ELSEVIER

A Process-Based Boreal Ecosystem Productivity Simulator Using Remote Sensing Inputs

J. Liu,* J. M. Chen,† J. Cihlar,† and W.M. Park†

This paper describes a boreal ecosystems productivity simulator (BEPS) recently developed at the Canada Centre for Remote Sensing to assist in natural resources management and to estimate the carbon budget over Canadian landmass (10^6–10^7 km^2). BEPS uses principles of FOREST biogeochemical cycles (FOREST-BGC) (Running and Coughlan, 1988) for quantifying the biophysical processes governing ecosystems productivity, but the original model is modified to better represent canopy radiation processes. A numerical scheme is developed to integrate different data types: remote sensing data at 1-km resolution in lambert conformal conic projection, daily meteorological data in Gaussian or longitude-latitude gridded systems, and soil data grouped in polygons. The processed remote sensing data required in the model are leaf area index (LAI) and land-cover type. The daily meteorological data include air temperature, incoming shortwave radiation, precipitation, and humidity. The soil-data input is the available water-holding capacity. The major outputs of BEPS include spatial fields of net primary productivity (NPP) and evapotranspiration. The NPP calculated by BEPS has been tested against biomass data obtained in Quebec, Canada. A time series of LAI over the growing season of 1993 in Quebec was derived by using 10-day composite normalized difference vegetation index images acquired by the advanced very high resolution radiometer at 1-km resolution (resampled). Soil polygon data were mosaicked, georeferenced, and rasterized in a geographic information system (ARC/INFO). With the use of the process-based model incorporating all major environmental variables affecting plant growth and development, detailed spatial distributions of NPP (annual and four seasons) in Quebec are shown in this paper. The accuracy of NPP calculation is estimated to be 60% for single pixels and 75% for 3×3 pixel areas (9 km^2). The modeled NPP ranges from 0.6 kg C/m^2/year at the southern border to 0.01 kg C/m^2/year at the northern limit of the province. The total annual NPP in Quebec is estimated to be 0.24 Gt C in 1993, which is about 0.3–0.4% of the global NPP.

* Intermap Technologies, Nepean, Ontario K2E 1A2, Canada
† Canada Centre for Remote Sensing, Ottawa, Ontario K1A 0Y7, Canada
Address correspondence to J. Liu, 400-588 Booth Street, Canada Centre for Remote Sensing, Ottawa, Ontario, Canada K1A 0Y7.
Received 4 September 1996; revised 21 April 1997.

INTRODUCTION

Net primary productivity (NPP) is defined as the difference between accumulative photosynthesis and accumulative autotrophic respiration by green plants per unit time and space (Leith and Whittaker, 1975). NPP provides highly synthesized information useful for natural-resources management to achieve sustainable development and is an important component in the global atmospheric CO_2 budget affecting climate.

Three types of models are generally used to estimate terrestrial NPP. As described by Ruimy et al. (1994), they are: (1) statistical models (Leith, 1975), (2) parameteric models (Law and Waring, 1994; Potter et al., 1993; Prince et al., 1995; Ruimy et al., 1994; Runyon et al., 1994) and (3) process models (Bonan, 1995; Foley, 1994; Melillo et al., 1993; Running et al., 1989). The first type links NPP with meteorological parameters or evapotranspiration or both through regression analysis; the second type uses the efficiency concept to derive NPP from incident solar radiation and its absorption coefficiency by plant canopies; and the third type simulates biological processes affecting NPP, such as photosynthesis, respiration, and transpiration.

Process models are useful tools for revealing the mechanisms of biomass production and plant-environment interaction and for investigating the responses of ecosystems to climate change. They should be more reliable than the other types of models because of their foundation on our understanding of ecosystems. However, models of this type are often sophisticated and re-

REMOTE SENS. ENVIRON. 62:158–175 (1997)

655 Avenue of the Americas, New York, NY 10010

0034-4257/97/$17.00
PII S0034-4257(97)00089-8

quire many inputs. The application of such models to large areas (at global and national scales) often depends on the availability and quality of required data. Many process models at the global scale had to be based on the assumptions of homogeneity of the vegetation and of environmental conditions within a 0.5–1.0 degree latitude-longitude grid cell (Bonan, 1995; Foley, 1994; Melillo et al., 1993). On the other hand, process models at stand level have been developed in great detail. At an intermediate scale, some work has been carried out to extend the process model from stand to a watershed or landscape level ($\sim 10^2$–10^3 km^2) (Band et al., 1991; 1993; Running et al., 1989). In this study, a boreal ecosystems productivity simulator (BEPS) is developed to simulate the NPP for the northern ecosystems at even larger scales ($\sim 10^6$–10^7 km^2) with a moderate resolution (1 km) by using data from different sources. The objectives of this paper are: (1) to describe the biological and physical principles and data processing techniques used in BEPS; (2) to show the first BEPS products for Quebec, Canada; and (3) to discuss the usefulness of this process model compared with other types of models.

MODEL DESCRIPTION

An Overview of BEPS

BEPS was built based on a site-level ($\sim 10^{-2}$ km^2) process model, FOREST-BGC (Running and Coughlan, 1988). The biological principles in FOREST-BGC were adopted for modeling the processes governing carbon and water flows in the soil-plant-atmosphere system because this model has been well documented and tested with measured NPP over various climatic zones in Oregon (Running, 1994). The model requires daily meteorological inputs and calculates NPP on a daily basis. This daily model captures, without excessive complexity, major ecosystem functionalities resulting from the diurnal variation in solar energy. It is computationally feasible for remote-sensing applications. The same model has also been extended to simulate ecological and hydrological processes at the landscape scale (Running et al., 1989) and has been incorporated into the regional hydroecological simulation system (RHESSys) at watershed scale ($\sim 10^2$–10^3 km^2) (Band et al., 1991, 1993). To use FOREST-BGC at provincial and national levels in Canada ($\sim 10^6$–10^7 km^2), challenges exist in (1) searching for available data sources to satisfy the basic model input requirements and (2) incorporating data from different sources in the model and making them spatially and temporally compatible.

Recent developments in remote sensing, the geographical information system (GIS), and meteorology have made it possible to overcome the first challenge. The most important inputs to BEPS include leaf area index (LAI), available water capacity (AWC) of soil, and daily meteorological variables (shortwave radiation, maximum and minimum temperatures, humidity, and precipitation). Through the recent work of Chen and Cihlar (1996) and Cihlar et al. (1996), algorithms were developed to derive LAI for various cover types from 10-day composites of the advanced very high resolution radiometer (AVHRR) measurements. A digital land-cover map of Canada compatible with the AVHRR composites was available from Pokrant et al. (1991). The land-cover information is used in BEPS to determine a vegetation-dependent foliage clumping index, biological parameters, and the initial carbon content of plant components for the modeling. Data on the available water-holding capacity of soil were compiled in a GIS soil database at Agriculture and Agri-Food Canada (Shields et al., 1991). For daily meteorological data, conducting spatial extrapolation for an area of 10^6–10^7 km^2 from only one meteorological station becomes inadequate—a scheme used in the original FOREST-BGC and RHESSys for small-area applications. Therefore, a new scheme was developed in BEPS to employ gridded meteorological data generated either by meteorological analysis models or from meteorological station measurements.

BEPS was designed to address the second challenge. BEPS is a simulation system that integrates the input data, automates the modeling, and produces output of NPP and other ecological parameters. The input data required by BEPS are from different sources and of various forms (vector, raster), resolutions, and grid systems, as summarized in Table 1. The vector and scattered raster data were preprocessed into a gridded raster format prior to simulation. Figure 1 shows the framework of BEPS, including the major modeling steps, the input data and their spatial resolutions, and temporal intervals. The input data were harmonized for their spatial and temporal compatibility. Vegetation and environment conditions were assumed to be homogeneous within an entity of 1 km^2. Each entity was georeferenced (see the detail in the subsequent section on processing LAI). For each entity, the meteorological data were bilinearly interpolated in BEPS from the input data with $\sim$1-degree resolution; whereas, for the soil data with 0.02-degree resolution, the nearest-neighbor interpolation was used. The calculations of soil water content, canopy conductance, photosynthesis, and respiration were based on the functionalities used in FOREST-BGC (see the next section). The outputs of the model include NPP, transpiration, evapotranspiration, soil water content, and other variables of interest. The outputs can be given for a user-defined period of time from 1 day to an entire year.

Biological Principles in BEPS

As shown in Figure 1, the NPP is modeled in five steps in BEPS. A brief description of the biological principles in each step is presented here. Further detail is available in Running and Coughlan (1988).

