

SPATIAL AND INTER-ANNUAL VARIABILITY OF CANADA'S NET PRIMARY
PRODUCTIVITY BASED ON SATELLITE IMAGERY.

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ABSTRACT

The Boreal Ecosystems Productivity Simulator (BEPS) developed at the Canada Centre for Remote Sensing (Liu et al., 1997, Remote Sensing of Environment, 62:158-175) has been further refined and applied to the whole Canada's landmass for multiple years from 1994 to 1996. The data used in the computation include leaf area index (every 10 days) and land cover type (annually) from measurements of the Advanced Very High Resolution Radiometer (AVHRR) at 1 km resolution, daily meteorological data (radiation, precipitation, temperature and humidity) and soil water holding capacity. Annual NPP calculations from BEPS in 1994 are compared with ground biomass data in Quebec, and the components (radiation interception, photosynthesis, respiration, rainfall interception, etc.) of the model are validated with data from the Boreal Ecosystem-Atmosphere Study (BOREAS). A new method for daily NPP calculation is developed through an analytical temporal integration of Farquhar's model. An innovative way of validating daily NPP calculation using two-level CO₂ flux measurements will be described. In this presentation, the spatial distribution of NPP in Canada will be shown, and the inter-annual variation will be analyzed against satellite and climate data.

1.0 INTRODUCTION

Net primary productivity (NPP) is a quantitative measure of the carbon absorption by plants per unit time and space and is an important component of the terrestrial carbon cycle. It is also an integrated measure of ecosystem performance. The spatial and temporal distributions of NPP are therefore of great concern in global change studies and in formulating policies for sustainable forest management. At the Canada Centre for Remote Sensing, a government-industry team is engaged in mapping NPP for Canada's landmass and studying the inter-annual variability. A process-based modelling approach is developed to utilize quantitative information derived from satellite images for NPP and carbon cycle modelling. In this paper, we will present the key equations for NPP calculation, an example NPP map of Canada in 1994 and some preliminary results for the inter-annual variability of NPP in Canada.

2.0 PRINCIPLE AND KEY EQUATIONS OF THE PROCESS MODEL

Among models of photosynthetic CO₂ assimilation by individual plant leaves, the mechanistic model proposed by Farquhar et al. (1980) has been widely used. The model describes the leaf gross photosynthesis rate at an instant of time for C₃ plants as the minimum of:

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$$W_c = V_m \frac{C_i - \Gamma}{C_i + K} \quad (1a)$$

and

$$W_j = J \frac{C_i - \Gamma}{4.5C_i + 10.5\Gamma} \quad (1b)$$

where W_c and W_j are Rubisco-limited and light-limited gross photosynthesis rates in $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively. V_m is the maximum carboxylation rate in $\mu\text{mol m}^{-2} \text{s}^{-1}$; J is the electron transport rate in $\mu\text{mol m}^{-2} \text{s}^{-1}$; C_i is the intercellular CO_2 concentration; Γ is the CO_2 compensation point without dark respiration; K is a function of enzyme kinetics. The dimension for C_i , Γ , K can be either in Pa or in ppmv (parts per million by volume). Pa is used in this paper. Both Γ and K are temperature-dependent parameters.

Because the Farquhar model is initially developed and validated for individual leaves, considerable skill is needed in using it for a plant canopy. Although the big-leaf approximation has been shown to be successful for modeling evapotranspiration for plant canopies (Monteith and Unsworth, 1990), the same approximation may be erroneous for photosynthesis because of the additional leaf internal control on carbon assimilation. For example, when stomatal conductance is replaced by canopy conductance (usually stomatal conductance times leaf area index) in the big-leaf model constructed using Farquhar's formulation, the calculated results will be very different from the sum of photosynthesis of individual layers of leaves calculated using the same formulation because the internal control of leaves causes nonlinear response of leaf photosynthesis to stomatal conductance. From this perspective, the big-leaf methodology was found to have several shortcomings when examined using experimental data (Chen et al., 1999). Many studies have demonstrated successful use of Farquhar's model at the canopy level using other approaches, such as vertical integration against radiation gradient (Baldocchi, 1993; Bonan, 1995) and separation of a canopy into sunlit and shaded portions (Kim and Verma, 1991; Norman, 1993; Foley et al., 1996; de Pury and Farquhar, 1997; Wang and Leuning, 1998). We adopted and modified the latter approach because of its simplicity and ability to capture the major variability within the canopy. However, the effective use of Farquhar's model at the daily time step has not been demonstrated in previous studies. We therefore developed a daily NPP model after analytical integration of the instantaneous Farquhar model over a diurnal cycle to consider the non-linear effects of meteorological variables on photosynthesis due to their diurnal variability. After several steps of mathematical development (Chen et al., 1999), the final equation for the daily total photosynthesis for either sunlit or shaded leaves is as follows:

