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OBSERVATIONS OF CANOPY LIGHT PENETRATION AND NET ECOSYSTEM EXCHANGE OF CO_2 UNDER DIFFERENT SKY CONDITIONS IN A MID-WESTERN MIXED DECIDUOUS FOREST

Andrew J. Oliphant[1], Will Rose[1], Hans-Peter Schmid[2] Sue Grimmond[3]

[1] San Francisco State University, Department of Geography
[2] Indiana University, Department of Geography
[3] Kings College, London, Department of Geography

1. INTRODUCTION

Recent evidence from terrestrial CO_2 flux tower sites has shown that for many ecosystems, increased atmospheric scattering from aerosols, including clouds increases the net ecosystem uptake of atmospheric CO_2. The role of scattering on net ecosystem exchange (NEE) has important implications for the global carbon cycle and presents a potentially important biosphere-atmosphere feedback for future climatic changes of cloud and aerosol regimes. Effects of aerosols include reduction of global incident PAR (PAR_G) and increases in the portion of diffuse beam PAR (PAR_D) relative to direct beam (PAR_S). The main mechanism is thought to be more effective light use efficiency (LUE) of PAR_D than PAR_S, especially in deep or dense canopies (Roderick et al. 2001, Cohan et al. 2002, Gu et al. 2002, Min 2005). This mechanism may be controlled in part by reducing shading of lower leaves within the canopy, reduced radiative heat stress on outer leaves or spectral shifts in scattered light with respect to photosynthetic efficiency. In addition, reduction in PAR_G may cause cooling at the leaf surface, thereby reducing leaf respiration (Gu et al. 1999).

The objective of this study is to examine the relation between atmospheric scattering, light penetration within the canopy and net ecosystem exchange of CO_2 for the Morgan-Monroe State Forest (MMSF) AmeriFlux flux tower site located in south-central Indiana, USA. Previous research has shown that CO_2 uptake in the MMSF is enhanced by up to 20% under optimal cloud conditions compared with equivalent clear sky conditions, despite reduction in total solar radiation of up to 50% (Oliphant et al. 2002).

2. PHYSICAL SETTING AND METHODS

Morgan-Monroe State Forest (MMSF) located at 39º19´N, 86º25´W is a successional broadleaf forest within the maple-beech to oak-hickory transition zone of the eastern deciduous forest, with a mean canopy height near the tower of 27 m and a total area of 95.3 km^2 (Oliphant et al. 2004). Twenty-nine tree species have been identified in the area surrounding the tower. Five tree species comprise 73% of the total basal area of 26 m^2 ha^{-1} and the average age of trees in the vicinity of the tower is approximately 55 years (Ehman et al. 2002).

Leaf area index (LAI) estimated throughout the year from 30 point measurements along three 150 m transects to the west of the flux tower using pairs of LAI-2000 (LiCor inc., Lincoln, NE) show a seasonal range from a maximum during leaf-on of approximately 5 m^2 m^{-2} to a consistent leaf-off value of 1 m^2 m^{-2} (Oliphant et al. 2004). Canopy vertical structure is fairly consistent across the study area with peaks in LAI occurring at the crown level (~20-30 m) and at the undergrowth level (~0-10 m). The spatial average LAI estimated from IKONOS 4 m NDVI values for the MMSF study area on a clear July day is 3.4 m^2 m^{-2}, and the spatial standard deviation is 0.85 m^2 m^{-2} (Oliphant et al. 2006). These values show a bimodal distribution with peaks in the vicinity of 4 m^2 m^{-2} (the undisturbed canopy) and near zero (lakes and clearings for roads, buildings and parking areas). Values in the vicinity of the flux tower are 4 - 4.5 m^2 m^{-2}, which compare closely with the summertime LAI-2000 observations.

A 46 m self supported tower provides an observational platform for eddy covariance measurements of CO_2, water vapor and energy fluxes and has provided near continuous measurements since March 1998. Details of the flux measurements at MMSF are provided by Schmid et al. (2000). In addition to the main tower, a second narrow 30 m guyed tower was erected in 2003 to protrude through the canopy without disturbing it and mounted with nine levels of PAR quantum sensors (LI190SB, LiCor, Lincoln, NE) and a BF3 sensor (Delta-T, Cambridge, UK) to obtain PAR_D and PAR_G at the top of the tower.

The site for the canopy tower was chosen in part based on the LAI observations mentioned above to ensure a representative siting with respect to canopy foliage. In addition, a 20 × 20 m grid with 2 m spacing was established around the canopy tower. The grid contained 95 trees and LAI was sampled at each of the 121 grid points. The mean of the nine samples immediately around the tower was 4.02 (standard deviation = 0.3), while the mean of the 121 samples in the 400 m^2 grid around the tower was 3.86 (standard deviation = 0.48). We therefore conclude that the forest canopy that the tower is sampling is broadly representative of the surrounding ecosystem, at least with respect to total canopy LAI observed from the surface.

