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On the relationship between cloudiness and net ecosystem carbon dioxide exchange in a peatland ecosystem[1]

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Abstract: The relationship between incident light intensity and net ecosystem CO_2 exchange (NEE) was examined at a low-shrub bog located near Ottawa, Canada. Shrub height was 0.25 m and maximum leaf area index was 1.3 at the peatland. Light intensity was expressed as a clearness index (CI), where values approaching zero indicate heavy overcast conditions and values approaching unity represent cloudless conditions. Light saturation with respect to net CO_2 uptake at the canopy scale occurred at low CI, near 0.3. Contrary to reports from some forest ecosystems, in which peak NEE occurred with CI in the range 0.4-0.7, at the peatland there were no differences in NEE across all ranges of CI above 0.3. At the same time, CI in the range of 0.4-0.7 was infrequent and of short duration relative to clear skies and thick overcast conditions. Finally, we show that the use of half-hourly average radiation measurements to determine CI can lead to significant overestimation of the CI index in the range between 0.4-0.7.
Keywords: clearness index, cloudiness, diffuse radiation, net ecosystem exchange, peatland.

Résumé : La relation qui existe entre l'intensité de la lumière incidente et l'échange net de CO_2 d'un écosystème (ENE) a été examinée dans une tourbière ombrotrophe dominée par de petits arbustes près d'Ottawa, au Canada. Dans cette tourbière, la hauteur moyenne des arbustes est de 0,25 m et l'indice de la surface maximale des feuilles est de 1,3. L'intensité lumineuse est exprimée sous la forme d'un indice de clarté (IC) : une valeur approchant zéro indique une forte nébulosité tandis qu'une valeur proche de l'unité témoigne d'un ciel sans nuage. Au niveau de la surface du couvert végétal, la saturation lumineuse se produit à un IC bas, près de 0,3, si l'on tient compte du prélèvement net de CO_2. Contrairement à ce qui est décrit pour certains écosystèmes forestiers, pour lesquels des ENE maximaux se produisent lorsque l'IC se situe entre 0,4 et 0,7, il n'y a pas de différence dans les ENE pour toute valeur de l'IC supérieure à 0,3 dans la tourbière. Il faut toutefois mentionner que nous n'avons pas mesuré très souvent, et seulement pour de courtes périodes, des IC entre 0,4 et 0,7 en conditions de ciels clairs ou de ciels couverts d'épais nuages. Nous montrons enfin que l'utilisation de moyennes de radiation mesurées aux demi-heures pour déterminer les IC peut mener à une surestimation significative des valeurs mesurées de façon instantanée, particulièrement pour les IC qui se trouvent entre 0,4 et 0,7.
Mots-clés : conditions météorologiques nuageuses, échange net d'un écosystème, indice de clarté, radiation diffuse, tourbière.

Nomenclature: Fernald, 1950; Anderson, 1990.

Introduction

It is well known that there is a significant benefit to ecosystem productivity from increased diffuse radiation because it is more effective at penetrating the canopy than direct incoming radiation (Goudriaan, 1977; Roderick *et al.,* 2001). Under cloudy skies and predominantly diffuse radiation, light-use efficiency (ratio of biomass accumulation to quantity of light received) is higher than for sunny skies. During sunny conditions, sunlit leaves at the top of the canopy experience light saturation and additional photons are not used in biomass production, while shaded leaves (which can represent the largest proportion of the canopy) often receive well below the light levels required for maximum photosynthesis (Gu *et al.,* 2002). Recently, however, several researchers have suggested that in forests not only is light use efficiency increased under diffuse conditions, but so too is the absolute magnitude of CO_2 exchange (Price & Black, 1990; Hollinger *et al.,* 1994; Fitzjarrald *et al.,* 1995; Gu *et al.,* 1999). These studies demonstrate that forest net ecosystem CO_2 exchange (NEE) was greater on cloudy/hazy days than on sunny days. So significant is this effect that it may be important for global carbon cycling, especially in terms of prolonged periods of enhanced diffuse radiation, such as following major volcanic eruptions (Roderick *et al.,* 2001; Farquhar & Roderick, 2003; Gu *et al.,* 2003). In practice, however, it is difficult to separate the beneficial effect of diffuse radiation to plant canopies from other factors that might influence NEE under cloudy skies. For example, cloudy skies may result in lower leaf temperature and vapour pressure deficit, which would both influence stomatal conductance, possibly confounding the effects of direct and diffuse light (Gu *et al.,* 2002).

