12.12 EFFECTS OF STAND AGE AND WEATHER ON CARBON DIOXIDE AND WATER VAPOUR FLUXES IN COASTAL DOUGLAS-FIR FORESTS

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1. INTRODUCTION

Forest harvesting and succession have a major impact on the dynamics of carbon and water vapour exchange between forests and the atmosphere. As part of the Fluxnet-Canada Research Network, eddy covariance measurements of stand-level carbon dioxide (CO_2) and water vapour (H_2O) fluxes were made in three Douglas-fir stands at different stages of development after harvesting. These stands were located within 50 km of each other on the east coast of Vancouver Island, British Columbia. Between 1998 and 2003, six years of measurements were made in a stand established in 1949 (DF1949), two years in a stand established in 1988 (DF1988), and three years in a stand established in 2000 (DF2000). These measurements are used to examine how net ecosystem production, respiration, photosynthesis, and evapotranspiration in these coastal Douglas-fir forests vary with seasonal and interannual variations in weather and with stand age.

2. METHODS

2.1 Site and Stand Characteristics

Selected site and stand characteristics of the three forests are listed in Table 1. In 2002, the stands were 53, 14, and 3 years old. DF1949 was a second growth Douglas-fir stand, which had regenerated after the previous old-growth forest was logged and slash-burned in 1937 and the remainder logged and slash-burned in 1943. Additional site details are found in Drewitt et al. (2003), Humphreys et al. (2003), and Morgenstern et al. (2004).

DF2000 was located about 3 km ESE of DF1949. The 60-year-old Douglas-fir in this area had been clearcut harvested in the winter of 1999/2000. In the early spring of 2000, the area was planted with 1-year-old seedlings (93% Douglas-fir, 7% western redcedar plug stock) at a density of 1500 trees ha^{-1}. In 2002, the trees were on average 0.6 m tall with a mean basal diameter of 1.5 cm. Maximum LAI increased from 0.2 in 2000 to a maximum of 2.5 in 2003. Within a growing season, LAI varied from a low of 0.6 in April 2002, for example, to a maximum of 2.2 in June and July 2002, mainly with the growth of pioneer and understory species from the previous stand. Some of the more common species included bracken and sword fern, fireweed, Oregon-

Table 1: Selected stand and site characteristics.

	DF1949	DF1988	DF2000
Stand characteristics in 2002:			
Current stand origin	1949	1988	2000
Stand height (m)	35	5.8	0.6
EC measurement height (m)	43	12	3
Stand density (trees ha^{-1})	1100	1240	1500
Douglas-fir (% of total trees)	80	75	93
Maximum LAI	8.4	4.8	2.2
Friction velocity threshold (m s^{-1})	0.32	0.16	0.08
Roughness length (m)	3.51	0.46	0.07
Site characteristics:			
Location	49°52'N, 125°20'W	49°31'N, 124°54'W	49°52'N, 125°17'W
Elevation (m)	300	170	175
Slope (degrees)	5 - 10	2 - 5	0 - 2
Aspect	NE	SE	level
Soil texture	gravelly loamy sand	gravelly loam	gravelly loamy sand/sand

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grape, salal, twinflower, various *Rubus* spp., and various asters, thistles, and grasses.

DF1988 was located about 48 km SE of DF1949. In 2002, the trees had not yet formed a closed canopy and were on average 5.8 m tall with a mean DBH of 7.5 cm. A dense understory of deciduous and evergreen species such as fireweed, sword and bracken fern, salal, *Rubus* spp., and red huckleberry resulted in a variable LAI with a maximum value of approximately 4.8 in late June 2002. This area had been harvested in 1987, broadcast burned and planted in 1988 with 75% Douglas-fir, 21% western red cedar, and 4% grand fir. Herbicide was applied in 1992. Prior to the 1987 harvest, the area was a mixed second growth stand of primarily Douglas-fir with western redcedar, western hemlock and red alder. An initial cut (and likely slash burn) of the original forest occurred in 1937-1938.

2.2 Flux and weather measurements

The eddy covariance (EC) technique was used to measure fluxes of CO_2 and H_2O. Fluctuations in wind velocity and temperature were measured with a three-dimensional sonic anemometer-thermometer (R3 or R2 Gill Instruments Ltd. or CSAT3, Campbell Scientific Inc.). Fluctuations in CO_2 and H_2O were measured with either a closed-path or open-path infrared gas analyser (LI-6262 or LI-7500 LI-COR Inc.). In either situation, air was sampled within 0.3 m of the center of the sonic anemometer array. For the closed-path IRGAs, air was drawn through a 3-4 m tube, a filter, and then the IRGA at a flow rate of 8-10 L min^{-1}.

