MODELING CO_2 FLUX OF BOREAL FORESTS USING NARROW-BAND INDICES FROM AVIRIS IMAGERY

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Introduction:

The boreal forest represents 11% of the earth's total land area (Bonan and Shugart, 1989), and contains more than 30% of all forest soil carbon (Schlesinger, 1991). Global climate simulations indicate that the boreal region will undergo significant warming in response to increasing atmospheric CO_2 (Houghton et al., 1990). Due to the large contribution of these forests to the global carbon budget, warming in these northern regions could have large implications for the global carbon cycle and climate regulation.

The need to better understand how the boreal forest will respond to climate change has been the main driving force behind a large scale study of the Canadian boreal region, named the "Boreal Ecosystem-Atmosphere Study" (BOREAS, Sellers et. al, 1995). One need of this study was to improve our current understanding of boreal carbon fluxes. Recently, there has been an ongoing debate about whether the boreal forest is a net sink or source of terrestrial carbon (Wang and Polglase, 1995). Some studies have suggested that it is a source (Quay et al., 1992). Other studies have suggested the opposite, that it is a sink, thus helping to offset the rising atmospheric CO_2 concentration (Keeling et al, 1996). A major focus of the BOREAS project was to examine the exchange of CO_2 between the boreal ecosystems and the atmosphere to clarify the spatial and temporal patterns of carbon flux.

Remote sensing provides one method of exploring spatial patterns of carbon flux. Multiple studies have shown that the optically based Normalized Difference Vegetation Index (NDVI) can be used to estimate carbon fluxes of vegetation (Goward et. Al., 1985, Whiting et al., 1991). NDVI is a function of the fraction of photosynthetically active radiation (f_{PAR}) absorbed by green vegetation (or f_{APAR}). When combined with a measurement of the photon flux density of photosynthetically active radiation (PFD_{PAR}), f_{APAR} can be used to determine the amount of photosynthetically active radiation absorbed by green vegetation (APAR):

$$APAR = f_{APAR} \times PFD_{PAR} \qquad (1)$$

APAR can be multiplied by an efficiency factor (ε) to derive the net primary productivity (NPP) or the net photosynthetic carbon gain of a biome type:

$$\text{Photosynthetic rate} = f\,(\varepsilon \times APAR) \qquad (2)$$

Usually, efficiency (ε) is not derived directly from remote sensing. However, some recent studies have shown that an optically based index derived from hyperspectral reflectance, called the Photochemical Reflectance Index (PRI), has considerable promise as a measure of vegetation radiation-use efficiency (ε). This link to efficiency occurs because this index detects the response of xanthophyll cycle pigments to changing conditions (Gamon et al. 1990, 1997). Because these pigments are responsible for regulating absorbed light energy within the leaf, they provide a useful optical indicator of changing photosynthetic activity detectable with spectral reflectance. Thus, it is possible to express photosynthetic rates as a function of two terms, one that measures APAR (derived in part from NDVI), and one that measures efficiency (derived from PRI):

$$\text{Photosynthetic rate} = f\,(PRI \times APAR) \qquad (3a)$$

$$\text{Photosynthetic rate} = f\,(PRI \times (NDVI \times PFD_{PAR})) \qquad (3b)$$

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A number of recent studies have shown that PRI can be significantly correlated with both photosynthetic radiation-use efficiency (ε) and actual photosythetic rates at the leaf, canopy, and stand scales (Gamon et al. 1992, 1997, 2000, Penuelas et al. 1995, Stylinski et al. 2000). However, tests of this index at the landscape scale have rarely been attempted, in part because of the shortage of appropriate data sets. To validate this index, it is helpful to have an independent set of carbon flux (photosynthesis) measurements, which is often impossible at the landscape scale. Recently, eddy covariance has been developed as a means of sampling net carbon fluxes over large landscapes. By integrating the high-frequency covariance between carbon dioxide concentration and vertical velocity, this method provides a direct means of sampling instantaneous landscape fluxes. An additional challenge is that remote sensing typically samples in the spatial domain, whereas flux towers sample a single point in the temporal domain, making it difficult to compare the two data types (see figure 1). Typically expressed at half-hourly to daily intervals, but only for a single location, eddy covariance can provide flux measurements suitable for comparison with a small portion of an AVIRIS image. Ideally, to validate a map of CO_2 fluxes from AVIRIS, it would be best to have multiple flux towers sampling in a landscape, but this is normally not possible. The BOREAS data set, containing multiple AVIRIS scenes and data from multiple eddy covariance flux towers, provided a unique opportunity to explore the relationships between surface reflectance characteristics and CO_2 fluxes (figure 1).