$$A = \frac{1.27}{2(g_n - g_{\min})} \left(\frac{a^{1/2}}{2} (g_n^2 - g_{\min}^2) + c^{1/2} (g_n - g_{\min}^2) - \frac{2ag_n + b}{4a} d + \frac{2ag_{\min} + b}{4a} e^{1/2} + \frac{b^2 - 4ac}{8a^{3/2}} \ln \frac{2ag_n + b + 2a^{1/2}d}{2ag_{\min} + b + 2a^{1/2}e} \right) \quad (2)$$

where for A_c , $a = (K + C_a)^2$, $b = 2(2\Gamma + K - C_a)V_m + 2(C_a + K)R_d$ and $c = (V_m - R_d)^2$ and for A_j , $a = 2.3\Gamma + C_a^2$, $b = 0.4(4.3\Gamma - C_a)J + 2(C_a + 2.3\Gamma)R_d$ and $c = (0.2J - R_d)^2$. For both, $d = (ag_n^2 + bg_n + c)^{1/2}$ and $e = (ag_{\min}^2 + bg_{\min} + c)^{1/2}$. g_n is the stomatal conductance at noon, and g_{\min} is the minimum values at dawn. The minimum is taken as zero in the results shown below.

Eq. 2 is the final equation for calculating the daily averaged A as the minimum of A_c and A_j . It is applied to sunlit and shaded leaves separately. It is noted that: (i) no additional parameters are introduced in this daily model, and all the constants are determined by the leaf biochemical parameters in the original Farquhar model; (ii) although Eq. 2 appears to be complex, it is numerically stable, and no numerical problems have been encountered in using this equation for remote sensing applications for large areas of extreme conditions; (iii) the analytical integration given by Eq. 2 is computationally efficient and avoids a daily loop using a numerical integration method.

In principle, Eq. 2 should be applied for every leaf in a canopy in order to get daily or monthly total canopy photosynthesis. In this study, we choose to stratify a canopy into sunlit and shaded leaf groups and apply this equation to these two groups separately. We prefer this to stratification by canopy layers because the greatest difference in leaf illumination in the canopy exists between sunlit and shaded leaves. The purpose of the multiple layer calculation is to consider the general decreasing trend of radiation with the increasing depth into the canopy. It is an improvement from the big-leaf model, by which the canopy is treated as one layer of leaves. However, within a layer at a given time the difference in illumination between sunlit and shaded leaves is very large and using the mean illumination value to represent the layer can result in considerable errors in modeled results. With the separation of sunlit and shaded leaf groups, the total canopy photosynthesis (A_{canopy}) can be calculated as (Norman, 1993):

$$A_{canopy} = A_{sun} LAI_{sun} - A_{shade} LAI_{shade} \quad (3)$$

where the subscripts “sun” and “shade” denote the sunlit and shaded components of photosynthesis and LAI. The method of Norman (1993) for calculating LAI_{sun} and LAI_{shade} is adopted in this study but modified to consider the effect of foliage clumping index on the canopy radiation regime. A new method for calculating the irradiance on sunlit and shaded leaves is presented in Chen et al. (1999).

3. NEW METHOD OF VALIDATING DAILY NPP USING FLUX MEASUREMENTS

When simultaneous CO_2 flux measurements above and below a canopy are made, it is possible to isolate the canopy from the ground surface for the canopy NPP validation. This was possible in BOREAS. In an old black spruce site (NOBS) in the BOREAS northern study area near Thompson, Manitoba, the above-canopy measurements were made using an eddy-covariance method, and the below-canopy was made using closed clear chambers on the forest floor including the understory grass and moss (Guolden et al., 1997). The flux measurements at these two levels can be used to differentiate between the overstory and the background (understory, moss and soil) in their role in the carbon cycle. The final expression becomes

$$NPP = FLUX_T - FLUX_C + R_{root} \quad (6)$$

Where $FLUX_T$ is the flux measured at the top of the canopy, $FLUX_C$ is the flux measured using chambers below the canopy, and R_{root} is the root respiration (Ryan et al., 1997). The root respiration term remains in the expression because of the transport of some fraction of carbon assimilates to roots from the overstory. Since the fluxes measured correspond to the

instantaneous photosynthesis and respiration processes, NPP calculated in this way is considered to be instantaneous.