High frequency data was processed in the same way for all three stands. Half-hour CO_2 and H_2O fluxes were computed from the covariance of vertical wind velocity and either the CO_2 (s_c) or H_2O (s_v) mixing ratios. Further calculation details are found in Humphreys et al. (2003) and Morgenstern et al. (2004).

It was important that CO_2 and H_2O fluxes were comparable when computed with either the open- or closed-path IRGAs in order to assess differences between stands attributable to factors other than instrumentation. As expected, fluxes computed with the open-path IRGA were generally greater than those computed with the closed-path IRGA in tests in DF1949 and DF2000, where closed-path IRGAs were used a majority of the time. Using the procedure described in Aubinet et al. (2000), transfer functions were developed to characterize the high frequency losses of CO_2 and H_2O fluxes due to sensor separation, differences in path averaging, and attenuation of fluctuations through the sampling tube. Cut-off frequencies of 0.75 and 1.17 Hz for closed-path CO_2 flux were found for DF2000 and DF1949, respectively. However, the proportion of CO_2 flux attributable to frequencies greater than 1 Hz was only about 3%, 1%, and 0.6% in DF2000, DF1988, and DF1949, respectively, while for frequencies greater than 0.1 Hz, these proportions increased to 28%, 16%, and 6%, respectively. As a result, a correction factor (CF) for closed-path measurements of CO_2 flux, developed from the sensible heat flux cospectra degraded by the transfer functions described above, was less than 1.02 in DF1949 90% of the time but larger at 1.08 in DF2000. As a result, CF were applied to both CO_2 and H_2O fluxes only in DF2000 using the following relationships with half-hour average wind speed (u), CF $= 0.05u + 1.00$ for CO_2 flux and CF $= 0.07u + 1.01$ for H_2O flux, following Aubinet et al. (2000). After applying the CF to fluxes measured with the closed-path IRGA in DF2000, excellent agreement was found between open-path and closed-path CO_2 and H_2O fluxes during rain-free and dew-free conditions.

Net ecosystem exchange (F_{NEE}) was equal to the sum of CO_2 flux and the rate of change of storage of CO_2 in the air column below the EC height. Net ecosystem production (F_{NEP}) is to a very good approximation assumed to equal -F_{NEE}. Positive values of F_{NEP} mean net C uptake by the stand and negative values mean net loss of C.

Half-hour fluxes of poor quality and nighttime measurements made when friction velocities were less than a threshold value (Table 1) were removed from the data set. These gaps were filled using a common procedure for all three stands. First, an exponential relationship between half-hour nighttime soil temperature (T_s) and nighttime F_{NEP} was determined using half hours from the entire year. Daytime ecosystem respiration (R_e) was estimated using this relationship with daytime T_s. Gross ecosystem production (F_{GEP}) was obtained by adding measured values of daytime F_{NEP} to these calculated daytime R_e values. A rectangular parabolic relationship between F_{GEP} and downwelling photosynthetic photon flux density (Q),

$$F_{GEP} = \frac{\alpha F_{GEP\infty} Q}{\alpha Q + F_{GEP\infty}} \tag{1}$$

where $F_{GEP}\infty$ is the asymptote and α is the effective quantum yield, was evaluated for June 15 to July 15. This relationship was used to estimate F_{GEP} for all daytime half hours. These estimates of F_{GEP} were then adjusted to the seasonal variations in F_{GEP} by finding the slope of the linear regression forced through zero between the estimates and measurements of F_{GEP} (independent variable) for 100 consecutive half-hour measurements moving through the year in increments of 20 half hours. Missing daytime half-hour F_{NEP} values were filled using the difference between the estimated F_{GEP} and R_e while missing nighttime half hours were filled using $-R_e$.

3. RESULTS AND DISCUSSION

3.1 Influence of Stand Age

In this section, the influence of stand characteristics associated with differences in age are examined using measurements made in 2002. In 2002, DF2000 was a large carbon (C) source, DF1988 was a small C source, and DF1949 was a moderate C sink (Table 2). Annual F_{NEP}, R_e, and F_{GEP} increased with increasing stand age. In contrast, annual evapotranspiration (E) was similar in the two older stands and about 150 mm less in DF2000.

Table 2: Annual F_{NEP}, F_{GEP}, R_e, and E in 2002.