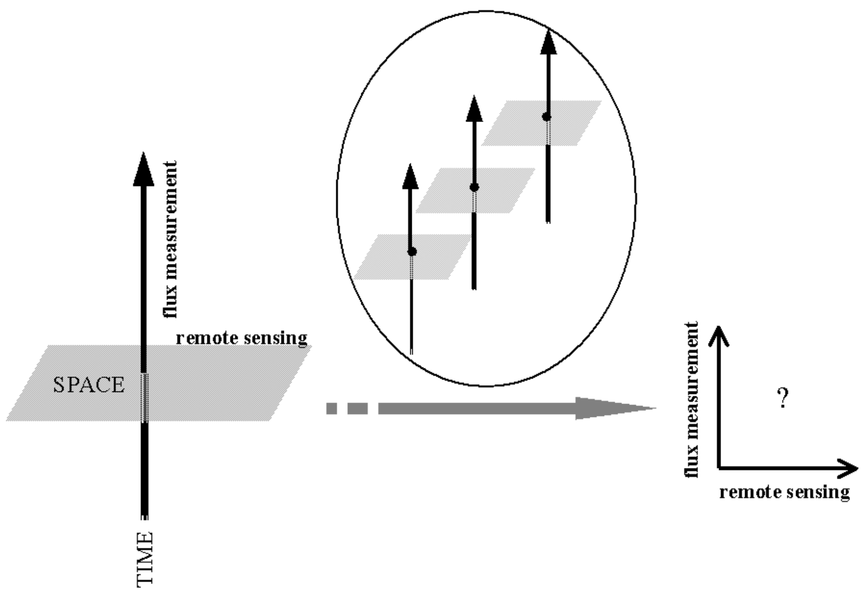

Figure 1: A schematic diagram illustrating the challenge of relating remotely sensed imagery to tower-based CO_2 flux data. Remote images are continuous in space but represent "snapshots" in time (grey rectangle on left), whereas flux measurements are continuous in time, but limited to a particular point in space (vertical arrow on left). By providing multiple images and flux towers, and thus multiple intersection points between AVIRIS imagery and flux data (circle at top), the BOREAS data set provided a unique opportunity to explore the relationship between remote sensing and flux measurements (diagram on right).

This study explores a simple method for mapping CO_2 flux (i.e. photosynthetic rate) based on a combination of AVIRIS imagery and flux tower data. First, we used a semi-empirical statistical approach to correlate hyperspectral remotely sensed surface characteristics to CO_2 fluxes from different vegetation cover types as a test of equation [3b]. Based on this correlation, we then derived maps of midday CO_2 fluxes that depict the midday peak photosynthetic rates for these boreal landscapes consisting of a range of vegetation types.

Study site:

In 1993, the BOREAS project was undertaken in the boreal forest of central Canada, called the BOREAS modeling region (~500,000 km^2). Two 50 x 50 km intensive study areas were selected the north and south ends of the modeling region. The northern study area (NSA) and the southern study area (SSA), as these two regions were named, were located near Thompson, Manitoba, and Prince Albert, Saskatchewan, respectively. They were about 500 km apart and each region contained flux towers located on relatively homogeneous vegetation and soil patches to measure water, vapor, heat and CO_2 fluxes using eddy covariance techniques. Our study utilized the CO_2 data collected during spring and fall seasons of 1994 from the SSA region flux towers. There were six flux towers in that region, covering sites dominated by black spruce (P*icea mariana*) , jack pine (P*inus banksiana*)and aspen (*Populus tremuloides*) patches. Each flux site was relatively level and the forest stand was horizontally homogeneous throughout the area deemed as the flux footprint, a region extending over 1 km upwind.