In step 1, soil water balance is estimated on the ba-

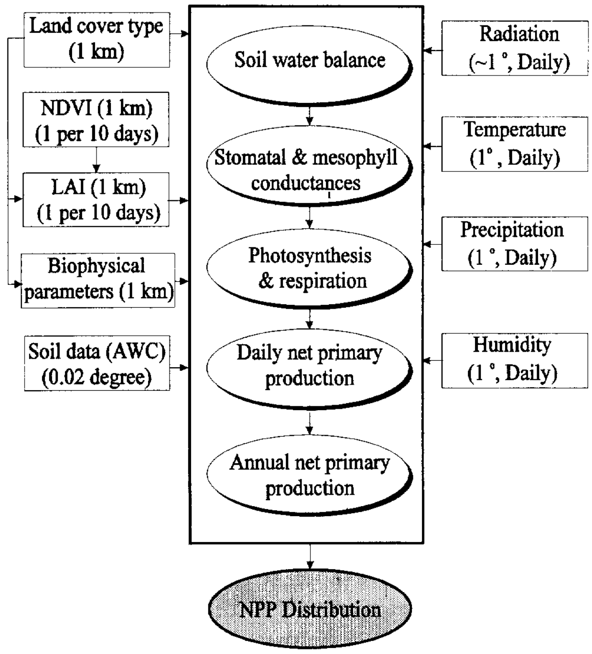
Table 1. Input Data Sources and Formats

Parameter	*Source*	*Agency*[1]	*Data Type*	*Grid System*	*Grid Size*
LAI	AVHRR	CCRS	Raster (gridded)	Pixel/Line	1 km
Land cover	AVHRR	MRSC	Raster (gridded)	Pixel/Line	1 km
AWC	SLC[2]	CLBRR	Vector		
Temperature	Global analysis model	CMC	Raster (gridded)	Lon/Lat	1 degree
Humidity	Global analysis model	CMC	Raster (gridded)	Lon/Lat	1 degree
Precipitation	Meteorological measurement	CMC	Raster (scattered)		
Radiation	The NMC medium range forecast model	NCAR	Raster (gridded)	Gaussian	~0.9 degree (varied with lat./long.)

[1] CCRS, Canada Centre for Remote Sensing, Natural Resources Canada; MRSC, Manitoba Remote Sensing Centre, Natural Resources Canada; CLBRR, Center for Land and Biological Resources Research, Agriculture and Agri-Food Canada; CMC, Canadian Meterological Centre; NCAR, National Centre for Atmospheric Research, USA.
[2] Soil landscapes of Canada.

sis of the soil "bucket" model, which includes the calculations of rainfall input, snowmelt, canopy interception, evapotranspiration, and overflow. In particular, transpiration is calculated by using the Penman-Monteith equation with fixed aerodynamic resistance at 5.0 s/m. Soil water content, one of the most important factors affecting canopy stomatal conductance, is a critical output from the step.

Figure 1. Framework of BEPS showing the major modeling steps, the input requirements, and the data's spatial resolutions and temporal intervals prior to simulation.



Step 2 calculates the mesophyll conductance and the canopy stomatal conductance. Mesophyll conductance is a function of radiation, air temperature, and leaf nitrogen concentration. Leaf nitrogen concentration was set to be a constant in this study, as in the early version of FOREST-BGC and RHESSys, because of a lack of data. This needs improvement in the future. Canopy stomatal conductance is calculated as a function of radiation, air temperature, vapor pressure deficit, and leaf water potential (LWP). Leaf water potential is, in turn, a function of soil water content; that is,

$$LWP=0.2/(SOIL_{water}/SOIL_{cap}), \tag{1}$$

where $SOIL_{water}$ is soil water content and $SOIL_{cap}$ is soil water capacity. By this equation, the water and carbon budgets are linked and vegetation response to environmental constraints, especially water stress, is considered in the model.

Step 3 is the core of the model. The daily gross photosynthesis (PSN) is calculated by equation analogous to Ohm's Law:

$$PSN=[\Delta CO_2 \times CC \times CM/(CC+CM)] \times LAI \times DAYL, \tag{2}$$

where CC and CM are canopy stomatal and mesophyll conductance (m/s), respectively. LAI is leaf area index, and DAYL is daylength (s). The ΔCO_2 is the CO_2 gradient between leaf and air, which is assumed to be a constant in FOREST-BGC (0.00013 kg/m^3). Daily maintenance respiration of leaves, stems, and roots is calculated separately, on the basis of their respiration coefficients, biomass, and temperatures (nighttime average air temperature for leaf and stem respiration and soil temperature for root respiration). Because few data are available on the maximum mesophyll conductance for boreal plant

Table 2. Biological Parameters and Initial Carbon Contents for Various Land-Cover Types in BEPS

Parameters	*Unit*	*Coniferous Forest*	*Deciduous Forest*	*Mixed Forest*	*Grass*
Specific leaf area	m^2/kg C	25	75	50	25
Maximum canopy conductance	m/s	0.0016	0.0025	0.0020	0.0050
Maximum mesophyll conductance	m/s	0.0006	0.0009	0.0008	0.0007
Leaf respiration coefficient	kg C/day/kg	0.0001	0.0005	0.0003	0.0004
Stem respiration coefficient	kg C/day/kg	0.0002	0.001	0.0006	0.0003
Root respiration coefficient	kg C/day/kg	0.0002	0.0002	0.0002	0.0011
Leaf water potential at stomatal closure	MPa	−2.0	−2.0	−2.0	−3.5
Leaf carbon	kg C/m^2	0.072	0.097	0.085	
Stem carbon	kg C/m^2	1.22	1.94	1.58	
Root carbon	kg C/m^2	0.65	1.02	0.83	

species, we adjusted this parameter according to a more sophisticated photosynthesis model (Farquhar et al., 1980) for the major vegetation types (Table 2).

In step 4, daily maintenance respiration is subtracted from daily gross photosynthesis.

Finally, the difference between daily gross photosynthesis and maintenance respiration is summed for the whole year. After 20% (Raich et al., 1991; Ryan, 1991) is subtracted from the yearly total for growth respiration, annual NPP is obtained.

Canopy Radiation Calculation in BEPS

Solar radiation is the driving force for biological activities in plants. The accuracy in the calculation of the amount of photosynthetically active radiation (PAR) absorbed by plant canopies is critical in determining the canopy conductance and therefore the photosynthesis rate. We found that the original equations in FOREST-BGC result in a considerable overestimation of radiation absorption and photosynthesis when accurate LAI data are used. This is because the effect of canopy architecture on radiation interception is not adequately considered in the original model. Another improvement made to the model considers the dependence of radiation absorption on solar zenith angle because of the variation in the path length through the canopy. In BEPS, we developed the following simple scheme for daily canopy radiation calculation.

Figure 2 shows measurements of canopy gap fraction (P) in boreal black spruce, jack pine and aspen stands as a function of solar zenith angle (θ) [see principle of measurements in Chen (1996a)], where canopy gap fraction is defined as the percentage of sky seen from underneath the canopy at a given zenith angle. It equals the probability of solar beam penetration through the canopy at the given angle. The distribution of gap fraction with zenith angle is approximately linear, especially in black spruce and jack pine because of the combined effects of tree crown, branch, shoot, and needle architecture. This linear relation helps simplify the calculation for daily radiation interception. Using this linear relation with the condition that $P(\theta)=0$ at $\theta=\pi/2$, we have

$$P(\theta)=P(0)(0.5\pi-\theta). \qquad (3)$$

The fraction of photosynthetically active radiation absorbed by the canopy (FPAR) is 1−reflection−penetration+absorption of PAR reflected by the background (Chen, 1996b); that is,

$$\begin{aligned}\mathrm{FPAR}&=(1-\rho_1)-(1-\rho_2)\int_{\theta_{noon}}^{\pi/2} P(\theta)\cos\theta d\theta \Big/ \int_{\theta_{noon}}^{\pi/2}\cos\theta d\theta\\ &=(1-\rho_1)-(1-\rho_2)P(\theta_{noon})[\cos\theta_{noon}-(\pi/2-\theta_{noon})\sin\theta_{noon}]\\ &\quad /[\pi/2-\theta_{noon})(1-\sin\theta_{noon})],\end{aligned} \qquad (4)$$

where ρ_1 and ρ_2 are the PAR reflectivities above and below the canopy, respectively. In BEPS, they are assigned the values of 0.05 and 0.06 according to the results of Chen (1996b). Cos θ is used as a weight for variation of solar irradiance with solar zenith angle. Compared with the original equation in FOREST-BGC, Eq. (4) includes the major physics of canopy radiation and requires only one additional parameter—that is, solar zenith angle at noon. This parameter is already available from the model and does not incur much additional computation. If this parameter were ignored, considerable errors would occur because of the wide latitudinal range covered in this study. A change of θ_{noon} from 30° to 60° from southern Quebec to northern Quebec results in a change in FPAR from 0.56 to 0.65 at LAI=2. The relative change is about 15%. The relative error in NPP would be the same under nonstressed conditions. In Eq. (4), $P(\theta_{noon})$ is the gap fraction at solar noon and is calculated from

$$P(\theta_{noon})=e^{(-0.4\Omega L/\cos\theta noon)}, \qquad (5)$$

where Ω is the foliage-clumping index characterizing the effect of foliage clustering on radiation transmission. On the basis of the work of Chen (1996a) and Chen and Cihlar (1995), the following values were assigned:

$$\Omega=\begin{cases} 0.5 \text{ conifer forest} \\ 0.6 \text{ mixed forest} \\ 0.7 \text{ deciduous forest} \\ 0.9 \text{ grass/crop} \end{cases} \quad (6)$$