	DF2000	DF1988	DF1949
C exchange (g C m^{-2} y^{-1}):			
F_{NEP}	-610	-130	250
F_{GEP}	430	1210	1960
R_e	1040	1340	1710
Evapotranspiration (mm y^{-1}):			
E	390	405	250

Differences in annual F_{NEP} between the three stands were related to the timing and magnitude of maximum F_{GEP} and R_e (Fig. 1). In all three stands R_e peaked in July and August when temperatures were warmest. Although R_e increased with increasing stand age, growing season R_e in DF2000 was as much as 77% of R_e in DF1988 and 57% of R_e in DF1949. Soil chamber measurements confirmed that belowground respiration rates were similar in magnitude in the three stands suggesting that R_e varied in part as a result of aboveground autotrophic respiration. Maximum light saturated F_{GEP} in all three stands related well to LAI (Fig. 2). In the closed canopy in DF1949, LAI remained approximately constant through the year. With the increase in light and daylength in March and April, a rapid increase in F_{GEP} was measured. F_{GEP} remained high until September. In the two younger stands, both LAI and F_{GEP} increased gradually through the spring until late June/early July and then decreased gradually with senescence of the large amount of herbaceous

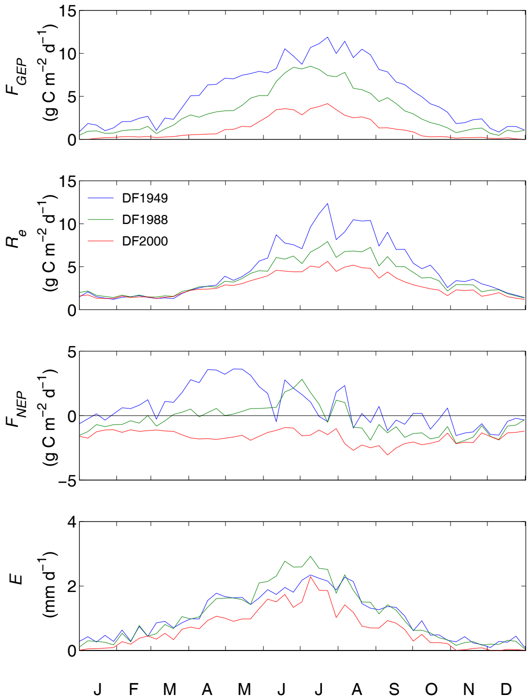

Figure 1: 7-day average F_{GEP}, R_e, F_{NEP}, and E for the three stands in 2002.

and deciduous species present in these two stands. Seasonal patterns in F_{NEP} were very different between stands. The greatest net C uptake occurred in April and May in DF1949 when temperatures were low but daylength and light levels were favourable for photosynthesis. Maximum annual LAI resulted in maximum F_{NEP} in late June/early July in DF1988, even exceeding rates observed in DF1949 at that time. R_e was always greater than F_{GEP} in DF2000 but the smallest net loss of C also occurred with maximum LAI in late June/early July.

Greater aerodynamic roughness and leaf, stem, and branch area for interception resulted in greater E in winter in the two older stands (about 83 mm between Oct and March in Df1949 and 72 mm in Df1988 vs. 35 mm in Df2000). In summer, E was lowest in DF2000 where less leaf area is available for transpiration. However, despite having the greatest leaf area, summer E in DF1949 was less than in DF1988. The 14-year-old Douglas-fir and abundant herbaceous and evergreen understory species at that site appeared to restrict water loss less than the 53-year-old Douglas-fir in the oldest stand. As a result, May - September water use efficiency (F_{GEP}/E) in these stands increased with increasing stand age (7.3,

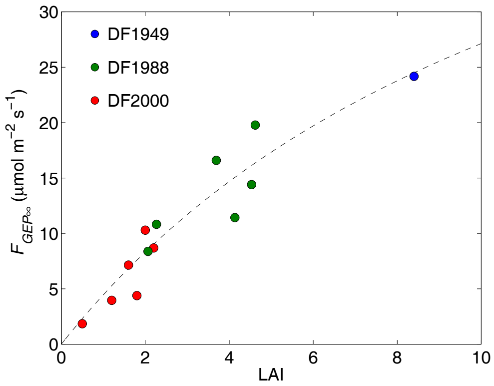

Figure 2: $F_{GEP\infty}$ (asymptotic F_{GEP} from monthly light response curves) observed at the three sites between May and September in 2002 vs. LAI.

11.3, and 19.4 g CO_2 / kg H_2O in DF2000, DF1988, and DF1949, respectively).

3.2 Influence of interannual variations in weather on annual C and H_2O exchange

All available annual F_{NEP} (Jan 1 - Dec 31) from the Vancouver Island Douglas-fir chronosequence are shown in Figs. 3 and 4. Although forest structure (or age) had a dominant role in determining net C exchange, interannual variations in F_{NEP}, especially in the oldest, most structurally stable forest, emphasized the important role of weather.