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Nevertheless, based on several studies, mostly from North America, it is generally accepted that cloudiness, by causing increased diffuse light, can increase carbon uptake in forested ecosystems.

The influence of diffuse radiation on NEE for short-stature canopies has received much less attention than for forests. Since leaf area index (LAI) is usually smaller in short canopies, the penetration of light through the canopy is greater. Thus, the beneficial effect of diffuse radiation on NEE may be reduced, or non-existent, in short canopies. The objective of the current study was to explore light intensity and NEE at an open, low-shrub bog peatland in eastern Canada. Specifically, we tested the hypothesis that diffuse light under cloudy skies significantly enhances NEE for this short-stature peatland canopy.

Site description and measurements

The research site is Mer Bleue, an ombrotrophic, 2,800-ha raised bog located 12 km east of Ottawa, Canada (45° 24′ N, 75° 30′ W). Evergreen shrubs (*Chamaedaphne calyculata, Kalmia angustifolia, Ledum groenlandicum*) and one deciduous shrub (*Vaccinium myrtilloides*) dominate the vegetation canopy. The mean height of the shrub canopy is 0.25 m, and maximum LAI is 1.3. Stunted trees (*Larix laricina*, *Betula papyrifera,* and *Picea mariana*) can also be found on the bog, but they cover less than 2% of the total peatland surface. Below the shrubs, the bog surface is covered by mosses (*Sphagnum magellanicum*, *S. angustifolium*, *S. capillifolium,* and *S. fuscum*). Above-ground biomass is 487 $g \cdot m^{-2}$, 70% of which is from shrubs (Moore *et al.,* 2002).

Measurements of CO_2 flux, incoming global solar radiation ($K\downarrow$), and photosynthetically active radiation (PAR) have been made continuously at Mer Bleue since May 1998. Average half-hourly fluxes of CO_2 were measured using the eddy covariance technique. A three-dimensional sonic anemometer (Model 1012R3 Solent, Gill Instruments, Lymington, UK) measured turbulence and heat fluctuations, while water vapour density fluctuations were measured with a krypton hygrometer (KH20, Campbell Scientific, Logan, Utah, USA) and CO_2 concentrations were measured using a closed-path infrared gas analyzer (IRGA Model 6252, LI-COR, Lincoln, Nebraska, USA). All signals were scanned at a frequency of 10 Hz and the covariance of CO_2 and vertical wind speed were used to compute the turbulent flux of CO_2. The rate of change in CO_2 storage in the air layer below the eddy sensors was computed from half-hourly changes in CO_2 concentration. NEE was then calculated as the sum of the storage and turbulent terms. Full details of the carbon flux measurement system and flux computations are described by Lafleur, Roulet, and Admiral (2001).

$K\downarrow$ was measured with a pyranometer (CM11, Kipp & Zonen, Delft, The Netherlands), and PAR was measured with a quantum sensor (QZ190, LI-COR, Lincoln, Nebraska, USA). Both instruments were mounted at a height of 2.5 m above the bog surface. Signals from the radiation instruments were scanned every 5 s, and half-hour averages were computed in a data logger (CR7X, Campbell Scientific, Logan, Utah, USA). Measurements of $K\downarrow$ were continuous throughout the study, while PAR measurements were periodically interrupted due to sensor malfunction. Therefore, the analyses presented here were based on the $K\downarrow$.

