameterized footprint model (Kljun et al., 2004; <http://footprint.kljun.net/index.php>) was used in criterion 6 to determine the extent of which measured turbulent fluxes were influenced by scalar sources outside of the early seral stands. A footprint size and shape varies according to receptor height (here the EC measurement height), surface or canopy roughness, and planetary boundary layer mixing conditions during which the fluxes were measured (i.e., the ratio of advective to turbulent transport). While the chosen model relies on a simplified scaling approach for the footprint functions, it has been thoroughly tested with a more complex 3D Lagrangian stochastic footprint model (Kljun et al., 2002). The estimated footprint (X_R) is calculated using user-defined values of standard deviation of vertical wind velocity (σ_w), friction velocity (u_*), planetary boundary layer height (1500 m during daytime and 600 m at nighttime), zero displacement height ($z_0 = 0.10 h_c$, where h_c is the canopy height) and EC measurement height. In this study all footprint estimates were based on X_R , the distance from the flux tower which includes 80% of

the source area influencing the EC measurement. For the model runs, we separated all turbulence data first into daytime (10:00–14:00) and nighttime (24:00–2:00) classes, and second into wind direction sectors (eight 45° bins).

A vertical and horizontal advection measurement system for CO₂ and H₂O vapor was set-up for a couple of seasons at the 500-year-old Wind River site as described by Paw U et al. (2004). Their study estimated that advection contributes between 10% and 20% of the above canopy flux at night at the old-growth forest (Paw U et al., 2004), although this contribution is predicted to vary depending on mean wind speed and effective transfer coefficients (Park and Paw U, 2004; Park, 2006). Hour-to-hour advection was difficult to measure and because the estimated contribution was relatively small we decided not to include measurement-based corrections for an advective component in the net ecosystem exchange.

3.4. Gap-filling and uncertainty analysis

Missing or excluded 30-min F_{NEE} and E measurements from the three flux towers were gap-filled using on-line algorithms given by Reichstein et al. (2005) (<http://gaia.agraria.unitus.it/database/eddyproc/>). The gap-filling method uses both a mean diurnal approach and look-up tables for filling periods of missing data and is an advancement of the methodology described by Falge et al. (2001). Latent energy fluxes were gap-filled to estimate daily or monthly evapotranspiration (E , mm). The meteorological data were gap-filled using a similar mean diurnal approach. Uncertainty estimates in total E (kg H₂O m⁻²) and monthly midday F_{NEE} (μmol m⁻² s⁻²) were assessed with bootstrapping simulations using the Monte Carlo approach (following Ma et al., 2007). Bootstrapping re-sampling was performed 5000 times on each of the time series and uncertainty estimates were based on the standard deviation of the simulations at the 90% confidence interval.

3.5. Energy budget and albedo

Energy budget closure (EBC) was assessed at all stands using daytime, half-hour flux data during periods of good fetch, adequate turbulence, and no precipitation. Energy budget closure was estimated from Eq. (7),

$$H + \lambda E = R_n - G - S_e \quad (7)$$

where R_n is net radiation (W m⁻²), G is ground heat flux (W m⁻²), and S_e is the rate of change of energy stored in the biomass, canopy air space, and soil above the ground heat flux plate (W m⁻²). S_e was calculated only for the old-growth stand and was assumed to be negligible in the short, low biomass canopies of the early seral stands. At the early seral stands, ground heat flux was estimated using half-hourly changes in soil temperature from vertical soil temperature profiles. A midday Bowen ratio (B) was defined as the ratio of the sensible heat flux to latent heat flux during half-hours, 10:00–14:00. Bowen ratio was used to assess site differences in partitioning of available energy into sensible heat and into latent heat or evapotranspiration.

Albedo at the Wind River old-growth forest was estimated using incoming and outgoing shortwave radiation from a 4-stream radiometer mounted at a height of 85 m on the canopy crane. Albedo at ESS07 was estimated from PAR-only wavelengths using up- and down-facing PAR sensors mounted at a height of 6 m above ground level. Albedo was calculated for all half-hours at ESS07 when incoming photosynthetic photon flux density (PPFD) > 100 μmol m⁻² s⁻¹ and at OG when incoming short-wave radiation > 50 W m⁻² to eliminate errors caused by low solar

elevation angles. At ESN06, albedo was not measured directly but was estimated using the 500 m, 16-day composite MODIS albedo product (MCD43A3) (ORNLDAAC, 2009), <http://daac.ornl.gov/MODIS/modis.html>.

3.6. LAI

LAI was indirectly measured at the early seral stands using digital hemispheric photography (DHP) and estimated using HemiView 2.1 (Delta-T Devices Ltd., Cambridge, UK) and Eq. (8) (Chen, 1996; Chen et al., 1997),

$$LAI = \frac{(1 - \alpha) LAI_{eff} Y_E}{Q_E} \quad (8)$$

where, LAI_{eff} effective, single-sided LAI and was calculated using the software program based on DHP gap fraction, α is wood-to-plant ratio and was set at 0.20, Y_E is needle-to-shoot ratio and was set at 1.61, and Q_E is the foliage element clumping index and was set at 0.91. The three parameter values are based on measurement data from a 14-year-old Douglas fir stand at Campbell River, Vancouver Island, British Columbia (Chen, 1996; Chen et al., 2006). The hemispheric photos were taken at a height of 10 cm with a Nikon COOLPIXE4300 digital camera adapted with a Nikon Fisheye Converter lens. Fern and other ground species were cleared before the photos were taken to ensure that only trees were included in the canopy LAI estimates. For logistical reasons DHP surveys were done just once at both sites. The photos were taken just past sunset on 1 September 2006 at ESN06 and 30–31 August 2007 at ESS07. At ESN06, 15 images were taken along a 150 m west-to-east transect (centered on the flux tower) at 10 m intervals. At ESS07, 17 images were taken along a 170 m west-to-east transect at 10 m intervals.

