Ecosystem-atmosphere exchange of CO_2 over a mixed hardwood forest in northern lower Michigan: 1999 - 2001

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Abstract:

We report results from the first three years (1999-2001) of continuous measurement of net ecosystem CO_2 exchange (NEE) over a mixed hardwood forest at the University of Michigan Biological Station AmeriFlux site (UMBS~Flux). Two methods were used to fill data gaps due to missing observations or rejection by quality control. 1) Using short-term ensemble averages of the daily course, and 2) by semi-empirical parametric models, based on the relationship between ecosystem respiration and soil temperature, and between gross ecosystem photosynthetic uptake and photosynthetically active radiation.

Differences in estimated annual net ecosystem production (NEP) due to different criteria of data acceptance, measurement height, or gap-filling methods were as large as the interannual variation in NEP over the three years. Our best estimate of annual NEP was achieved at a measurement level of 2.1 times canopy height and by replacing data gaps and measurements during low-u_* conditions with site and period specific parametric models,. These estimates of annual NEP were 170 g C m^{-2} (1999), 160 g C m^{-2} (2000) and 80 g C m^{-2} (2001).

Site & Instrumentation:

The UMBS~Flux site is at the University of Michigan Biological Station (45°33'35.4"N, 84°42'49.7"W) in northern lower Michigan (Fig. 1). It is in the transition zone between mixed hardwood and boreal forests on a level to gently sloping high outwash plain derived from glacial drift. Soils are mostly excessively drained spodosols.

Data for this study were collected on a 46 m tower in a secondary successional hardwood forest (mean canopy height ~22 m). The minimal forest fetch, to Douglas Lake in the north, is 1 km. The terrain gently drops (~ 20 m over 1 km) to Douglas Lake and to Burt Lake (3.5 km to the southeast), but rises ~20 m over 1 km to the southwest, before dropping abruptly in a steep escarpment formed by an interlobate moraine.

Bigtooth aspen-*Populus grandidentata* and trembling aspen-*P. tremuloides* dominate within a 1 km radius of the tower. In a 1.1 ha plot surrounding the tower, total aboveground biomass was ca. 125 tons ha^{-1}, typical of forests on soils of intermediate fertility in northern lower Michigan (Table 1).

Table 1. Biomass distribution (kg/ha) within the 60 m plot, 1997.

Tree Species	Leaves and twigs	Live branches	Dead branches	Bole	Total	Total %
Populus grandidentata	1,014	6,184	1,992	57,460	66,649	53.1
Quercus rubra	507	4,019	742	16,029	21,297	17.0
Pinus strobus	2,027	5,608	8	5,618	13,261	10.6
Betula papyrifera	237	1,072	2,997	7,783	12,089	9.6
Acer rubrum	349	1,575	298	8,936	11,158	8.9
Fagus grandifolia	12	85	167	274	538	0.4
Pinus resinosa	36	47	17	403	504	0.4
Grand Total	4,184	18,597	6,223	96,550	125,554	100

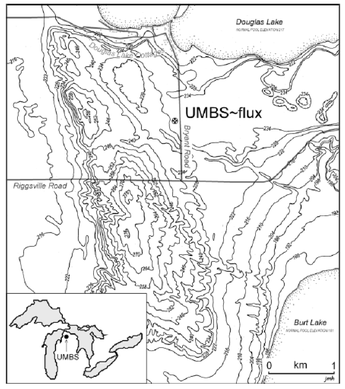

Figure 1: Map of the location of UMBS~flux site, in the north Michigan's lower peninsula. The location of the tower is indicated by the symbol ❖. The nearest town is Pellston (MI), about 7 km to the west. Access to the tower is from an unimproved driveway off Bryant Road. The cottage community on Douglas Lake is mostly seasonal-residential.

The micrometeorological instrumentation is organized into two observation levels for flux measurements: 46 m and 34 m, corresponding to 2.1 and 1.5 times canopy height (Table 2).

