ISSN 1195-8898

CMOS BULLETIN SCMO

Canadian Meteorological and Oceanographic Society

La Société canadienne de météorologie et d'océanographie

February / février 2000 Vol. 28 No. 1

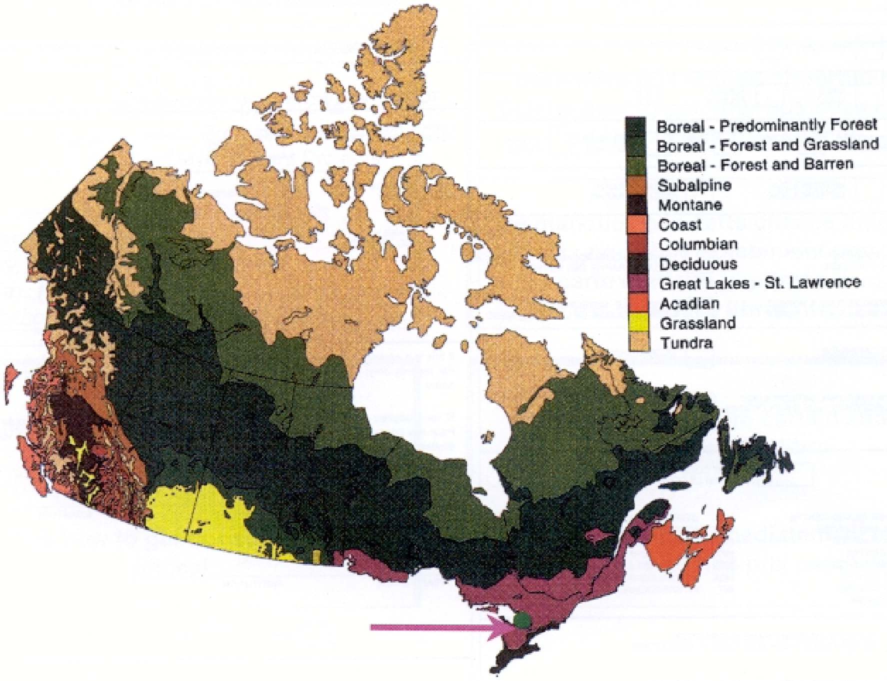

Figure 1. Location of the Borden forest and associated vegetation throughout Canada.

Long Term Flux Measurements at the Borden Forest

by

R.M. Staebler[1], J.D. Fuentes[2], X. Lee[3], K.J. Puckett[1], H.H. Neumann[1], M.J. Deary[1], J.A. Arnold[1]

Résumé

Ce manuscrit donne une vue d'ensemble des activités de recherche qui ont été menées au site de recherche de Environnement Canada à Borden, située près de Angus, Ontario. Ce site forestier fut une des premières installations de recherche établies en Amérique du nord pour étudier les échanges à long terme d'énergie, momentum, gaz à faible concentration et particules de matière entre la surface et l'atmosphère. L'accent initial fut mis sur le développement d'une compréhension théorique du transport turbulent sous un couvert végétal, et sur l'étude du rôle des écosystèmes forestiers dans la réduction des espèces chimiques réactives et des particules de matière. Plus récemment, l'accent de la recherche a été l'étude de l'efficacité des écosystèmes forestiers à séquestrer le dioxyde de carbone et à produire des hydrocarbones biogéniques. On sait que ces derniers composés sont des précurseurs efficaces d'oxydants dans des environnements riches en oxydes d'azote. Sur la foi de cinq ans de mesures continues de dioxyde de carbone au dessus des cimes, la forêt de Borden est un puits efficace de dioxyde de carbone. Comme on s'y attend, l'extraction de dioxyde de carbone est fortement modulée par le climat. Par exemple, l'absorption nette de carbone par la forêt Borden durant 1995, 1996, et 1997 se chiffraient respectivement à 1.0, 1.2 et 2.8 tonnes de carbone par hectare. Les différences inter-annuelles dans la séquestration de carbone dépendaient des conditions environnementales existantes; la quantité élevée de carbone capturé en 1997 était causée par une plus basse température du sol durant la saison de croissance, qui favorisait une moins grande respiration du sol.