4. Results

4.1. Local meteorology

Meteorological data from the nearby CFHNOAA station showed that annual mean air temperature was near the long-term (1977–1997) average (8.8 °C) in both 2006 (8.9 °C) and 2007 (8.7 °C). Total water-year (October–September) precipitation was also near average (2366 mm) in 2006 (2361 mm) and 2007 (2129 mm). Although 2006 and 2007 were similar in terms of total precipitation and mean annual temperature, the spring and summer seasons were in fact climatologically distinct. Spring 2006 was cooler and wetter (409 mm) and led into a very dry (72 mm) and warm (17.2 °C) drought season. In 2007, the spring months were drier (217 mm) than in 2006 although late-season rains made the summer much wetter (316 mm) and cooler (16.4 °C). For comparison, the long-term averages for the drought season are 314 mm and 16.2 °C.

4.2. Site micrometeorology

Table 2 shows that the early seral stands were warmer and less humid than the dense old-growth forest during summer daylight hours. Average May–August VPD was 1.6 kPa at ESN06 and 1.2 kPa at OG06, and 1.3 kPa at ESS07 and 1.1 kPa at OG07 during the hours of 10:00–16:00. Soil moisture also varied amongst stands and years although the drought-season pattern remained a dominant feature. Near-surface (0–30 cm depth) θ_v was similar at both ESN06 and OG06: after June 2006 soil moisture began to steadily decrease and approached 0.15 m³ m⁻³ until rains returned to the area in October. At ESS07, 0–30 cm θ_v did not drop below 0.20 m³ m⁻³ while the near-surface θ_v approached 0.15 m³ m⁻³ at OG07. The additional measurement depths in 2007 revealed that while near-surface θ_v at OG07 fell below the critical threshold of

Table 2

Micrometeorological conditions at the flux towers and local precipitation for the months of April–September, 2006–2007. Months with dashes indicate incomplete data.

	Early seral				Old-growth				CFH
	T _{max} (°C)	T _{min} (°C)	VPD* (kPa)	θ_{0-30} (m ³ m ⁻³)	T _{max} (°C)	T _{min} (°C)	VPD* (kPa)	θ_{0-30} (m ³ m ⁻³)	P (mm)
2006									
April	–	–	–	–	13.7	3.2	0.5	–	112.3
May	20.0	9.5	1.1	0.33	18.6	7.4	0.9	0.34	59.2
June	25.8	9.2	1.8	0.31	22.0	11.2	1.0	0.33	52.3
July	27.2	11.4	1.7	0.21	25.6	13.4	1.5	0.24	1.0
August	27.1	9.9	1.7	0.18	25.3	11.8	1.4	0.19	1.3
September	24.0	7.2	1.3	0.18	22.4	9.5	1.2	0.18	14.2
2007									
April	–	–	–	0.39	11.8	3.0	0.5	–	59.2
May	21.0	7.1	1.2	0.37	18.7	6.1	1.0	0.28	34.3
June	21.6	10.2	1.0	0.34	19.1	8.9	1.0	0.26	30.0
July	28.8	14.7	1.5	0.29	26.0	13.5	1.5	0.23	18.8
August	25.1	12.1	1.3	0.26	22.8	11.0	1.2	0.20	15.5
September	23.0	9.5	–	0.27	19.0	8.4	0.9	0.18	57.7

* VPD average is daylight hours (10:00–16:00) only. CFH = Carson Fish Hatchery NOAA meteorological station.

0.2 m³ m⁻³ for inducing ecosystem water stress (Falk et al., 2005, 2008), deeper θ_v in the rooting zone (1–1.5 m) of the old-growth stand stayed above 0.3 m³ m⁻³. Daily maximum soil temperatures were higher at the early seral stands and differences up to 15°C were observed between ESS07 and OG07.

4.3. Early seral turbulence and footprint statistics

We observed fundamental differences between normalized mean wind speed (U), u_* , and u_{TKE} depending on the time of day and site location (Fig. 2). In Fig. 2 each of the average half-hourly measurements are normalized by the average 24-hr maximum value. At night, u_{TKE} and u_* were on average between 15% and 30% of their daily peak values, while U dropped below 30% of its daily maximum for only a few hours before sunrise. Fig. 2 also shows that u_{TKE} tends to be closer than u_* to the daily maximum during the morning to mid-afternoon hours while normalized u_* is greater in the late afternoon. Fig. 3 shows all half-hour measurements of u_* and I_u at ESN06 (Fig. 3a) and ESS07 (Fig. 3b). Maximum u_* frequently occurs when the I_u turbulence scale is between 0.5 and 1.0. This is because maximum friction velocity and maximum u_{TKE} do not occur together. As I_u values in Fig. 3 u_{TKE} approach zero (mean wind velocity $\ll$ turbulence velocity), u_* actually indicates

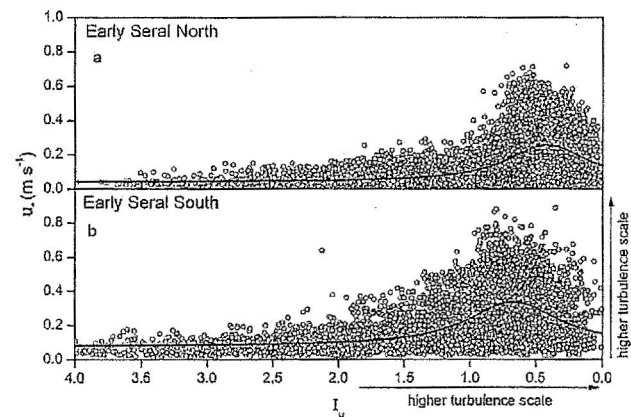


Fig. 3. The relationship between u_* and I_u plotted for half-hourly data at ESN06 and ESS07. The line of best fit is described with a Lorentz peak function (solid black line). Note that u_* decreases at the lowest I_u ratios (i.e., times when advection can be neglected and u_{TKE} is high) instead of following an expected exponential decay function (dashed line).