The use of the clumping index is critical in radiation and photosynthesis modeling because LAI is used for both canopy conductance and radiation calculation. If LAI is reduced to fit observed radiation data (as done in many studies), canopy conductance will be considerably underestimated. For accurate calculations, we need both LAI and the clumping index to characterize the canopy architectural effect on the radiation regime and in the mean to produce a realistic estimate of canopy conductance. If the clumping effect is ignored (i.e., $\Omega=1$), the FPAR calculation will be in error by 21% for a conifer stand with $L=4$ at $\theta_{noon}=30°$. In Eq. (5), the projection coefficient is taken as 0.4 rather than the usual 0.5 to consider the multiple scattering effect on direct and diffuse PAR transmission (Chen, 1996b).

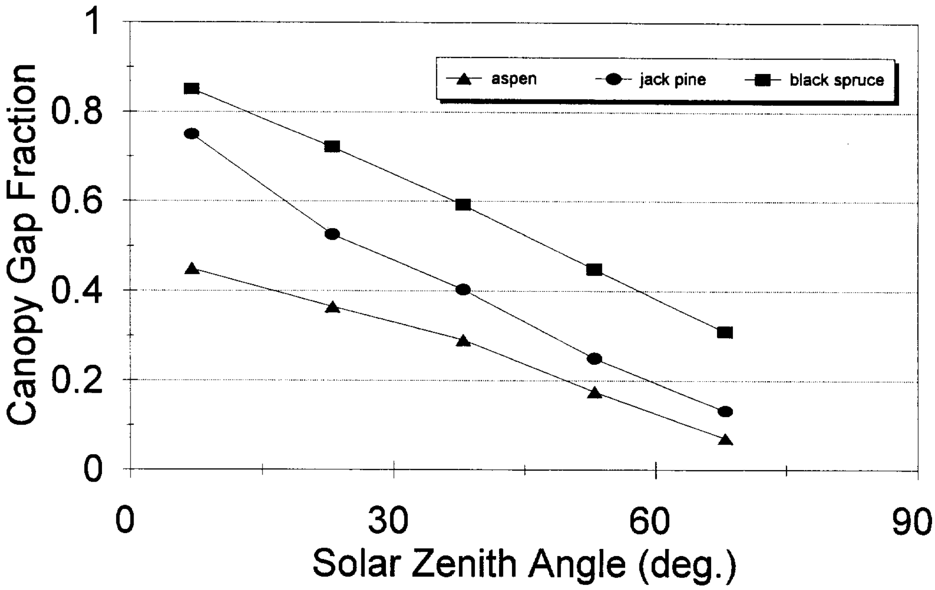
DATA SOURCES AND PROCESS METHODOLOGY

The province of Quebec was chosen as the first location for developing and testing BEPS because of the range of ecosystem conditions and ground data availability. The area spans a large range of latitudes (45° N to 63° N) and longitudes (57° W to 79° W), which occupies an area of about 1.5×10^6 km^2, and covers numerous land-cover types, from temperate and agricultural areas in the south to tundra and barren land in the north (Fig. 3a). A large part of the area is boreal forest, which is known to play an important role in the global carbon budget. It will be of interest to compare, in future studies, the characteristics of NPP of the boreal forest in eastern Canada with those in central Canada, where an international experiment named the Boreal Ecosystem-Atmosphere Study (BOREAS) has taken place. Quebec has a fairly even elevation, half of the province lying between 300 and 600 m and only 7% above 600 m. The data for 1993 were collected for the modeling. The annual temperature and precipitation records for the area indicate that 1993 was a relatively normal year, with normal spring, relatively wetter summer, cooler autumn, and dryer winter. Descriptions of all the input data collected and processed for Quebec are presented next.

LAI

Remote sensing is the only means of obtaining the spatial distribution of LAI. Figure 3b shows a LAI image of Quebec in midsummer 1993. This image was calculated by using an AVHRR 10-day composite image of the normalized difference vegetation index (NDVI). Similar LAI images were calculated in BEPS for each 10- (or 11-) day period from early April to late October 1993 by using the 10-day composites. LAI before April was assumed to be the same as that at the beginning of April

Figure 2. Measured canopy gap fraction in boreal forests and its approximation in BEPS for daily fPAR calculations.



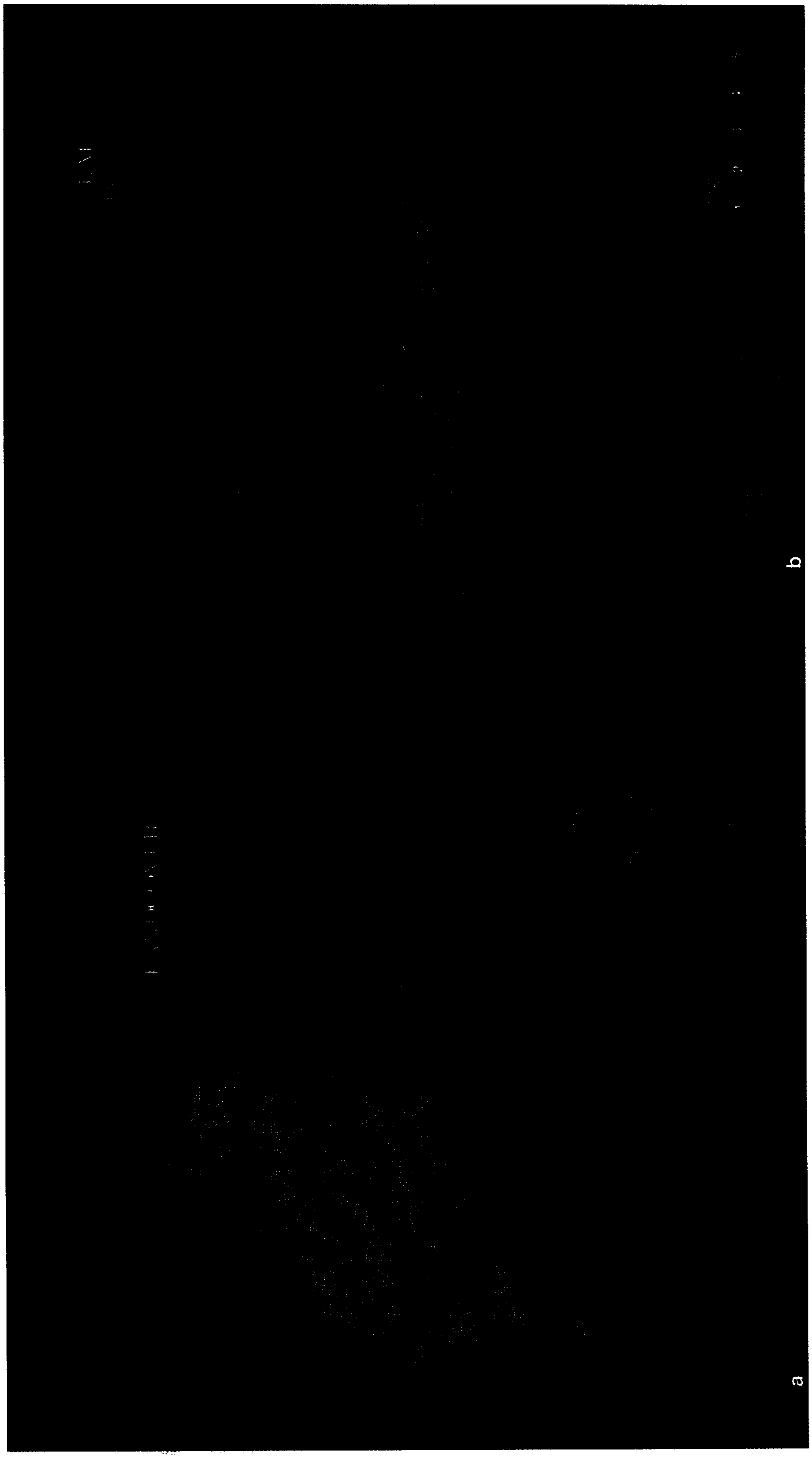


Figure 3. Landcover (a) and LAI in late July 1993 (b) in Quebec derived from AVHRR. In (a), MIXE denotes the mixed forest, DECI the deciduous forest, TRAN the transitional forest, CONI the coniferous forest, TUND arctic or alpine tundra or both, BARR barren lands, ARGI agricultural land, and CITY urban area.

and LAI after October to be the same as that at the end of October. The NDVI composites were produced from single-day coregistered images by using the maximum NDVI criterion (Robertson et al., 1992) to obtain cloud-free pixels. Further processing was performed to remove residual and subpixel cloud effects by using the CECANT (cloud elimination from composites using albedo and NDVI trend) procedure (Cihlar, 1996), to remove directional effects by using a semiempirical bidirectional reflectance model (Li et al., 1996), to replace contaminated pixels (Cihlar et al., 1996), and to mitigate the effects of residual random variations by using a five-step moving average. The final NDVI after the processing was corrected uniformly to a constant solar zenith angle of 45° under clear sky conditions. To use the algorithms developed by Chen and Cihlar (1996) for deriving LAI from NDVI obtained from Landsat thematic mapper (TM) images, a transformation of AVHRR NDVI to TM NDVI was performed by using a correction factor obtained by coregistering the two images at the same date. TM NDVI was found to be 10% higher than AVHRR NDVI over land surfaces. The algorithms are presumably most accurate for conifer and deciduous stands but are less reliable for agriculture and tundra areas because of the lack of field measurements for validation.