Remotely sensed data and footprint area:

Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) images from 1994 were used for this study. Images were available from April 19th, July 21st, and September 16th of 1994, covering nine 'flux-tower' sites in total (Table 1). The fly-over time of the acquired images was approximately 11:30 a.m. local time. The original radiance images were corrected for atmospheric degradation using algorithms developed by Green et. al (1991). The atmospherically corrected images were then georeferenced, using a geo-corrected Landsat TM image of the area as a base map, and resampled to 30m pixel resolution.

Table 1: Southern Study Area data availability matrix based on the dates of AVIRIS overflight. F_c stands for CO_2 flux and Ref stands for reflectance data. Bold lettered points are the ones that have both image and CO_2 flux data available, and were used for the present study.

TF \ Date	4/19/94	7/21/94	9/16/94	Biome
TF-2	**F_c, Ref**	Ref	**F_c, Ref**	OA
TF-4	Ref	Ref	**F_c, Ref**	YJP
TF-5	Ref	**F_c, Ref**	**F_c, Ref**	OJP
TF-7	Ref	**F_c, Ref**	**F_c, Ref**	OBS
TF-9	Ref	Ref	Ref	OBS
TF-11	Ref	**F_c, Ref**	**F_c, Ref**	FEN

The atmospheric- and geo-corrected AVIRIS images were used to produce NDVI and PRI images using the following equations:

$$NDVI = \frac{R_{B47} - R_{B30}}{R_{B47} + R_{B30}} \tag{4}$$

and

$$PRI = \frac{R_{B17} - R_{B21}}{R_{B17} + R_{B21}} \tag{5}$$

In the above equations *R* represents reflectance, and the subscript *B* followed by a number represents the AVIRIS band represented by that number. AVIRIS bands #30, #47, #17 and #21 represent reflectance at wavelengths 660, 800, 531 and 570 nm respectively.

In order to make a scaled value of PRI (or sPRI) to represent it as a measure of efficiency, we did the following algebraic manipulation:

$$sPRI = \frac{(PRI + 1)}{2} \tag{6}$$

Footprint areas of the flux towers were determined based on the prevailing wind direction during the image acquisition time, as recorded by the tower instruments. Following the theoretical discussion of Kaharabata et al. (1997), a 300m X 900m rectangular area towards the upwind direction from each tower site was selected as an optimal footprint area. Average values of NDVI and PRI of those footprint areas were calculated for this study. Since NDVI itself can be expressed as a function of APAR, following the equation [3b], we then estimated a relative photosynthetic rate as a product of NDVI and scaled PRI:

$$\text{Photosynthetic rate} = f\ (\text{sPRI x NDVI}) \qquad (7)$$

CO_2 flux data:

The 'Tower-Flux' science group of BOREAS research team collected CO_2 and other physiological fluxes from both SSA and NSA sites (http://eosims.esd.ornl.gov/BOREAS/bhs/Science_Groups.html). Although intended to operate continuously, most of the flux towers reported data sporadically during the 1994 season (Table 1). The eddy flux densities were determined by calculating the covariance between vertical velocity and scalar fluctuations (Baldocchi et al., 1988). Scalar fluctuations of CO_2 and other fluxes were computed in real-time, using a running mean removal method (McMillen, 1988). Then these flux data were averaged and stored at half-hour intervals. The measurement units were μmol m^{-2} s^{-1}. Negative (-) flux values indicated net carbon uptake (i.e. photosynthesis) by the surface, and positive values indicated carbon loss to the atmosphere (i.e. respiration). We used CO_2 flux data from flux towers #2, #4, #5, #7, #9 and #11 for this study (Table 1), obtained through the courtesy of the respective "Tower-Flux" teams (http://eosims.esd.ornl.gov/BOREAS/boreas_home_page.html).