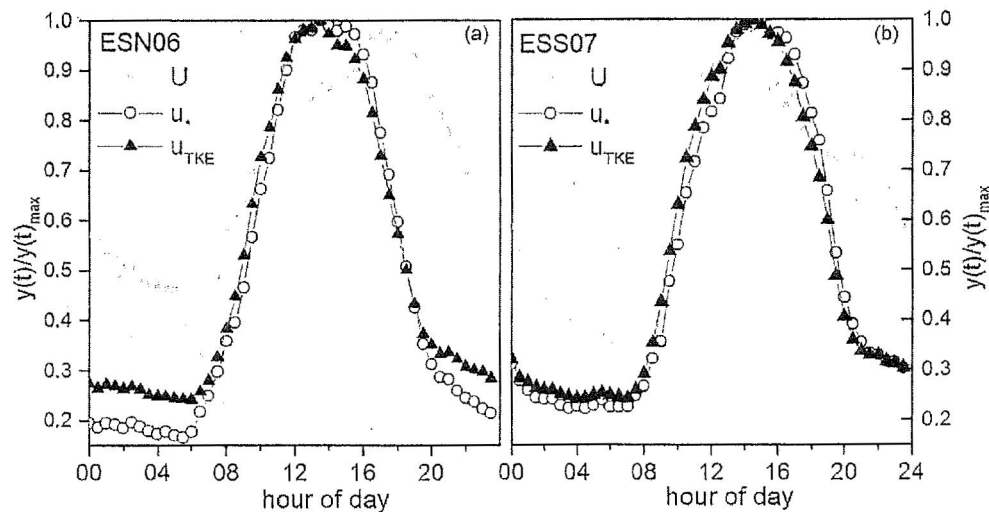


Fig. 2. Mean diurnal plots for mean wind speed, u_* and u_{TKE} as a fraction of the daily maximum value at ESN06 (a) and ESS07 (b). Maximum wind speeds and turbulence parameters typically occur midday while minimum values occur during the hours prior to sunrise.

less turbulent conditions. There are a large number of half-hours when u_* is near zero and suggests very low turbulent conditions but I_u is showing a high degree of turbulence (between 0.0 and 0.5).

The critical thresholds for insufficient turbulent mixing are: $I_{u\text{crit}} = 1.5$ at ESN06 and $I_{u\text{crit}} = 2.0$ at ESS07, and $I_{w\text{crit}} = (0.15)$ at ESN06 and $I_{w\text{crit}} = (0.15)$ at ESS07. We determined $I_{u\text{crit}}$ and $I_{w\text{crit}}$ based on the time series mean plus one standard deviation. To check the appropriateness of this threshold we also examined:

- (1) Footprint model runs from criterion 6 of Section 3.3. We found that when $I_u > I_{u\text{crit}}$ or $I_w > I_{w\text{crit}}$, the flux footprints extended beyond the clear-cut stands over 90% of the time.
- (2) Flux statistics. During conditions when $I_u > I_{u\text{crit}}$ we observed a "leveling-off" or systematic decline to zero in the daylight fluxes. For example, when $I_u > I_{u\text{crit}}$ during daylight hours, mean F_{NEE} was $0.77 \text{ umol m}^{-2} \text{ s}^{-1}$ at ESN06 and $-0.36 \text{ umol m}^{-2} \text{ s}^{-1}$ at ESS07, compared to $-6.3 \text{ umol m}^{-2} \text{ s}^{-1}$ (ESN06) and $-4.3 \text{ umol m}^{-2} \text{ s}^{-1}$ (ESS07) during daylight hours when $I_u < I_{u\text{crit}}$.

To test the robustness of our new I_u and I_w parameters we also looked at how sensitive the flux data were to our choosing of a critical turbulence threshold based on U_{TKE} instead of u_* . Fig. 4 shows that a greater number of "real" daytime H fluxes would be excluded from the measurement period if a critical turbulence threshold was based on u_* rather than U_{TKE} at ESS07. Both $U_{* \text{crit}}$ and U_{TKEcrit} were determined from one standard deviation of the mean (dotted line in Fig. 4a and b). 13% of sensible heat fluxes (mean = 53 W m^{-2}) were excluded using the U_{TKE} critical threshold while 21% (mean $H = 86 \text{ W m}^{-2}$) were excluded using the u_* critical threshold. Data in Fig. 4 were binned by net radiation classes to show that H fluxes $> 150 \text{ W m}^{-2}$ were measured more often during very low u_*

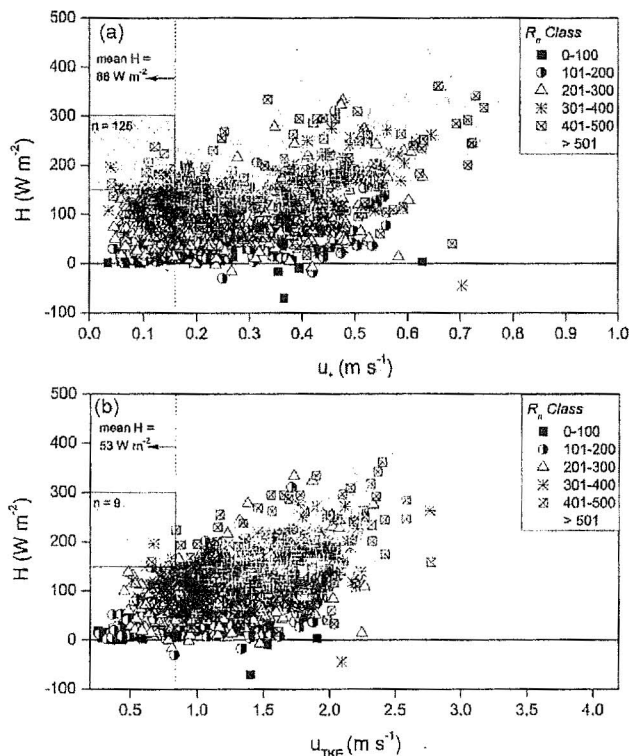


Fig. 4. Daytime (10:00–16:00) sensible heat fluxes at ESS07 binned by net radiation under varying turbulence conditions shown by u_* (a) or U_{TKE} (b). The dashed line indicates a critical threshold based on one standard deviation of the mean. The gray boxes highlight H fluxes $> 150 \text{ W m}^{-2}$ which were measured during low turbulent conditions according to either $u_{* \text{crit}}$ or U_{TKEcrit} .

conditions than during very low U_{TKE} (boxed gray regions). The fluxes when $u_* < U_{* \text{crit}}$ are most likely 'real' sensible heat fluxes since net radiation was greater than 400 W m^{-2} nearly 90% of the time u_* . The average half-hour in the boxed region in Fig. 4a is 12:00. Additional statistics for the boxed 126 data points include: $H = 183 \text{ W m}^{-2}$, $u_* = 0.12 \text{ m s}^{-1}$, $U_{\text{TKE}} = 1.18 \text{ m s}^{-1}$, $U = 1.14 \text{ m s}^{-1}$, and $I_u = 0.98$. Since $I_u < I_{u\text{crit}} = 2.0$, the turbulent fluxes in the shaded box would not be excluded using the I_u critical threshold approach as they were using $I_{* \text{crit}}$.