1. Introduction

The Environment Canada research facility at the Canadian Forces Base (CFB) Borden was established in 1985 to conduct investigations in the general area of biosphere-atmosphere interactions [den Hartog and Neumann 1984]. The first Canadian investigations on dry deposition of gaseous pollutants (such as ozone, nitrogen dioxide and sulfur dioxide) to forests were carried out at Borden during 1985 and 1986. This research involved pioneering applications of the eddy covariance technique to characterize pollutant deposition rates during fall and winter conditions [Edwards et al. 1988; Padro and Edwards 1991; Padro et al. 1992]. In 1986, an unprecedented study took place in which seven three-dimensional sonic anemometers were deployed on a 45-m tower to investigate characteristics of atmospheric turbulence above and inside the Borden forest [den Hartog et al. 1987; Shaw et al. 1988; Leclerc et al. 1990; Maitani and Shaw 1990; Shaw et al. 1990; Shaw and Zhang 1992]. In 1987, a comprehensive tree survey, combined with leaf area index (LAI) measurements using leaf litter collection and hemispherical photography, provided detailed information on the amount and distribution of foliage in the forest canopy [Neumann et al. 1989]. From 1988 to 1990 major field campaigns were carried out in support of the Canadian acid deposition research program. In particular, a major component of the Eulerian Model Evaluation Field Study took place at Borden during 1988. These investigations [Padro et al. 1991; Fuentes et al. 1992; Barr et al. 1994] provided not only the observational data bases to develop and test photochemical models to estimate regional pollutant deposition to terrestrial environments, but also a fundamental understanding of the atmospheric and biological controls on vegetation pollutant uptake. Because the vegetation at Borden remains wet for a substantial period (~50%) of the growing season, specific studies [Fuentes et al. 1994a, b] were carried out to discern the role of foliage wetness on pollutant deposition. In the context of long-term flux measurements, we must mention the first Canadian year-round measurement of forest carbon dioxide (CO_2) fluxes using micrometeorological methods attempted by Ken King in 1987 [Perttu 1990].

Since its establishment, Borden has been the staging facility to test sophisticated atmospheric measurement systems. In 1993, the flux measuring systems employed in the BOREAS (BOReal Ecosystem-Atmosphere Study) project by several Canadian research teams were fully tested and inter-compared at Borden. One specific focus of these studies was to unveil the reasons for high uncertainties associated with nocturnal trace gas fluxes [Lee et al. 1996; Lee 1996]. Also, since Borden is situated in the southern region of Canada impacted the most by anthropogenic activity [Fuentes and Dann 1994], intensive field measurement campaigns were initiated in 1993 to ascertain the biogenic hydrocarbon source strength from deciduous forests [Fuentes et al. 1996; Fuentes and Wang 1999; Fuentes et al. 1999]. These field studies were required to assess the influence of biogenic chemical species in local and regional oxidant formation. Recognizing the importance of these biogenic

---

[1] Environment Canada, Downsview, Ontario, Canada
[2] University of Virginia, Charlottesville, Virginia, U.S.A.
[3] Yale University, New Haven, Connecticut, U.S.A.

hydrocarbons in oxidant formation in southern Ontario, Environment Canada scientists pioneered investigations to understand the seasonal and environmental controls on hydrocarbon emissions from forested ecosystems in 1995 [Fuentes et al. 1996]. At the same time, intensive field campaigns were undertaken to learn the degree of photochemical processing within forest canopies [Makar et al. 1999]. To develop and test photochemical models, it was necessary to understand the disposition of total global radiation and actinic irradiance inside the Borden forest canopy [Staebler et al. 1997]. A trolley system carrying radiometers was used near the forest floor to establish averaged quantities as the trolley traversed a 30-m distance. These studies were augmented with shorter field campaigns to test theoretical developments on the calculation of trace gas fluxes from or to forests using gradient methods [Simpson et al. 1998]. The data sets obtained at Borden have been critical to develop and test biospheric and photochemical modeling systems [Fuentes et al. 1999; Huber et al. 2000; Makar et al. 1999].

Recognizing that most temperate forests in Canada were undergoing rapid growth, we initiated a continuous, long-term measurement program in 1995 with the goal to understand the sequestration capability of the Borden forest and how climatic perturbations such as drought can impact forest carbon uptake. To address the inter-annual and inter-seasonal variability of carbon uptake, we have been taking a plethora of ancillary measurements including the fluxes of water vapor, sensible heat, and momentum. Additionally, to explain the physical and edaphic variables controlling the forest-atmosphere gas and energy exchange, microclimate measurements have been made inside and immediately above the forest canopy. Thus, in this article, we report sample data sets to illustrate the magnitude of forest carbon dioxide sequestration and associated controls on the fluxes. Other articles [Lee et al. 1999; Fuentes et al. 1999; Hollinger et al. 2000] provide full description of data analysis results concerning the carbon sequestration capability of the Borden forest and hydrocarbon emissions.

2. Site description, climatology and measurements

The Borden forest is located in southern Ontario, Canada (44°19' N, 80°56' W; Figure 1 shown on back cover page). The research infrastructure at the site comprises a 45-m instrumented scaffolding tower and associated trailers to house gas analyzers, data logger, and computing equipment. The forest around the tower extends about 4 km from the south-southeast to the west-northwest sector, and about 2 km to the east. The forest is about 95 years old, representing natural re-growth on farmland that was taken out of cultivation in the early 1900s. Based on a survey conducted in 1995, the forest consists of 36% red maple, 21% trembling aspen, 14% white ash, 12% large tooth aspen, 5% white pine, 4% black cherry, and 8% other species. In 1995 the average canopy height was 22 m. Mid-growing season LAI averaged 4.2 (Figure 2A). The seasonal LAI measurements in this figure were obtained using a plant canopy analyzer and verified with area measurements of autumnal leaf litter fall [Staebler et al. 1997]. Defined from leaf emergence to complete leaf fall, the average growing season is from 20 April (day of year 111) to 20 October (DOY 294). Based on three years of data and in terms of carbon uptake by the forest, the growing season can range from the second week of May (DOY 125) to the second week of October (DOY 280).