LAI observations were made at each instrument level (sampled at nine locations around the canopy tower for each level approximately 2 m outstretched from the tower). Sky-view photos were also taken using a fisheye lens over each quantum sensor during the summer of 2005 and 180 degree sky view factors were calculated using the method of Grimmond et al. (2001). A clearness index (K_T) was derived for each hour from PAR_G / PAR_{EX}, where PAR_G is global PAR measured above the canopy with an unobstructed view at 30 m and PAR_{EX} is the extraterrestrial radiation at a hypothetical horizontal surface at the top of the atmosphere. PAR_{EX} and solar elevation angle (α) are based on the sun-earth geometric formulations used by Whiteman and Allwine (1986) and Oliphant et al. (2003).

3. RESULTS

3.1. Effect of scattering on NEE

Using seven years of growing season hourly data, the relation between PAR and NEE for the MMSF is negatively correlated with a saturating of net uptake as PAR levels get above approximately 1200 μmol m^{-2} s^{-1} (Figure 1). It also appears that different levels of clearness are essentially responsible for different parts of that curve. Furthermore, the largest ecosystem uptake seems to occur at moderate levels of clearness ($0.4 > K_T < 0.6$).

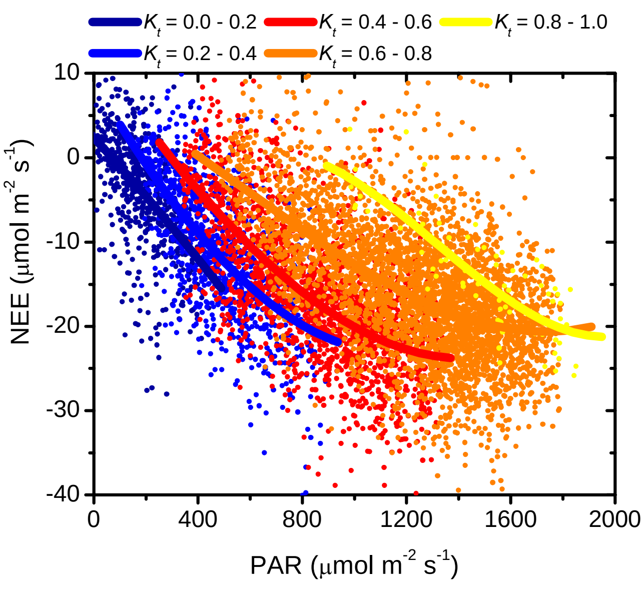

Figure 1. Relation between PAR and NEE for five categories of K_T, using hourly data from 1998-2004 growing seasons at MMSF.

Figure 2 illustrates the relation between NEE and K_T evaluated for a range of solar elevation angle (α) bins, producing the characteristic cubic polynomial curve (Figure 2a), which has also been found over several other forest ecosystems (Gu et al. 1999, 2002, Oliphant et al. 2002, Min 2005). NEE decreased as K_T decreased from a clear sky value of approximately 0.8 until an optimal productivity level (minimum NEE, greatest uptake) occurred at an average K_T of 0.55. Below this level, it is likely that the overall reduction in PAR is responsible for the steady increase in NEE (reduced uptake).

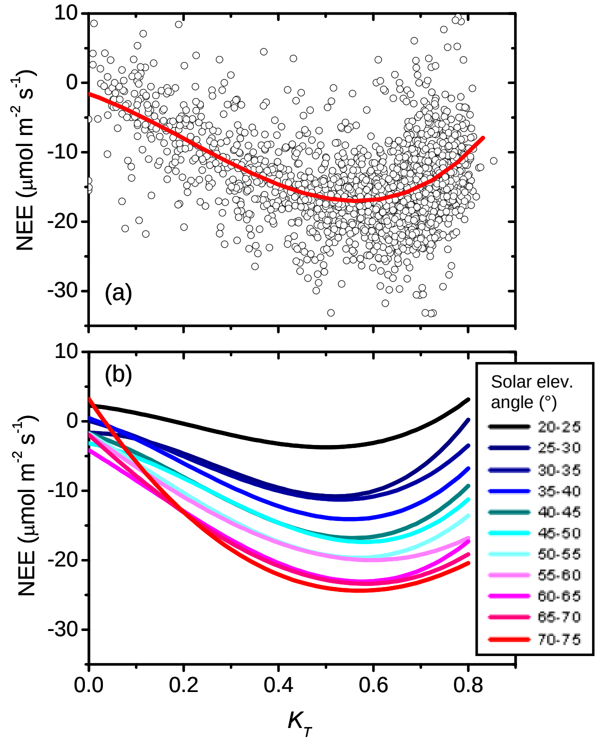

Figure 2. Relation between K_T and NEE for a) all hours from α bin 40-50º and b) 5º α bins between 20º and 75º, using hourly data from 1998-2004 growing seasons at MMSF.