Table 2. Micrometeorological instrumentation at the UMBS~flux site

Instrument	Manufacturer	Model #	Location[1]	Measurement
3D Sonic Anemometer	Campbell Scientific	CSAT-3	46 m, 34 m	3D turbulence, sonic temperature
Infrared gas analyzer	LI-COR	LI-6262	46 m, 34 m	CO_2, H_2O, for eddy covariance
Infrared gas analyzer	LI-COR	LI-6262	Canopy Tower	CO_2, H_2O, for mean profile
Mass Flow Controller	Aalborg	GFC-171	46 m, 34 m	IRGA flow rate
Datalogger	Campbell Scientific	CR23X	46 m, 34 m	Data collection
Datalogger	Campbell Scientific	CR23X	Lab	Data collection and valve control
Datalogger	Campbell Scientific	CR10X	BC1	Data collection
Multiplexer	Campbell Scientific	AM416	BC1	(CR10X)
Net Radiometer	REBS	Q*7.1	46 m, 34 m	Net Radiation (.25-60 µm)
Quantum Sensor	LI-COR	LI-190SZ	46 m, 34 m, BC1	PAR, .4-.7 µm (µmol m^{-2} s^{-1})
Quantum Sensor Profile	LI-COR	LI-190SZ x 5	Canopy Tower	PAR, .4-.7 µm (µmol m^{-2} s^{-1})
Pyranometer	LI-COR	LI-200SA	46 m, 34 m, BC1	Short Wave, 0.4 - 1.1 µm (W m^{-2})
Relative Humidity/ Temperature Probe	Rotronic	HPO-43	46 m, 34m, 21 m, 15 m, 3.5 m	RH/Temp, aspirated shields
Rain Gauge	Texas Electronics	TR-525-M	46 m, BC1	Rain (mm), tipping bucket
Soil Heat Flux Plate	REBS	HFT3 x 2	BC1	Soil heat flux (W m^{-2})
Barometer	Vaisala	PTB101B	Lab	Atmospheric Press. (hPa)
Cup Anemometer and Wind Vane	Met One	034A-L Windset	48 m, 26 m, 21 m	Wind speed/ Direction
Soil Temp Profile		24 Ga Type E Thermocouples	BC1-a,b,c	Depths of 2, 7.5, 20, 50, 100 cm
Tree stem temp		24 Ga Type E Thermocouples	BC1	4 trees, 1 cm depth
2 m air temp	Campbell Scientific	Campbell Thermistor & Type t thermocouple	BC1	Passive gill shield
Soil Water Profile	Vitel	Type A probes	BC1	%H2O volume, depths of 5, 10, 20, 51, 102 cm

[1] Location codes: 46 m = top of tower, 34 m = 34 m height on tower, BC1 = below canopy station 1, Canopy Tower (CO_2/H_2O profile) = 0.25, 0.6, 3.5, 7, 11, 14, 17, and 22 m, Canopy Tower (PAR profile) = 1.5, 6.5, 11, 14, 17m. IRGA locations refer to gas inlet, the IRGAs themselves are in the climatized Lab.

Results:

Growing season length was very similar across these three years (Table 3, Fig.2). Vegetation area index (VAI) was measured in the 1.1 ha plot using a LiCor LAI-2000 plant canopy analyzer. In 1999, bud-break was observed May 1 (day 121). VAI increased rapidly until May 26 (day 146), when the first full sized leaves were observed and VAI was about 90% of its peak value. After that, increases in VAI were gradual and maximum VAI of ~3.3 was reached near the end of June. Canopy development in 2000 and 2001 was very similar, although in 2002 leaf out was delayed and a greater maximum VAI was observed.

Table 3. Estimates of vegetative season length at UMBS~flux for the years 1999 and 2000

	1999	2000
carbon assimilation period (year days)	128-282	128-285
duration (days)	155	158
period with T_a > 13 °C (year days)	120-271	124-265
duration (days)	152	142
leaf-bud break (year day)	121	125

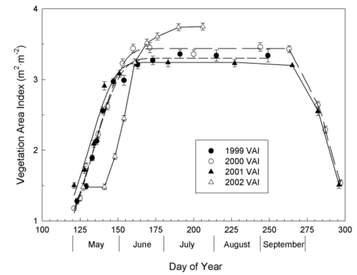

Figure 2: Seasonal course of vegetation area index (VAI) for 1999 - 2002 in the 1.1 ha main plot measured with a LI-COR LAI-2000 Plant Canopy Analyzer. Each point represents the mean VAI measured along multiple transects.