Methods

Solar radiation intensity was converted to a clearness index (CI) by dividing measured solar radiation by a computed top-of-atmosphere flux ($K\downarrow_{obs}/K\downarrow_{TOA}$). Observed NEE was plotted against this index. Here we employ the sign convention that negative NEE indicates uptake of CO_2 by the bog (*i.e.,* more negative values mean greater uptake). To minimize the effects of solar angle, time of day, and changing leaf area, the data analysis was restricted to the diurnal period 1000 to 1400 EST and the months of June through September during 1998 through 2001. Data were amalgamated to produce monthly NEE *versus* CI curves. Over the 4-y study, a broad range of environmental conditions was encountered. Temperature was above average and precipitation was near the long-term mean in 1998 and 1999, though there was a brief drought in late July and early August 1999. The year 2000 was very wet and experienced average temperatures, while 2001 was very dry, with temperatures above average (Lafleur *et al.,* 2003). From June 1 to September 30, average light-saturated NEE was greatest in 1998 (-5.3 ± 1.7 $\mu mol \cdot m^{-2} \cdot s^{-1}$), followed by 2000 (-4.8 ± 1.8 $\mu mol \cdot m^{-2} \cdot s^{-1}$), 1999 (-4.3 ± 1.8 $\mu mol \cdot m^{-2} \cdot s^{-1}$), and 2001 (-3.8 ± 1.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

The relationship between NEE and CI was examined using curve-fitting procedures. The rectangular hyperbolic form, adapted from the Thornley and Johnson (1990) formulation for photosynthesis, has been used extensively to model canopy NEE for forests (Ruimy *et al.,* 1995) and peatlands (Frolking *et al.,* 1998). However, one drawback of this curve is that it cannot account for a reduction in NEE at high light intensity. Because of this limitation, cubic regressions have been employed in recent studies of the effect of cloudiness on forest carbon uptake, providing evidence that NEE is greater when solar radiation is above light-saturating levels but mostly diffuse in nature (Gu *et al.,* 1999; Oliphant *et al.,* 2002). Therefore, we explored various polynomial functions (quadratic, cubic, and quartic). Analysis of these curves included qualitative comparison of the form of the curves and quantitative examination of root mean square error (RMSE) and coefficient of explained variance (r^2).

Further analysis included dividing CIs for each month into intervals of 0.1 and computing mean NEE for each interval. A Student's *t*-test was used to compare the average NEE recorded within each CI interval to that of the full light interval ($0.8 < CI < 0.9$). The degree to which NEE increased with cloudiness was assessed, and the significance of any change was considered in light of the frequency of occurrence of various light levels as indicated by the proportional distribution of CI. In addition, the standard deviation of half-hourly measurements from 1000 to 1400 was plotted against the mean CI for each day. This provided an indication of whether middle-range CIs were more often the result of mean calculations from partly cloudy skies or thin clouds such as cirrus and fog.

Finally, we tested the hypothesis that the frequency of intermediate clearness indices (0.4-0.7), those most likely to enhance NEE, were overestimated through the use of half-hourly averages. For this analysis, a pyranometer was set up to measure and record K_{obs} every 6 s from September 26 to October 9, 2002 at the Trent University weather station (Peterborough, Canada, 44° 21' N, 78° 17' W). The proportional distribution of recorded 6-s values was plotted against half-hourly averages.

Results

Clearness index typically ranged from 0.05 to 0.85, though values exceeding unity were recorded because of scattered direct radiation from cloud flanks on partly cloudy days. The monthly relationships between observed NEE and CI indicated that for all months NEE reached its light saturation near CI = 0.3, with NEE showing considerable scatter for larger CI (Figure 1). There was little

