USING AIRBORNE LIDAR FOR THE ASSESSMENT OF CANOPY STRUCTURE INFLUENCES ON CO$_2$ FLUXES

L. Chasmer [a, *], A. Barr [b], A. Black [c], C. Hopkinson [d], N. Kljun [e], J. H. McCaughey [a], and P. Treitz [a]

[a] Department of Geography, Queen's University, Kingston Ontario, K7L 3N6 - lechasme@yahoo.ca,
mccaughe@post.queensu.ca; paul.treitz@queensu.ca
[b] Climate Research Branch, Meteorological Service of Canada, Saskatoon SK
[c] Faculty of Agricultural Sciences, University of British Columbia, Vancouver BC
[d] Applied Geomatics Research Group, NSCC, Middleton NS
[e] Institute for Atmospheric and Climate Science, ETH Zurich, Universitätsstrasse 16 ETH Zentrum,
CHN CH-8092 Zurich

Commission VI, WG VI/4

KEY WORDS: airborne lidar, carbon dioxide, eddy covariance, flux footprint, canopy structure, photosynthesis, respiration.

ABSTRACT:

Fluxes of carbon dioxide (CO$_2$), water, and energy measured using the eddy covariance method (EC) will vary spatially and temporally within the catchment area of the EC system, especially if parts of the forest are structurally heterogeneous. This is important because within site vegetation structural and topographic heterogeneity may tip the balance between an ecosystem being a net sink or source of CO$_2$ within a given year. Further, if wind directions are non-varying, the EC method may possibly either over- or under-estimate energy and mass fluxes if source locations are not representative of the entire ecosystem. The following study will use airborne lidar assessments of canopy structure, a simple flux footprint parameterisation, and EC estimates of net ecosystem productivity (NEP), ecosystem respiration (Re), and gross ecosystem productivity (GEP) to test the hypothesis that vegetation structural heterogeneity has some influence on CO$_2$ fluxes within a mature jack pine forest in Saskatchewan, Canada. The results found in this study indicate that vegetation structural variability (canopy height, depth, and foliage amount) within the site have significant influences on the variability in CO$_2$ flux estimates of uptake and respiration made using the EC method. However structural heterogeneity is not more important than meteorological driving mechanisms. The influences of structure may therefore become more influential in more heterogeneous ecosystems. Variability in vegetation fractional cover (a proxy indicator for foliage amount) and height, observed from airborne lidar, have the greatest influences on NEP and GEP, where increased fractional cover is directly related to increased CO$_2$ uptake on most days studied.

1. INTRODUCTION

Fluxes of CO$_2$, water vapour, and energy vary spatially and temporally due to changes in solar radiation, soil and air temperature, soil type, the photosynthetic capacity of vegetation and foliage density (e.g. Baldocchi et al. 1997; Griffis et al. 2003). Therefore, it is likely that variability in the conditions required for the transfer of CO$_2$ into the ecosystem, via photosynthesis, and fluxes of CO$_2$ out of the ecosystem, via ecosystem respiration, may be manifested in the vegetation structural and topographic heterogeneity within the ecosystem. Canopy structural and ground surface topographic variability are important considerations when examining the annual carbon balance of forests, especially if these affect the differences between annual net CO$_2$ uptake and release. Ecosystem respiration (Re) plays an important role in the carbon balance of many climatically sensitive boreal forests (e.g. Lindroth et al. 1998) because Re may alter the ecosystem from being a sink for atmospheric CO$_2$ to a source. For example, Griffis et al. (2003) determined that 46% of net ecosystem productivity resulted in CO$_2$ loss through respiration at a mature jack pine site, indicating the importance of ecosystem Re to the carbon balance. At OJP, CO$_2$ uptake and respiration processes are often dependent on canopy foliage cover and solar heating of the ground surface, whereby interception of solar radiation by greater numbers of leaves results in increased photosynthesis and CO$_2$ uptake as well as decreased warming of the soil surface, and possibly, decreased Re (Baldocchi et al. 1997). Further, within canopy radiation scattering during sunlit (direct radiation) and cloudy (diffuse radiation) periods will also affect the efficiency with which light is used for photosynthesis, especially when the canopy becomes isotropic (Baldocchi et al. 1997). If water stress is a limitation to vegetation growth, then a positive feedback may result whereby productivity (and leaf area) will decrease or remain low, and penetration of radiation through the canopy will increase causing soils to warm and the possibility of respiration increase (Baldocchi et al. 1997).