4. RESULTS

Using the simultaneous CO₂ flux measurements above and below the NOBS forest canopy, the daily NPP for the canopy is calculated after considering the contribution of root respiration to the flux at the lower level (Eq. 6). These calculated NPP values are referred to as "measured NPP" and compared with a big-leaf model and BEPS (Figure 1). All leaf biochemical and biophysical parameters are the same in these two models, the difference between Fig. 1(a) and Fig. 1(b) is purely the result of the different mathematical manipulations of the original Farquhar's model. The lack of response of the big-leaf model to the day-to-day variations in NPP is obvious from the very small slope in the one-to-one plot. The slope is very much improved after sunlit and shaded leaf separation. Before the daily integration scheme (Eq. 2) was applied, the daily NPP values calculated using the daily mean meteorological variables were larger than the measured values by a factor of about 2.8, although the slope is improved. After considering the effect of the diurnal variability of the variables (mainly radiation) using the daily integration scheme, the mean values were greatly reduced to a level within about 30% of the measured values. The large differences between the cases with and without sunlit/shaded leaf separation and between the cases with and without the daily integration suggest the importance of the spatial scaling from leaf to canopy and temporal scaling from minute to day in regional estimation of NPP. The scatter of the data points in Fig. 1(b) is still large. Through a hourly to daily model comparison, about 50% of the scatter was found to be due to measurement uncertainty caused by the representativeness of the five chambers used for measuring the lower level flux and about 50% was caused by the daily step calculation. At another site, where CO₂ flux measurements at both heights were made using eddy covariance techniques, the scatter in a similar plot was much less (Chen et al., 1999).

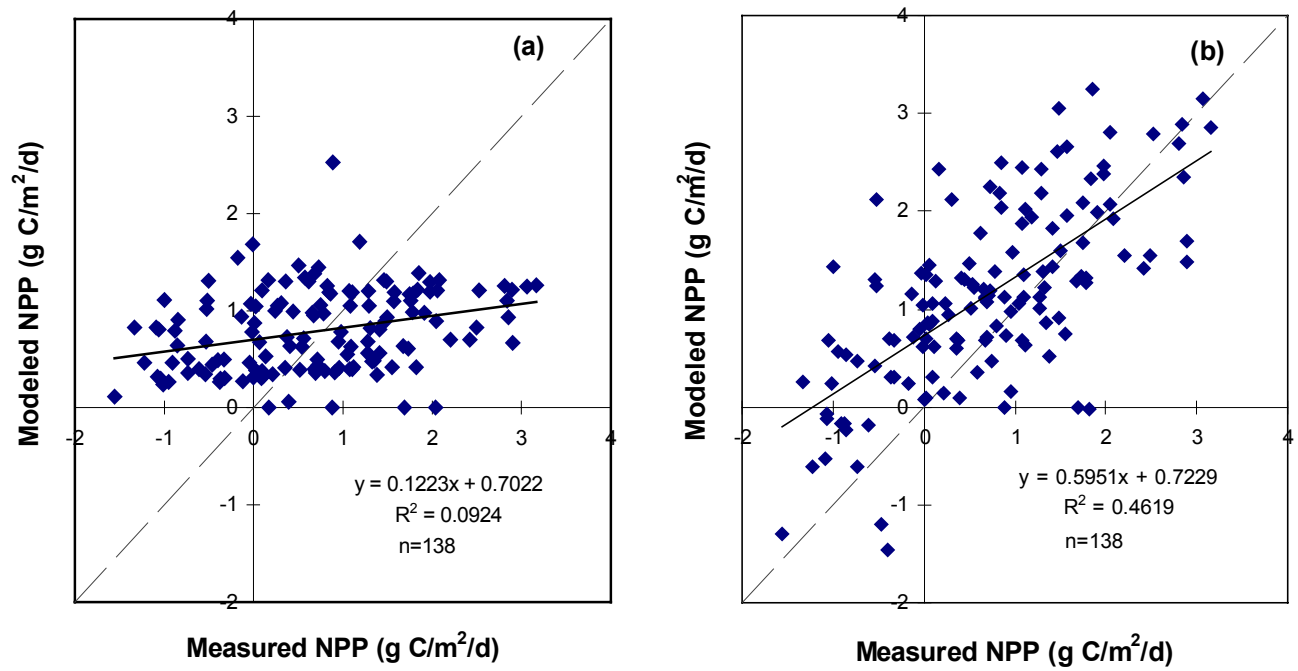


Figure 1. Comparison of modelled daily NPP results with "measured NPP" derived using CO₂ flux measurements in an old black spruce forest near Thompson, Manitoba. (a) Big-leaf model, and (b) Sunlit-shaded leaf model with daily integration (i.e. BEPS).