Figs. 5 and 6 show conditions when the mean flow contribution (i.e., possible advection from Bunker Hill and Trout Creek Hill) could no longer be a neglected component of the vertical flux ($I_u > I_{u\text{crit}}$ or $|U_{\text{H}}| > I_{u\text{crit}}$). Non-negligible horizontal mean flow was more prevalent at ESN06 during nighttime hours than non-negligible vertical mean flow (frequency of 24:1), while non-negligible vertical mean flow and horizontal mean flow conditions occurred in roughly equal frequencies at ESS07. Also, non-negligible horizontal mean flow ($I_u > 1.5$) was occasionally

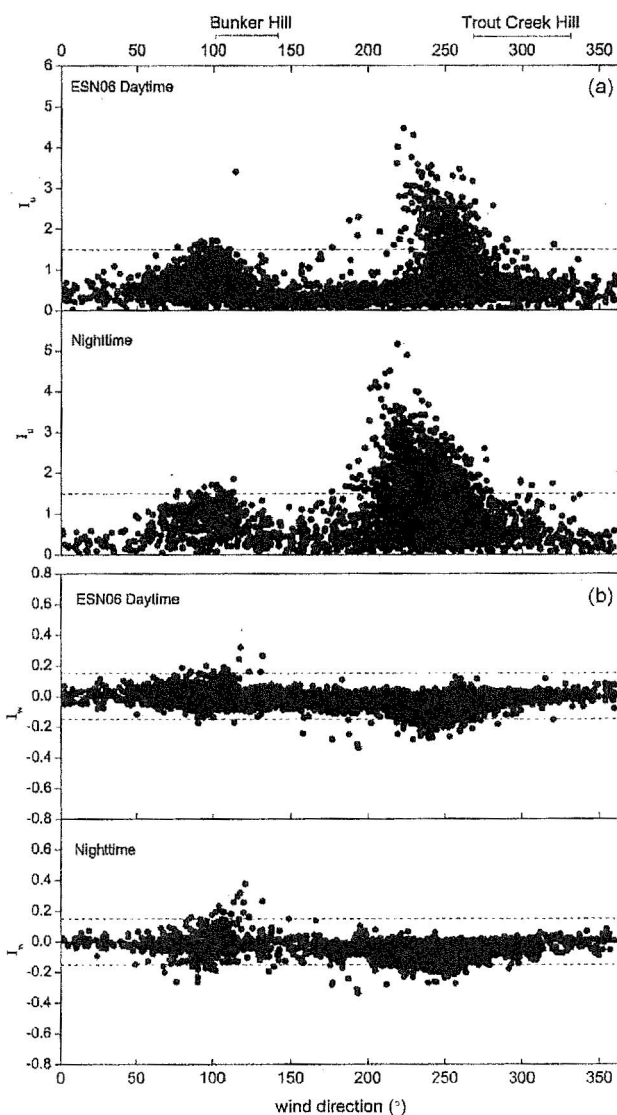


Fig. 5. Half-hourly horizontal-mean-flow-to-turbulence-intensity ratios (a) and vertical-mean-flow-to-turbulence-intensity ratios (b) for daytime and nighttime hours at ESN in 2006 by wind direction. Critical values for I_u and I_w are indicated by the dashed lines. The directions of Bunker Hill and Trout Creek Hill from the flux towers are labeled.

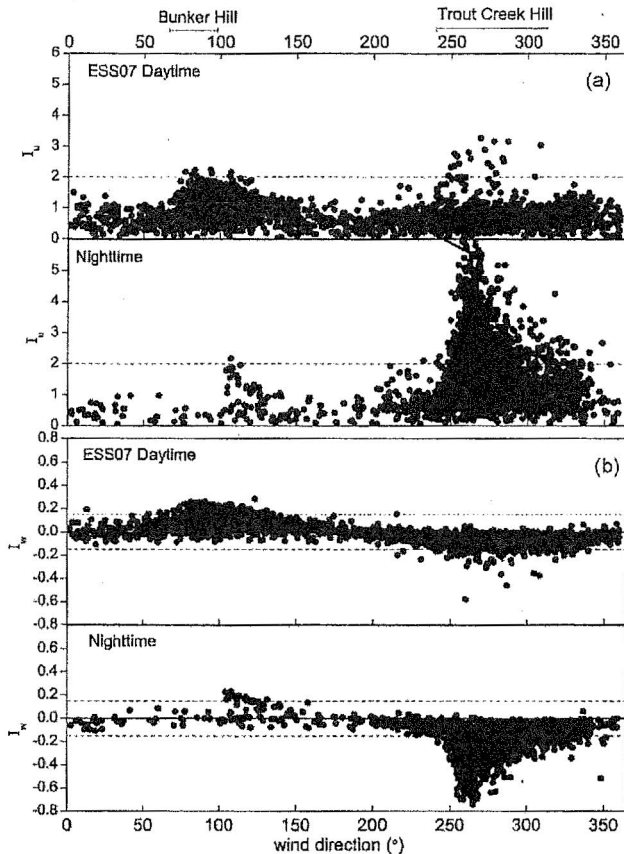


Fig. 6. Half-hourly horizontal mean flow-to-turbulence-intensity ratios (a) and vertical-mean-flow-to-turbulence-intensity ratios (b) for daytime and nighttime hours at ESS in 2007 by wind direction. Critical values for I_u and I_w are indicated by the dashed lines. The directions of Bunker Hill and Trout Creek Hill are labeled.

observed (7.8%) at ESN06 during daylight hours (Fig. 5a) but not at ESS07 as very few daylight hours (<1%) approached I_{ucrit} (Fig. 6a). Nighttime (2:00–4:00) flux footprints (x_R) extended at least 350 m in the westerly direction and went beyond the boundaries of both clear-cuts during high I_w and I_u conditions. Nighttime fluxes measured while I_w and I_u were less than I_{ucrit} and I_{ucrit} came from scalar sources closer to the towers (at least 200 m) but the flux footprints were still beyond the boundaries of the stands for most wind directions (82% and 85% of the time at ESN and ESS, respectively). For this reason, and because I_w and I_u went beyond the critical thresholds an additional 5% of the time at ESN and 13% at ESS, we do not include estimates of nighttime ecosystem exchange in this paper.

