BOREAS FOLLOW-ON DSP-05 PROCESS-MODELED NET PRIMARY PRODUCTIVITY
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Summary

The BOREAS DSP-05 team generated an NPP image over the BOREAS region from a process-based ecosystem model, the Boreal Ecosystem Productivity Simulator (BEPS). The NPP image was created from a series of composited AVHRR images from April 11 - September 10, 1994. This document describes how the NPP is generated. The NPP data are stored in a binary image file.

Data Citation

Cite this data set as follows (citation revised on October 30, 2002):

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1. Data Set Overview

1.1 Data Set Identification

BOREAS Follow-On DSP-05 Process-Modeled Net Primary Productivity

1.2 Data Set Introduction

The Net Primary Productivity (NPP) results over the BOREAS region were estimated from a process model, the Boreal Ecosystems Productivity Simulator (BEPS), which is driven by satellite and surface data. BEPS is a computer simulation system developed for assisting in natural resources management and estimating the carbon budget over Canadian landmass [Liu et al., 1997, Liu et al., 1999, Liu et al., 2001].

1.3 Objective/Purpose

To produce a NPP image over the BOREAS region.

1.4 Summary of Parameter

NPP

1.5 Discussion

BEPS uses principles of the Forest BioGeochemical Cycles (Forest-BGC) model [Running and Coughlan, 1988] for quantifying the biophysical processes governing ecosystem productivity. However, the original model was modified in the following aspects: (1) implementation of a more advanced photosynthesis model with a new temporal and spatial scaling scheme [Chen et al., 1999a]; (2) inclusion of an advanced canopy radiation model to describe the specific boreal canopy architecture; and (3) adjustments of biophysical and biochemical parameters for the main boreal land cover types.

Computationally, BEPS differs from the original version of Forest-BGC in several respects: (1) it extends stand-level calculations to a large area (watershed, province or a region) using gridded meteorological and soil data rather than single weather station data; (2) land cover information derived from satellite data is used to set biophysical and biochemical parameters [Cihlar et al., 1997a]; and (3) satellite data are used to provide the spatial and seasonal distributions of LAI.

In addition to the satellite data, the model requires input of daily meteorological data (radiation, temperature, humidity and precipitation), and soil data (available water holding capacity) (see section 1.6). The temporal interval is daily for meteorological data, 10-day for LAI, annual for land cover, and long term for available water holding capacity (AWC). BEPS integrates the input data and produces output of NPP and other carbon and water cycle components such as autotrophic respiration and evapotranspiration.

The computation is made pixel by pixel in daily time steps assuming vegetation and environment conditions are uniform within each pixel, currently being 1 km^2. BEPS can be set up to run for Canada in its entirety or for a defined area inside Canada.

1.6 Related Data Sets

BOREAS Level-3b AVHRR-LAC Imagery: Scaled At-sensor Radiance in LGSOWG Format
BOREAS Level-4c AVHRR-LAC Ten-Day Composite Images: At-sensor Radiance
BOREAS Level-4c AVHRR-LAC Ten-Day Composite Images: Surface Parameters
BOREAS RRS-07 LAI, Gap Fraction, and fPAR data
BOREAS TF-01 SSA-OA Understory Flux, Meteorological, and Soil Temperature Data
BOREAS TF-02 SSA-OA Tower Flux, Meteorological, and Precipitation Data
BOREAS TF-03 NSA-OBS Tower Flux, Meteorological, and Soil Temperature Data

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2. Investigator(s)

2.1 Investigator(s) Name and Title

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2.2 Title of Investigation

BOREAS Follow-on DSP-5 Primary Productivity in the Boreal Forest

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3. Theory of Model

NPP is estimated from gross primary productivity (GPP) and autotropic respiration (R_a):

$$NPP = GPP - R_a \qquad (1)$$

In this study, BEPS was modified to incorporate Farquhar's model [Farquhar et al., 1980] for GPP calculation. The Farquhar's model describes the instantaneous leaf gross photosynthesis rate for C_3 plants as the minimum of

$$W_c = V_m \frac{C_i - \Gamma}{C_i + K} \qquad (2a)$$

$$W_j = J \frac{C_i - \Gamma}{4.5C_i + 10.5\Gamma} \qquad (2b)$$

where W_c and W_j are Rubisco-limited and light-limited gross photosynthesis rate in μmol m^{-2} s^{-1}, respectively. V_m is the maximum carboxylation rate in μmol m^{-2} s^{-1}; J is the radiation-dependent electron transport rate in μmol m^{-2} s^{-1}; C_i is intercellular CO_2 concentration; Γ is temperature-dependent CO_2 compensation point without dark respiration; and K is a temperature-dependent function of enzyme kinetics. The unit for C_i, Γ, K can be either in Pascal (Pa) or in ppmv (parts per million by volume). The procedure to calculate all the parameters is described in Table 1. Symbols and their definitions and units are listed in the Notation at the end of this section.