Airborne lidar, in combination with a spatially and temporally varying flux footprint model parameterisation and the eddy covariance method (EC) offer one method for which mass and energy exchanges can be assessed within complex vegetated ecosystems. Footprint parameterisations of the upwind distribution area can be used to examine the sources and sinks of fluxes such that the relative contributions of elements from different places within the ecosystem diffuse with atmospheric turbulence to the EC measurement system (Schmid, 1994). Particle diffusion is strongly dependent on wind direction, wind velocity, the height of the EC system, atmospheric stability, roughness length, and land surface heterogeneity (Kljun et al.

---

* Corresponding author.

2004). Flux footprints, therefore, plot the shape in x and y coordinates of the source/sink area as well as the probability density function (PDF), defined as the probability of the distribution of flux throughout the site by continuous sampling of that flux, via relative frequency. Airborne lidar can be used to determine the relative variability of vegetation structural characteristics and topography within an individual flux footprint or source/sink area per unit time. The combination of source/sink area defined by the footprint model parameterisation, flux exchanges measured using the EC method, and detailed structural and topographic information from lidar will continue to become important mechanisms for understanding some of the physical mechanisms associated with temporal and spatial variability in CO_2 uptake and respiration within vegetated environments.

In this study, we use airborne lidar to characterise vegetation structural heterogeneity within the contours of half-hourly flux footprint maximum area PDFs (approximately 80% of flux contribution area) in order to quantify the magnitude of influence that within-site canopy structural variability has on CO_2 uptake and respiration estimated using the EC method. A simple footprint climatology parameterisation of Kljun et al. (2004) is applied at a naturally regenerating, mature jack pine forest in Saskatchewan, Canada.

2. METHODOLOGY

2.1 Study Area

The study site consists of a fairly homogeneous mature jack pine (*Pinus banksiana* Lamb.) forest (OJP) located near the southern edge of the boreal forest in Saskatchewan (520230 E, 5974262 N, zone 13). The site is maintained by Environment Canada for the Fluxnet-Canada Research Network (www.fluxnet-canada.ca) and is part of the Boreal Ecosystem Research and Monitoring Sites (BERMS). BERMS contains multiple chronosequence, fire, and a fen sites for which flux, meteorological and mensuration data have been collected consecutively since 2005 (Table 1).

Plot #	Elevation (m)	DBH (cm)	Tree height (m)	Canopy depth (m)	LAI	Stem density (m^{-1})
1	494.3	15.9	14.9	6.3	1.36	0.12
2	495.1	14.6	13.6	6.1	1.54	0.08
3	494.1	11.7	13.0	5.9	1.06	0.17
4	492.5	12.9	13.3	5.2	1.26	0.15
5	489.5	17.5	15.7	8.8	1.35	0.09
6	491.9	16.1	14.9	8.1	1.44	0.1
7	487.0	11.8	11.4	6.2	1.00	0.14
8	492.4	23.6	13.4	11.2	1.76	0.04

Table 1. Average stand characteristics measured at eight plots. DBH = diameter at breast height, LAI = Leaf area index. Corrections for canopy clumping, woody-to-total area ratios and needle-to-shoot area ratios were used to adjust LAI according to Chen et al. (2006).

Elevation within the EC catchment area at OJP (1000 m radius) varies between 482 and 494 m, and cross-site variability in tree heights range from approximately 13 m and 18 m. Mensuration data were collected at eight plots during the growing season of 2005, coincident with the airborne lidar survey (Table 1). Mensuration plots (11.3 m diameter) were set up and georeferenced using survey-grade (differential, post-processed)

GPS such that four plots were located within 100 m of the flux measurement tower, and four plots were located within 500 m of the tower for spatial representivity. Understory vegetation consists of alder (*Alnus crispa* Ait.), reindeer lichen (*Cladina* spp.), and bearberry (*Arctostaphylos uva-ursi* L.). Soils within the site tend to be sandy and dry with little nitrogen content (Baldocchi et al. 1997).

2.2 EC Flux Estimates

Three, approximately one to two week periods of flux and meteorological data were examined during the dry growing season of 2002. CO_2 observations were excluded during periods of rainfall and low wind speed. Average tree height growth since 1996 was approximately 1 m, therefore growth between 2002 and 2005, when the lidar survey was performed, is minimal and within the range of error of the lidar system used. Vegetation growth likely has an insignificant influence on the results of the analysis.