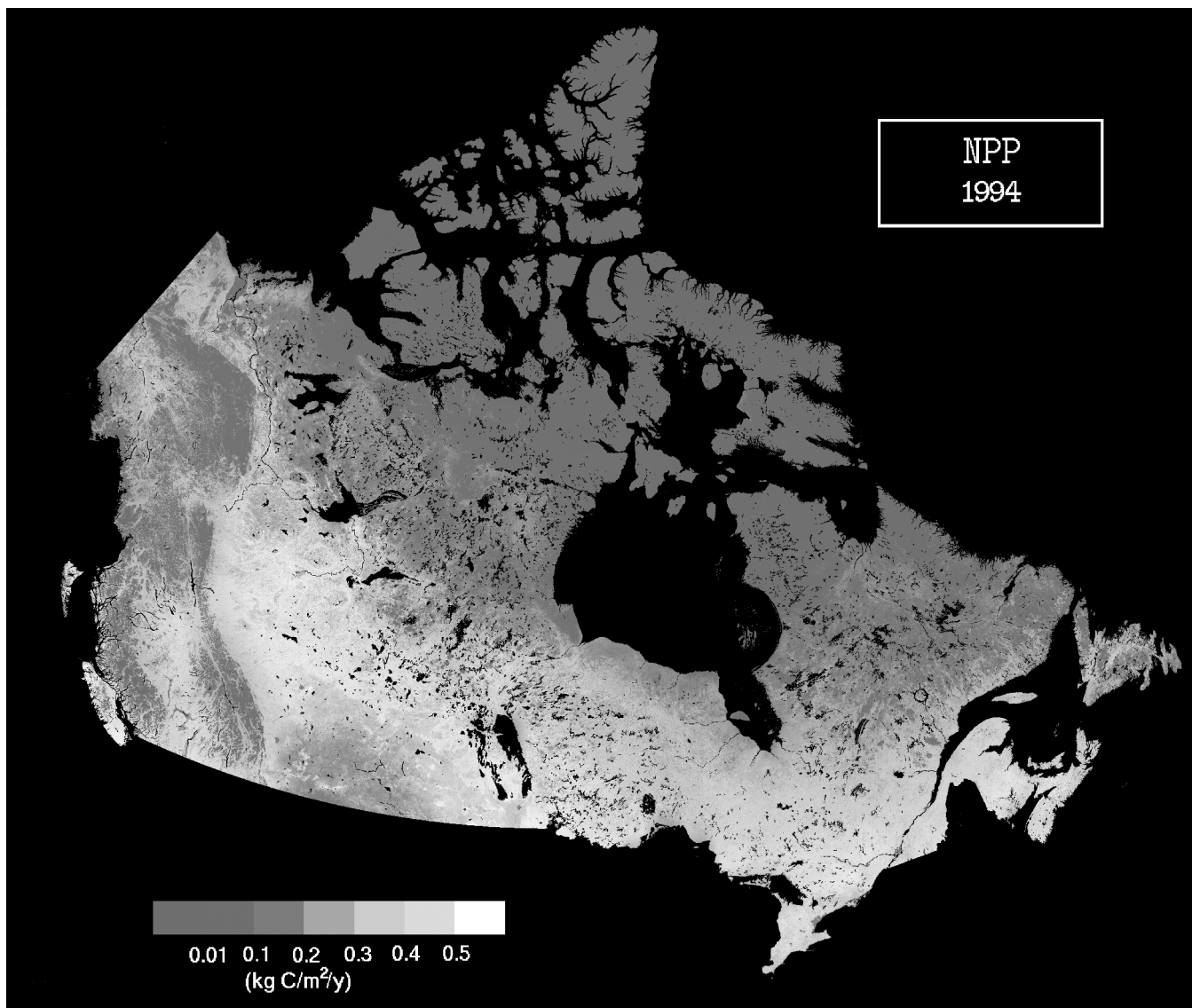


Figure 2. Canada-wide NPP map in 1994 derived using the Advanced Very High Resolution Radiometer (AVHRR) images, soil and daily meteorological data.

Other components of BEPS, including radiation interception, stomatal conductance, evapotranspiration, rainfall interception, root respiration, etc. were also compared with existing BOREAS field measurements. Using LAI (every 10 days) and landcover maps derived from AVHRR and a soil water holding capacity map in combination with gridded daily meteorological data, a Canada-wide NPP map (Figure 2) was produced. The overall values of NPP in Canada are smaller than many models applied to the global scale (Cramer et al., 1999). Our values are smaller for several reasons: (1) in the derivation of LAI, efforts have been made to exclude the contribution of non-tree species, and hence the forest NPP here is for the tree canopy only; (2) foliage clumping in boreal forests is considered. Clumping reduces radiation interception and hence productivity; (3) the water stress on growth is considered through the use of rainfall and soil water holding capacity data and a dependence of stomatal conductance on water potential of leaves and soils. Comparison of NPP values in the map has been made with ground NPP measurements in Quebec and in Saskatchewan and Manitoba. Uncertainty of the values at the pixel level is about 25%.