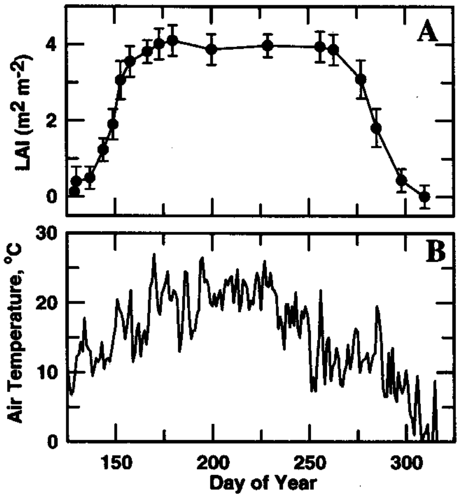

Figure 2. Leaf area index and daily average temperature for the 1995 growing season.

Based on 30-year climate averages, the Borden forest site receives 858 mm of precipitation annually with August and September being the rainiest months when total monthly precipitation can reach 100 mm. The average annual air temperature is 6.4°C and the daytime average vapor pressure deficit is 0.38 kPa. As shown in the air temperature signal for 1995 (Figure 2B), June, July and August are the warmest months when daily mean temperature can reach 20°C. In terms of availability of energy (net radiation), Borden experiences a total of 2.36 GJ per m^2 on average.

Current, continuous microclimate measurements are made inside and immediately above the forest canopy as shown in Figure 3. Measurements of air temperature (using ventilated copper-constantan thermocouples) at 12 levels above ground, wind speed and direction (R.M. Young anemometer model 0571, Traverse City, MI) at 45 m, incoming solar radiation (Model PSP pyranometer, Eppley Laboratory, Newport, RI), photosynthetically active radiation (PAR, Model LI190SA, LiCor Inc.) above the forest, and relative humidity (Model MP-100, Rotronic Instrument Corp., Huntington, NY) at 33 and 44 m above ground are continuously taken every minute. These data are subsequently reduced to derive half-hourly averaged quantities. Mixing ratios of CO_2 and water vapor (H_2O; Model LI-6262, LiCor Inc.) are determined at 6 heights. Both microclimate and gas mixing ratio measurements are acquired using data loggers (model CS21XL, Campbell Scientific Inc., Logan, UT). Gas profile measurements are made with a single gas analyzer, utilizing a manifold system and sequentially sampling air from individual intakes. At two sites soil temperature and moisture are measured at 6 depths. Additionally, bole temperatures are measured at four levels by inserting temperature probes in selected trees.

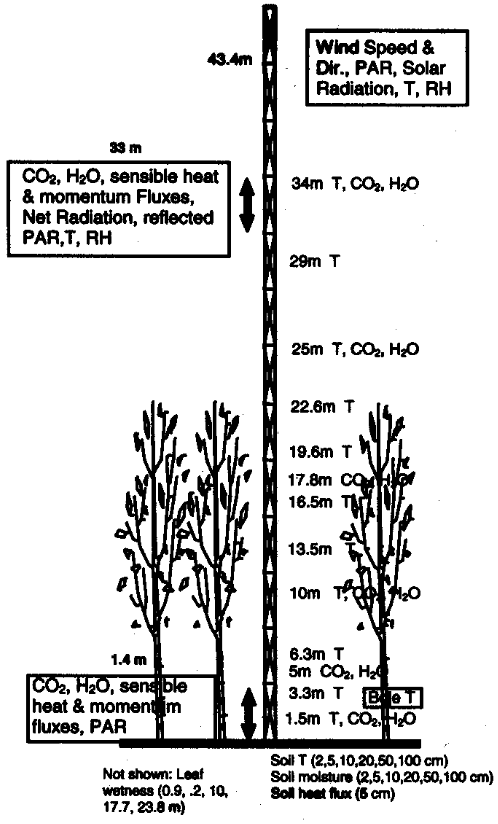

Figure 3. Schematic of the instrumented Borden flux tower.

For the long-term flux measurements, an eddy covariance system has been deployed at 33 m above ground since 1995. For this height, flux 'footprint' analyses indicate the source area contributing to 80% of the fluxes emanates from an upwind distance of ~1300 m during periods of neutral atmospheric stability. Under unstable atmospheric conditions footprints contract to less than 150 m. Eddy covariance fluxes are determined at 33 m above the ground using triaxial sonic anemometers (Model DAT-310, Kaijo Denki Ltd., Tokyo, Japan) in combination with fast-response gas analyzers. The fast-response measurements of CO_2 and H_2O vapor for eddy covariance are made with an infrared gas analyzer (model LI-6262, LiCor Inc.), operated in differential mode. Based on the flow rate of 6 L per min and the nominal sample cell volume of 11.9 cm^3, the gas analyzer time constant is 0.12 s. A second eddy covariance system was installed in the summer of 1999 to collect data on understory fluxes at 1.4m above the forest floor.

