10B.1 FOOTPRINT APPLICATION TO LONG-TERM CO_2 FLUX OBSERVATIONS

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1. INTRODUCTION

Exchange processes of carbon dioxide (CO_2) and water vapour (H_2O) between the earth's surface and the lower atmosphere are usually analysed based on micrometeorological measurements from tall flux towers, thought to be representative of large area averages. A limitation of this approach is that the actual source areas of these fluxes are not always known and that the impact of land-surface heterogeneity (at small or large scale) on the fluxes is not yet completely understood. For example, vegetation structural heterogeneity likely contributes to within-stand spatial variability in the measured fluxes (e.g., Leuning et al. 2004). This impact is thus important to consider when examining the representativeness of a forest biome at regional, national or even global scale.

The objective of this study is to determine whether within-stand canopy structural variability and local elevation changes influence CO_2 fluxes, and if so, to what extent. This is achieved by incorporating information on topography and structure of vegetation into footprint estimates, and combining this source information with CO_2 observations.

2. FLUX DATA

The study area consists of an extensive, fairly homogeneous old jack pine forest stand (Pinus banksiana Lamb.). The stand is currently around 80 years old, with tree height varying between 13 and 18 m (cf. Baldocchi et al., 1997). The forest is located near the southern edge of the boreal forest, Saskatchewan, Canada, and ranges in elevation between 482 m and 495 m.

Meteorological observations, CO_2 and H_2O flux measurements at the old jack pine site (OJP) have been collected since 1997 and previously 1993-1996 during the Boreal Ecosystem-Atmosphere Study (BOREAS). The site is now part of the Canadian Carbon Program. Details about the eddy covariance (EC) system measuring the fluxes and the data processing can be found in Griffis et al. (2003). In the present study, we refer to 30-min averages of CO_2 fluxes, namely net ecosystem productivity (NEP) and gross ecosystem photosynthesis (GEP). For the meteorological impact on the fluxes, incoming photosynthetic radiation (PAR), relative humidity (RH), soil temperature (T_{soil}), air temperature (T_{air}), and soil moisture (θ) are taken into account.

Three periods during the growing season of 2002 are examined: P1 (June 10–15), P2 (July 5-13), and P3 (August 7-13). The predominant weather during the three study periods has been comparable, with P2 being slightly warmer and drier than P1 and P3.

3. LIDAR DATA

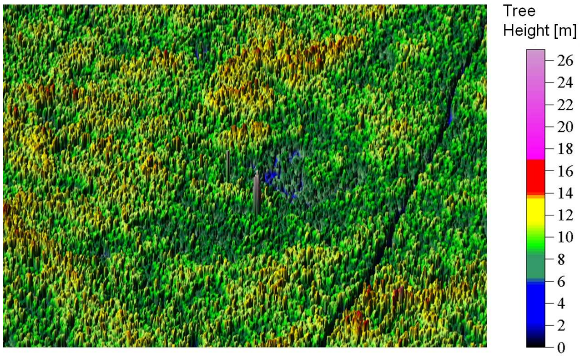

Fig. 1: Tree height at OJP after removing topography. The flux tower is located in the center (purple spire).

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A LiDAR survey of the study area has been conducted on August 12, 2005, using a scanning discrete pulse return system (ALTM3100, Optech Inc. North York, Ontario), owned and operated by the Applied Geomatics Research Group, Nova Scotia. A scan angle of ±19° and a scan line overlap of 50% enabled penetration of laser pulses through to the base of the canopy, whilst also obtaining returns on all sides of individual trees, with a resolution of 35 cm (Chasmer et al. 2006a).

Average tree heights and canopy depth (Fig. 1) are derived from the LiDAR data using percentile distributions (Chasmer et al. 2006b). Differences in canopy structure between summer 2002 and summer 2005 are expected to be less than 30 cm.

The canopy fractional cover (f_{cover}) is determined from laser returns for columns of 1 m x 1 m x 30 m, based on the ratio of the number of canopy returns to canopy and ground returns:

$$f\text{cover} = \frac{\#\ \text{of LiDAR returns of canopy}}{\#\ \text{of all LiDAR returns}},$$

where f_{cover} equals 1 for full canopy cover and 0 for no canopy cover (Hopkinson and Chasmer, 2007).

4. FOOTPRINT CALCULATIONS

4.1. Footprint Estimates

A footprint estimate describes the probability that an emitted trace gas is measured at the receptor; i.e. it denotes the spatial extent of the area contributing to the measured quantity. Atmospheric conditions, such as wind speed and stability, and surface characteristics, determine the spatial extent of the footprint (e.g., Kljun et al. 2002). Heterogeneous surfaces and hilly terrain, as commonly found at measurement sites, further complicate the interpretation of such measurements. A fortiori, the knowledge of the source/sink characteristics of the footprint is crucial.