To obtain the net CO_2 assimilation rate (A), daytime leaf dark respiration (R_d) is subtracted from equation

(2):

$$A = \min(W_c, W_j) - R_d \qquad (3)$$

According to fluid physics, the photosynthesis rate can also be described in the form

$$A = (C_a - C_i)g \qquad (4)$$

where C_a is CO_2 concentration in the atmosphere, and g is the conductance to CO_2 from the leaf cells to the atmosphere outside of leaf boundary layer in μmol m^{-2} s^{1} Pa^{-1}.

$$g = 10^6 g_s / (R_{gas} (T + 273)) \qquad (5)$$

where g_s is stomatal conductance in m s^{-1}; R_{gas} is the molar gas constant, equal to 8.3143 m^2 Pa mol^{-1} K^{-1}; and T is the air temperature in ºC. Combining equations (2), (3), and (4) and choosing the solution of the quadratic equations with the smaller roots, we obtain the net CO_2 assimilation rate as

$$A = \frac{1}{2}(a^{1/2} g + c^{1/2} - \sqrt{ag^2 + bg + c}) \qquad (6)$$

where A is the minimum of A_c and A_j, corresponding to W_c and W_j. 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=$(0.2J-R_d)^2$.

Theoretically, the diurnal integration of A_c and A_j for daily total photosynthesis should be made with respect to time. Our attempt to obtain an analytical solution to such an integration was not successful because of the complication introduced by the non-linear relationship between time and stomatal conductance, which is approximately sinusoidal. We therefore found an alternative by integrating with respect to conductance (g). The major assumptions are that the daily course of solar radiation follows a cosine function of solar zenith angle with a peak at solar noon and that this variation determines the diurnal pattern of stomatal conductance. Therefore the daily averaged A can be obtained from

$$A = \frac{\mu}{2g_n}\int_0^{g_n}[a^{1/2} g + c^{1/2} - \sqrt{ag^2 + bg + c}]dg \qquad (7)$$

where g_n is the conductance at noon, and μ is a coefficient for adjusting nonlinear change of g with time. It can be calculated from

$$\mu = \frac{1}{0.5\pi/2}\int_0^{\pi/2}\cos\theta d\theta = \frac{4}{\pi} \approx 1.27 \qquad (8)$$

Finally, equation (7) is solved analytically:

$$A = \frac{1.27}{2g_n}\left(\frac{a^{1/2}}{2}g_n^2 + c^{1/2}g_n - \frac{2ag_n + b}{4a}d + \frac{b}{4a}c^{1/2} + \frac{b^2 - 4ac}{8a^{3/2}}\ln\frac{2ag_n + b + 2a^{1/2}d}{b + 2a^{1/2}c^{1/2}}\right) \qquad (9)$$

where d=$(ag_n^2 + bg_n+c)^{1/2}$. It is noted that (1) no additional parameters are introduced in this daily model, all the constants are determined by the leaf biochemical parameters in the original Farquhar model (see Table 1); (2) although equation (9) appears to be complex, it is numerically stable, and no numerical problems have been encountered in its use over large areas and under extreme conditions; (3) the analytical integration given by equation (9) is computationally efficient and avoids a daily loop using a numerical integration method.

Table 1 Procedure to Calculate Parameters in the Farquhar Model

Step	Equation	Reference
1	K_c (Michaelis-Menton constant for CO_2) and K_o (Michaelis-Menton constant for O_2)	Collatz et. al. [1991]

	$K_c = 30 \times 2.1^{(T-25)/10}$ $K_o = 30{,}000 \times 1.2^{(T-25)/10}$	
2	K (function of enzyme kinetics) $K = K_c(1+O_2/K_o)$	Farquhar et al. [1980]
3	Γ (CO_2 compensation point in the absence of dark respiration) $\Gamma = 4.04 \times (1.75)^{(T-25)/10}$	Collatz et al. [1991] Sellers et al. [1992]
4	V_m (the maximum carboxylation rate) $f(T) = 1/(1+\exp((-220{,}000+710(T+273))/(R_{gas}(T+273))))$ $f(N) = N/N_m$ $V_m = V_{m25}\ 2.4^{(T-25)/10} f(T)f(N)$	Bonan [1995]
5	J (electron transport rate) $J_{max} = 29.1+1.64V_m$ $J = J_{max} PPFD/(PPFD + 2.1J_{max})$	Wullschleger [1993] Farquhar and Caemmerer [1982]
6	R_d (daytime leaf dark respiration) $R_d = 0.015V_m$	Collatz et al. [1991]

For the spatial integration from leaf to canopy, a method for stratifying a canopy into sunlit and shaded leaf components has been used to upscale Farquhar's model. This is a preferable approach because the largest difference in leaf illumination in a canopy exists between sunlit and shaded leaves. The daily integration of A_c and A_j can then be made separately for each component. The calculation of sunlit leaf area and shaded leaf area is based on Norman [1982], with some modifications. One of the important modifications is the consideration of forest clumping index (see Table 2 in detail).