Midday (10:00–14:00) estimated footprints (x_R) ranged from 75 m (east upwind direction) to 100 m (north-west upwind direction) at ESN06 and 77 m (east upwind direction) to 115 m (north upwind direction) at ESS07, and require fetch-to-instrument ratios ranging from 14 to 23:1. Actual fetch: instrument ratios averaged 33:1 and 34:1 at ESN and ESS, respectively, but ranged from 10 to 44:1 depending on wind direction (Table 3). Most wind directions at ESN06 included footprints within the clear-cut stand. Greatest uncertainty arose when winds were from the southeasterly direction (23% of the data points) because these source footprints extended outside of the clear-cut stand into an adjacent 80-year old Douglas-fir forest. These fluxes were removed from the time series and gap-filled. Daytime footprints were less of a concern at ESS07 as nearly all upwind directions had sufficient fetch. The only exception was when winds arose from the

northerly and southerly directions but this occurred less than 15% of the time.

4.4. Energy balance and albedo

Mean midday (10:00–14:00) energy fluxes and albedo estimates are listed in Table 4 and show energy exchange during the beginning, middle, and end of the drought seasons. Early seral north energy budget closure was 81% ($R^2 = 0.93$) during mid-June–mid-September in 2006 and slightly lower (79%, $R^2 = 0.89$) at ESS during the same period in 2007. During the summer months old-growth EBC was 76% ($R^2 = 0.67$) in 2006 and 73% ($R^2 = 0.62$) in 2007. Available energy was partitioned into 40% sensible heat and 41% latent heat at ESN during the 2006 summer with 19% of the available energy unaccounted for, although Table 4 shows high month-to-month variability in the energy partitioning variable, B . At ESS, 45% of available energy was partitioned into sensible heat and 34% into latent heat with 21% unaccounted for. On average a higher B was measured at the old-growth stand than at either early seral forest. April–August mean midday B was 2.2 ± 0.9 at OG06 and 1.5 ± 0.6 at ESN06, and 2.0 ± 1.2 at OG07 and 1.2 ± 0.6 at ESS07. The largest site differences were measured in July during both years. Mean July B was 2.6 ± 1.0 at OG06 and 0.78 ± 0.3 at ESN06, and 2.2 ± 1.4 at OG07 and 0.94 ± 0.8 at ESS07. The low B at the early seral sites in mid-summer was caused by large latent heat fluxes. Ground heat storage accounted for less than 1% of the available net energy at the old-growth stand. In the more open canopies of the early seral stands, ground heat storage was 8–15% of the available energy. Albedo was also higher at the early seral stands (12–15%) than at the old-growth forest (7–8%). A summer decline in albedo was not observed at OG during either year but was observed at ESS in 2007. PAR albedo declined from 14.9% in May to 12.9% in October at early seral south following structural changes to the canopy including bud break and fern growth (illustrated in Fig. 7).

4.5. Seasonal and monthly flux dynamics

Midday (10:00–14:00) CO_2 fluxes peaked seasonally in April at the old-growth stand and were $-14.0 \pm 3.4 \text{ umol m}^{-2} \text{ s}^{-1}$ in 2006 and $-12.3 \pm 2.1 \text{ umol m}^{-2} \text{ s}^{-1}$ in 2007 (Fig. 8a and b). In contrast, April midday F_{NEE} magnitudes were significantly ($P < 0.0001$) smaller (less net carbon uptake) at the early seral stands, $-4.0 \pm 1.4 \text{ umol m}^{-2} \text{ s}^{-1}$ at ESN06 and $-3.8 \pm 1.3 \text{ umol m}^{-2} \text{ s}^{-1}$ at ESS07, and peak midday CO_2 fluxes were observed two to three months later in June and July. Maximum CO_2 fluxes were measured in July at ESN06 ($-10.2 \pm 2.0 \text{ umol m}^{-2} \text{ s}^{-1}$) and in June at ESS07 ($-8.7 \pm 0.9 \text{ umol m}^{-2} \text{ s}^{-1}$) while net CO_2 uptake dropped in June at the old-growth forest and continued to decline throughout the summer months in both 2006 and 2007. E_T was relatively constant between April and June at the OG stand and a seasonal-summer decline was not observed until July in 2006 and August in 2007 (Fig. 8c and d). Strongest ET seasonality was observed at ESN. June–August E_T averaged 85 mm per month while April–May E_T was 40 mm lower. Not enough data were available at ESS to make the same seasonal comparisons. Total May–August E_T was $305 \pm 11 \text{ mm}$ at ESN06 and $231 \pm 9 \text{ mm}$ at OG06, and $289 \pm 9 \text{ mm}$ at ESS07 and $230 \pm 8 \text{ mm}$ at OG07.

We found a correlation between monthly midday Bowen ratio and midday F_{NEE} at the early seral stands ($R^2 = 0.68$ in 2006 and $R^2 = 0.74$ in 2007) so that a higher B was associated with less negative CO_2 fluxes (Fig. 9). This relationship was also weekly observed at the old-growth stand in 2007 ($R^2 = 0.16$) but not in 2006 ($R^2 = 0.00$) (Fig. 9). Note that the positive correlation between B and F_{NEE} weakens during the month of May at OG07. The month was relatively warm and dry with moderate VPD and non-limiting, below-surface θ_v . This combination of factors produced a relatively

Table 3

Midday (10:00–14:00) estimated footprint (x_R) and actual fetch (x_A) distance for all wind direction sectors at the early seral flux towers. The bolded text shows the percentage of time when the required fetch was available ($x_A > x_R$), and for those times, mean x_R :instrument height and x_A :instrument height.