For both eddy covariance systems, a pumping system is used to bring the sampled air from the sonic anemometer level to the gas analyzers inside a hut at the base of the tower through tubing (Dekoron, aluminum tube with polyvinyl chloride coating and polypropylene lining). Air flow in the sampling tubes is maintained turbulent at all times as verified from calculations of Reynolds number. The fast response data provided by the sonic anemometers and gas analyzers are collected via a data acquisition and electronic signal conditioning system (model AT-MIO-16X, National Instruments, Austin, TX) that is interfaced with a computer which makes the computations of resulting eddy fluxes. The system records sensor outputs at 10 Hz and thus resolves frequencies of up to 5 Hz. Spectral analyses of the data collected at 33 m has revealed no appreciable fluxes beyond the frequency of 2 Hz.

In order to understand the atmospheric controls on the carbon dioxide fluxes, several eddy covariance measurements are also obtained. The momentum flux (τ) is determined from the covariances of longitudinal wind speed (u') and vertical wind speed (w') fluctuations, as shown in [1]. The air density (ρ) in [1] represents the average value obtained for the 30-min measurement period.

$$\tau = -\rho\,\overline{u'w'} \qquad [1]$$

From the τ data the friction velocity (u^*) is calculated as shown in [2]. In our flux data interpretation, the u^* is used to verify the turbulence regime above the forest. At Borden reliable eddy covariance fluxes are obtained when $u^* > 0.1$ m s^{-1} [Lee et al. 1999].

$$u^* = \sqrt{\tau/\rho} \qquad [2]$$

Furthermore, the virtual heat flux (H_v) is necessary to discern the atmospheric stability conditions, and to learn how such factors can impact trace gas fluxes. As shown in [3], we derive H_v from the covariance of and virtual temperature fluctuations (T'_v) from the mean value. The sonic anemometer provides T_v. The ρC_P in [3] represents the air volumetric heat capacity.

$$H_v = \rho\, C_p \overline{W'\, T_V'} \qquad [3]$$

Net fluxes of H_2O and CO_2 (F_n) are determined as shown in [4]. The term ρ'_x represents the fluctuating quantity of H_2O vapor or CO_2 density, and F_c denotes the flux correction due to heat and humidity fluctuations in air density.

$$F_n = w' \rho_{x'} + F_c \qquad [4]$$

By convention a negative value of $\overline{w'\rho'}$ implies a downward flux whereas a positive quantity denotes the opposite. Thus, negative CO_2 fluxes denote forest CO_2 uptake whereas positive quantities imply CO_2 emissions (from soil and plant respiration). Over tall forests the CO_2 flux determined with the eddy covariance system does not necessarily yield net exchange during the period of integration. Errors can occur when CO_2 is stored in the air layer below the eddy covariance system. Thus, for the Borden forest we approximate the storage term by determining the temporal change in CO_2 ($\Delta\rho_{CO2}/\Delta t$) measured over a 30-min period at the height (z_r) of the eddy flux system. From this we estimate the net ecosystem exchange (NEE) of CO_2, or F_{eco}, as shown in [5].

$$F_{eco} = F_n - \Delta\rho_{CO2}/\Delta t \; Zr \qquad [5]$$

3. Forest-atmosphere carbon exchange

In this section we report sample data sets to illustrate the magnitude of CO_2 fluxes at scales ranging from hours to years. We also discuss the principal atmospheric controls on the variability of the fluxes.

The daytime eddy covariance fluxes represent the integration of two opposing CO_2 fluxes: one released from the soil and the other taken up by the forest. During the nighttime the CO_2 fluxes result from respiratory processes in soil and vegetation. Thus, because vegetation CO_2 uptake is energy driven, it is expected to have strong diurnal flux variability. Figure 4 shows a typical daily course of both H_2O (latent heat = LE) and CO_2 fluxes with strong diurnal variations for a day dominated by clear skies (see PAR in the top figure) and relatively warm conditions (maximum air temperature reaching ~25°C). For this day there was no evidence of soil moisture deficit, and both LE and CO_2 fluxes reached noontime peak values of 400 W m^{-2} and -1.0 mg (CO_2) m^{-2} s^{-1}, respectively.

A lag of almost 2 hours between the rise of PAR (starting at 6:30 h) and commencement of CO_2 uptake is apparent. Reasons for this include different threshold PAR levels for photosynthesis for the different tree species, penetration of sufficient amounts of light deeper into the canopy as the solar elevation angle increases, and the weak atmospheric turbulence during the night and early morning, which is enhanced significantly once the nocturnal stable layer has been eroded. The diurnal fluxes shown in Figure 4 are typical of those determined at Borden during mid-June to end of August, the time of the foliage senesce onset.