Similar NPP maps for Canada were also produced for 1995 and 1996. The statistics for three forest types, i.e. conifer, deciduous and mixed forest, are shown in Figure 3. Conifer forests have much lower NPP than deciduous forests on average because of their lower photosynthetic capacity and higher latitudes of their locations. The productivity of all forests showed declining

trends in the three year period. The changes were driven by inter-annual climatic variability, which affected both the growing season length and growing conditions during the growing season. These two types of changes were detected by the satellite sensors (NOAA-11 AVHRR for 1994 and NOAA-14 AVHRR for 1995 and 1996) from the onset of new leaves and the maximum LAI in the growing season. For conifer forests, the changes in LAI were small because of the long lifespan of needles, resulting in small inter-annual variation. These changes were detectable by satellites because of the effects of temperature on the timing of the new needle growth and on the level of photosynthesis in the early growing season which was mostly controlled by the soil temperature. Deciduous and mixed forests exhibited larger inter-annual variations than conifers because of their larger changes in LAI. Some uncertainties exist in these multi-year estimates. The main uncertainty is caused by the change of the satellite sensors in late 1994. The sensor calibration coefficients and the local overpass time and viewing geometry relative to the sun changed between 1994 and 1995, causing some uncertainty in the calculation of LAI. Much effort has been made to remove artifacts in the multi-year data set, but some small corrections may still be needed.

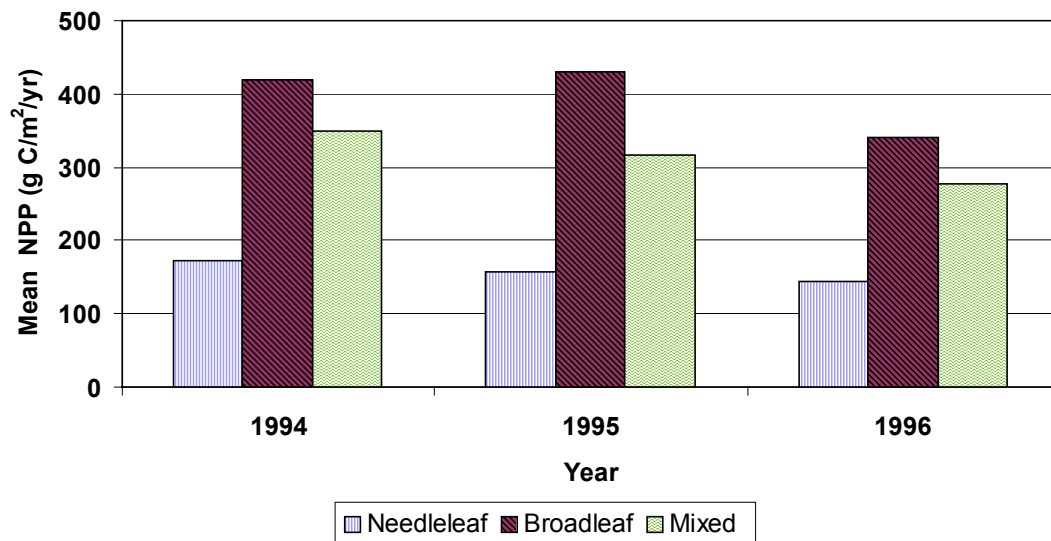


Figure 3. The mean NPP values for Canada's forest in the 1994-1996 period.

5. DISCUSSION

With the continuous improvement in our computation power, it is now feasible to apply process models to moderate resolution images for regional and global NPP modelling. The key steps for implementing such models are the spatial scaling from leaf to canopy and temporal scaling from minute to day or longer periods. The daily NPP model presented here is therefore useful for this purpose.

It is shown above that satellite images can be successfully used to quantify the spatial variation of NPP as well as to study its inter-annual variability. The knowledge of such spatio-

temporal carbon dynamics in terrestrial ecosystems will greatly enhance our ability to understand the processes controlling the terrestrial carbon cycle and quantify the spatial distribution of the carbon sink and source. The work presented here is a useful step toward this goal but much research is still needed to quantify the full carbon cycle including heterotrophic respiration.

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