The LAI images from the composites were resampled to 1.0-km resolution in the lambert conformal conic (LCC) projection (49° N and 77° N standard parallels, 90° W meridian). The image size for Quebec is 1740 pixels by 1960 lines. In BEPS, the geographical location, in degrees north and west, of the center of each pixel in the LAI images were calculated by using the procedures provided by Snyder (1989). All images in this paper are in LCC projection, but all calculations in BEPS were made by matching spatial locations in geographical coordinates among input data types.

Land-Cover Map

The digital land-cover map for Quebec shown in Figure 3a was extracted from the Land Cover Maps of Canada provided by the Manitoba Remote Sensing Centre (MRSC) (Pokrant et al., 1991). The land-cover map was produced from National Oceanic and Atmospheric Administration AVHRR imagery. After panoramic correction, geographic registration, and radiometric calibration, the images were composited by using the highest NDVI criterion. Then, a combination of techniques including supervised maximum likelihood, parallelepiped, and manual classification was used. The classified image was reviewed by each province's forest department to ensure good accuarcy. The image displays the majority of the landscape in Quebec, including deciduous forest, coniferous forest, mixed forest, transitional forest, agricultural cropland, tundra, and barren land. The map is also resampled to a 1.0-km resolution in LCC projection, matching exactly with LAI images. A digital provincial boundary mask (provided by Pokrant of MRSC) was applied to the land-cover and LAI images to constrain the calculations.

The land-cover information was used in the LAI algorithms and for assigning, to each pixel, the biological parameters, the initial carbon content of plant components, and the foliage-clumping index. There is a series of biological parameters to be used in BEPS. Table 2 lists only the vegetation type–dependent biological parameters for the three major forest stands and grass. All other unlisted parameters remain the same as those in FOREST-BGC in the simulation, similar to the treatment in BIOME-BGC (Running and Hunt, 1993). The parameters in the table for deciduous and coniferous forests were based on Band (1993), except for the maximum mesophyll conductance, which was adjusted on the basis of Farquhar's photosynthesis model (Farquhar, 1980). An intermediate value for each parameter was taken for mixed forest. The parameters for grass, cited from Running and Hunt (1993), were tentatively used for agricultural cropland. For the other land-cover types, the parameters for coniferous forest were applied. In Table 2, the values of initial carbon contents of leaf, stem, and root for each type of forest were adjusted according to Quebec forest biomass data in RESEF (Gagnon et al., 1994) (see explanation in the section on ground measurement for model validation). These values for Quebec forest are lower than those set in the original FOREST-BGC (Running and Coughlan, 1988).

Soil Data

Soil data were acquired from the Soil Landscapes of Canada (SLC) database (Shields et al., 1991). The SLC consists of a number of coverages compiled in a GIS (ARC/INFO) at a scale of 1:1 million. Each mapped polygon was delineated according to the major characteristics of soil described by a standard set of attributes. The AWC in the upper 120 cm was included in a dominant soil landscape file as one of the attributes (SLC version 1.0). The AWC map was produced on the basis of soil texture information by using methods described by De Jong et al. (1984). Also from the SLC, the unrestricted rooting depth was found to be generally less than 120 cm in Quebec. Therefore, the attribute of AWC in the upper 120 cm was considered to be a good representation of the soil water characteristics, but some uncertainty is expected for vegetation with shallow rooting depth. With the use of ARC/INFO, the coverages containing AWC data for different regions of Quebec were mosaicked within the provincial boundary after careful edge matching along each boundary of the original coverages. The AWC data for the mosaic were rasterized into a digital file as an input to BEPS after the data were converted into grid cells of 0.02 degree in size. The AWC value ranges from 0.05 to 0.25 m in Quebec, with most grid cells falling in a narrow range of 0.05 to 0.15 m.

No AWC data are available north of 56° N, where the landscape is dominated by alpine tundra and barren lands with low productivity. A constant value of 0.1 m was used for this area with missing data. The location of the center of each grid cell was calculated within BEPS to match with other data sets.

Daily Meteorological Data

The meteorological data required by BEPS include daily temperature, humidity, shortwave radiation, and precipitation. Snowpack also is required as an initial condition. These data were collected from various sources in different data formats and grid systems, such as shown in Table 1. Because the gridded precipitation data were not available, a 1-degree grid system for this parameter was generated from the measurements. Figure 1 shows the spatial resolution and temporal intervals of input meteorological data prior to the simulation.

The gridded data of temperature and humidity were simulated by Canadian Meteorological Centre by using their global and regional analysis models and meteorological station data. The simulations have taken into account the topographic effects (Canadian Meteorological Centre, 1995). The gridded temperature values, after interpolation, were compared with more than 40,000 daily measurements from as many as 60 meteorological stations. The mean absolute difference between the two sets of data was found to be 1.2 degree, and the standard deviation of the difference was 1.3.

The shortwave radiation data were obtained from National Center for Atmospheric Research (NCAR), USA. The sum of the four 6-hourly readings was used as the daily total. The gridded data were 6-hourly forecasts by the National Meteorological Center (NMC) of NCAR, using their global spectral model (the MRF model). For the data before January 1995, the algorithm for calculating solar radiation was based on Lacis and Hanen's scheme (Lacis and Hanen, 1974) on clear-sky condition and did not account for the absorption by aerosols. This led to an overestimation of solar radiation at the surface, as discussed by Li et al. (1997). To quantify the overestimation, the gridded daily total solar radiation was compared with observations at as many as 40 stations in Canada in 1993 and 1994. The comparison results in an average reduction coefficient of 0.62 (38% overestimation) for the NCAR data, although the coefficient varies monthly. For these 2 years, the monthly average coefficient (standard deviation), in the sequence from January to December, is 0.567 (0.145), 0.660 (0.131), 0.665 (0.111), 0.719 (0.125), 0.671 (0.122), 0.692 (0.103), 0.674 (0.119), 0.606 (0.140), 0.605 (0.152), 0.588 (0.120), 0.583 (0.116), and 0.516 (0.133). The mean for the growing season from May to November was 0.62. Because the standard deviation was generally larger than the monthly difference in the coefficient, this constant correction factor was applied to NCAR gridded daily radiation data throughout the year. A similar comparison was made between the values from NCAR and the observed 10-day-total solar radiation averaged over 20–30 years from 20 stations within and around Quebec, and the average reduction coefficient was found to be 0.68. We realize that inaccuracies in the daily radiation data must have existed, but believe that the final NPP results will be little affected by such inaccuracies when the seasonal total is made accurate through the simple correction. Errors in daily NPP calculation due to random errors in daily radiation data are generally averaged out for the whole season where NPP is linearly related to radiation under nonstressed conditions, which was generally the case in Quebec in 1993. However, we expect that improvements in NPP estimation in drier areas can be substantial when accurate daily radiation data are used. Such data can be obtained by processing satellite data with the use of the methodologies described by Gauthier et al. (1980) and Eck and Dye (1991). Examples of NCAR reanalyzed data are given in Figure 4, which shows the distribution of daily total shortwave radiation after the correction (Fig. 4a) and the daily mean air temperature (Fig. 4b) in Quebec in 1993. In both cases, the large south–north gradients are evident, and the coastal effects are seen in the northward curvatures of the temperature isolines in the northeastern region.

For the daily precipitation and initial snowpack data, a 1-degree grid system was generated by interpolating or extrapolating the point values measured in as many as 60 stations in Quebec after quality control and removal of anomalous reported values. The following equation was used for the interpolation or extrapolation.

$$P_i=\sum W(i,j)\times Ps(j)/\sum W(i,j) \qquad \text{if no } d(i,j)=0,$$
$$P_i=Ps(j) \qquad \text{if one of } d(i,j)=0, \quad (7)$$

where P_i is the precipitation or snowpack in grid cell i, $Ps(j)$ is the observed value at meteorological station j, and $W(i,j)=1/d^2(i,j)$, in which $d(i,j)$ is the distance from grid i to meteorological station j.