Site	Upwind direction	Frequency	Source footprint (x_R) (m)	Actual fetch (x_A) (m)	x_R :instrument height	x_A :instrument height	Enough fetch? ($x_A > x_R$)
ESN06	0–45	2%	83.5	80	15:1	14:1	No
	45–90	6%	75.8	150	14:1	27:1	Yes
	90–135	23%	78.8	80	14:1	14:1	No
	135–180	12%	78.0	130	14:1	24:1	Yes
	180–225	15%	83.4	170	15:1	30:1	Yes
	225–270	28%	95.8	210	17:1	38:1	Yes
	270–315	11%	99.3	240	18:1	44:1	Yes
	315–360	3%	92.5	90	17:1	16:1	No
		72%			16:1	33:1	Yes
ESS07	0–45	4%	89.1	80	18:1	16:1	No
	45–90	29%	77.2	190	15:1	38:1	Yes
	90–135	14%	83.0	200	17:1	40:1	Yes
	135–180	5%	94.5	70	19:1	14:1	No
	180–225	13%	105.9	140	21:1	28:1	Yes
	225–270	17%	105.3	160	21:1	32:1	Yes
	270–315	14%	102.4	170	21:1	34:1	Yes
	315–360	3%	114.2	50	23:1	10:1	No
		87%			19:1	34:1	Yes

Table 4

Mean midday net radiation, soil heat flux, Bowen ratio and albedo measurements for May, July, and September (early drought-, mid drought-, and late drought-season) at the three flux towers. Months with dashes indicate incomplete data.

	ESN06			OG06			ESS07			OG07		
	May	July	September	May	July	September	May	July	September	May	July	September
R_n ($W\ m^{-2}$)	384	553	410	620	661	518	487	463	345	666	698	506
G ($W\ m^{-2}$)	–	44.8	41.9	5.4	6.2	2.3	54.1	52.7	47.2	5.8	3.7	1.5
β	2.8 ± 1.1	0.8 ± 0.3	1.6 ± 0.8	2.2 ± 0.9	2.6 ± 1.0	1.9 ± 0.7	1.3 ± 0.6	0.9 ± 0.8	–	2.6 ± 1.5	2.2 ± 1.4	2.0 ± 1.3
Albedo	12–15%	12–15%	12–15%	7.2%	7.3%	7.9%	14.9%	13.7%	12.9%	7.9%	7.7%	8.4%

high Bowen ratio and larger negative (more net carbon uptake) CO_2 fluxes at the old-growth stand while CO_2 fluxes at the early seral stands were significantly less negative (less net carbon uptake).

5. Discussion and conclusions

Before we could confidently compare fluxes amongst stands we first needed to answer the following question: Were the clear-cut patches large enough in size so that we were measuring fluxes over the vegetation of interest? We were not satisfied with the friction velocity scale being able to indicate periods of inadequate turbulent mixing during both daytime and nighttime hours at the early seral stands so we created new parameters I_w and I_r . Our turbulence-intensity methodology for the early seral stands revealed that most of the nighttime CO_2 fluxes were measured during non-negligible vertical mean flow, non-negligible horizontal mean flow or from scalar sources outside the boundaries of the clear-cuts. These findings support the theoretical calculations made by Park and Paw U (2004) and Park (2006) whose models predict significant advection along abrupt forest edges. We decided not to include any nighttime CO_2 flux data in this paper because we believed that the EC technique was not accurately measuring turbulent CO_2 exchange at night (i.e., the respiration flux) in the early seral stands. For consistency we also did not include any nighttime data at the old-growth site. Other clear-cut studies have reported nighttime flux data including those by Kolari et al. (2004) and Humphreys et al. (2005). Kolari et al. (2004) were able to use 41% of their nighttime flux data based on a u_* critical value of $0.2\ m\ s^{-1}$ in a 7 ha clear-cut that had maximum fetch of 200 m, while Humphreys et al. (2005) found that nighttime F_{NEE} was no longer positively correlated with u_* after a threshold of

$0.08\ m\ s^{-1}$ was reached and were able to keep 80% of the nighttime data from a clear-cut flux tower. We suggest two primary reasons for why we in contrast rejected our nighttime flux data:

- (1) *Differences in footprint and fetch:* Wind River ES tree height and fast growth rates required that we measure at least 5 m above the ground surface and in doing so we increased the footprint size so that it often extended beyond the stand boundaries at night. Humphreys et al. (2005), in comparison, measured over a younger, shorter, and smoother Douglas-fir canopy which shifted the turbulence frequency distribution towards smaller eddies and which requires smaller footprints to resolve. Footprint issues are not an uncommon feature for forest flux studies particularly since most EC towers are now located in non-homogeneous terrain (Gockede et al., 2008). Additionally, our early seral stands had a drastic rough-to-smooth surface change (the transition from a 40 m, 80-year-old forest to 4 m, 10-year-old forest) which increased the amount of fetch needed to ensure that we were measuring within the atmospheric equilibrium layer. Our fetch: instrument height ratios from the footprint model were close to 35:1. This is slightly less than the general 40:1 rule given by Schmid (1994) but close to ratios given by van Breugel et al. (1999) and Kolari et al. (2004) for similar sized clear-cuts.
- (2) *Differences in turbulence methodology:* Our paper introduces a novel method to determine adequate turbulence conditions for flux measurements. We suggest that a velocity scale based on TKE (e.g., u_{TKE}) is a better way to assess ABL mixing because it includes turbulence generated by buoyancy as well as from mechanical forces. Also, turbulence regimes based on a u_* scale can be misclassified during mesoscale exchange while a TKE-

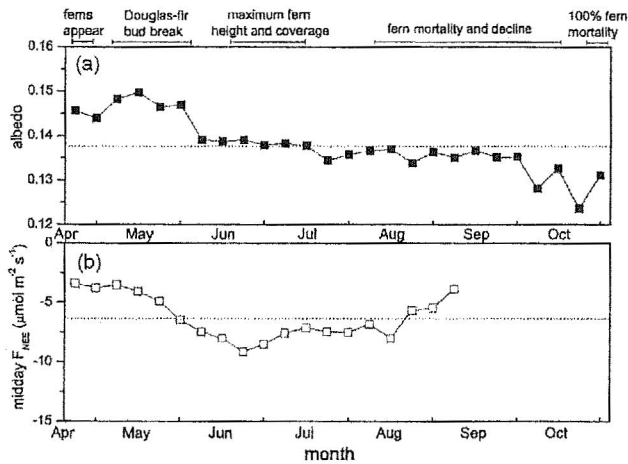


Fig. 7. Time series of weekly PAR albedo (a) and midday F_{NEE} (b) along with the timing of major phenological events at early seral south from April to October, 2007. The dashed lines indicate the mean.