Table 2. Procedure to Calculate Leaf Area Index and Irradiance for Sunlit and Shade Leaves

Step	Equation	Reference
1	θ (daily mean solar zenith angle) $\theta_n = \arccos(\sin(-23.4\cos(360(D+10)/365))\sin\varphi + \cos(-23.4\cos(360(D+10)/365))\cos\varphi)$ $\theta = ((pi/2+\theta_n)/2+\theta_n)/2$	Oke [1990]
2	LAI_{sun} (sunlit leaf area index) and LAI_{shade} (shaded leaf area index) $LAI_{sun} = 2\cos\theta(1-\exp(-0.5\Omega LAI/\cos\theta))$ $LAI_{shade} = LAI - LAI_{sun}$	Norman [1982] Chen et al. [1999a]
3	S_{dir} (direct solar irradiance) and S_{dif} (diffuse solar irradiance)	Erbs et al. [1982] Black et al. [1991]

	$R = S_g/(S_o \cos\theta)$ $\frac{S_{dif}}{S_g} = \begin{cases} 0.943 + 0.734R - 4.9R^2 + 1.796R^3 + 2.058R^4 & R < 0.8 \\ 0.13 & R > 0.8 \end{cases}$ $S_{dir} = S_g - S_{dif}$	
4	C (irradiance from multiple scattering of direct radiation) $\cos\bar{\theta} = 0.537+0.025LAI$ $S_{dif,under} = S_{dif} \exp(-0.5\Omega LAI/ \cos\bar{\theta})$ $C = 0.07(S_{dir}(1.1-0.1LAI)\exp(-\cos\theta)$	Norman [1982] Chen et al. [1999a]
5	S_{sun} (sunlit-leaf irradiance) and S_{shade} (shaded leaf irradiance) $S_{shade} = (S_{dif} - S_{dif, under})/LAI + C$ $S_{sun} = S_{dir} \cos\alpha/\cos\theta + S_{shade}$	Norman [1982] Chen et al. [1999a]

The stomatal conductance at noon can be estimated by a species-dependent maximum, which is reduced by the departure of environmental conditions from the optimum. The reduction is described by a set of environmental functions, including photosynthetic photon flux density (PPFD), temperature (T), vapor pressure deficit (VPD), and leaf water potential (LWP); that is,

$$g_s = g_{s,max} f(PPFD)\, f(T)\, f(VPD)\, f(LWP) \qquad (10)$$

where the environmental functions produce scalars between 0 and 1. Leaf water potential can be derived from relative soil moisture [Running and Coughlan, 1988], i. e., LWP=0.2/(volumetric soil water content/soil water holding capacity). Equation (10) considers the environmental constraints to stomatal conductance in a way similar to NPP formulations in a light use efficiency (LUE) model which forces the maximum NPP to the actual rates using stress terms [Prince and Goward, 1995]. However, equation (10) describes stomatal conductance at leaf level, and the environmental functions can be determined with measurements, while the formulation of NPP in the LUE model is at stand level and it is difficult to resolve the environmental functions experimentally. The environmental functions in BEPS are illustrated in Liu et al. [1999].

Autotrophic respiration (R_a) is separated into maintenance respiration (R_m) and growth respiration (R_g) [Running and Coughlan, 1988]:

$$R_a = R_m + R_g = \sum_i (R_{m,i} + R_{g,i}) \qquad (11)$$

where i defines a plant component (1 for leaf, 2 for stem, and 3 for root). Maintenance respiration is temperature-dependent:

$$R_{m,i} = M_i r_{m,i} Q_{10}^{(T-Tb/10)} \qquad (12)$$

where M_i is biomass (sapwood for stems) of a plant component i; $r_{m,i}$ is maintenance respiration coefficient for component i, or respiration rate at base temperature; Q_{10} is the temperature sensitivity factor, and T_b is the base temperature. Growth respiration is generally considered to be independent of temperature and is proportional to GPP:

$$R_{g,i} = r_{g,i} r_{a,i} GPP \qquad (13)$$

where $r_{g,i}$ is a growth respiration coefficient for plant component i, and $r_{a,i}$ is carbon allocation fraction for plant component i.

In this study, Q_{10} and T_b are set to 2.3 and 20°C, respectively. Biomass and respiration coefficients for forest covers are determined on the basis of earlier BOREAS studies and listed in Liu et al [1999]. The carbon allocation fraction is the same as in Forest-BGC for leaf, stem, and root [Running and Running, 1988].