This half-hourly averaged CO_2 flux data showed considerable short-term fluctuation, which masked any trend over a diurnal period, even on a totally clear day. A further averaging of the half-hourly data to a two-hour running average produced a pattern smooth enough to show some diurnal trend (Figure 2). For comparison with AVIRIS imagery, we took an average value of CO_2 flux data from one hour before to one hour after the AVIRIS image acquisition time from the smoothed data as representative flux values for the tower region. This process was repeated for each of the nine tower sites and dates indicated in Table 1.

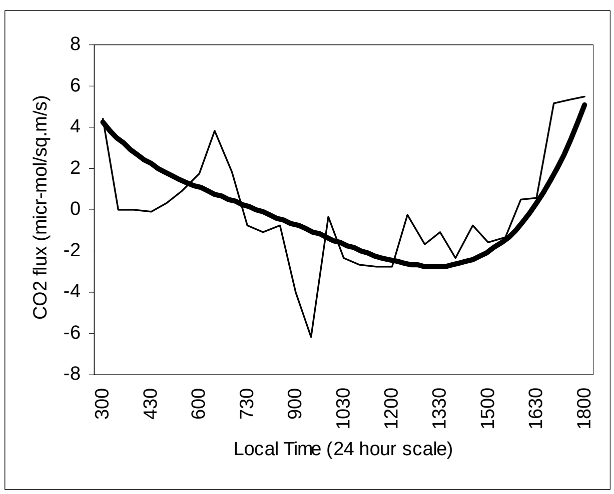

Figure 2: Representative tower flux data from the Old Black Spruce tower site on July 21st, 1994, showing fluctuation in CO_2 flux data at half-hourly average (thinner line), and the diurnal trend visible with a two hourly running average (smooth, thicker line).

Results and Discussion:

Averaged NDVI and PRI values from the footprint areas of nine tower flux sites were plotted against the two-hourly running average CO_2 flux values. The results are shown in Figure 3-A and -B respectively. The CO_2 flux data showed weak but significant correlations with both of these spectral indices, having an R^2 value of 0.57 with NDVI and that of 0.4 with PRI. NDVI and PRI were found to be not correlated with each other (Figure 3-C), indicating that in these landscapes NDVI and PRI detect two different aspects of green vegetation.

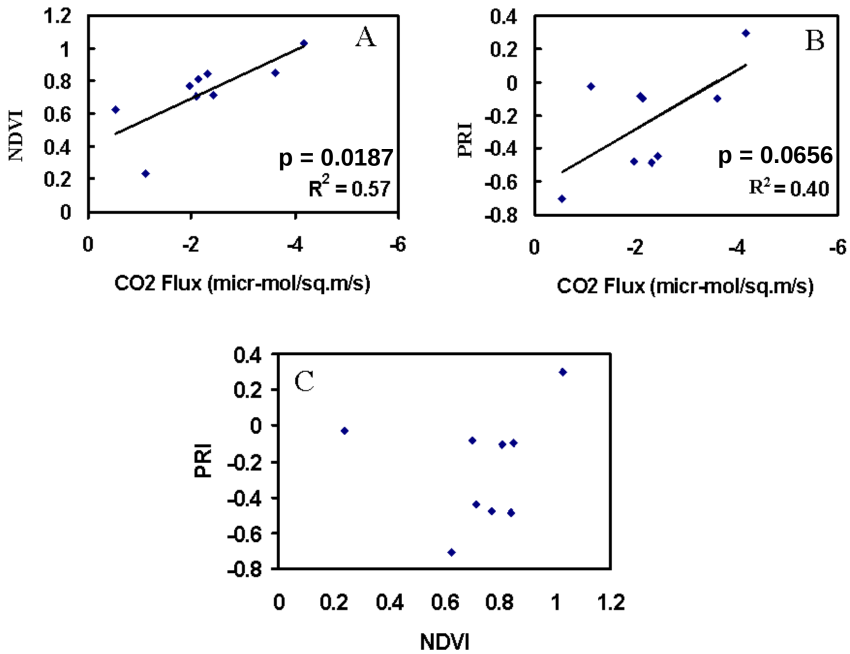

Figure 3: Comparison of CO_2 with NDVI and PRI (A & B) shows positive correlations, with R^2 values of 0.57 and 0.4 respectively. A separate comparison of NDVI and PRI shows no correlation between them.