Above canopy CO_2 fluxes were measured at approximately 30 m above the ground surface using the eddy covariance method at 10 Hz and aggregated to 30-minute periods. EC instrumentation and methodology are discussed in Barr et al. (2004). In this study, net ecosystem productivity (NEP) ($\mu mol \cdot m^{-2} \cdot s^{-1}$) is directly measured by the EC system where NEP = net ecosystem exchange (-NEE) ($\mu mol \cdot m^{-2} \cdot s^{-1}$). Therefore, a positive NEP indicates that the ecosystem uses more CO_2 for photosynthesis than it releases. Re ($\mu mol \cdot m^{-2} \cdot s^{-1}$) is modelled via the relationship between night-time respiration and soil temperature (Barr et al. 2004). Gross ecosystem productivity (GEP) ($\mu mol \cdot m^{-2} \cdot s^{-1}$), defined as the uptake of CO_2 by the ecosystem for photosynthesis, is calculated from NEP and Re whereby GEP = NEP + Re. It is important to note that NEP is the most direct estimate of CO_2 flux measured using the EC. GEP and Re, on the other hand, are modelled based on soil temperature relationships and may possibly be over- or under-estimated. Fluxes have been averaged over coincident 30-minute periods during daylight conditions. Daytime is defined as the above-canopy incoming shortwave radiation >0.5 $W \cdot m^{-2}$ to avoid errors in EC measurements, occasional condensation on radiation sensors, and footprint model parameterisation during generally stable nocturnal atmospheric conditions. Uncertainties in measuring carbon fluxes occur because, during calm and stable conditions, the transfer of carbon dioxide by non-turbulent exchanges is not detected by the EC system (Griffis et al. 2003). Further, early morning and late afternoon periods were not examined due to CO_2 storage and 'flushing' of CO_2 out of the ecosystem, not related to canopy structure.

Variability in CO_2 fluxes caused by meteorological influences such as soil moisture, soil temperature, air temperature, relative humidity, incoming photosynthetically active radiation (PAR), and vapour pressure deficit have been removed using residual analysis (not shown) (e.g. Chen et al. 2002). Therefore, influences of vegetation structure on CO_2 fluxes are examined after all meteorological driving mechanism influences have been removed. Average 24-hour energy balance closure for each day and each period studied was determined using the Energy Balance Ratio method (Wilson et al. 2002). Average energy balance closure during the first period of study was ~88% (standard deviation = ~10%), during the second period was ~83% (standard deviation = ~8%), and during the third period was ~85% (standard deviation =~14%).

2.3 Lidar Data Collection and Processing

Lidar data were obtained at OJP using a small-footprint, discrete pulse return ALTM 3100 (Optech Inc., North York, Ontario), owned and operated by the Applied Geomatics Research Group, Nova Scotia on August 12, 2005. Up to four laser pulse returns were obtained per laser pulse emitted, at a rate of 71 kHz and at a flying height of 950 m a.g.l. The scan angle was set at ± 19° with 50% overlap of adjacent flight lines. This enabled penetration of the laser pulses through to the base of the canopy, whilst also obtaining returns on all sides of individual tree canopies (Chasmer et al. 2006). Cross-track and down-track resolutions, with the 50 percent overlap of scans, are 35 cm ("post spacing").

Percentile distributions, frequently used to estimate average tree canopy heights using lidar data (e.g. Magnussen and Boudewyn 1998) were used to approximate average tree heights and base of live crown height (used to determine live canopy depth, where depth = canopy height – canopy base height) at the plot level and also within-footprint probability density function (PDF) contours using a canopy height model (CHM). Height and live canopy base height percentile distributions were calculated on individual laser pulse returns greater than or equal to 2 m above the ground surface so that laser pulse returns from the ground surface would not influence and shift the percentiles downwards. Also, the 2 m threshold was used to receive pulses from the canopy only, as opposed to stems and understory. Percentile distributions were also compared at eight individual plots to determine the most accurate and descriptive percentiles to use. The 90th and 8th percentiles were most appropriate for determining average tree heights and base of live crown height at the plot level at OJP. Accuracy in predicting tree heights and base of live crown height were 0.94 and 0.77 (coefficients of determination) for the 90th (corresponding to canopy height) and 8th (corresponding to base of live crown height) percentiles, respectively. Differences between average measured canopy height, canopy height derived from airborne lidar (L90 = 90th percentile), and average canopy base height, canopy base height derived from airborne lidar (L8 = 8th percentile) are shown on a per plot basis in Table 2. These were then applied to laser pulse returns within the 30-minute footprint 80% PDF contour lines.