The temporal and spatial scaling method on the Farquhar's model was tested by using the tower flux measurement data. See Chen et al.,[1999a] and Liu et al. [1999] for detail.

Notation

A	net photosynthesis rate, μmol m^{-2} s^{-1}
A_c	Rubisco-limited net photosynthesis rate, μmol m^{-2} s^{-1}
A_j	light limited net photosynthesis rate, μmol m^{-2} s^{-1}
C	irradiance from multiple scattering of direct radiation, W m^{-2}
C_i	intercellular CO_2 concentration , Pa
C_a	CO_2 concentration in the atmosphere , Pa
D	day of year
g	total conductance to CO_2 from cell to air, μmol m^{-2} s^{1} Pa^{-1}
g_n	conductance at noon, μmol m^{-2} s^{1} Pa^{-1}
g_s	stomatal conductance to CO_2, m s^{-1}
$g_{s,max}$	maximum stomatal conductance to CO_2, m s^{-1}
J	electron transport rate, μmol m^{-2} s^{-1}
J_{max}	light saturated rate of electron transport, μmol m^{-2} s^{-1}
K	function of enzyme kinetics, Pa
LAI	leaf area index
LAI_{sun}	sunlit leaf area index
LAI_{shade}	shaded leaf area index
O_2	intercellular O_2 concentration (=21,000), Pa
PPFD	photosynthetically active flux density, μmol m^{-2} s^{-1}
M_i	biomass (or sapwood for stems) of a plant component i, kg C m^{-2}
N	foliage nitrogen concentration, %
N_m	maximum foliage nitrogen concentration, %
P	atmospheric pressure (=100,000), Pa
R_a	autotropic respiration, g C m^{-2} d^{-1}
R_d	daytime leaf dark respiration, μmol m^{-2} s^{-1}
R_{gas}	molar gas constant (= 8.3143), m^3 Pa mol^{-1} K^{-1}
R_m	plant maintenance respiration, g C m^{-2} d^{-1}
R_g	plant growth respiration, g C m^{-2} d^{-1}
$r_{a,i}$	carbon allocation fraction for plant component i
$r_{m,i}$	maintenance respiration coefficient for plant component i, kg C kg^{-1} d^{-1}
$r_{g,i}$	growth respiration coefficient for plant component i
S_{dir}	direct solar irradiance, W m^{-2}
S_{dif}	diffuse solar irradiance, W m^{-2}
$S_{dif,under}$	diffuse solar irradiance under plant canopy, W m^{-2}
S_g	global solar irradiance, W m^{-2}
S_o	solar constant (=1360), W m^{-2}
S_{sun}	sunlit-leaf irradiance, W m^{-2}

S_{shade}	shaded leaf irradiance, W m^{-2}
T	air temperature, °C.
V_m	maximum carboxylation rate, µmol m^{-2} s^{-1}
V_{m25}	maximum carboxylation rate at 25°C, µmol m^{-2} s^{-1}
W_c	Rubisco-limited gross photosynthesis rate, µmol m^{-2} s^{-1}
W_j	light-limited gross photosynthesis rate, µmol m^{-2} s^{-1}
α	mean leaf-Sun angle (=60º for a canopy with spherical leaf angle distribution)
Γ	CO_2 compensation point in the absence of dark respiration, Pa
θ	solar zenith angle, degrees
θ_n	solar zenith angle at noon, degrees
$\bar{\theta}$	representative zenith angle for diffuse radiation transmission, degrees
φ	latitude of a location, degrees
Ω	foliage-clumping index

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4. Equipment

4.1 Sensor/Instrument Description

4.1.1 Collection Environment
See AVHRR data set document in Section 1.6.

4.1.2 Source/Platform
See AVHRR data set document in Section 1.6.

4.1.3 Source/Platform Mission Objectives
See AVHRR data set document in Section 1.6.

4.1.4 Key Variables
NDVI, SR, LAI, and land cover.

4.1.5 Principles of Operation
See AVHRR data set document in Section 1.6.

4.1.6 Sensor/Instrument Measurement Geometry
See AVHRR data set document in Section 1.6.

4.1.7 Manufacturer of Sensor/Instrument
See AVHRR data set document in Section 1.6.

4.2 Calibration

4.2.1 Specifications
See AVHRR data set document in Section 1.6.

4.2.1.1 Tolerance
See AVHRR data set document in Section 1.6.

4.2.2 Frequency of Calibration

See AVHRR data set document in Section 1.6.

4.2.3 Other Calibration Information

See AVHRR data set document in Section 1.6.

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5. Data Acquisition Methods

With spatially explicit input data described in 7.3, NPP or other parameters, such as respiration or evapotranspiration, can be generated by running BEPS. Spatial values of NPP over a defined period of time are stored in a binary file. Temporal variation of NPP for a pixel (a site) is stored in a text file. The area, period, and output parameters can be predetermined in a control file prior to the simulation.