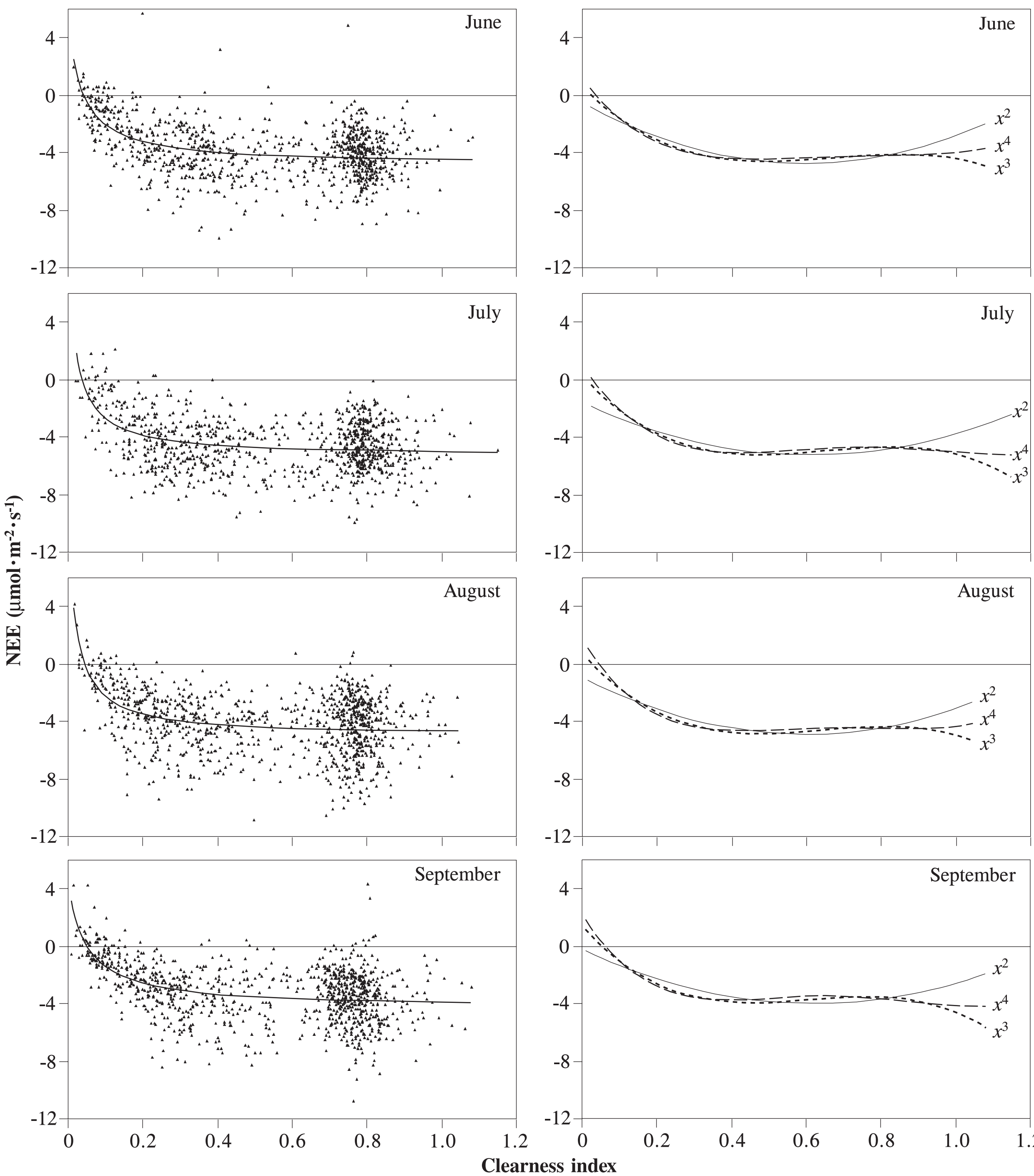

FIGURE 1. Relationship between net ecosystem CO_2 exchange (NEE) and clearness index (CI) by month at Mer Bleue bog (left-hand panels). Data are for hours between 1000 and 1400 EST for months June to September and years 1998 to 2001. Solid line is the best-fit rectangular parabola model. Right-hand panels show best-fit polynomial models (x^2 - quadratic, x^3 – cubic, and x^4 - quartic) of NEE *versus* CI. See Table I for model statistics.

difference in test statistics, r^2 and RMSE, between the rectangular hyperbola model and any of the regression models fit to the NEE *versus* CI data (Figure 1; Table I). The quadratic expression appeared to produce a maximum NEE (*i.e.,* most negative) near CI = 0.6 for all months. However, it produced negligible statistical improvement over the rectangular hyperbolic model in either r^2 or RMSE, suggesting that the visual difference was due to model form rather than to real trends in the data. When regressions of higher-order polynomials (x^3 and x^4) were applied, they began to take on a hyperbolic appearance at CI ≤ 1.0 and resulted in similar statistical fit.