Figure 2b shows the relation was similar for each α bin, with an overall lowered NEE as α increased as well as a slight increase in the optimal K_T. The mean r^2 value for each set of cubic regressions is 0.46. The coefficients of determination for the fit of all the curves in Figures 1 and 2 however remains between 0.34-0.63 suggesting the importance of broader environmental controls.

That decreased clearness implies an increased scattering of PAR was tested with a small (~50 day) dataset of PAR_D and PAR_G measured with a BF3 PAR sensor at the top of the canopy tower during the second half of the growing season of 2005. Figure 3 shows that the fraction of radiation arriving in diffuse form was negatively and approximately linearly related to K_T (the r^2 value for the simple linear equivalent to the polynomial fit shown in Figure 3 was 0.79, with a slope of -1.5 and an offset of +1.5). The relatively good agreement of fit suggests that simple indices such as K_T which use minimal observational input can usefully describe the degree of atmospheric scattering where (or when) only PAR_G observations are available. The estimation of PAR_D from such empirical models is useful for modeling sub-canopy light environments. A longer dataset of PAR_D observations should improve empirical parameterization of PAR_D at a site specific level as well as provide the opportunity to explore the reasons for the variability shown in Figure 3, which suggests for example that PAR_G can be almost completely dominated by PAR_D, with K_T up to approximately 0.57.

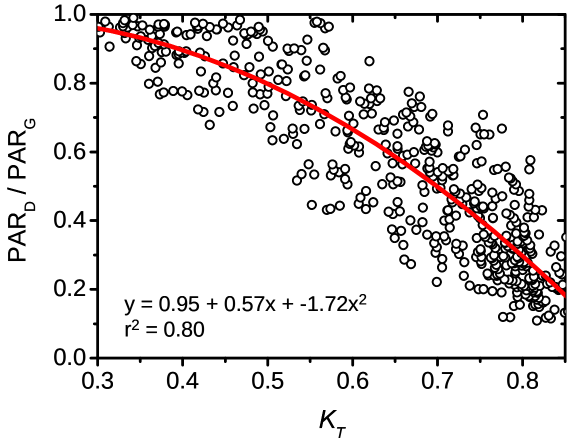

Figure 3. Relation between K_T and the diffuse fraction of global PAR, using hourly data from July –September, 2005.

3.2. Effect of diffuse beam radiation on canopy penetration

Three growing seasons of 15-min PAR observations at nine levels in the forest canopy were used to characterize the vertical profile of canopy light. When the sub-canopy PAR observations are normalized by above-canopy PAR observations, the pattern of light attenuation shows the distinctive control of phenology (Figure 4). The profile for the non-growing season produces a fairly linear decay through the depth of the canopy while during the growing season the decay in transmission follows an inverted Beers Law form, with the most rapid decay of transmission through the forest crown.

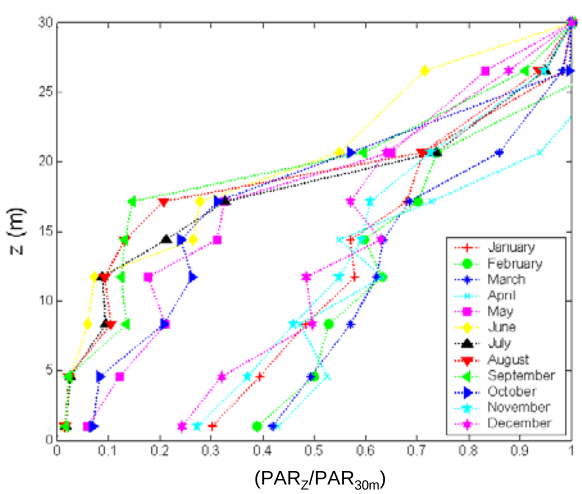

Figure 4. Monthly average vertical profiles of the fraction of above-canopy PAR (PAR_{30m}) received at eight below-canopy levels on the MMSF canopy tower, 2003-2005.

The phenological structure of the forest canopy is most likely to explain the transmission of PAR observed in Figure 4. Observations of VAI from the canopy tower using Li2000 pairs (Figure 5a) allow estimation of the LAI between each level (Figure 5b) and sky-view photos allowed estimation of sky view factors (SVF, Figure 5c). These show a dense forest crown from approximately 15-25 m above the surface, a relatively clear mid-section with a secondary lower peak in LAI at the level of undergrowth at about 5 m.