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6. Observations

6.1 Data Notes

None.

6.2 Field Notes

None.

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7. Data Description

7.1 Spatial Characteristics

7.1.1 Spatial Coverage

The NPP image contains 1,200 pixels in each of the 1,200 lines and cover the entire 1,000-km x 1,000-km BOREAS region. This includes the Northern Study Area (NSA), the Southern Study Area (SSA) and the transect between the SSA and NSA.

The North American Datum of 1983 (NAD83) corner coordinates and the image coordinates for the study region and the study areas are listed in Table 3.

Table 3. Coordinates of Study Area, Study Region, and NPP Image

		Degrees		Image Coordinates	
Scope	**Corner**	**Longitude**	**Latitude**	**Pixel**	**Line**
Image	NW	-115.412	59.362	0	0
	NE	-93.286	61.01	1200	0
	SE	-93.739	50.027	0	1200
	SW	-110.254	48.83	1200	1200

Study region	NW	-111	59.979	251	4
	NE	-93.502	58.844	1194	235
	SE	-96.97	50.089	970	1192
	SW	-111	51	7	954
Northern study area (NSA)	NW	-98.82	56.247	879	511
	NE	-97.24	56.081	974	534
	SE	-97.49	55.377	955	610
	SW	-99.05	55.54	860	587
Southern study area (SSA)	NW	-106.23	54.319	396	665
	NE	-104.24	54.223	520	696
	SE	-104.37	53.419	499	782
	SW	-106.32	53.513	374	751

7.1.2 Spatial Coverage Map

Not available.

7.1.3 Spatial Resolution

The size for all pixels is 1 km.

7.1.4 Projection

The coordinate system is the Lambert Conformal Conic (LCC), with the two standard parallels at 49°N and 77°N, respectively, and the meridian at 95°W.

7.1.5 Grid Description

The NPP image is projected into the LCC projection at a space of 1.0 km per pixel (grid cell) in both the X and Y directions.

7.2 Temporal Characteristics

7.2.1 Temporal Coverage

NPP in this data set represent annual values. The model is run at daily time-step. Output for given period(s) can be obtained by setting up some parameters in the model.

7.2.2 Temporal Coverage Map

Not available.

7.2.3 Temporal Resolution

The model is run at daily time-step. Output for given period(s) can be obtained by setting up some parameters in the model. NPP in this data set represent annual values.

7.3 Input Data Characteristics

7.3.1 Parameter/Variable

To execute BEPS over the BOREAS region, spatially explicit input data were required. These include land cover, leaf area index, available soil water holding capacity and daily meteorological (radiation, temperature, humidity, and precipitation) data.

7.3.2 Variable Description/Definition

7.3.2.1 Land Cover

The land cover map of the BOREAS region is part of a 1995 Canada-wide map prepared using data from the AVHRR sensor onboard the NOAA-14 satellite. Prior to the classification, a series of data correction procedures were applied to correct atmospheric and bidirectional reflectance effects, remove contaminated pixels, and determine the growing season length [Cihlar et al., 1997a]. The average growing-season values in AVHRR channel 1 (C1, red), channel 2 (C2, near infrared) and the normalized difference vegetation index ($NDVI_m$) were then used in the classification process. A combined enhancement-unsupervised classification methodology was used [Beaubien *et al.,* 1999; *Cihlar and Beaubien*, 1998]. The resulting spectral clusters were labeled with the use of Landsat Thematic Mapper (TM) images and field observations. Accuracy was evaluated by provincial forest inventory agencies and in comparison with Landsat TM classifications. Land cover patterns in the AVHRR-derived map were found to be consistent with provincial maps, after allowing for scale differences. Numerical accuracy is variable, mainly because of the mixed land cover within AVHRR pixels [Cihlar et al., 1996]. Based on a digital comparison with Landsat Thematic Mapper classification [Klita et al., 1998], the per-class accuracy varied between 21.8% and 97.9%.