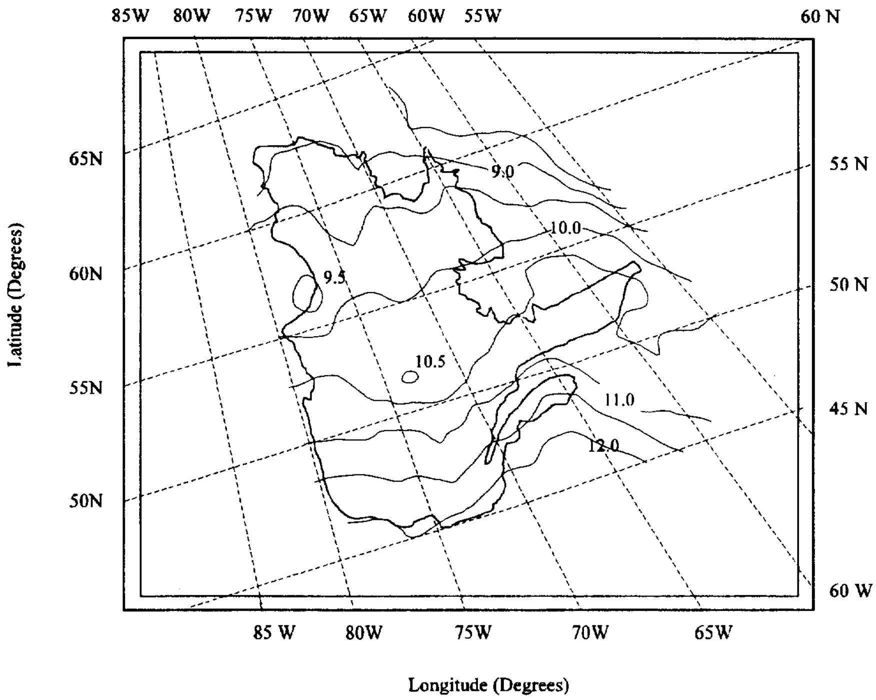
Figures 5a and 5b show, respectively, the spatial and temporal distributions of the precipitation in Quebec, 1993.

The gridded data at approximately 1-degree intervals are much coarser than remote-sensing data. In BEPS, the gridded data were bilinearly interpolated for each pixel of 1 km² to match the remote-sensing data (Mather, 1987) after the geographic location of the pixel had been determined (see the section on LAI). Such interpolation increases computation time considerably but, without the interpolation, patches in the NPP results are evident in the southern areas.

GROUND MEASUREMENT FOR MODEL VALIDATION

To validate BEPS, we used the ground-based measurements in forest stands in Quebec from the Le réseau de surveillance des écosystèmes forestiers (RESEF) database (Gagnon et al., 1994). The RESEF was established

(a)



(b)

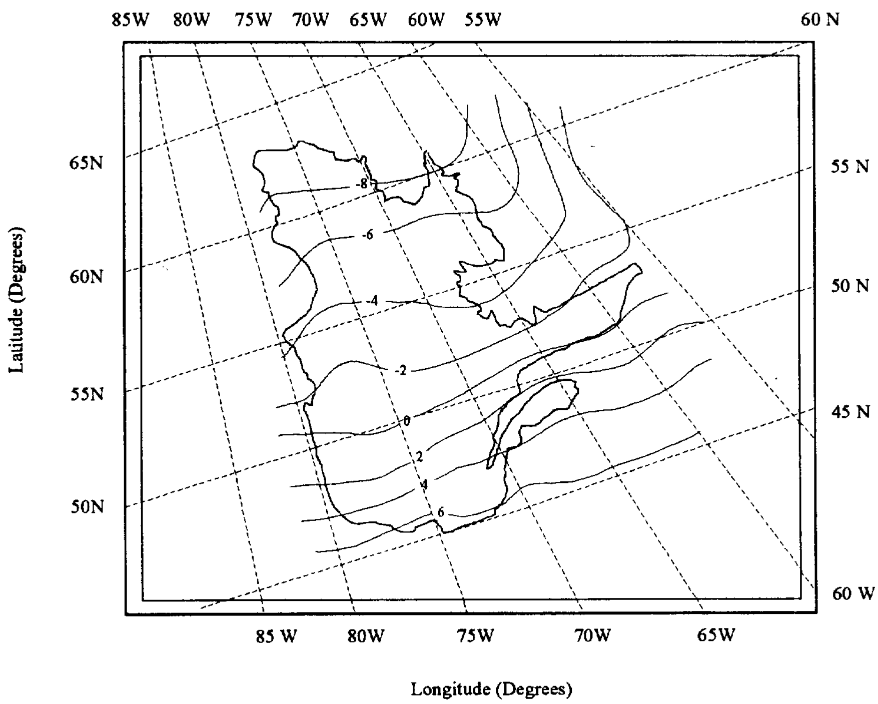


Figure 4. Spatial distribution of (a) mean daily shortwave radiation ($MJ/m^2/day$) and (b) mean daily air temperature (°C) in Quebec, 1993.

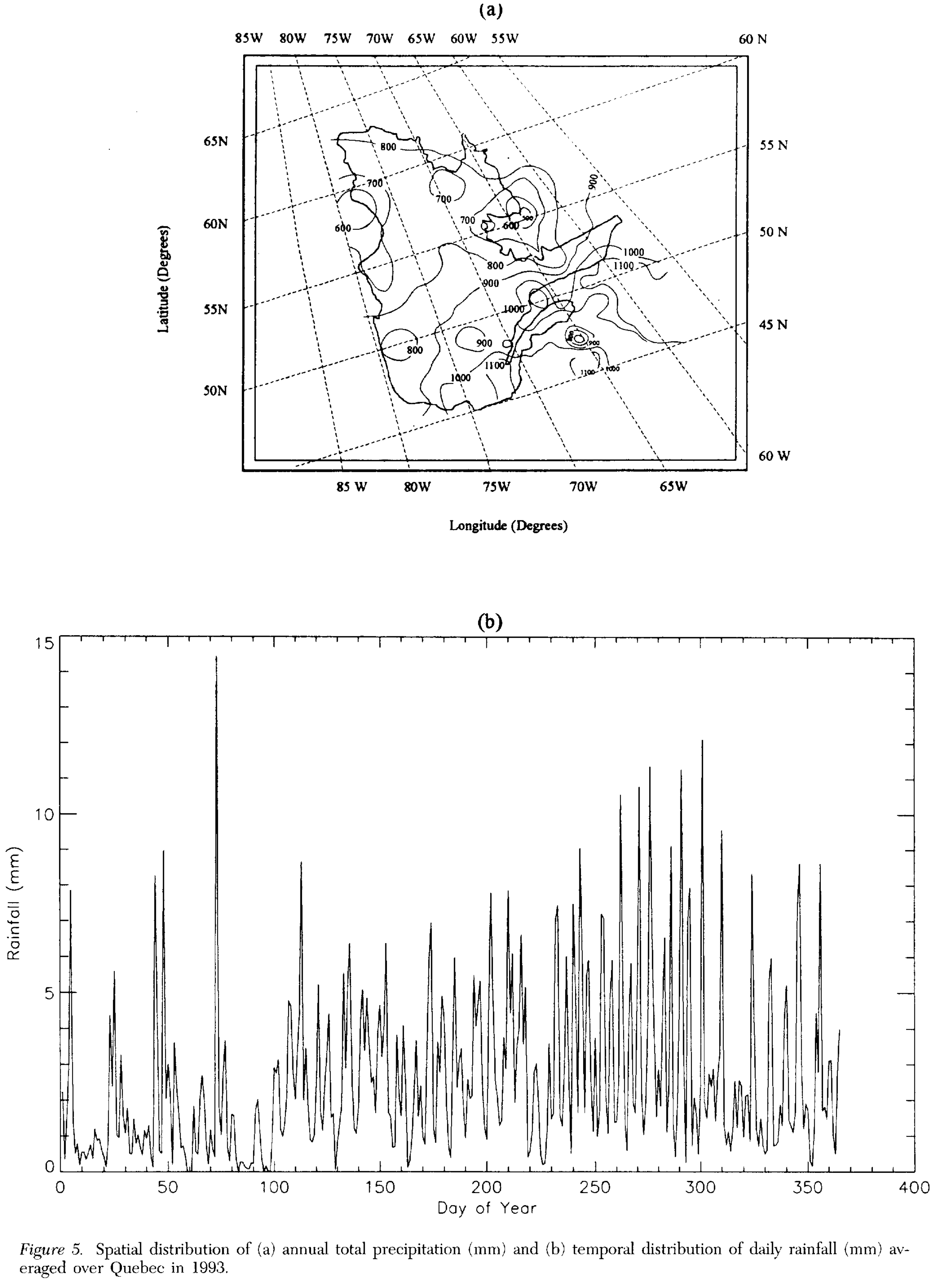


Figure 5. Spatial distribution of (a) annual total precipitation (mm) and (b) temporal distribution of daily rainfall (mm) averaged over Quebec in 1993.