Twenty pair-wise comparisons of mean NEE for CI intervals greater than light saturation (CI > 0.3) to mean NEE for full sun (CI = 0.8-0.9) were conducted (Table II). In 16 of the 20 cases examined, there was no significant difference, including all cases in August and September. In June and July, mean NEE was significantly larger than at the 0.8-0.9 level in two cases and significantly smaller in two others. Of the four comparisons for CI > 0.9, mean NEE was significantly different than at CI = 0.8-0.9 in one case only. Although not shown, the same analysis broken down by year produced similar results. Combining all months and years, the average NEE for CI in the 0.4-0.6 range was -4.05 ± 2.01 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (mean ± SD), which was indistinguishable from the mean NEE at CI = 0.8-0.9 (-4.03 ± 1.89 $\mu mol \cdot m^{-2} \cdot s^{-1}$).

Examination of the distribution of half-hourly average CI at Mer Bleue revealed a bimodal distribution, with peaks in the 0.3-0.4 and 0.7-0.8 intervals (Figure 2). CI in the 0.4-0.7 ranges occurred less than 17% of the time during the study. In addition, CI was more variable on days when such clearness indices predominated (Figure 3), demonstrating the transient nature of middle-range clearness indices. Finally, because of the highly variable nature of radiation, measurement interval can influence the apparent frequency distribution of radiation intensity levels. Frequency distributions of CI derived from 6-s data and half-hour means were compared (Figure 4). Frequencies of CI between 0.4 and 0.7 produced from 30-min mean data were two times larger than for the 6-s data. In contrast, frequencies for 30-min mean data underestimated the frequencies from 6-s data in all other CI intervals.

TABLE I. Monthly models of net ecosystem exchange (NEE) against clearness index (CI) shown in Figure 1. Model forms are rectangular hyperbolic (hyperbolic) and three polynomials (quadratic, cubic, and quartic). Test statistics are explained variance (r^2) and root mean square error (RMSE, $\mu mol\ C \cdot m^{-2} \cdot s^{-1}$).

	June		July		August		September	
Model	RMSE	r^2	RMSE	r^2	RMSE	r^2	RMSE	r^2
Hyperbolic	1.49	0.26	1.85	0.18	1.77	0.18	1.52	0.23
Quadratic	1.47	0.25	1.85	0.15	1.81	0.15	1.53	0.20
Cubic	1.47	0.28	1.84	0.20	1.80	0.18	1.54	0.25
Quartic	1.48	0.28	1.83	0.20	1.76	0.19	1.52	0.26

Discussion

In temperate forests, peak NEE uptake often occurs under diffuse conditions corresponding to the middle ranges (0.4-0.7) of the CI (Gu *et al.,* 1999; Oliphant *et al.,* 2002). Analysis of NEE *versus* CI at Mer Bleue

TABLE II. Pair-wise comparisons of mean net ecosystem exchange (NEE) at a variety of clearness index ranges (CI) against mean NEE measured under full sun (CI = 0.8-0.9). *t* is Student's *t* statistic, *P* significance of *t* at 0.05 level, NS means *t* was not significant.