based scale does not suffer from the same time-dependent variance errors (Acevedo et al., 2009). When the mass budget exchange equations, such as those presented by Lee (1998), Paw U et al. (2000), and Park and Paw U (2004) are carefully examined, it is clear that the kinematics of turbulent transport are related to the velocity fluctuations (in this case, as measured by u_{TKE}) and the kinematics of advective transport are driven by the mean velocity field. I_w or I_u is a form of the dimensionless number ($xK/1U_h^2$) shown by Park and Paw U (2004) and Park (2006) to be related theoretically to the ratio of turbulent exchange to mean advective exchange for any given site. A relationship between I_w or I_u and ($xK/1U_h^2$) is gleaned by parameterizing the turbulent transport coefficient K as a constant multiplied by a turbulent fluctuation, represented by u_{TKE} and by recognizing that the ratio of fetch to canopy height

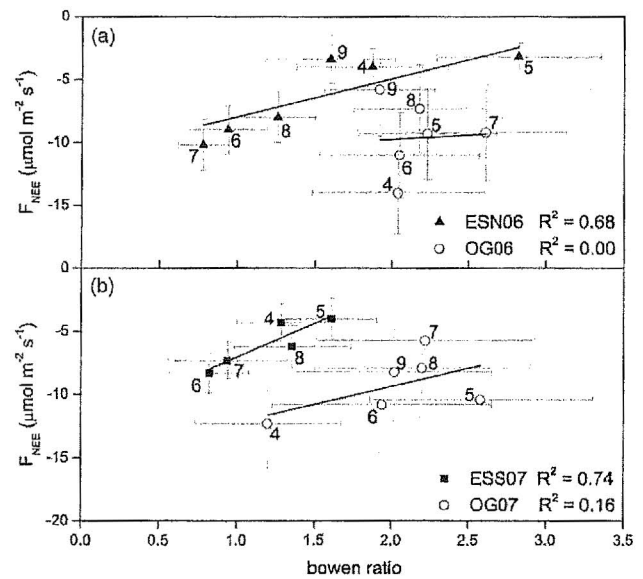


Fig. 9. Relationship between mean monthly Bowen ratio and CO_2 flux at ESN and OG in 2006 (a) and ESS and OG in 2007 (b) during midday half-hours. The months are labeled numerically (e.g., 4=April). The error bars are based on one standard deviation from the mean.

(x/h^2) is a constant for any given site and measurement location. Hence, the reciprocal of our empirically-derived I_w or I_u multiplied by constants, then is equivalent to the modeled dimensionless number given by Park and Paw U (2004).

The daytime EC data in our study were carefully screened by examining the footprint model results, mean velocity-to-turbulence flow ratios, and energy budget closure, and we feel confident in reporting a high fraction of daytime ecosystem fluxes from the early seral stands. Continuous failure to close the energy budget ($H + \lambda E < R_n - G - S_e$) during the daylight hours can indicate

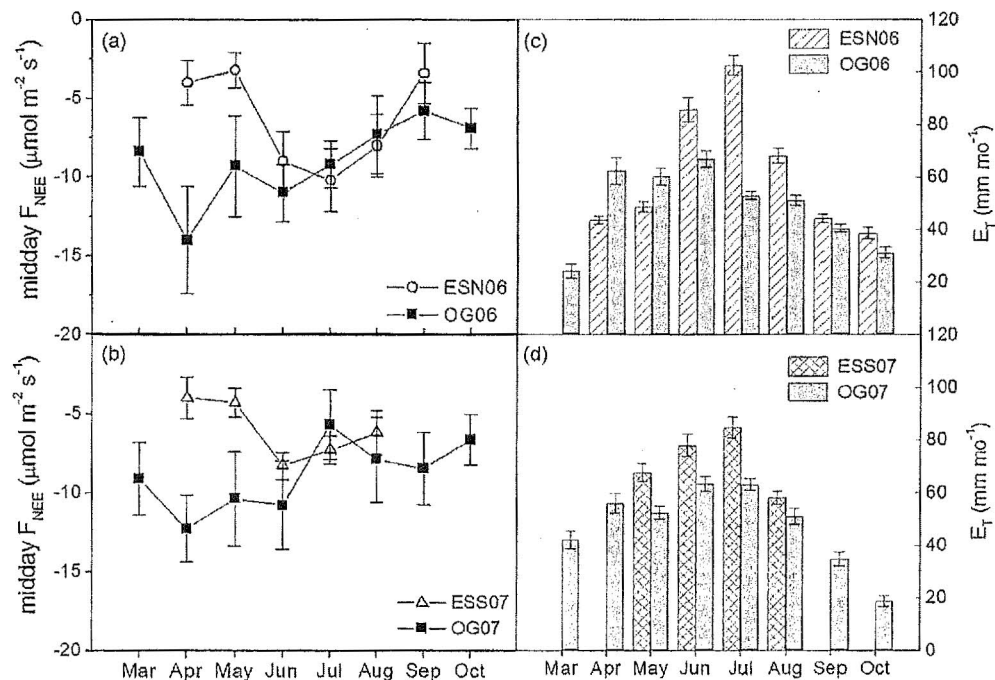


Fig. 8. Relationship between Mean midday CO_2 fluxes by month at early seral north and old-growth (2006) (a) and early seral south and old-growth (2007) (b). Total monthly E_T at ESN06 and OG06 (c) and ESS07 and OG07 (d). Bootstrapping uncertainties in the monthly fluxes are also shown.

systematic underestimation of the turbulent eddy fluxes (Foken, 2008). An 80% energy closure at the ES stands suggests that daytime fluxes were not largely underestimated and our EBC percentages are comparable with those reported at other FLUXNET sites (Wilson et al., 2002a). 28% and 13% of the daytime data at ESN and ESS, respectively, occurred when the footprint model runs indicated inadequate fetch and these data points were removed. In addition I_u and I_w went beyond the critical thresholds occasionally during daylight hours. Our observations correspond with studies by Feigenwinter et al. (2004) and Marcolla et al. (2005) which show that midday advective fluxes can make up to 10% of the eddy flux. Although these two studies in addition to our data suggest that vertical advection is present and at times non-negligible in clear-cuts, the number of studies which have looked at this phenomenon are at present very limited (Belcher et al., 2008).