7.3.2.2 Leaf Area Index (LAI)

LAI images in 1994 for the BOREAS region were derived from the same AVHRR sensor using 10-day cloud-free composite images [Cihlar et al., 1997b]. For the calculation of LAI, the NDVI was first transformed into the simple ratio (SR). Land cover specific linear SR-LAI relationships were then used to convert SR to LAI. The use of SR reduces the problem of signal saturation at high LAI values. Because the LAI of boreal vegetation is generally low and the foliage clumping reduces the effective LAI, no saturation was found for boreal forests when SR was used [Chen and Cihlar, 1996]. The algorithm for boreal conifer forests was developed by Chen and Cihlar [1996]. The algorithm for deciduous forests is based on Chen et al. [1999b], but is less accurate because of insufficient field data for the seasonal coverage and variable understory. Mixed forest was treated as an intermediate case between coniferous and deciduous forests. An algorithm for the cropland was formulated using published relationships and validated using 1996 ground measurements in 14 agricultural fields in Saskatchewan. The grassland was treated as cropland because of lack of independent measurements. To consider the effect of the seasonal greenness change in the background (understory, moss and soil/litter) of coniferous stands, a seasonal background SR trajectory was derived from AVHRR SR time series to ensure that the seasonal variation in the conifer overstory LAI was equal to or less than 25%. The formulae for the various land cover types are

```
Deciduous forest                      LAI = 0.475 (SR - 2.781)
Coniferous forest                     LAI = 1.188 (SR - Bc)
Mixed forest                          LAI = 0.592 (SR - Bm)
Crop land and other land cover types  LAI = 0.325 (SR - 1.5)
```

where SR is the simple ratio; B_c and B_m are background SR trajectory for coniferous forest and mixed forest. They are calculated from $B_c= 0.1(1.2x10^{-10}D^5 - 1.1x10^{-7}D^4 + 4.1x10^{-5}D^3 - 6.8x10^{-3}D^2 + 5.4x10^{-1}D - 15)$, and $B_m= (B_c+2.781)/2$, where D is the day of year. The error in a single LAI value is estimated to be ±25%.

The AVHRR data temporal coverage was as follows, for 1994:

```
  Period   Julian Day     Season
---------  ----------     ------
Apr 11-20   101-110       Spring
Apr 21-30   111-120         ,,
May 01-10   121-130         ,,
May 11-20   131-140         ,,
May 21-31   141-151         ,,
Jun 01-10   152-161       Summer
Jun 11-20   162-171         ,,
Jun 21-30   172-181         ,,
Jul 01-10   182-191         ,,
Jul 11-20   192-201         ,,
Jul 21-31   202-212         ,,
Aug 01-10   213-222         ,,
Aug 11-20   223-232         ,,
Aug 21-31   233-243         ,,
Sep 01-10   244-253       Fall
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7.3.2.3 Available Water-Holding Capacity (AWC)

Soil AWC data were acquired from the Soil Landscapes of Canada (SLC) database [Shields et al., 1991]. In SLC, the land is divided into landscape polygons within which the soils are characterised by a set of attributes. The available water holding capacity (AWC) in the upper 120 cm of soil is one of the attributes contained in SLC version 1.0. About 10% of the BOREAS region was missing data (mostly in the north) in SLC version 1.0. In order to fill in the data gaps, soil texture data in SLC version 2.0 were processed, and the dominant soil texture in each polygon was determined. AWC was then assessed according to its relationship with soil texture [De Jong et al., 1984]. The AWC data in different polygons and coverages were combined, rasterized, and resampled to the same LCC projection and spatial resolution as the land cover and LAI maps. There were five levels of AWC ranging from 5 cm to 25 cm in 5 cm increments.

7.3.2.4 Meteorological Data

The meteorological data were generated by the National Meteorological Center (NMC) of the National Center for Atmospheric Research (NCAR) from a medium range forecast model and provided with a grid size of about 0.9°. All meteorological data were bilinearly interpolated to each pixel at 1 km resolution after determining the geographical location of the pixel in the LCC projection.

7.3.4 Input Data Source and Format

Parameter	Source	Agency#	Data Type	Grid System	Temporal Interval	Grid Size

LAI	AVHRR*	CCRS	Raster	pixel/line	10 days	1 km
Land cover	AVHRR*	CCRS & CFS	Raster	pixel/line	Annual	1 km
AWC	SLC@	CLBRR	Vector		long term	
Radiation Temperature Humidity Precipitation	NMC medium range forecast model	NCAR	Raster	Gaussian	daily	~0.9° (varied with lat/long)

#CCRS, Canada Centre for Remote Sensing, Natural Resources Canada; CFS, Canadian Forest Service, Natural Resources Canada; CLBRR, Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada; NCAR, National Center for Atmospheric Research, Boulder, Colorado.
*Advanced very high resolution radiometer.
@Soil Landscapes of Canada.

7.3.5 Input Data Range

Parameter	Unit	Range
Growing Season Mean LAI	-	0-6
Land Cover	-	N/A
AWC	m	0-0.25
Daily Mean Radiation	MJ m d^{-1}	9.0-11.0
Daily Mean Temperature	°C	-7.5-4.5
Daily Mean Vapour Density	g m^{-3}	4.1-7.4
Annual Total Precipitation	mm y^{-1}	180-480

7.4 Output Data Characteristics

The NPP map is in binary format, two bytes per pixel. Values (grey levels) range from 0-32767.

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8. Data Organization

8.1 Data Granularity

Annual total NPP is contained in a separate file for the entire set of image.

8.2 Data Format(s)