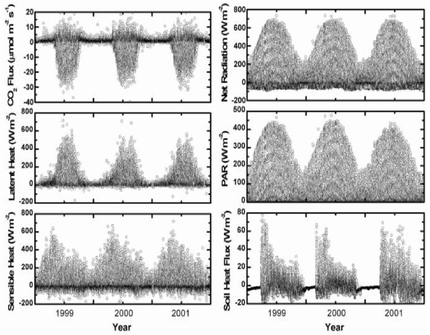

Figure 3: Hourly CO_2, latent and sensible heat fluxes, net radiation, PAR (all measured at the 46 m level), and soil heat flux from 1999 to 2001.

There were no significant gaps in our measurements of carbon, water and energy fluxes from 1999 to 2001. Mid-summer water stress occurred in both 2000 and 2001 as illustrated by the reduction in hourly latent heat fluxes (Fig. 3). This was also seen in reduced daytime carbon uptake and increased sensible heat fluxes (Fig. 4). However, net radiation, PAR, short-wave radiation and soil heat fluxes were similar in July for these three years. Soil temperature in 2000 and 2001 was cooler than 1999, leading to reduced soil respiration and gross photosynthetic uptake. Little difference was observed in the ensemble average of CO_2 storage fluxes estimated from measurements of concentration profiles (Fig. 5).

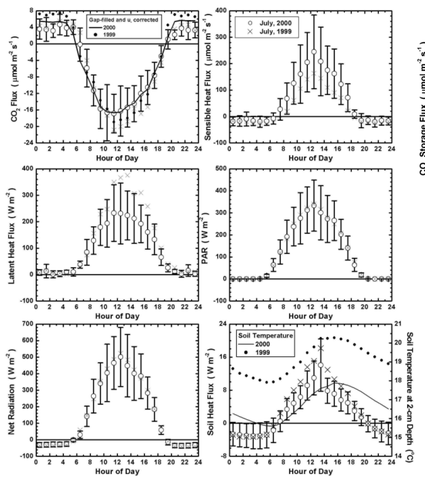

Figure 4. Ensemble-average of daily course of eddy-covariance fluxes of CO_2, sensible and latent heat, net radiation, PAR, soil heat flux and soil temperature at 2 cm depth in July 1999 (crosses) and 2000 (open symbols). The panel for CO_2 flux also shows the mean daily course of the gap-filled fluxes, using the u^* criterion described in the text. Vertical bars indicate one standard error around the mean.

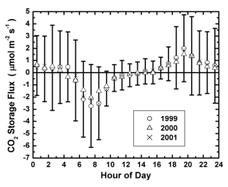

Figure 5: Average diurnal courses of CO_2 storage flux in the canopy air layer during the growing season 1999 to 2001.

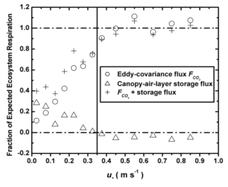

Figure 6: Fraction of expected nighttime ecosystem respiration (modeled) accounted for by the measured eddy-covariance flux of CO_2 and storage change vs. friction velocity.

The u^* threshold for rejecting nighttime measurements was 0.35 m s^{-1} (Fig. 6). The consequences for annual estimates of NEP of replacing rejected measurements with modeled values is shown in Table 4, as are differences using various data rejecting criteria.

Consistent differences in estimated annual NEP from measurements at the two heights were also observed (Table 4, Fig. 7), with 34 m yielding greater annual NEP over each of the three years. Interannual variation was similar at both heights, but of a smaller or similar magnitude as differences between heights.

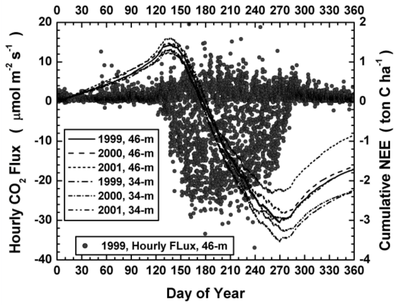

Figure 7: Annual NEE estimates at UMBS~Flux for 1999-2001. The curves represent the best estimates of cumulative NEE, where data gaps and measurements in low u^* conditions were replaced by parametric model values at all times. The dots are measured hourly CO_2 fluxes for the year 1999.

Table 4. Net ecosystem exchange estimated using different analysis criteria. The numbers in bold are considered our best estimates of NEP. Values are rounded to the nearest 10 g C m^{-2}.