Month	CI	NEE mean	NEE SD	NEE_{max}	NEE_{min}	*t*	*P*	df
June	0.3-0.4	-4.14	1.63	0.19	-9.42	-1.72	0.05	260
	0.4-0.5	-4.80	1.94	3.17	-9.90	1.24	NS	201
	0.5-0.6	-4.23	1.72	0.55	-8.36	-0.82	NS	183
	0.6-0.7	-4.78	1.50	-1.85	-8.65	1.31	NS	188
	0.7-0.8	-3.99	1.63	4.84	-8.97	-3.09	< 0.005	407
	0.8-0.9	-4.46	1.33	-0.87	-8.91	-	-	-
	> 0.9	-4.04	1.81	-0.38	-8.20	-1.13	NS	167
July	0.3-0.4	-4.64	1.55	-0.03	-8.13	-0.06	NS	274
	0.4-0.5	-4.89	1.73	-1.21	-9.55	0.96	NS	233
	0.5-0.6	-5.22	1.77	-2.46	-9.18	1.76	0.05	201
	0.6-0.7	-5.32	1.69	-2.30	-8.42	2.44	0.01	214
	0.7-0.8	-4.65	1.62	-0.85	-9.95	-0.06	NS	407
	0.8-0.9	-4.66	1.53	-0.12	-8.81	-	-	-
	> 0.9	-5.16	1.79	-1.15	-8.71	1.67	0.05	207
August	0.3-0.4	-4.42	1.71	-0.49	-8.75	0.10	NS	220
	0.4-0.5	-4.60	1.80	-1.22	-10.89	0.70	NS	184
	0.5-0.6	-4.67	1.64	-1.47	-8.18	0.76	NS	144
	0.6-0.7	-4.53	1.99	0.77	-10.59	0.44	NS	185
	0.7-0.8	-4.40	2.10	0.84	-10.11	0.02	NS	439
	0.8-0.9	-4.40	1.91	-0.13	-9.28	-	-	-
	> 0.9	-4.41	1.52	-2.06	-7.80	0.04	NS	139
September	0.3-0.4	-3.72	1.71	0.42	-8.17	-0.44	NS	194
	0.4-0.5	-3.80	2.01	0.47	-8.26	-0.15	NS	178
	0.5-0.6	-3.74	2.07	-0.16	-7.46	-0.26	NS	150
	0.6-0.7	-3.15	2.10	7.28	-7.23	-2.17	NS	186
	0.7-0.8	-3.58	1.74	0.41	-10.80	-1.20	NS	425
	0.8-0.9	-3.84	2.10	4.36	-8.86	-	-	-
	> 0.9	-3.85	1.80	-0.62	-7.93	0.01	NS	141