```
NPP format: binary file, 2 byte for 1 pixel
NPP unit:   g Carbon m-2 yr-1
NPP value:  If Grey Level=0, NPP=0 (water pixel)
            If Grey Level=1, NPP=0.01 (very small)
            If Grey Level>1, NPP=Grey Level-1
```

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9. Data Manipulations

9.1 Formulae

See Section 3.

9.1.1 Derivation Techniques and Algorithms

See Section 3.

9.2 Data Processing Sequence

9.2.1 Processing Steps

BEPS is driven by land cover, leaf area index, meteorological and soil data. The temporal interval is daily for meteorological data, 10-day for LAI, annual for land cover, and long term for available water holding capacity (AWC). BEPS integrates the input data and produces output of NPP and other carbon and water cycle components. The computation is made pixel by pixel in daily time steps.

9.2.2 Processing Changes

As the model is modified for a better description of ecosystems, and as more accurate spatial data become available, simulated NPP values will be more realistic. The improved can be made available when completed. See section 13.

9.3 Calculations

9.3.1 Special Corrections/Adjustments

None.

9.3.2 Calculated Variables

See Section 3.

9.4 Graphs and Plots

None.

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10. Errors

10.1 Sources of Error

Sources of errors include within-pixel heterogeneity, simplification of natural processes with a daily photosynthesis model, errors in input data (land cover, LAI, meteorological and soil data), assignment of biological parameters for the various cover types, and the accuracy of image registration and processing (resampling, radiance-to-reflectance conversion, etc).

10.2 Quality Assessment

10.2.1 Data Validation by Source

Not available.

10.2.2 Confidence Level/Accuracy Judgment

Because of the additive effects of sources of errors, the NPP values for individual pixels can be as large as 25-50%. However, since the model parameters and the final NPP results have been carefully calibrated using tower flux data, the major bias errors are much reduced and therefore the errors in the regional NPP estimates are expected to be smaller than 25%. The daily NPP model with sunlit and shaded leaf separation has been validated using simultaneous CO_2 flux measurements made above and below forest stands [Chen et al., 1999a] and map validation was also made (see Section 10.2.3).

10.2.3 Modeling Error for Parameters

In comparing modeled NPP with ground data at six forest sites [Ryan et al. 1997], close agreement is found ($r=0.88$, and $p<0.05$). The mean difference between the two data sets is 10%, with a maximum of 28% at the old jack pine in the northern study area. The root-mean-square error of modeled NPP is 34 g C /m^2/yr, 12% of mean NPP in ground data set.

10.2.4 Additional Quality Assessments

See Liu et al. [1999].

10.2.5 Data Verification by Data Center

The data center has viewed the imagery to verify file size, format, and data range.

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11. Notes

11.1 Limitations of the Data

The NPP data is for 1994, a relatively normal year.

11.2 Known Problems with the Data

None.

11.3 Usage Guidance

Before uncompressing the Zip files on CD-ROM, be sure that you have enough disk space to hold the uncompressed data files. Then use the appropriate decompression program provided on the CD-ROM for your specific system.

11.4 Other Relevant Information

We emphasize that the NPP results for forests represent tree canopy only. The background (understory and moss) contribution is not included since LAI for forest stands only includes the overstory LAI. The LAI algorithm development only considers the overstory LAI. Another important aspect of our calculation is the consideration of the foliage clumping effect. We use cover type specific clumping indices [Liu et al., 1997]. The clumping reduces sunlit leaves and increases shaded leaves, and the NPP results calculated using the sunlit/shaded leaf model are sensitive to the clumping index. Therefore, in any attempt to compare the results with other model results, this should be considered. For the users' reference, a ground study on understory contribution to total NPP at several BOREAS sites is cited here [Ryan et al., 1997].

Study Area	Species	NPP_{total} (g C m^{-2} yr^{-1})	$NPP_{understory}$ (g C m^{-2} yr^{-1})	$NPP_{understory}$/ NPP_{total} (%)
NSA	Old Black Spruce	252	9	3.6

NSA	Old Jack Pine	229	11	4.8
NSA	Old Aspen	416	30	7.2
SSA	Old Black Spruce	307	9	2.9
SSA	Old Jack Pine	237	7	3
SSA	Old Aspen	440	66	15

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12. Application of the Data Set

NPP is a measure of plant growth. It provides highly synthesized, quantitative information for sustainable resource management. It is also an important component of the global atmospheric CO_2 budget affecting climate. Our NPP data have been used in the following aspects: (1) to supply a key parameter for estimating net ecosystem productivity [Chen, W. et al. 2000; Chen, J. et al. 2000]; (2) to study regeneration trends following forest fire [Amiro et al., 2000]; and (3) to assess vegetation growth in the national parks.

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13. Future Modifications and Plans

1. Consideration of sub-pixel heterogeneity by using high resolution remote sensing data. Chen [1999] showed that the largest errors of this type result from mixed water and land pixels. Using sub-pixel water area fraction can make a large improvement.