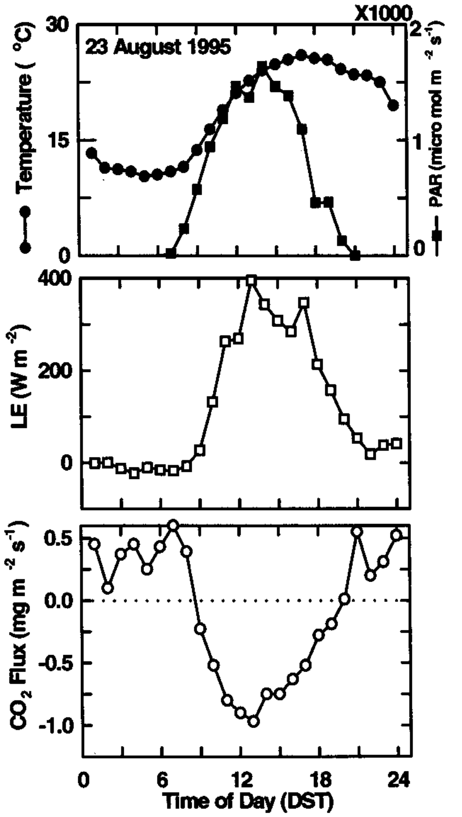

Figure 4. Diurnal variations of air temperature (•), Photosynthetically active radiation (PAR) (■), latent heat flux (□), and carbon dioxide flux (○) measured above the Borden forest during 23 August 1995.

Modulations on the fluxes occur if the forest experiences drought or other climatic perturbations.

To establish the seasonal patterns in CO_2 fluxes, integrated daily NEE quantities are calculated. These calculations have been made since 1995 to present, and Figure 5 shows a sample data set for the period from July 1995 to December 1997. Several features are important to note concerning Figure 5. First, the forest was a source carbon from October (day of year 275) to the end of May (DOY 145). For this period, average daily and maximum NEE values reached 2 and 5 mgC m^{-2} d^{-1}, respectively. Second, the growing season typically lasted 120-130 days. During the middle of the growing season, the forest carbon consumption reached nearly -10 mgC m^{-2} d^{-1}, respectively.

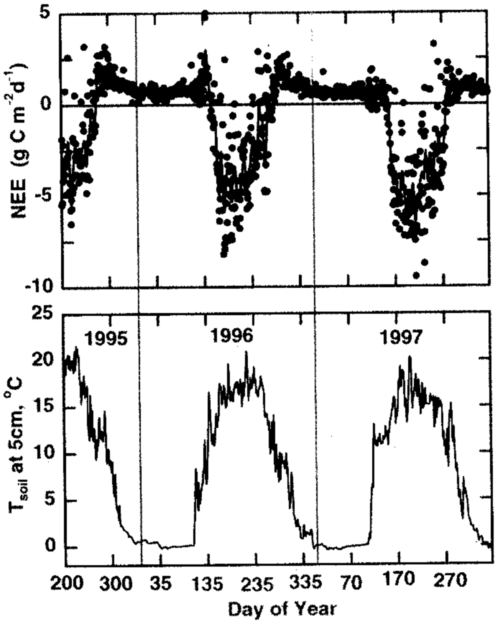

Figure 5. Daily NEE and daily mean 5-cm soil temperature for the Borden forest during the period of July 1995 to December 1997. For the upper figure the dots represent the measurements and the solid line corresponds to the average values.

The solid line represents the best to the data points. Integrating the daily NEE values over a year, the Borden forest sequestered carbon at the rate of 1.3, 1.4 and 2.8 tones ha^{-1} yr^{-1} during 1995, 1996 and 1997, respectively. Below we elucidate some of the environmental controls on the variability in the forest carbon sequestration.

The discrepancy between the annual integrated NEE during 1996 and 1997 (Figure 6) may be related to the differences in soil temperature. Soil temperature was 1°C and 0.25°C lower over the growing season and the full year, respectively, in 1997 than in 1996 (see Lee et al. [1999] for further details). Air temperature averages for both years were nearly the same. Thus, the effect of lower soil temperature in 1996 was to reduce litter decomposition rates and hence decrease soil respiratory losses. Two drought periods (data not shown) during the growing season in 1996 also contributed to the lower NEE. One occurred around DOY 150 and the other around DOY 225. Data shows that during these two periods, the noontime forest-atmosphere CO$_2$ exchange was suppressed. Also, soil temperature exerts a strong influence on CO$_2$ fluxes. In Figure 7 we show an example of the relationship between nocturnal CO$_2$ fluxes and soil temperature at 5 cm during the 1997 growing season.