A proxy for plant area index (PAI) has been created from laser pulse returns within the canopy and the total number of laser pulse returns, following a simple methodology discussed in Morsdorf, et al. (2006) for gap fraction and fractional cover. Gap fraction increases when gaps within the canopy increase, thereby resulting in increased radiation passing through the open canopy without intercepting foliage. The inverse of this is "fractional coverage" or *fcover* whereby gaps are represented by a foliage cover of zero, and increased radiation interception results in increased fractional coverage of foliage. Laser pulses can exhibit similar properties to solar radiation as they pass through the canopy. Laser pulses that are returned from within the canopy have been effectively 'blocked' by the canopy from reaching the ground. Laser pulses that reflect from the ground surface likely passed through gaps within the canopy. Therefore, the ratio of the laser pulses returned from within the canopy to those returned from the ground surface is a reasonable proxy for the gaps within the canopy and the fractional coverage of leafy and woody material intercepting radiation.

To obtain spatial estimates of *fcover*, laser pulses have been classified using "canopy" and "non-canopy" pulse returns

within Terrascan (Terrasolid, Finland) such that all laser pulses located 1.3 m above ground level were classified as "canopy" and all pulses located below 1.3 m, including ground were classified as "low vegetation and ground", coincident with the height of the digital camera, and photographs. Vegetation fractional coverage from lidar has been determined by counting the total number of "canopy" laser pulse returns and then, by counting the total number of "low vegetation and ground" laser pulse returns within corresponding 1 m x 1 m x 30 m columns. Counts were performed within Surfer (Golden Software Inc., Golden, Colorado) and *fcover* was determined for the entire area within the EC catchment using the SAS statistical package (SAS Institute Inc., Cary, North Carolina). *fcover* is calculated as:

$$f\mathrm{cov}er = \left(\frac{\sum Pcanopy}{\sum(Pcanopy + Pground)} \right) \quad [1]$$

where *Pcanopy* is the total frequency of laser pulse returns within the canopy, and *Pground* is the total frequency of laser pulse returns for low vegetation and ground within each 1 m x 1 m x 30 m column (Figure 1) throughout the catchment area of the EC (approximately 750 m radius). *Fcover* has been compared with estimates of gap fraction (1-*fcover*) and effective leaf area index (LAIe) for 9 of 10 analus rings determined from digital hemispherical photography (DHP) ($r^2 = 0.68$) (Leblanc et al. 2005). This indicates that *fcover* is a reasonable estimate of leaf area at this site, when compared with DHP. In order to correct LAIe obtained from DHP, the needle-to-shoot area ratio, woody-to-total area ratio, and clumping index from Chen et al. (2006) were used.

Plot #	Ave. height (m)	L90 (m)	Diff. (m)	Ave. canopy base height (m)	L8 (m)	Diff. (m)
1	14.9	14.8	-0.1	6.3	6.1	-0.2
2	13.6	14.1	0.4	6.1	5.9	-0.2
3	13.0	13.0	0	5.9	6.1	0.2
4	13.3	13.7	0.4	5.2	5.3	0.1
5	15.7	14.7	-1.0	6.9	7.0	0.1
6	14.9	14.7	-0.2	6.8	6.5	-0.3
7	11.4	12.0	0.6	5.2	6.1	0.9
8	13.4	14.9	-1.5	5.2	6.0	0.8

Table 2. Average canopy height and canopy base height measured on a per tree basis within individual 11.3 m radius mensuration plots compared with lidar estimated canopy heights and canopy base height determined using percentile distributions (L90 and L8, respectively).

The amount of vegetation fractional cover (*fcover*) is illustrated at OJP in Figure 1. The site tends to be relatively homogeneous, with *fcover* ranging between 0.2 and 0.5. The area immediately surrounding the EC flux station tends to have the lowest *fcover*, on average. Areas to the north and south tend to have large gaps within the canopy and little foliage cover. Interestingly, low-lying areas, which often contain alders, tend to correspond with areas of higher *fcover* and tree height (not shown) due to the nitrogen fixing capabilities of alder and increased resources for jack pine growth (Vogel and Gower, 1998).
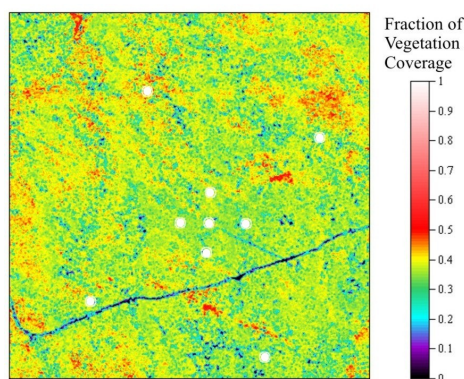
Figure 1. Vegetation fractional cover mapped at 1 m resolution at OJP. White circles represent field mensuration plot locations, and the central white circle represents the location of the EC flux station. All plots were located using survey-grade, post processed GPS with base and rover within 4 kms of each other at all times.