5.1. Albedo and LAI changes and flux exchange

The relationship between PAR albedo and LAI is often significant for low LAI ecosystems (e.g., Ryu et al., 2008). With this in mind we used weekly changes in PAR albedo at ESS to track changes in LAI since we did not have multiple LAI measurements at this site. PAR albedo declined by nearly 3% from May to October and is consistent with the canopy expansion associated with bud break (10–28 May 2007) and bracken fern growth (>50% ground coverage in June–August). Bud break in Pacific Northwest Douglas-fir trees occurs in late spring to early summer and the production of new needles as well as the summer-time growth of ground species has significant impacts on a stand with very low biomass ($LAI \sim 1\text{--}2\text{ m}^2\text{ m}^{-2}$). At the old-growth forest, these phenological changes appeared to not significantly increase net carbon uptake as we observed maximum uptake rates in April before bud break. The occurrence of peale CO_2 fluxes during spring-time has also been observed at an old-growth Ponderosa pine forest in central Oregon (Law et al., 2000) and at an intermediate-age coastal Douglas-fir ecosystem on Vancouver Island, British Columbia (Humphreys et al., 2006), and may be a universal trait associated with intermediate- to mature-age Pacific Northwest conifer forests.

5.2. Age-class flux differences

Old-growth E_f varied little ($\sim 3\text{ mm}$) between the 2006 and 2007 summer months even though rainfall and average θ_v showed that 2007 was wetter. While it is true that there is some uncertainty involved with E_f measurements, the uncertainty should remain the same from year to year at each site as long as the IRGA is carefully calibrated. We inadvertently introduced different instrument-related errors by using a closed-path IRGA at the old-growth stand and an open-path IRGA at the early seral stands. In lieu of assessing the instrument errors directly, we used bootstrapping to quantify uncertainties on E_f . The results showed that the differences in E_f from the early seral stands and the old-growth forest were significant. The evapotranspiration and Bowen ratio measurements presented here are unusual compared to other stand-age studies because we report higher E_f and lower B at the younger sites. In comparison, Anthoni et al. (2002) measured E_f over a 15-year-old and a mixed-age old-growth Ponderosa pine forest during the 2000 summer drought season and reported lower E_f over the younger stand even though weather anomalies were similar at both sites. Considering our site differences in E_f and B , it is worth noting that a wide range of summer-time B (0.46–2.2, mean = 1.1) have been published for conifer forests (Wilson et al., 2002b) and variability can be high even within the same study site because B is sensitive to canopy wetness. Humphreys et al. (2003) reported a mean summer-time B of 1.1 at the intermediate-age Douglas-fir, Vancouver Island stand in 1998, although monthly

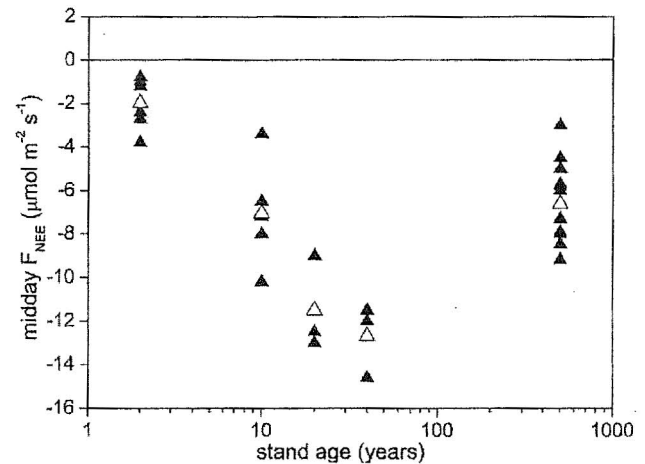


Fig. 10. A Pacific Northwest Douglas-fir chronosequence of late-summer CO_2 fluxes. Plotted are mean midday F_{NEE} during July–September. Sites include the Vancouver Island, B.C. initiation stand (2–3 years old, measured in 2002 and 2003, Humphreys et al., 2006), Wind River early seral stands (0–15 years old, measured in 2006 and 2007, this study), Wind River 20-year-old stand (measured in 1999, Chen et al., 2004), Wind River 40-year-old stand (measured in 1998, Chen et al., 2004), and Wind River old-growth stand (shown for 1998 and 1999, Chen et al., 2004; and 2006 and 2007, this study). Open triangles are the stand mean F_{NEE} .

mean values ranged from 0.8 to 1.91 and even broader ranges were observed over a 24-h or weekly period.

If we add an additional Douglas-fir stand from Vancouver Island (Humphreys et al., 2006) to our chronosequence then the very youngest age class (0–3 years, initiation stage) is available for our stand-age discussion. Fig. 10 summarizes the Pacific Northwest Douglas-fir EC data and shows how mean, midday July–September CO_2 fluxes differ by stand age. At the end of the drought season, highest to lowest rates of net carbon uptake occurred in the 40-year-old stand, 20-year-old stand, early seral stands (~ 10 years old), old-growth stand, and initiation stand. There is no significant difference between the early seral stand and old-growth fluxes here. The initiation Douglas-fir stand shows the smallest, but still net CO_2 uptake during summer-time midday hours (Humphreys et al., 2006).

Here we have reported crucial data from the early seral age class for understanding how stand-age affects flux exchange. While other EC studies have shown that net carbon uptake is greater in mature conifer stands than in the 0–20-year-age class, we stress that our study shows how highly sensitive this young age class is to seasonal drought and phenological events. Our study also sheds light on how important it is to quality-control daytime fluxes based on footprint estimates and ABL turbulence statistics in small clear-cut stands to ensure that the eddy covariance technique is valid.

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