Comparison of CO_2 fluxes with this scalar product (i.e., NDVI * sPRI) derived from equation 7 yielded an R^2 value of 0.78 (Figure 4) and the following linear equation:

$$CO_2 = -5.6(NDVI * sPRI) - 0.69 \tag{8}$$

From equation 8, we derived CO_2 flux (midday net photosynthesis) maps from the AVIRIS images covering the tower sites. Representative flux maps of two tower site locations are shown in Figure 5. These two maps included the old black spruce and fen tower sites and their vicinity, and provided an empirically calibrated regional image of midday CO_2 fluxes.

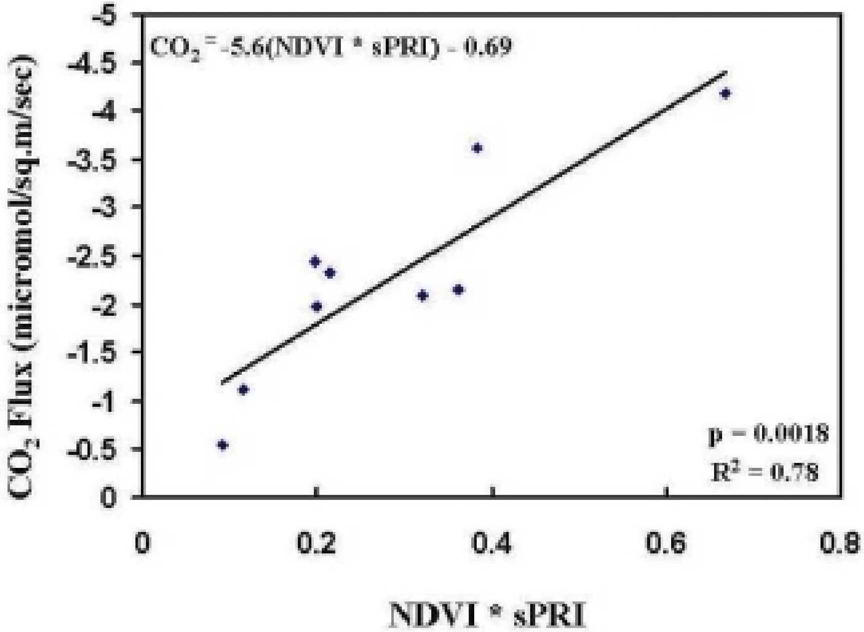

Figure 4: Relation between CO_2 flux and a product of NDVI and scaled PRI from the nine tower sites in 1994. A linear relation was derived to relate CO_2 to the spectral indices, with an R^2 value of 0.78.