2.4 Footprint Parameterisation

The footprint parameterisation used in this study follows that discussed in Kljun et al. (2004). The parameterisation was chosen because a) the cross-wind integrated footprint is considered; b) it incorporates variables that are easy to derive from measurements obtained from EC; c) it is neither computationally difficult nor time-intensive; and d) it has been thoroughly applied and tested using a variety of meteorological (e.g. varying stability, roughness length, etc.) and technological (instrument measurement height) applications.

Briefly, the crosswind-integrated footprint ($\overline{f^y}$) as discussed in detail in Kljun et al. (2004), is scaled based on the along-wind distance from the receptor (x), the receptor height (z_m), roughness length (z_0), and the height of the planetary boundary layer (H). Directionality and origin of the flux is also determined from wind direction. Particle advection and diffusion is accounted for in the surface friction velocity (u_*), whereas buoyancy and the formation and size of eddies within the planetary boundary layer are described as the standard deviation of the vertical velocity (σ_w). These parameters create the non-dimensional form of the cross-wind integrated footprint F_* based on four dimensionless contributions and a function of the non-dimensional along-wind distance X_* (see Kljun et al. 2004). Dispersion in the y direction (the cross-wind distance from the centre-line) has been estimated using a Gaussian function (e.g. Amiro, 1999). Roughness length (z_0) at OJP has been calculated from Choudhury and Monteith, (1998) based on the height of the canopy, soil surface roughness, LAI, the height of the understory and zero-plane displacement. Therefore z_0 for OJP, using an average measured tree height of 14.16 m is 1.93 m and varies between 1.55 m and 2.23 m for averaged shortest and tallest trees within measured plots (11.4 and 16.4 m, respectively). The location of maximum flux varies between 200.2 m and 175.8 m from the flux tower for footprints containing shorter trees to footprints containing taller trees, respectively. The 80% origin of the flux area varies between 438 m (short trees) to 384 m (tall trees). Therefore the along wind distance (and subsequent error in footprint extent) may vary by as much as 50 m or approximately 10% of the total footprint ($\geq$ 80%) in the x direction. However, variable wind speed and boundary layer height will also alter the length of the footprint (not shown). Finally, Richardson number (Ri) is used to determine approximate stability of the atmosphere (Monteith

and Unsworth, 1990) using air temperature and windspeed at 30-minute periods during relatively unstable conditions when u_* is >0.2 ms^{-1}. Ri can therefore be used to approximate the height of the planetary boundary layer (H). Measured boundary layer heights were found to sometimes exceed 1.75 km during the growing season at OJP. A flux footprint example with maximum and 80% contour lines is provided in Figure 3 overlaid onto a canopy height model at OJP on June 13, 2002 at 10:00 (LST). The 80% contour (outer) line is used to extract within footprint canopy structural information for each 30-minute period throughout the day.
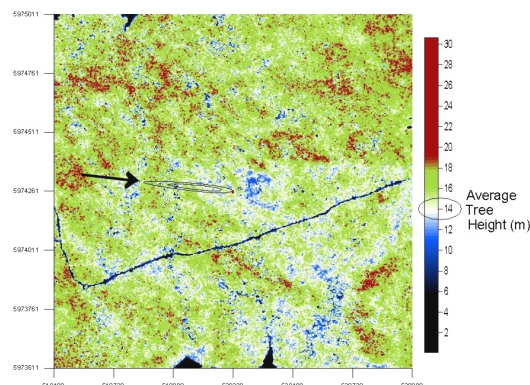

Figure 2. 30-minute flux source contour lines at 80% (outer contour) and maximum (inner contour) total integrated footprint on June 13, 2002 at 10:00 LST. The footprint has been overlain onto the lidar CHM at OJP. The arrow represents average wind direction during the 30-minute period.