For the present study, footprint estimates are derived based on the footprint parameterisation of Kljun et al. (2004). This parameterisation has been improved for the case of stable boundary layers and extended to include lateral dispersion.

4.2. Footprint Climatology

The footprint parameterisation is applied to 30-minute averaged turbulence data of P1, P2 and P3. Taking into account the prevailing wind direction during each sample period provides high temporal resolution spatial information on the actual sources/sinks contributing to the measured fluxes.

The LiDAR data, i.e. the 3D-information of the forest structure and the topography, is integrated within the footprint estimates (cf. Fig. 2). This approach yields information on the tree height, f_{cover}, and elevation per sampling period which then, in a final step, is correlated with the according CO_2 fluxes (see Section 5).

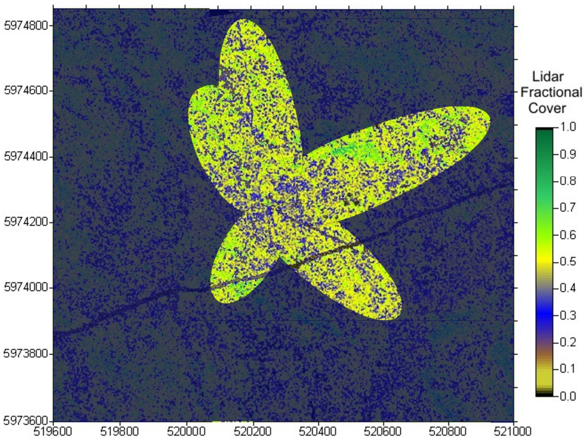

Fig. 2: Example of vegetation structural data (f_{cover}) within footprint estimates per sample period.

The peak location of the footprint estimates (location with maximum impact at the receptor) for the study periods lies within 500 m of the EC tower. The remainder of the footprints extends to a 1 km radius surrounding the tower and beyond in more stable conditions.

If wind directions are prone to originate from some directions more than others, the EC system may not be adequately sampling all of the within-site heterogeneity in fluxes. During the study periods, approximately 45% of fluxes originated from areas NW of the EC system (Fig. 3). These areas are characterised by taller trees, greater canopy fractional cover, and higher elevations (Tab. 1). 17% of the winds originated from SE quadrants, i.e. from areas with typically lower elevations, shorter trees, and lower f_{cover}. Since the measured fluxes predominantly origin from areas of high f_{cover}, CO_2 uptake at OJP might be slightly over-estimated (assuming the higher f_{cover}, the more CO_2 uptake).

Wind Direction	Frequency [%]	Tree Height [m]	*f* cover [ ]	Elevation [m]
NW	45%	16.4	0.74	495
SW	20%	14.9	0.55	491
NE	18%	15.2	0.67	490
SE	17%	11.6	0.43	487
Site Average		14.8	0.63	491

Tab. 1: Prevailing wind directions during P1, P2 and P3 and according averaged structural information.

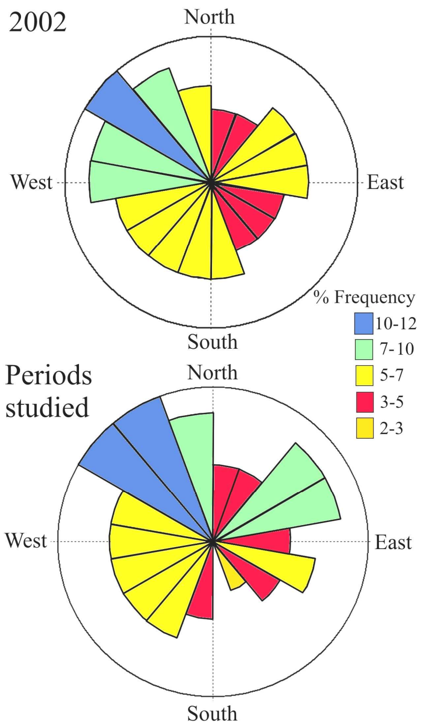

Fig. 3: Prevailing wind directions during study year (top panel) and during study periods (bottom panel).

5. IMPACT ON CO_2 FLUXES

In a first step, a Landsberg light response curve is applied to examine the relationship between incoming PAR and NEP or GEP, respectively, during the individual periods. It can be shown that 25% to 65% of the variation in the fluxes cannot be explained by incoming PAR (Tab. 2).