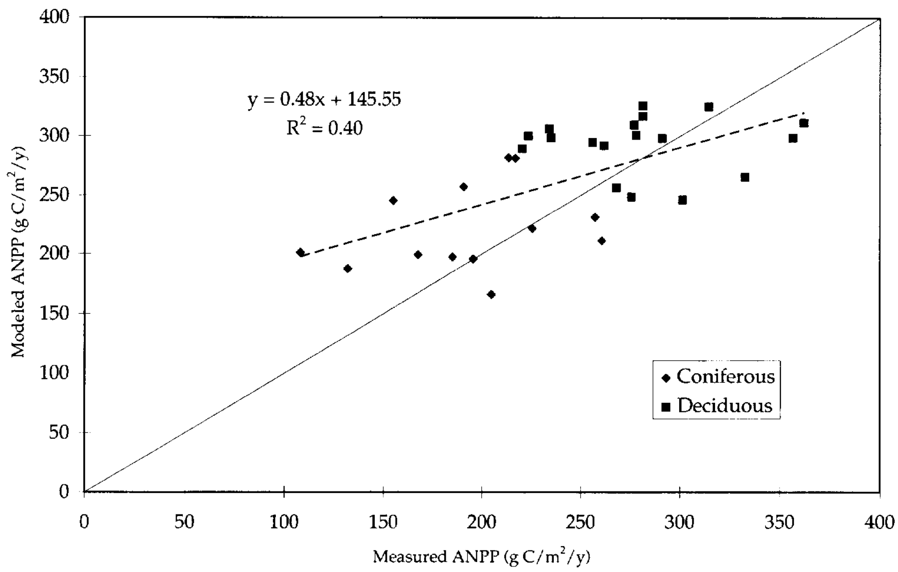


Figure 6. Comparison of measured and modeled annual above-ground NPP for 18 coniferous forest stands and 13 deciduous forest stands.

to evaluate the effect of environmental stress on the forest ecosystems in Quebec. Thirty-one sites, 50×50 m in size with a 100-m-wide buffer strip around each site, were chosen to represent various forest conditions in the commercial zone of Quebec's forests. The measurements include: diameter at breast height, defoliation, density of trees, coloration, insects and disease, and other parameters. By analyzing the RESEF data, Chouinard (1996) derived the above-ground NPP values at the 31 sites that vary from ~240 to ~800 g dry matter/m²/year. This is equivalent to ~110 to 360 g C/m²/year if a conversion coefficient of 0.45 between carbon and dry matter is taken (Jackson, 1992).

The corresponding pixels containing the individual sites in the AVHRR images were found from the geographical locations of the sites. However, because the accuracy of AVHRR geometrical correction is ±1 pixel, we have to select a 3×3 pixel window to ensure that the site is included. This implies that the accuracy in the comparison between model results and ground measurements depends on the representativeness of the site in the surrounding 3×3 pixel (9 km²) area.

RESULTS

Annual NPP

The modeled annual NPP was first compared with ground measurements at the 31 sites in the RSEEF database (Fig. 6). The ratio of below-ground to above-ground NPP was taken to be 0.5 for the conversion of whole plant NPP into above-ground NPP (ANPP) (Ruimy et al., 1994). The ANPP simulations and measurements at the locations compare reasonably well (r^2=0.40, n=31), with a range from 100 to 300 g C/m²/year for the coniferous forest and a range from 200 to 400 g C/m²/year for the deciduous forest. The total range of the modeled ANPP is smaller than that of the ground data because the remote-sensing area (3×3 km) used in the model is much larger than the typical dimensions (50×50 m) of ground-truth sites. It is expected that the variability in NPP or other parameters for the same cover types decreases as the sampling area increases. It is therefore difficult to completely validate the model output at the 3-km scale. Further work is required to study this scaling effect, using high-resolution remote-sensing data. Nevertheless, the good agreement between the average measured and modeled values provides a critical validation to the model. The agreement appears to be better for deciduous species than for conifer species. In general, the model overestimates NPP for conifer species in comparison with the ground data. The sources for this discrepancy include: (1) inaccurate assignment of the biological parameters (especially maximum stomatal conductance and biomass), (2) error in remote-sensing measurements, and (3) bias in ground-based measurements. We are not able to determine the correct source, because of a lack of data. From remote-sensing measurements, conifer species have higher LAI than do deciduous species; without considering the different clumping effects as given in Eq. (6), these two cover types would have similar NPP ranges. This suggests that it is important to consider canopy architectural effect on PAR absorption in productivity simulations. The other weakness in the comparison is that

Figure 7. Spatial distribution of annual NPP in Quebec in 1993 modeled by BEPS.

ground measurements of NPP are available only for the lifetime (60–90 years) average for the sites, whereas modeled NPP is for 1993, a relatively normal year.

Figure 7 shows the annual NPP distribution in Quebec in 1993 calculated by BEPS. The highest NPP (~300–600 g C/m^2/year) appeared in southern Quebec, where land-cover types are predominantly deciduous forest, mixed forest, and agricultural land. North of these areas, NPP gradually decreased from about 200–400 g C/m^2/year for coniferous forest to about 10–200 g C/m^2/

Table 3. NPP Results from Various Models°

Vegetation Type	This Study	Leith (1975)	Potter et al. (1993)	Melillo et al. (1993)	Bonan (1995)	Prince et al. (1995)	In 30°–60° N (% Global)
Broadleaf deciduous forest	381	771	315	763	433	781	75
Mixed forest	384	386	316	669	338	920	85
Needleleaf evergreen forest	231	340	226	276	509	833	59
Cropland	433	—	288	—	437	468	67
Tundra	23	171	80	120	143	130	8

° Values are derived from Bonan (1995), Table 5, and Prince et al. (1995), Table 1.
Unit is g C/m²/year. To be consistent with Bonan, a coefficient of 0.50 for converting biomass into carbon is used. BEPS results are for Quebec in 1993, and all other model results are for the globe for different periods. The percentage of each cover type in 30°–60° N region is given to indicate the representativeness of BEPS results at the global scale.

year for transition forest. Farther north are mostly alpine tundra and barren lands, with NPP below 10 g C/m²/year.

The annual NPP values for various cover types in Quebec simulated with BEPS are within the ranges of other NPP results for the globe, such as those by CASA (Potter et al., 1993), TEM (Melillo et al., 1993), and DEMETER (Foley, 1994); that is, from 200 to 600 g C/m²/year. However, BEPS provides much more detailed information with spatial resolution about 10^2 times higher than that of other models. Such higher-resolution data not only enable us to study the spatial variability, but also provide better statistics for each cover type. Table 3 shows the mean NPP for various vegetation types estimated by BEPS and other models. In Quebec, most broadleaf forests are deciduous and most needleleaf forests are evergreen. Therefore, only these vegetation types are included in Table 3. An exact comparison of the model results is not possible because the statistics of all other models were given as the global averages over different time periods, whereas BEPS results so far are confined to Quebec and only for 1993. However, Table 3 is of interest because it compares the model performance with those of others. Included in Table 3 also is the percentage of the various cover types within the 30° N to 60° N zone reported by Potter et al. (1993). It may be noted that NPP ranges widely among the models. BEPS and most models obtain higher NPP in broadleaf deciduous forest than in evergreen needleleaf forest and intermediate values for mixed forest, except for the models by Bonan (1995) and Prince et al. (1995), which calculated higher values for conifer than for deciduous forest, indicating the difficulty in model representation for the physiological processes of different species. The values of NPP for these three types of forests from BEPS are within the lower range of other models and are in close agreement with those from CASA (Potter et al., 1993). NPP values in Quebec are expected to be lower than the global averages for the various forest types because much of the forest of the same types is located south of 45° N. Note also that BEPS's estimates are relatively high for cropland and low for tundra compared with other model results. The comparison here is intended to indicate only existing results rather than the evaluation of BEPS and other models because of the difference in time periods and spatial scales. However, the large ranges of NPP values for each vegetation type from the different models clearly indicate that much effort is needed to improve our estimates at the global scale.

Beaudu (1994) and Royer et al. (1995) used a parameteric model that estimates NPP by relating an efficiency production coefficient to the total amount of shortwave radiation intercepted by the canopy. In their results, an average NPP over several years was from about 310 to 340 g C/m²/year for mixed or pure deciduous forests, about 200 g C/m²/year for coniferous forest, about 60 g C/m²/year for transitional forest, and about 50 g C/m²/year for tundra. Although their land-cover classification was slightly different from ours, the NPP for different vegetation types closely agrees with our values in spite of the small discrepancy for transitional forest and tundra.