3. RESULTS AND DISCUSSION

3.1 Vegetation Structural Influences on CO_2

In this study, the maximum part of the footprint is plotted such that a PDF of CO_2 flux ≥ 0.001 m^{-1}, and is within 500 m of the EC system (limited to the upwind areas only). The remaining parts of the footprint often extend up to and beyond the 1 km radius of the EC system, especially during stable conditions. Parts of the footprint that are outside of the 80% PDF tend to contribute relatively little compared to the maximum source of flux area. As such, canopy structural variability within the footprint (e.g. tree height, canopy depth, and *fcover*), play an important role on the residual variability in CO_2 fluxes after accounting for meteorological influences. Topography also plays an important role, but is not examined here. Table 3 provides summary results on remaining (residual) variability in 30-minute fluxes due to structural variability after accounting for meteorological driving mechanisms.

NEP at OJP is significantly influenced by within site canopy structural heterogeneity (vegetation height, canopy depth, and *fcover*) on 16 of 22 days examined (p<0.1) (Table 3). Further, the magnitude of influence tends to vary on a daily basis, often with respect to variations in meteorological driving mechanisms and likely, resource use. On five days, average structural variability accounts for 25% of the total variability in NEP, but does not play a more significant role than meteorological driving mechanisms on any given day. Meteorological driving mechanisms account for 74%, 75% and 52% of the variability in NEP, on average, during the periods studied (June, July, and August, respectively). Throughout the three periods of study, structural variability accounts for ~16% of the total variability in NEP on average during 18 of 22 days or 81% of the time

period. In most cases, increased biomass associated with increased tree heights, base of canopy height, and increased *fcover* were positively related to increased CO_2 uptake used for photosynthesis. However, during three of the days studied, the opposite was found to be true, especially in June, and one day in August, when the source was located within upland areas. This may be related to cooler air temperatures, lower incoming PAR and reduced carbon uptake on June 11, 2002, and increased air temperatures and respiration on June 13, and August 10 2002, leading to a reduction in NEP.

Date (2002)	Tree Height (r^2)	Canopy Depth (r^2)	*fcover* (r^2)	% of total varia-bility in NEP	# of days affec ted
June 10	0.03	0.06	0.07	4	4 of 6
June 11	-0.41	-0.36	-0.36	-29	
June 13	-0.05	-0.05	-0.2	-8	
June 14	0.08	0.05	0.03	4	
July 6	0.11	0.18	0.04	8	5 of 9
July 7	0.2	0.001	0.45	16	
July 8	0.06	0.09	0.22	9	
July 10	0.021	0.09	0.013	3	
July 12	0.7	0.57	0.43	43	
Aug. 7	0.26	0.1	0.18	26	7 of 7
Aug. 8	0.02	0.04	0.16	11	
Aug. 9	0.09	0.05	0.07	10	
Aug. 10	-0.09	-0.06	-0.02	-8	
Aug. 11	0.18	0.12	0.09	19	
Aug. 12	0.16	0.02	0.35	25	
Aug. 13	0.27	0.24	0.1	29	

Table 3. Coefficients of determination of the residual of NEP flux variability for individual canopy structural components, as well as the percent of the total variability in NEP accounted for by canopy structure. Negative signs indicate that NEP is negatively correlated with increases in biomass (e.g. via height, depth, or *fcover*) per day studied. Missing days indicate relationships that were not significant (p<0.1).

In the case of GEP, estimated as the total CO_2 used for photosynthesis, it is expected that footprint areas containing taller trees and increased *fcover*, as well as greater depth of canopy will be positively related to increased CO_2 uptake for photosynthesis. During 14 of the 22 days studied, structural variability in vegetation characteristics have a significant influence on GEP (p<0.1) (Table 4), but also does not have a greater influence than meteorological driving mechanisms, which account for 74.5%, 47.5%, and 82% of GEP variability during the three periods of study (June, July, and August, respectively). On average, ~12% of the total variability in GEP is influenced by vegetation structural characteristics. Positive and significant increases in GEP with increased *fcover* tend to correspond during certain days with greater average incoming photosynthetically active radiation (PAR), especially in July and to a lesser extent, in August. Canopy height and *fcover* have the most significant influence on NEP and GEP flux variability. Canopy depth, although correlated with vegetation height, tends to have a lower influence on CO_2 uptake.

Within footprint average structural heterogeneity has a lower influence on modelled Re because atmospheric and hydrological driving mechanisms play more of a key role in ecosystem respiration (Table 5). Meteorological driving mechanisms account for more than 80% of the variability in Re. On 13 of 22 days studied, structure has a significant influence on Re, and on 10 of these days, structural influences are ≥ 5% of the total variability in Re. Average structural influences

throughout the 13 of 22 days studied account for ~9% of the total variability in Re. It is likely that ground surface topography also plays an important role in GEP, NEP, and Re, and will be examined in a future study.