2. Improving the biomass data quality. We expect that the NPP spatial distribution pattern would be more accurate if a biomass map was used rather than assigning the value by cover type. The feasibility of estimating biomass distribution from active microwave images has been demonstrated [Moghaddam et al., 1994]. Optical measurements can also be useful for this purpose for sparse canopies [Hall et al., 1995].
3. Reducing the computation time step. Although the problem associated with diurnal variability is much smaller when using the integrated daily NPP model, errors are still inevitable in the daily step calculations which cannot capture sub-daily extreme events [Chen et al., 1999a]. With the improvement in computational capacity, it will soon be feasible to compute a moderate-resolution NPP distribution at much smaller time steps (minutes to hours). Such work is only possible in conjunction with a global circulation model to avoid data limitation.

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14. Software

14.1 Software Description

The model BEPS version 1999 is written in C and runs on a PC. The code can be easily transferred for usage in a UNIX environment. No machine-specific commands are used. Input data are in binary format. Output data are in binary format for an area and in text format for a pixel.

14.2 Software Access

The source code can be provided by contacting Jane Liu (see section 2.1).

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15. Data Access

15.1 Contact for Data Center/Data Access Information

These BOREAS data are available from the Earth Observing System Data and Information System (EOS-DIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC). The BOREAS contact at ORNL is:

ORNL DAAC User Services
Oak Ridge National Laboratory
(865) 241-3952
ornldaac@ornl.gov
ornl@eos.nasa.gov

15.2 Procedures for Obtaining Data

BOREAS data may be obtained through the ORNL DAAC World Wide Web site at http://www.daac.ornl.gov/ [Internet Link] or users may place requests for data by telephone or electronic mail.

15.3 Output Products and Availability

Requested data can be provided electronically on the ORNL DAAC's anonymous FTP site or on various media including, CD-ROMs, 8-MM tapes, or diskettes.

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16. Output Products and Availability

16.1 Tape Products

The NPP image over the BOREAS region can be made available on 8-mm media or on a CD-ROM.

16.2 Film Products

None.

16.3 Other Products

These data are available on the BOREAS CD-ROM series.

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17. References

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17.2 Journal Articles and Study Reports

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17.3 Archive/DBMS Usage Documentation

None.

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18. Glossary of Terms

None.

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19. List of Acronyms

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APAR     - Absorbed Photosynthetically Active Radiation
ASCII    - American Standard Code for Information Interchange
AVHRR    - Advanced Very High Resolution Radiometer
AWC      - Available Water Holding Capacity
BOREAS   - BOReal Ecosystem-Atmosphere Study
BORIS    - BOREAS Information System
BEPS     - Boreal Ecosystem Productivity Simulator
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CCRS     - Canada Centre for Remote Sensing
CFS      - Canadian Forest Service
CLBRR    - Centre for Land and Biological Resources Research, Agriculture and Agro-Food Canada
CD-ROM   - Compact Disk-Read-Only Memory
CPIDS    - Calibration Parameter Input Dataset
DAAC     - Distributed Active Archive Center
DN       - Digital Number
EOS      - Earth Observing System
EOSDIS   - EOS Data and Information System
EROS     - Earth Resources Observation System
FPAR     - Fraction of Photosynthetically Active Radiation
GEOCOMP  - Geocoding and Compositing System
GIS      - Geographic Information System
GPP      - Gross Primary Productivity
GSFC     - Goddard Space Flight Center
LAC      - Local Area Coverage (of AVHRR)
LAI      - Leaf Area Index
LCC      - Lambert Conformal Conic
LUE      - Light Use Efficiency
MRSC     - Manitoba Remote Sensing Centre
NAD83    - North American Datum of 1983
NASA     - National Aeronautics and Space Administration
NCAR     - National Center for Atmospheric Research
NBIOME   - Northern Biosphere Observation and Modeling Experiment
NDVI     - Normalized Difference Vegetation Index
NMC      - National Meteorological Center
NOAA     - National Oceanic and Atmospheric Administration
NEP      - Net Ecosystem Productivity
NPP      - Net Primary Productivity
NSA      - Northern Study Area
ORNL     - Oak Ridge National Laboratory
PANP     - Prince Albert National Park
PAR      - Photosynthetically Active Radiation
RMS      - Root Mean Square
SLC      - Soil Landscape of Canada
SR       - Simple Ratio
SSA      - Southern Study Area
TE       - Terrestrial Ecology
TF       - Tower Flux
TIROS    - Television and Infrared Observation Satellite
URL      - Uniform Resource Locator
VPD      - Vapor Pressure Deficit
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NPP
Plant respiration
Primary production

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