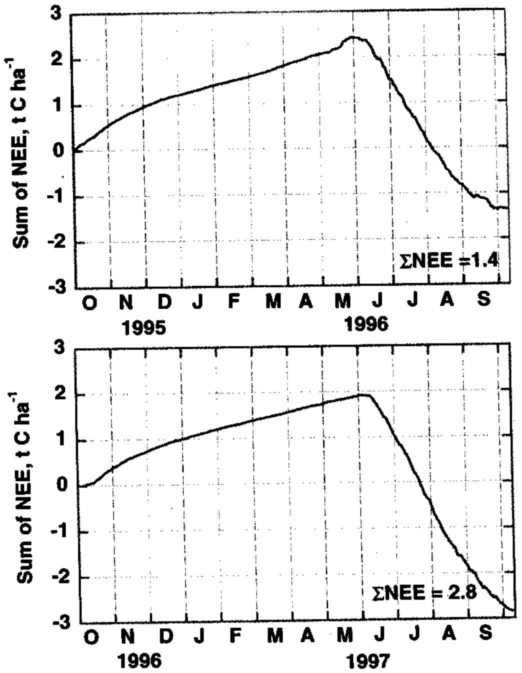

Figure 6. Yearly sums of net ecosystem exchange for carbon dioxide during 1995, 1996, and 1997.

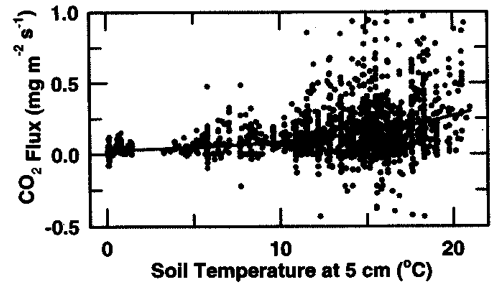

Figure 7. Nocturnal CO$_2$ fluxes during the growing season in 1997 as a function of soil temperature at 5 cm.

A multitude of physical and biological factors are influencing the capacity of the Borden forest to exchange carbon with the overlying atmosphere. One important biological factor is foliage ontogeny. Even though the forest retains its full LAI, drastic changes in NEE area observed towards the end of the growing season. For example, Figure 8 shows that even though the forest had a LAI of 4.2 (see Figure 2A) until DOY 270, systematic declines in NEE started around DOY 250. We believe that this early decrease in NEE capacity is related to leaf senescence, which reduces leaf photosynthetic capacity. Changes in leaf optical properties may also contribute due to smaller absorption of PAR, as revealed by the decrease in the light extinction coefficients (for PAR and global solar radiation) before the onset of falling of leaves (Figure 8). These measurements establish a link with remote sensing, and show how satellite data may be used to discern when these systematic declines in NEE occur in deciduous forested ecosystems.

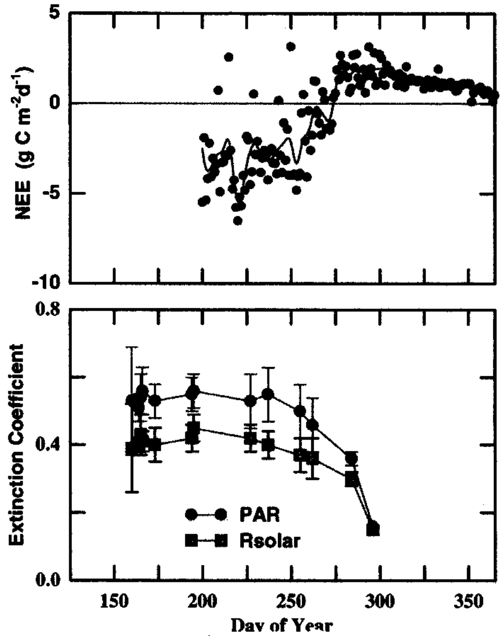

Figure 8. Daily NEE and canopy extinction coefficients for both PAR and short-wave (solar) radiation in the fall of 1995.

There is evidence that the atmosphere is becoming more cloudy and turbid, and thus enhanced diffuse radiation levels have been reaching the Earth's surface [Abakumova et al. 1996]. These climatic perturbations have direct implications in the manner in which forest ecosystems respond. Because diffuse radiation can more readily penetrate deeper depths in forest canopies, the radiation use efficiency can increase with increasing cloudiness up to a certain point, and thus CO_2 uptake can increase.

We have examined this effect for Borden [Gu et al. 2000]. In Figure 9, we report changes in NEE with the clearness index (the ratio of measured solar irradiance to clear-sky irradiance; for Borden under completely clear skies the index is ~0.8). For 1997 (Figure 9), the maximum enhancement of NEE ranges between 10 and 40% due to clouds. The changes in NEE varied with solar elevation angle (β).

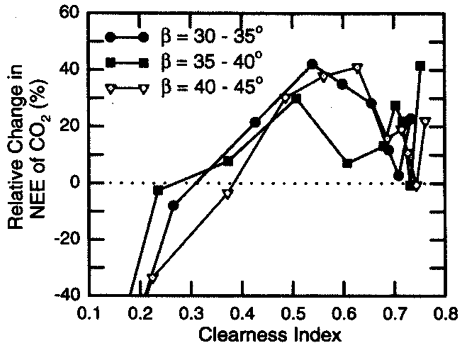

Figure 9. Relationship between relative changes in NEE of CO2 relative to clear skies and the clearness index for different intervals of solar elevation angles for Borden during 1997 (see Gu et al. 2000 for further details).