Date (2002)	Tree Height (r^2)	Canopy Depth (r^2)	*fcover* (r^2)	% of total varia-bility in GEP	# of days affect-ed
June 11	0.28	0.26	0.2	20	1 of 6
July 6	0.14	0.10	0.05	7	6 of 9
July 7	0.16	0.0002	0.35	13	
July 8	0.23	0.03	0.17	11	
July 10	0.02	0.12	0.007	4	
July 11	0.008	0.17	0.03	5	
July 12	0.7	0.6	0.014	33	
Aug. 7	0.24	0.08	0.23	14	7 of 7
Aug. 8	0.02	0.04	0.15	5	
Aug. 9	0.14	0.09	0.11	9	
Aug. 10	0.001	0.17	0.06	11	
Aug. 11	0.09	0.05	0.16	14	
Aug. 12	0.09	0.04	0.28	20	
Aug. 13	0.02	0.03	0.11	8	

Table 4. Coefficients of determination of the residual GEP flux variability due to within-footprint variations in canopy structure after the influence of meteorological driving mechanisms have been removed. Negative signs indicate that GEP is negatively correlated with increases in biomass. Missing days indicate relationships that were not significant within p<0.1.

Date (2002)	Tree Height (r^2)	Canopy Depth (r^2)	*fcover* (r^2)	% of total varia-bility in Re	# of days affect-ed
June 10	-0.34	-0.34	-0.025	-13	5 of 6 days
June 11	-0.15	-0.12	-0.014	-5	
June 13	0.46	0.42	0.53	25	
June 14	-0.12	-0.10	-0.11	-6	
June 15	-0.15	0.07	0.003	-4	
July 5	-0.35	-0.38	0.08	-13	4 of 9 days
July 7	-0.11	-0.0008	-0.26	-6	
July 8	-0.16	-0.19	-0.28	-10	
July 13	-0.26	-0.28	-0.29	-13	
Aug. 7	-0.38	-0.46	-0.17	-12	4 of 7 days
Aug. 8	0.001	0.008	0.15	2	
Aug. 12	-0.31	-0.26	-0.23	-10	
Aug. 13	0.07	0.05	-0.13	-3	

Table 5. Coefficients of determination of the residual Re flux variability due to canopy structural variability as well as the total variability in Re accounted for by canopy structure. Negative signs indicate that variability in Re is negatively correlated with canopy structure (e.g. increased Re is associated with locations with decreased biomass).

3.2 Potential Uncertainties and Future Research

The results from this study corroborate results from other studies, with respect to canopy structural influences on CO_2 fluxes, however, in this study, we have also quantified the magnitudes of influence that canopy structure has on CO_2 fluxes. Despite this, some potential uncertainties may slightly alter the results of the analysis and could be examined in the future. We will discuss each of these in turn.
Within footprint canopy height, depth and *fcover* will likely depend on the configuration of the lidar survey, especially where the calculation of *fcover* depends on a ratio of canopy to below canopy laser pulse returns. Changing lidar survey specifications *will* slightly alter the canopy structural

characteristics (e.g. Chasmer et al. 2006). Because a ratio is used, it is likely that lower densities of laser pulse returns will yield the same results as higher densities, so long as the probability of distribution of laser pulse returns between the canopy and the ground surface does not change. Tests on the influence of changing lidar survey specifications, etc. may be the focus of future research or a flux footprint sensitivity analysis.

In this study, we also assume that the canopy is non-varying throughout the growing season, and therefore ignore periods of needle flush in June, which will alter the photosynthetic capacity and uptake of CO_2 at this site.

The flux footprint parameterisation used in this study, like all models, is a simplification of the processes that are believed to be occurring within the EC catchment area. It therefore has assumptions that may alter the size and accuracy of the location of the footprint. By using 80% of the footprint probability density function, we have effectively reduced the error to the most probable location of the footprint, if wind directions are not highly variable within the period. Another source of error may be caused as a result of temporal lag effects of turbulent transfer of fluxes to the EC system. Further, variability in the spatial distribution of vegetation heights associated with roughness length, leaf area, photosynthetic capacity, and elevation will influence the extent and probability of flux in x and y directions. Geographic information systems are now able to include complex layers of data, as well as a variety of indices, such as topographic wetness index, vegetation indices, spectral characteristics, and so on. These can be integrated to form more complete and operational flux footprint parameterisations for individual sites.