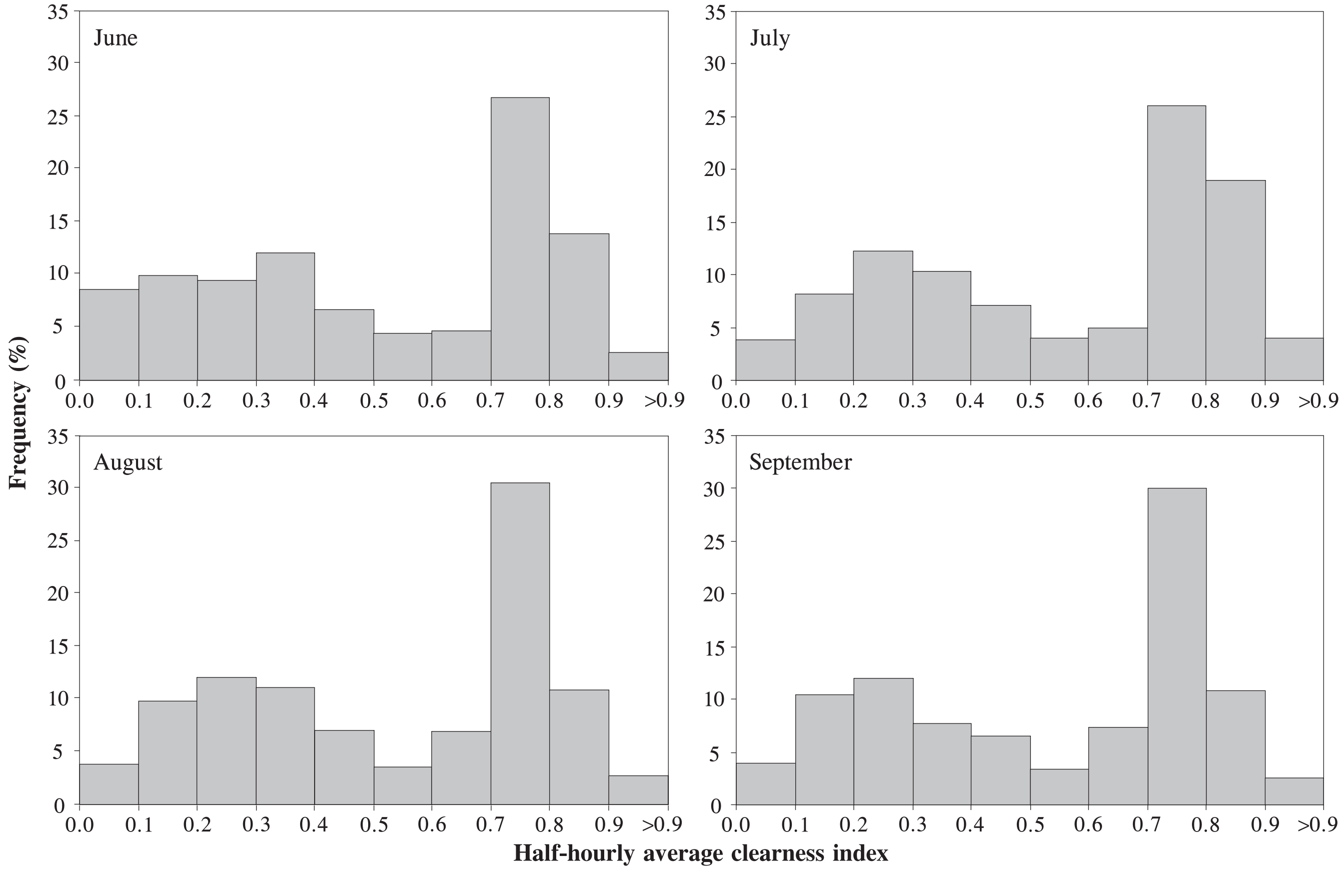

FIGURE 2. Frequency distribution of half-hourly average clearness indices (CI) from June to September, 1998-2001.

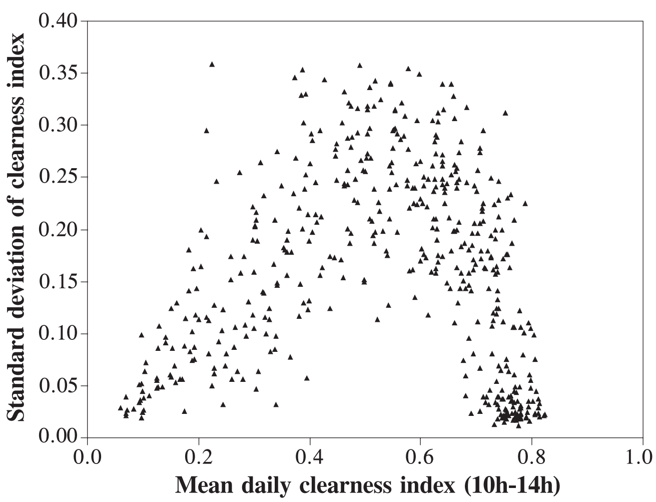

FIGURE 3. Daily average half-hourly clearness indices (CI) from 1000 to 1400 EST *versus* daily standard deviation of half-hourly clearness indices from June through September 1998 to 2001.

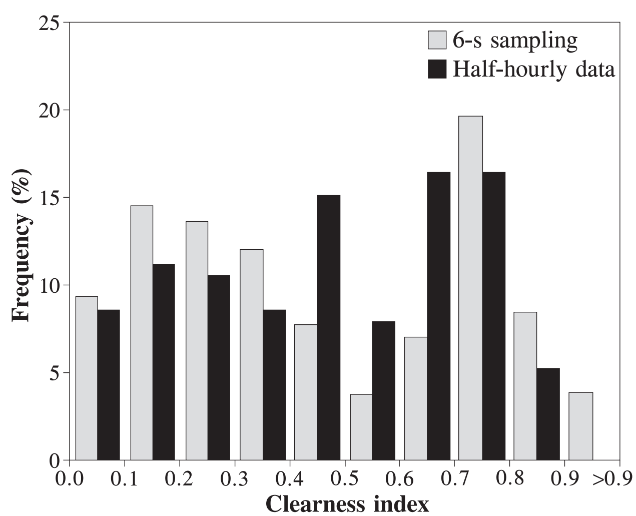

FIGURE 4. Frequency distribution of 6-s (grey) and half-hourly (black) clearness indices (CI) at the Trent University weather station from day 269 through day 287 of 2002.