In a second step, a multiple linear regression is performed to examine the combined influences of meteorological variables, canopy structure (f_{cover}) and elevation on the fluxes. Pearson's r correlation is used to determine the relative correspondence between fluxes and meteorological driving variables, canopy structure, and elevation as a correlation matrix.

Flux	Period	r^2	*p-value* of Contribution						$r^2_{adjusted}$	
		PAR	PAR	RH	T_{soil}	θ	f_{cover}	Elev.	Meteo	All
NEP	P1	0.59	0.00	0.23	0.000	0.00	0.04	0.21	0.65	0.75
	P2	0.35	0.00	0.00	0.000	0.05	0.10	0.63	0.59	0.61
	P3	0.61	0.00	0.25	0.004	0.36	0.02	0.32	0.78	0.67
GEP	P1	0.74	0.00	0.15	0.000	0.00	0.02	0.15	0.78	0.81
	P2	0.42	0.00	0.00	0.000	0.79	0.07	0.53	0.54	0.60
	P3	0.66	0.00	0.85	0.150	0.11	0.03	0.66	0.69	0.72

Tab. 2: Combined impact of meteorological and canopy structure driving variables on CO_2 fluxes from multiple linear regression. r^2 has been adjusted in order to account for multiple linear regression. Significant contributions are highlighted (red).

For the present study site and when analysing the data per study period, including f_{cover} in the analysis improves the prediction of NEP and GEP during most periods. Furthermore, in some of the cases, f_{cover} proves a more important component of the CO_2 fluxes than daily variability in soil moisture. Elevation changes, however, do not significantly contribute to the combined influence on the fluxes, as demonstrated by the p-values in Tab. 2.

When analysing the data on a daily basis rather than per study period, of the 22 days studied, 13 days (59%) and 9 days (41%) show significant positive relationships ($p < 0.01$) between increased biomass and increased NEP and GEP, respectively (Fig. 4). Here, biomass, for simplicity, is a combination of f_{cover} and tree height. NEP and GEP are also significantly negatively affected by increased elevation for 10 and 8 days, respectively (Fig. 5).

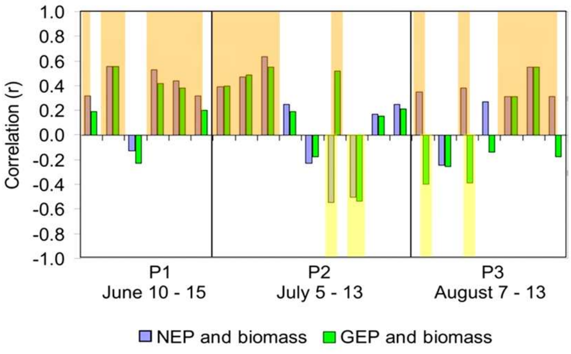

Fig. 4: Bar graph of Pearson's correlation between daily NEP and GEP and canopy structural influence (biomass). Significant contributions ($p < 0.01$) are highlighted. *n* ≈ 17 per day but may vary due to applied u_*-threshold.

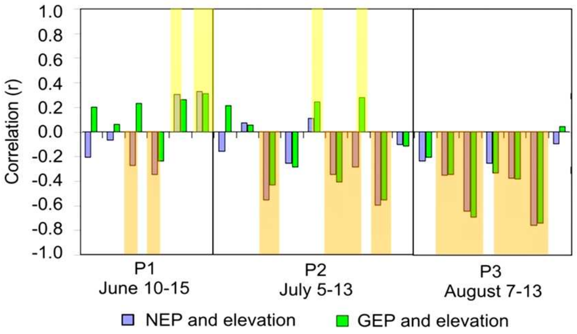

Fig. 5: Same as Fig. 4 but for influence of elevation changes.

6. CONCLUSIONS

The presented footprint parameterisation is capable of producing a temporal high-resolution footprint climatology for long-term data sets and can be applied on an operational basis. It is shown that the combination of a footprint climatology with vegetation structural data and topography data yields important additional information, which can, for example, be highly valuable for accuracy improvements of regional or global carbon budgets.

In this study, it is found that CO_2 fluxes vary spatially and temporally due to variations in meteorological variables, canopy structure and elevation gradients within a jack pine forest stand. Combined meteorological variables have, as expected, stronger influence on NEP and GEP than f_{cover} or elevation. However, f_{cover} is shown to be more important than some individual meteorological variables when the ecosystem is not limited by soil moisture constraints.

The footprint climatology also reveals that observed CO_2 fluxes at OJP predominantly originated from areas with f_{cover} higher than the site average. Future studies will thus have to investigate the representativeness of the observed annual fluxes for an old jack pine biome.

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