Table 4 shows the annual NPP in 1993 averaged for land-cover types and the number of pixels occupied by each land-cover type in Quebec. A summation of the NPP for all land-cover types reveals that the total NPP in Quebec is estimated to be 0.24 Gt C in 1993, which is 0.3–0.4% of the global NPP (Leith, 1975; Ruimy et al., 1994).

Seasonal Variations in NPP

The seasonal NPP distributions in Quebec in 1993 are illustrated in Figure 8. The NPP values in the first and the last quarter of the year were about two orders of magnitude lower than those in spring and summer seasons. This suggests that the annual NPP can be modeled only over the span of the spring and summer months in Quebec with adequate accuracy, because most of NPP is accumulated during that period. The NPP appeared slightly negative in some areas in the first and the last three months of the year, indicating that the autotrophic respiration exceeded the gross primary production during those periods.

Modeled results show that, in 1993, there was more NPP accumulated from July to September than from April

Table 4. Annual NPP for Different Land-Cover Types in Quebec, 1993

Vegetation Type	*NPP (g C/m²/year) Mean (Std)*	*No. Pixel*	*Total NPP (Mt C/year)*
Deciduous forest	381 (97)	47,821	18.2
Mixed forest	348 (144)	240,656	83.8
Coniferous forest	231 (129)	380,422	85.5
Transitional forest	102 (80)	339,983	34.8
Agricultural cropland	433 (134)	31,257	13.5
Arctic/alpine tundra	23 (33)	239,118	5.5
Barren lands	8 (0.04)	59,167	0.5
City	8 (0.42)	569	0.0
Total NPP (Mt C/year)			**241.9**

to June in Quebec. There are probably two reasons for the seasonal distribution: (1) rainfall was greater in the summer than in the spring (Fig. 5b) and (2) maximum LAI was in late summer according to the remote-sensing input. In the NPP results calculated by the TEM model for South America (Raich et al., 1991), the opposite distribution pattern existed for all cover types except for evergreen forest, mainly because of the dry season in the summer. By the use of daily meteorological data and remotely sensed LAI data for each pixel at 10-day intervals, BEPS can detect the seasonality of NPP more realistically than can other process models, such as DEMTER (Foley, 1994) and LSM (Bonan, 1995), in which a constant value of LAI for each classified vegetation type was taken from the literature at monthly or seasonal steps.

Evapotranspiration

Estimated annual evapotranspiration in Quebec ranged from less than 20 mm in the most northern area to ~800 mm in the southern area (Fig. 9). The spatial distribution of the evapotranspiration bore some resemblance to the land-cover pattern shown in Figure 3a, but other environmental conditions also affected evapotranspiration. The highest evapotranspiration rates were associated with the agricultural cropland and the deciduous forest, followed by the mixed forest, the coniferous forest, and the transitional forest. As expected, the evapotranspiration rate in the tundra land was the lowest (Fig. 9, Table 5).

DISCUSSION

As highly synthesized quantitative information, NPP is one of the most important parameters characterizing the performance of a stand and an ecosystem. In this paper, we present the first-ever NPP map for Quebec at 1-km resolution for a specific year. This spatial information is useful for natural-resource management and for global-change studies. With the simple validation using ground-based NPP data, we estimate that the accuracy of a 3×3 pixel area is about 75% of the true ground value. This accuracy estimate is largely based on the mean absolute difference of 48 g C/m²/year between modeled and measured NPP values, or 19% relative error in the modeled results. If biophysical parameters can be scaled linearly, the error in the modeled results based on remote-sensing measurements will reduce as the size of the averaging area increases. For a large area, the random error is eliminated and only the bias errors remain, which will be considerably smaller than 19%. At 3×3-km resolution, much of the 19% error is due to variation of NPP within the pixels (i.e., nonrepresentativeness of a 50×50 m ground plot for the 3×3-km area). The same principle of error estimation can be applied to the ground data. The error in the individual ground data was estimated to be about 30% (Beaudu, 1994). If all sources of the error are random, the error in the mean of the 31 ground measurements will be 5.5%. The 75% accuracy for a 3×3-km area is a conservative estimate as unity less the sum of 19% and 5.5% without consideration for the reduction of random error within the area. However, there are also other unknown additive bias errors such as representativeness of 1993 for the life span of the stands. If we judge from the smoothness in the NPP variation in neighboring pixels, the accuracy of individual pixels is only slightly lower than the 3×3 pixel average. With support of ground-based data, the NPP map presented in this paper can therefore be used as a test bed for many models applied on the global scale. However, we caution that the accuracies for cropland and grassland and for the four season NPP and annual evapotranspiration results are unknown, because of a lack of ground data for comparison. The accuracy of these results depends on how closely the model represents biological and physical processes controlling plant growth and development. Although we do not have sufficient data to validate all components of the model, we believe that it has captured the major canopy processes and the four-season results have similar accuracy. We are in the process of validating the components of BEPS by using data from the BOREAS and applying it to the entire Canadian landmass.

Compared with statistical and parameteric models, a process model such as BEPS has the following advantages:

Figure 8. Seasonal variation of NPP in Quebec, 1993.

1. Remote-sensing data are effectively used in the model to obtain spatially explicit distributions of NPP. Such spatial information not only provides visual aids in resources management, but also allows for improved regional estimation of NPP by land-cover type.
2. Changes in vegetation detected by remote sensing can be immediately considered in NPP estima-

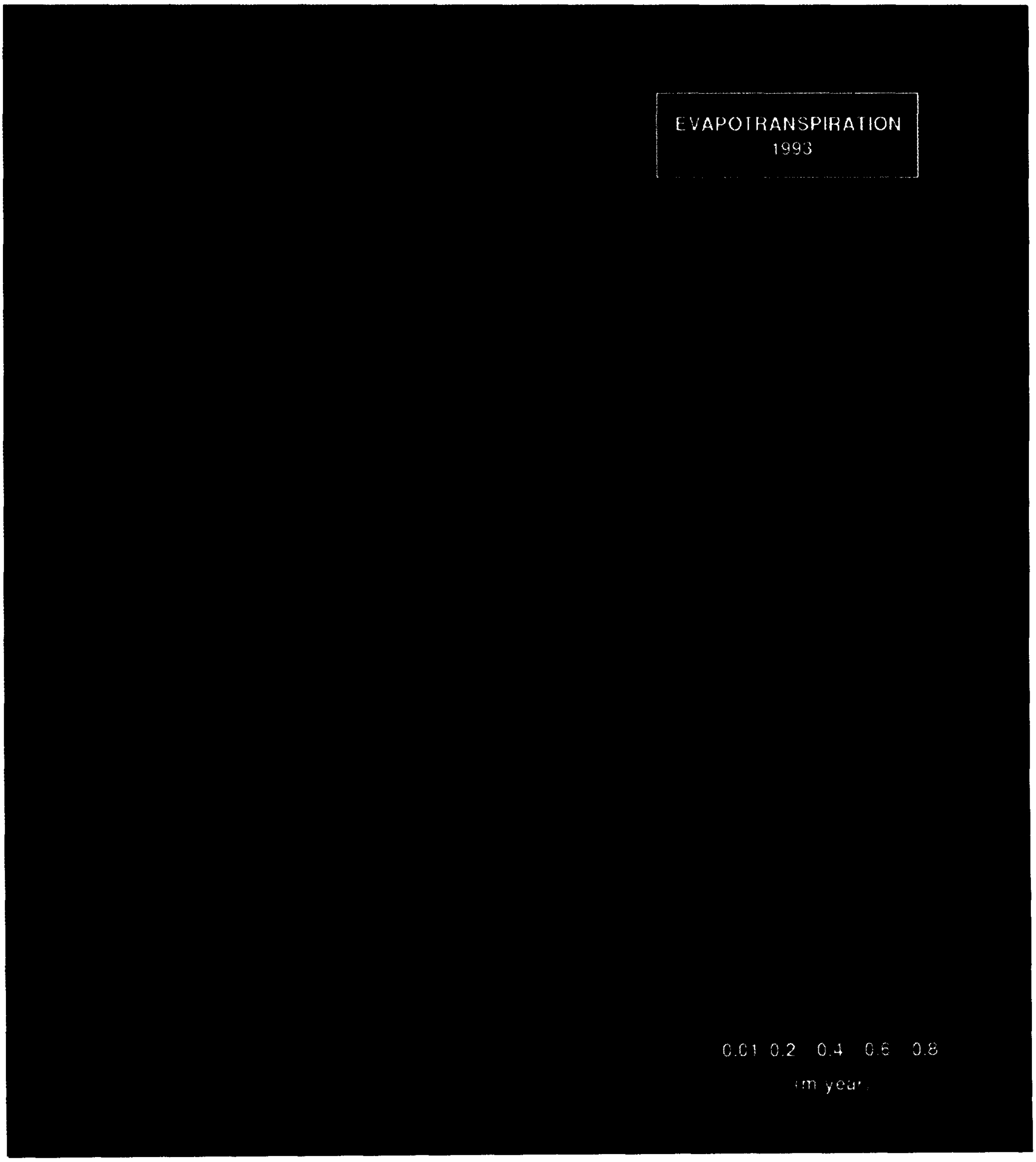


Figure 9. Spatial distribution of evapotranspiration in Quebec, 1993.

tion. Both land-cover type and LAI are dynamic variables in an ecosystem. Timely remote sensing data are important in accurate NPP calculation.