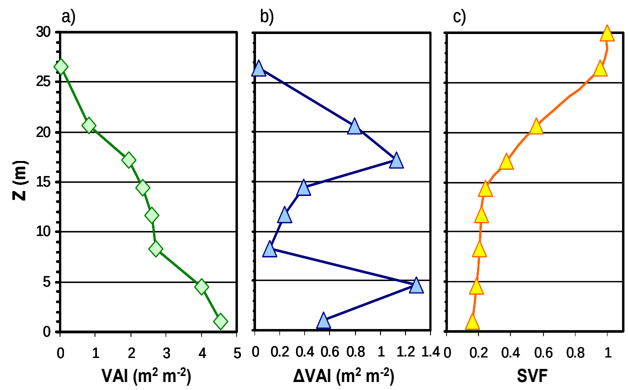

Figure 5. Average vertical profiles of forest canopy characteristics including a) cumulative VAI determined from Li2000 observations on the canopy tower, b) the change in cumulative VAI from one level to the next and c) sky view factors above quantum sensors for each level on the canopy tower, all collected in summer 2005.

The vertical profile of the fraction of PAR absorbed by leaves in photosynthesis (FPAR) was estimated from vertical LAI profiles using the empirical model of Baret and Guyot (1991). Combined with PAR profiles for a range of K_T, absorbed PAR (APAR) was then calculated for each level. This simplistic approach assumes the same rate of absorption of PAR by leaves at all levels of the canopy, which is unlikely, but is useful to observe the combined influence of PAR and leaf density (Figure 6) on photosynthetic rates. This shows that canopy APAR is not linearly diminished as K_T decreases, especially in the middle K_T bins (close to optimal K_T) and especially at lower solar elevation angles. This suggests a diminishment of sub-canopy shading under conditions of higher atmospheric scattering. This effect is likely to be under-estimated by the observations presented here. This is because the sub-canopy PAR under high K_T (clear skies) is likely to be dominated by the green portion of the PAR spectrum from transmission through and reflection from leaves Min (2005). The broadband quantum sensors in this situation would therefore likely over-estimate the PAR availability for photosynthesis. Assuming PAR_D is isotropic, this difference is a function of the SVF of each sensor. Future research will attempt to model this difference using empirically modeled PAR_D (Figure 3) and SVF (Figure 5c) for each level of the ecosystem canopy.

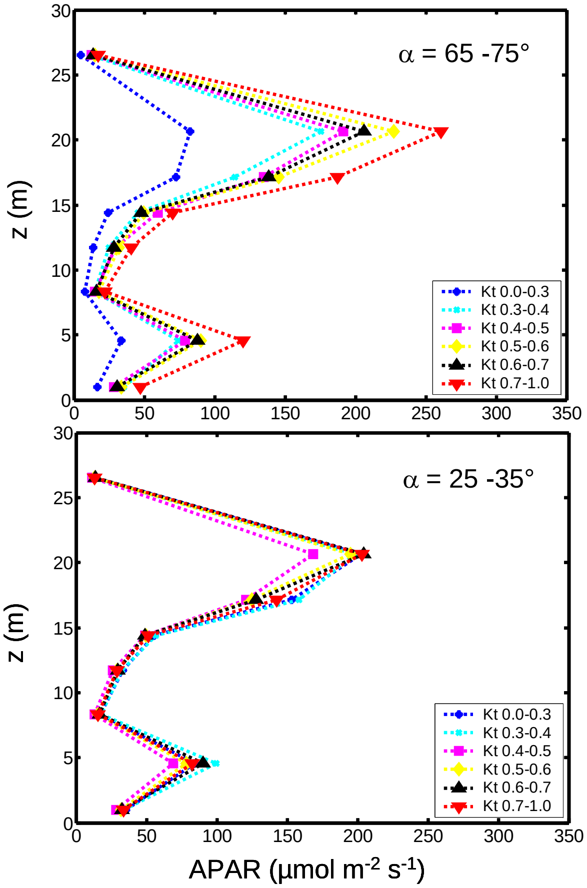

Figure 6. Vertical profiles of APAR calculated for a range of K_T bins, using 15-minute average PAR_G observations from two solar elevation angle bins (α) and vertical profiles of VAI collected during the 2005 growing season at MMSF.

4. CONCLUSIONS

Atmospheric scattering of PAR appears to play a significant role in the net ecosystem exchange of CO_2 at MMSF. Peak CO_2 uptake for a given solar angle occurred when the clearness index for PAR (K_T) was 0.55 (approximately 50% atmospheric attenuation of PAR). This effect was consistent at a wide range of solar elevation angles although the magnitude of enhanced CO_2 uptake increased at higher solar elevations and the optimal K_T increased slightly. K_T was also found to be closely and negatively correlated with PAR_D/PAR_G. The profiles of PAR within the canopy show strong phenological control, with reduced shading below canopy under less clear skies, especially at lower α.

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