4. CONCLUSIONS

The results of this analysis indicate that CO_2 fluxes within this relatively homogeneous ecosystem are frequently related to differences in vegetation structural heterogeneity within the site. Variability in structure and fluxes of CO_2 and H_2O throughout the EC catchment area will also have influences on spatial and temporal variability in light use efficiency (LUE) and water use efficiency (WUE) frequently used in ecosystem and remote sensing-based ecosystem models. CO_2 fluxes within heterogeneous forests may have increased dependency on canopy structure and topography (not examined), and these may be a deciding factor in whether the annual carbon balance of a vegetated ecosystem is a net sink or a net source.

5. REFERENCES

Amiro, B. D., 1998. Footprint climatologies for evapotranspiration in a boreal catchment. *Agricultural and Forest Meteorology*. 90:195-201.

Baldocchi, D. D., C. A. Vogel, and B. Hall, 1997. Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest. *Ag. For. Met.* 83, pgs. 147-170.

Barr, A.G., T.A. Black, E.H. Hogg, N. Kljun, K. Morgenstern, and Z. Nesic, 2004. Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production. *Ag. For. Met.* 126, pgs. 237-255.

Chasmer, L., C. Hopkinson, B. Smith, and P. Treitz, 2006. Examining the influence of changing laser pulse repetition frequencies on conifer forest canopy returns. *PE&RS.* 72(12), pgs. 1359-1367.

Chen, J., M. Falk, E. Euskirchen, K. Tha Paw U., T. Suchanek, S. Ustin, B. Bond, K. Brosofske, N. Phillips, and R. Bi, 2002. Biophysical controls of carbon flows in three successional Douglas-fir stands based on eddy-covariance measurements. *Tree Physiology*. 22:169-177.

Chen, J.M., A. Govind, O. Sonnentag, Y. Zhang, A. Barr, and B. Amiro, 2006. Leaf area index measurements at Fluxnet-Canada forest sites. *Ag. For. Met.* 140, pgs. 257-268.

Choudhury, B., and J. Monteith, 1988. A four-layer model for the heat budget of homogeneous land surfaces. *Quart. J. Roy. Meteorol. Soc.* 114, pgs. 373-398.

Griffis, T. J., T. A. Black, K. Morgenstern, A. G. Barr, Z. Nesic, G. B. Drewitt, D. Gaumont-Guay, J. H. McCaughey, 2003. Ecophysiological controls on the carbon balances of three southern boreal forests. *Ag. For. Met.* 117, pgs. 53-71.

Kljun, N., P. Calanca, M. Rotach, H. Schmid, 2004. A simple parameterisation for flux footprint predictions. *Bound.-Lay. Met.* 112, pgs. 503-523.

Leblanc, S., J. Chen, R. Fernandes, D. Deering, and A. Conley, 2005. Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests. *Ag. For. Met.* 129, pgs. 187-207.

Lindroth, A., A. Grelle, and A.-S. Morén, 1998. Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity. *Global Change Biology*. 4:443-450.

Magnussen, S., and P. Boudewyn, 1998. Derivations of stand heights from airborne laser scanner data with canopy-based quantile estimators. *Canadian Journal of Forest Research.* 28:1016-1031.

Morsdorf, F., B. Kötz, E. Meier, K. Itten, and B. Allgöwer, 2006. Estimation of LAI and fractional cover from small footprint airborne laser scanning data based on gap fraction. *Rem. Sens. of Environ.* 104, pgs. 50-61.

Monteith, J., and M. Unsworth, 1990. Principles of Environmental Physics. 2nd ed. Edward Arnold, New York. 291 pgs.
Schmid, H. P., 1994. Source areas for scalars and scalar fluxes. *Bound. Lay. Met.* 67, pgs.293-318.

Shuttleworth, W., and J. Wallace, 1985. Evaporation from sparse crops – An energy combination theory. *Quart. J. Roy. Met. Soc*. 111, pgs. 839-855.

Vogel, J., and S. Gower, 1998. Carbon and nitrogen dynamics of boreal jack pine stands with and without a green alder understory. *Ecosystems*. 1(4):386-400.

Wilson, K.B., A. Goldstein, E. Falge, et al. 2002. Energy balance closure at FLUXNET sites. *Agricultural and Forest Meteorology*. 113:223-243.