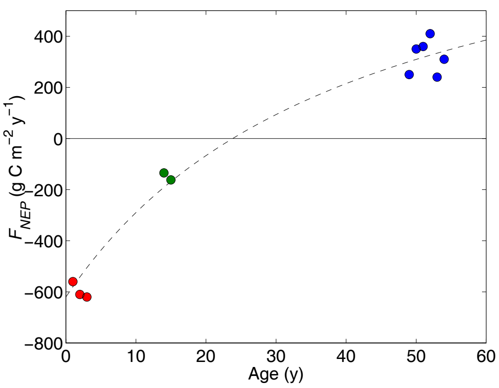

Figure 3: Annual F_{NEP} observed in the three stands between 1998 and 2003.

Interannual variations in F_{NEP} were greatest in DF1949 (Figs. 3 and 4). Differences in F_{NEP} were slightly less in DF2000 but the increase in both F_{GEP} and R_e with time since harvest and replanting, were dramatic (Fig. 4). In contrast to these two sites, all three measures of C exchange in DF1988 were remarkably consistent during the two study years.

The response of R_e to temperature and F_{GEP} to light, the main driving variables for these C exchange processes in DF1949, varied only slightly between years (Morgenstern et al. 2004). As a result, variations in annual F_{NEP} were due to often subtle differences in average air and soil temperatures and cloud cover, particularly during spring and early summer. In contrast, Humphreys et al. (2004) emphasized that changes in forest structural characteristics, such as LAI, due to the rapid establishment and growth of pioneer and understory species, were important in determining variations in C exchange in DF2000. Weather did play a slightly smaller role as drought appeared to limit the increase in F_{GEP} and to a smaller extent, R_e in the third year after harvesting. This resulted in even greater loss of C from the site in the third vs. the second year. Although conditions were drier in 2003 than in 2002, temperature and cloudiness were similar. In DF1988, there was a difference of only 30 g C m^{-2} in F_{NEP} between those two years with slightly lower F_{GEP} in the drier 2003 but no difference in R_e.

Annual E was relatively insensitive to variations in weather in all three stands, varying between years by less than 20 mm from the average E (Fig. 4). A strong negative feedback response of canopy conductance to saturation vapour deficit and declining soil moisture moderates transpiration rates (Humphreys et al. 2003). In addition, compensations between transpiration processes and the evaporation of intercepted precipitation or understory or soil evapotranspiration further limit interannual variations in E.

4. SUMMARY AND CONCLUSIONS

The seasonal variations and magnitudes of F_{NEP} and E differed between stands and were related to differences in stand structural characteristics such as canopy roughness, LAI, species composition and phenology. Variability in weather such as warmer spring temperatures and drought resulted in significant interannual differences in F_{NEP} but only small differences in E. Results from this study emphasize the importance of both weather and stand age in determining annual C exchange in these Douglas-fir stands, however, the relative importance of these factors differs with the stage of forest development.

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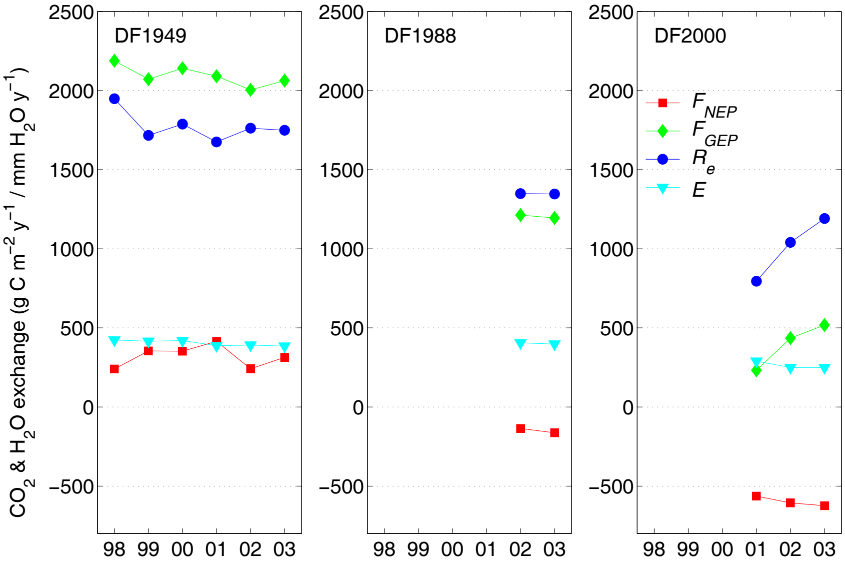

Figure 4: Annual F_{NEP}, F_{GEP}, R_e, and E for the three Douglas-fir stands in 1998-2003

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