bog provides little support for the notion of enhanced NEE under diffuse conditions. Neither non-linear curve fitting nor comparisons of mean NEE for CI ranges above light saturation suggested that NEE was greater at middle CI compared to clear skies (CI ≥ 0.8). The most likely factors contributing to the lack of a response of NEE to increased cloudiness at this bog are the small stature and LAI of the shrub overstorey canopy and low light saturation in the understorey moss. The small stature (0.25 m) and LAI (1.3) for the shrubs contribute to relatively low light extinction and limited shading of leaves within the vascular canopy and of the moss below (Frolking *et al.*, 2002). Mosses have very low PAR-saturation levels, ranging from 50 ∝mol·m^{-2}·s^{-1} in feather moss to 300 ∝mol·m^{-2}·s^{-1} in *Sphagnum* spp. moss (Goulden & Crill, 1997). Corresponding rates of light-saturated photosynthesis (A_{max}) are just 0.5 to 1.0 μmol C·m^{-2}·s^{-1} in feather mosses and 2.0 μmol C·m^{-2}·s^{-1} in *Sphagnum* (Goulden & Crill, 1997). Others have found similar values of light saturation and A_{max} for *Sphagnum* mosses (Harley *et al.*, 1989; Jauhiainen & Silvola, 1999; Swanson & Flanagan, 2001). These rates are well below those of the vascular shrubs that overlie the moss, for which A_{max} ranges from 5.0 to 9.7 μmol C·m^{-2}·s^{-1} and photosynthesis light saturation occurs at 500-700 μmol·m^{-2}·s^{-1} (Reimer, 2002). Thus, under most sky conditions the moss ground cover is almost always light saturated and ecosystem photosynthesis tends to be dominated by the vascular canopy. Therefore, diffuse radiation is not likely to enhance NEE in any part of the vegetation canopy compared to full sunlight. Variations in NEE above the light-saturation levels (*i.e.,* CI = ~0.3; PAR > 600-700 μmol·m^{-2}·s^{-1} at this location in summer) are likely due to the transient influences of leaf temperature, humidity, moisture status, changes in stomatal conductance, and varying ecosystem respiration.

The nature of the radiation regime at Mer Bleue also suggests that benefits to NEE from cloudiness, even if they existed, might be small. Only 17% of the data measured over 4 y fell into the category that theoretically would be most beneficial for enhanced NEE. In addition, it appears that this middle level of CI is a difficult condition to quantify. Using time-averaged (30-min) measurements, middle-range CI are often the result of variably cloudy skies rather than persistent high cloudiness. Half-hourly average radiation measurements cannot, therefore, be reliably used as an indicator of diffuse radiation. Our analysis reinforces the recent suggestion by Gu *et al.* (2002) that direct measurements of diffuse radiation are clearly preferred over estimates from time-averaged measurements of solar radiation or PAR.

Recently, peatlands have received attention in terms of global carbon cycling. In Russia, Canada, the United States, and Fennoscandia, peatlands cover 3.46 × 10^6 ha of land, which represents ≈2.4% of the Earth's terrestrial surface. Short-stature or open vegetation canopies together cover more than two-thirds of the Earth's terrestrial surface, and this vegetation contributes almost one-quarter of global, or one-third of terrestrial, net primary productivity (Barbour, 1987). If our results are generally true of other low-growing canopies with low LAI, then the significance of the enhanced productivity of plant canopies under cloudy skies to the global carbon balance may be overestimated. Clearly, future studies on other low-growing vegetation types are needed to determine the overall significance of cloudiness on these ecosystems.

Conclusion

Based on 4 y of data at Mer Bleue bog we cannot find evidence of increased net ecosystem CO_2 exchange for diffuse light conditions (as defined by intermediate CI). This finding is likely a function of the unique physical and physiological character of peatland ecosystems and needs confirmation for other low-growing vegetation classes.

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