UMBS~flux, 1999-2001		46 m	34 m
1999 Net Ecosystem Production, annual (NEP) [g C m^{-2}]*			
gaps; ensemble averages		290	330
gaps; modeled,	no u_*-crit.	250	300
gaps; modeled,	u_* < 0.35, cond.	140	200
gaps; modeled,	u_* < 0.2, cond.	160	230
gaps; modeled,	u_* < 0.35, all	**170**	**220**
gaps; modeled,	u_* < 0.2, all	170	230
modeled		180	240
1999 Gross Ecosystem Production, annual (GEP) [g C m^{-2}]			
modeled,	5 periods	1350	1350
modeled,	14 periods	1350	1360
1999 Net Ecosystem Respiration, annual (R_E) [g C m^{-2}]			
modeled,	all year	1190	1140
modeled	3 periods	1170	11.10
2000 Net Ecosystem Production, annual (NEP) [g C m^{-2}]*			
gaps; modeled,	u_* < 0.35, all	**150**	**210**
2001 Net Ecosystem Production, annual (NEP) [g C m^{-2}]*			
gaps; modeled,	u_* < 0.35, all	**80**	**170**

*: 100 g C m^{-2} = 0.1 kg C m^{-2} = 10^3 kg C ha^{-1} = 1 ton C ha^{-1} = 1 Mg C ha^{-1}

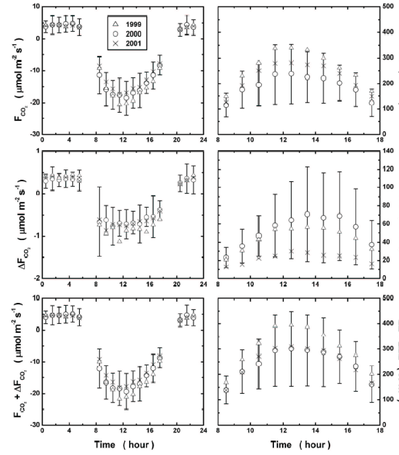

Figure 8: Year to year variations in the ensemble-averaged diurnal course of CO_2 (F_{CO2}) and latent heat (LE) fluxes, their corrections ΔF_{CO_2} and ΔLE, and corrected fluxes. Data shown are for June through August at the 46 m level.

Cospectral corrections for high frequency losses due to tube-damping for CO_2 fluxes were ~3-4% in the daytime and 6-10% at night (Fig. 8). Corrections for LE fluxes were much greater, < 10% for newer tubes and > 20% for aged tubes, with a significant impact (~15%) on the energy balance closure (Fig. 9).

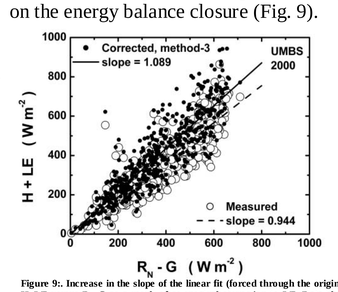

Figure 9:. Increase in the slope of the linear fit (forced through the origin) of H+LE versus R_N-G as a result of co-spectral correction to LE. Data shown are for June through August at the 46 m of the MMSF tower (H sensible heat, R_N net radiation, G soil heat flux - uncorrected).

Summary:

- The forested ecosystem surrounding the UMBS~Flux tower has been a consistent carbon sink of moderate strength over the last three years. We estimated an annual NEP of 170 g C m^{-2} in 1999, 160 g C m^{-2} in 2000, and 80 g C m^{-2} in 2001, totaling 410 g C m^{-2} for these three years. This interannual variation in NEP underscores the importance of obtaining long-term observations of ecosystem exchange, spanning the relevant climatic and ecophysiological time scales involved.
- The choice of data quality control criteria and gap-filling methods can affect estimates of annual NEP by a factor of two.
- Differences in estimated annual NEP due to measurement height were as large as the observed interannual variation in NEP, and were consistent in each of the three years. Work is underway to determine the causes of these height related differences in estimated NEP.
- Cospectral corrections show that high-frequency losses due to tube damping are much greater for latent heat flux than for CO_2 flux, especially for aged tubes. Thus, care should be taken in correcting carbon fluxes using energy imbalance based methods.