4. Summary and conclusions

Environment Canada established a research facility at CFB Borden in 1995 to undertake field studies of turbulence and fluxes of energy and mass within and above a deciduous forest in southern Ontario, Canada. Research programs conducted there in the subsequent decade have contributed significantly to our understanding of atmosphere-forest interactions. Since 1995, Environment Canada scientists have sustained an uninterrupted research program of flux measurements together with supporting microclimate observations at the Borden forest. This research program has identified and evaluated key environmental controlling factors on carbon exchange between temperate deciduous forests and the overlying atmosphere. Links between the inter-annual variability in exchange rates and the main controlling factors such as soil temperature, soil water availability, length of growing season, and light conditions have been studied. A growing data base on the interactions between the forest and the atmosphere at Borden has been established which can be used for further research.

Borden has also served international programs such as the Ameriflux network [Hollinger et al. 2000] because of its location at the northern edge of the temperate forest biome, and because of the unprecedented historical record of measurements dating back to the early days of micrometeorological experimentation in forests. Given that anthropogenic carbon dioxide emissions remain under international scrutiny as identified in the Kyoto Protocol [IGBP 1998], the information and knowledge being generated at the Borden forest will help in establishing a Canadian baseline for the magnitude of the biospheric carbon sink. Continued research at Borden can also assist Canada to meet its obligations under the Kyoto Protocol to improve our understanding of the role of forests in the carbon cycle, and how this role is affected by climate change.

Although the Borden research indicates that temperate deciduous forests in Canada sequester carbon at rates ranging from 1.5 to 3.5 tonnes of carbon per hectare per year [Lee et al. 1999, Hollinger et al. 2000], we do not know what portion of anthropogenically produced carbon is consumed by forests. Determining this will depend on obtaining a better understanding of the roles of respiration, soil exchange and advective factors in the carbon budget. Such information is critical to assess the progress being made in reducing atmospheric carbon dioxide levels. The Borden research group is currently developing research strategies to provide insights into quantifying the portions of biogenic versus anthropogenic carbon dioxide sequestered by forests.

Acknowledgements

Thanks are expressed to the Ontario Ministry of Natural Resources, who first suggested Borden as a suitable research site; to the Department of National Defence for allowing the work to proceed on their property; and to ARQB (Environment Canada) for supporting the project. We especially want to acknowledge the central role of Dr. Gerry den Hartog, our Site Captain, in establishing the site and running it for 10 years. We also want to thank Wes Kobelka, who looked after the installation of the facilities and the first tower.

Corresponding author: Ralf M. Staebler, Atmospheric Sciences Research Center, 251 Fuller Road, Albany, NY, 12203, USA; email: staebler@asrc.cestm.albany.edu

References

Abakumova, G.M., E.M. Feigelson, V. Russak, and V.V. Stadnik, *Evaluation of long-term changes in radiation, cloudiness and surface temperature on the territory of the former Soviet Union*, Journal of Climate, 9, 1319-1327, 1996.

Barr, A. G., King, K.M., Gilespie, T.J., den Hartog, G., and Neumann, H.H., *A comparison of Bowen ratio and eddy correlation sensible and latent heat flux measurement above deciduous forest*, Boundary-Layer Meteorol., 71, 21-41, 1994.

Den Hartog, G., and H.H. Neumann, *An empirical study on dry deposition of air pollutants to forests - Project description*, Report AQRB-84-Q11-L, Atmospheric Environment Service, Downsview, Ontario, Canada, 1984.

den Hartog, G., H.H. Neumann, and K.M. King, *Measurements of ozone, sulphur dioxide and carbon dioxide fluxes to a deciduous forest*, 18th Conference on Agricultural and Forest Meteorology, 1987.

Edwards, G.C., F.J. Northrup and G.W. Thurtell, *The investigation of dry deposition processes: Phase II - The measurement of dry deposition fluxes*, Ontario Hydro Research, Toronto, ON, 1988.

Fuentes, J.D., T.J. Gillespie, G. den Hartog and H.H. Neumann, *Ozone deposition onto a deciduous forest during dry and wet conditions*, Agric. For. Meteorol., 75, 1-19, 1992.

Fuentes, J.D., G. den Hartog, H.H. Neumann, and T.J. Gillespie, *Measurements and modelling of ozone deposition to wet foliage.* In: K.E. Percy et al. (Eds), Air Pollutants and the Leaf Cuticle, pp 239-253, 1994a.

Fuentes, J.D., T.J. Gillespie, and N.J. Bunce, *Effects of foliage wetness on the dry deposition of ozone onto red maple and poplar leaves*, Water, Air and Soil Pollution, 74, 189-210, 1994b.