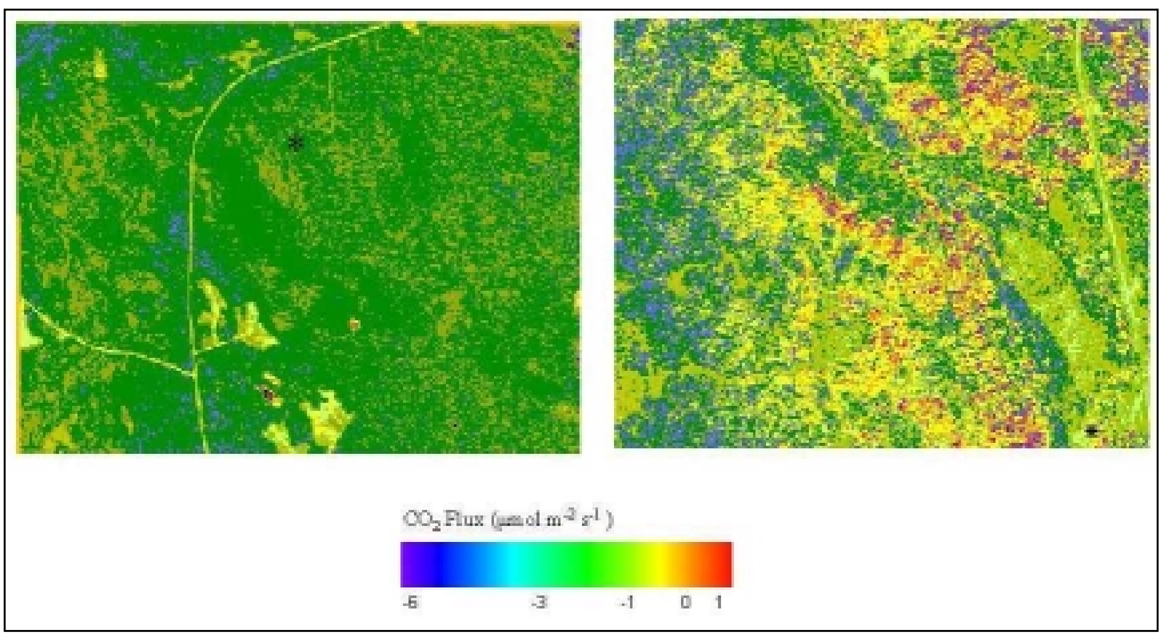

Figure 5: Maps of CO_2 flux from the BOREAS Southern Study Area old black spruce site on July 21st of 1994 (image on left) and fen site on September 16th of 1994 (image on right). The flux tower sites are shown by the asterisk marks on each image.

Conclusions and future directions:

The primary conclusion of this study is that a simple, two-parameter model based on APAR (NDVI) and efficiency (PRI) can capture most of the variation in net photosynthetic fluxes across the boreal forest landscape. Although both parameters were significantly correlated with net CO_2 fluxes, NDVI had a more significant correlation than PRI, indicating that light absorption by green vegetation was the dominant factor driving CO_2 fluxes for these landscapes. The significant correlation between PRI and CO_2 fluxes are consistent with previous studies at the leaf and canopy scales indicating a relationship between this index and photosynthetic light use efficiency. The improved correlation with fluxes when both indices are used together (Figure 4) parallels other recent studies at the leaf and canopy scales that illustrate how a simple empirical model based on two optically derived parameters can readily capture much of the spatial variation in photosynthetic rates within sunflower stands (Gamon et al. 2000). To our knowledge, a direct correlation between this index and landscape fluxes has never before been possible, although previous studies of AVIRIS imagery have suggested the potential utility of this index as a measure of photosynthetic activity (Gamon et al. 1995a&b).

The approach presented here has many limitations that must be overcome if this method is to be used for routine mapping of CO_2 fluxes. The primary limitation derives from the empirical nature of this method, which requires the availability of flux tower data for calibration of AVIRIS imagery. In order to develop a process-based model of CO_2 flux assessment using hyperspectral imagery, there is a need of more coordinated flux and optical data collection from different biome types. Also the effects of view and solar zenith angles (bi-directional reflectance distribution) and atmospheric degradation on the remotely sensed data has to be quantified and modeled properly in order to use the remotely sensed data with confidence. Other studies not shown here suggest that errors in interpreting two-band indices can occur when pixels contain mixes of vegetation with other cover types, as was the case in our study. Despite these many limitations, the strong correlation between our simple two-parameter model and tower flux data indicates that considerable potential exists for mapping photosynthetic fluxes over large landscapes using narrow-band reflectance. Although not explored in this paper, it is likely that incorporation of improved surface cover maps (e.g. Fuentes et al., this volume) could lead to further refinements of this model.

Since AVIRIS images are not available for all seasons or all vegetation types, and atmospheric correction poses a problem due to lack of ground truthing during AVIRIS over flights, our next goal is to use tram- and light aircraft-based hyperspectral data collection platforms for the further development of this model. We are currently testing a hardware system and protocol to collect hyperspectral data from a chaparral stand near San Diego where an operational flux tower is also available to collect CO_2 and other flux data continuously.

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