Fuentes, J.D., and T.F. Dann, *Ground-level ozone in eastern Canada: seasonal variations, trends and occurrences of high concentrations*, Journal of the Air and Waste Management Association, 44,1019-1026, 1994.

Fuentes, J.D., D. Wang, H.H. Neumann, T.J. Gillespie, G. den Hartog and T.F. Dann, *Ambient biogenic hydrocarbons and isoprene emissions from a mixed deciduous forest*, J. Atmos. Chem., 25, 67-95, 1996.

Fuentes, J.D., and D. Wang, *On the seasonality of isoprene emissions from a mixed temperate forest*, Ecological Applications, 9,1118-1131, 1999.

Fuentes J.D., D. Baldocchi, and B. Lamb, *Biogenic hydrocarbons in the atmospheric boundary layer: an overview*, Journal of Applied Meteorology, 38, 849-854, 1999.

Gu, L., J.D. Fuentes, H.H. Shugart, R.M. Staebler, and T.A. Black, *Significantly enhanced carbon uptake by two contrasting North American deciduous forests due to increased cloudiness*, J. Geophys. Res., In press, 2000.

Hollinger et al., Ameriflux: *Results from a network of long-term CO2 flux measurement sites*, submitted to Science, 2000.

Huber L., P. Laville, and J.D. Fuentes, *Uncertainties in isoprene emissions due to improper plant canopy microclimate characterization*, J. Appl. Met., In press, 2000.

IGBP Terrestrial Carbon Working Group, *The Terrestrial Carbon Cycle: Implications for the Kyoto Protocol*, Science, 280, 1393-1394, 1998.

Leclerc, M.Y., K.C. Beissner, R.H. Shaw, G. den Hartog, and H.H. Neumann, *The influence of atmospheric stability on the budgets of the Reynolds stress and turbulent kinetic energy within and above a deciduous forest*, J. Appl. Met., 29, 916-933, 1990.

Lee, X., T.A. Black, G. den Hartog, H.H. Neumann, Z. Nesic and J. Olejnik, *Carbon dioxide exchange and nocturnal processes over a mixed deciduous forest*, Agric. For. Meteorol., 81, 13-29, 1996.

Lee, X., *Turbulence spectra and eddy diffusivity over forests*, J. Appl. Met., 35, 1307-1318, 1996.

Lee, X., J.D. Fuentes, R.M. Staebler, and H.H. Neumann, *Long-term observation of the atmospheric exchange of CO2 with a temperate deciduous forest*, J. Geophys.Res., 104, 15975-15984, 1999.

Makar P., J.D. Fuentes, D. Wang, R.M. Staebler, and A. Wiebe, *Modeling of biogenic hydrocarbon oxidation at a forested site in southern Ontario*, J. Geophys.Res., 104, 3581-3603, 1999.

Maitani, T. and Shaw, R.H., *Joint probability analysis of momentum and heat fluxes at a deciduous forest*, Boundary-Layer Meteorol., 52, 283-300, 1990.

Neumann, H.H., G. den Hartog and R.H. Shaw, *Leaf area measurements based on hemispheric photographs and leaf-litter collection in a deciduous forest during autumn leaf-fall*, Agric. For. Meteorol., 45, 425-345, 1989.

Padro, J., and G.C. Edwards, *Sensitivity of ADOM dry deposition velocities to input parameters: A comparison with measurements for O_3, SO_2 and NO_2 over three land use types*, Atmos.-Ocean, 29, 667-685, 1991.

Padro, J., G. den Hartog, H.H. Neumann and D. Woolridge, *Using measured variances to compute surface fluxes and dry deposition velocities: A comparison with measurements from three surface types*, Atmos.-Ocean, 30, 363-382, 1992.

Perttu, K., Modelling forest growth processes: *Review of the Second Uppsala Workshop 1988*, Agric. Forest Met., 50, 1-22, 1990.

Shaw, R.H., G. den Hartog, and H.H. Neumann, *Influence of foliar density and thermal stability on profiles of Reynolds stress and turbulence intensity in a deciduous forest*, Boundary-Layer Met., 45, 391-409, 1988.

Shaw, R.H., Paw U, K.T., Zhang, X.J., Gao, W., den Hartog, G., Neumann, H.H., *Retrieval of turbulent pressure fluctuations at the ground surface beneath a forest*, Boundary-Layer Meteorol., 50, 319-338, 1990.

Shaw, R.T., and Zhang, X.J., *Evidence of pressure-forced turbulent flow in a forest*, Boundary-Layer Meteorol., 58, 273-288, 1992.

Simpson, I.J., G.W. Thurtell, H.H. Neumann, G. den Hartog, and G.C. Edwards, *The validity of similarity theory in the roughness sublayer above forests*, Boundary-Layer Met., 87, 69-99, 1998.

Staebler, R.M., J.D. Fuentes, H.H. Neumann and J.M. Chen, *Light interception by a temperate deciduous forest*, 9th Conference on Atmospheric Radiation, 1997. ●