3. Meteorological and environmental variables are mechanistically incorporated into the model. With large temporal and spatial variations in these variables, the model can be used to capture seasonal and interannual variabilities in NPP over large ar-

Table 5. Mean Evapotranspiration Rate for Different Vegetation Types

Vegetation Type	Evapotranspiration (mm/year) Mean (Std)
Decidious forest	514 (95)
Mixed forest	458 (135)
Coniferous forest	369 (154)
Transitional forest	161 (103)
Agricultural cropland	614 (144)
Arctic/alpine tundra	26 (27)

eas and to study the effect of climate change on ecosystems.

4. The model can be improved as knowledge and data availability and quality improve. The improved model can be run retrospectively to investigate long-term variability in NPP.

SUMMARY

A daily process model, named Boreal Ecosystems Productivity Simulator was developed for estimating NPP for large areas by using remote sensing, gridded daily meteorological data, and soil data. With current computing technology, it is feasible to implement the daily process model at a regional scale with moderate resolutions (0.25–1.0 km). The combination of this relatively high spatial and temporal resolution modeling enables us to obtain reliable and spatially explicit NPP distribution.

Through the development of BEPS and its implementation in Quebec, we conclude the following modeling methodological points:

1. The canopies of boreal forests, either deciduous or conifer as well as mixed species, have a highly organized architecture. Such architecture has important effects on radiation absorption by the canopy and on the productivity and should be considered in productivity models.
2. The accuracy in LAI strongly affects almost all components of the model, including radiation absorption, transpiration, photosynthesis, respiration, rainfall interception, and soil water balance. For open boreal stands where radiation interception is far from the asymptotic value, the accuracy in LAI is especially important. Reliable remote-sensing LAI data are a prerequisite for regional application of a process model.
3. Land-cover type information also is important because the functionalities of the various species are very different. Changes in cover type affect NPP statistics for a region.

This study is part of the Northern Biosphere Observation and Modelling Experiment (NBIOME). The biological principles adopted in BEPS from the original FOREST-BGC, before the modification, are the same as those in RHESSys (1992 version), which was developed by Dr. L. Band and colleagues at the University of Toronto. The authors are grateful to Dr. A. Royer of the University of Sherbrooke, for providing the RESEF data and the normal radiation data, and Dr. Z. Li of the Canada Centre for Remote Sensing, for helpful discussion and review. We acknowledge the data acquired from Environment Canada, Agriculture and Agri-Food Canada, NCAR, and MRSC. The assistance of Mr. David Fraser, Tony Richichi, and Martin Guilbeault in data handling and analysis is appreciated.

REFERENCES

Band, L. E. (1993), A pilot landscape ecological model for forests in central Ontario. Forest Fragmentation and Biodiversity Project, Report 7. Ontario Forest Research Institute, Ontario, Canada.

Band, L. E., Patterson, P., Nemani, P., and Running, S. W. (1993), Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology. *Agric. For. Meteorol.* 63: 93–126.

Band, L. E., Peterson, D. L., Running, S. W., Coughlan, J., Lammers, R., Dungan, J., and Nemani. R. (1991), Forest ecosystem process at the watershed scale: basis for distributed simulation. *Ecol. Model.* 56:171–196.

Beaudu, F. (1994), Modeling boreal forest productivity in Quebec using NOAA satellite imagery. M.S. Thesis, CATEL, University of Sherbrooke, Canada.

Bonan, G. B. (1995), Land-atmosphere CO_2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model. *J. Geophys. Res.* 100: 2817–2831.

Canadian Meteorological Centre (1995), *CMC Reference Guide*. Canadian Meteorological Centre. Dorval, Quebec.

Chen, J. M. (1996a), Optically-based methods for measuring seasonal variation of leaf area index in boreal conifer stands. *Agric. For. Meteorol.* 80:135–163.

Chen, J. M. (1996b), Canopy architecture and remote sensing of the fraction of photosynthetically active radiation absorbed by boreal conifer forests. *IEEE Trans. Geosci. Remote Sens.* 34:1353–1368.

Chen, J. M., and Cihlar, J. (1995), Quantifying the effect of canopy architecture on optical measurements of leaf area index using two gap size analysis methods. *IEEE Trans. Geosci. Remote Sens.* 33:777–787.

Chen, J. M., and Cihlar, J. (1996), Retrieving leaf area index of boreal conifer forests using landsat TM images. *Remote Sens. Environ.* 55:153–162.

Chouinard, M. (1996), Évaluation et analyse de la productivité primaire nette de la forêt au Québec. Essai de maîtrise en environment, Université de Sherbrooke (rédection en cours).

Cihlar, J. (1996), Identification of contaminated pixels in AVHRR composite image for studies of land biosphere. *Remote Sens. Environ.* 56:149–163.

Cihlar, J., Chen, J. M., Li, Z. (1996), Seasonal AVHRR multichannel data sets and products for scaling up biospheric processes. *J. Geophys. Res.* (in press).

De Jong, R., Shields, J. A., and Sly, W. K. (1984), Estimated soil water reserves applicable to a wheat-fallow rotation for generalized soil areas mapped in southern Saskatchewan. *Can. J. Soil Sci.* 64:667–680.

Eck, T. F., and Dye, D. C. (1991), Satellite estimation of incident photosynthetically active radiation using utraviolet reflectance. *Remote Sens. Environ.* 38:135–146.

Farquhar, G. D., von Caemmerer, S., and Berry, J. A. (1980), A biochemical model of photosynthetic CO_2 assimulation in leaves of C_3 species. *Planta* 149:79–90.

Foley, J. A. (1994), Net primary productivity in the terrestrial biosphere: the application of a global model. *J. Geophys. Res.* 99:20,773–20,783.

Gagnon, G., Gravel, C., Ouimet, R., Dignard, N., Paquin, R., and Jacques, G. (1994), Le réseau de surveillance des écosystèmes forestiers (RESEF) II: description des places d'étude et données de base. Mémoire de Recherche Forestière No. 116, Ministères des Ressources Naturelles Québec.

Gauthier, C., Diak, G., and Masse, S. (1980), A simple physical model to estimate incident solar radiation at the surface from GEOS satellite data. *J. Appl. Meteorol.* 19:1005–1012.

Jackson, R. B., IV (1992), On estimating agriculture's net contribution to atmospheric carbon. *Water Air Soil Pollut.* 64:121–137.

Lacis, A. A., and Hansen, J. E. (1974), A parameterization for the absorption of solar radiation in the earth's atmosphere. *J. Atmos. Sci.* 31:118–133.

Law, B. E., and Waring, R. H. (1994), Combing remote sensing and climate data to estimate net primary production across Oregon. *Ecol. Appl.* 4:717–728.

Li, Z., Cihlar, J., Zhang, X., Moreau, L., and Ly, H. (1996), Detection and correction of the bidirectional effects in AVHRR measurements over northern regions. *IEEE Trans. Geosci. Remote Sens.* 34:1308–1322.

Li, Z., Moreau, L., and Arking, A. (1997), On solar energy disposition: a perspective from observation and modeling. *Bull. Am. Meteorol. Soc.*. 78:53–70.

Lieth, H. (1975), Modeling the primary productivity of the world. In *Primary Productivity of the Biosphere* (H. Lieth and R. H. Whittaker, Eds.), Springer-Verlag, New York.

Lieth, H., and Whittaker, R. H. Eds. (1975), *Primary Productivity of the Biosphere.* Springer-Verlag, New York.

Mather, P. M. (1987), *Computer Processing of Remotely-Sensed Images: An Introduction.* Wiley, Chichester, New York, Brisbane, Toronto, Singapore.

Melillo, J. M., McGuire, A. D., Kicklinghter, D. W., Moore B., III, Vorosmarty, C. J., and Schloss, A. L. (1993), Global climate change and terrestrial net primary production. *Nature* 363:234–240.

Pokrant, H., Palko, S., and Jowe, J. (1991), The use of remote sensing in producing the *National Atlas of Canada.* Geographic Information Systems Seminar, Canadian Institute of Surveying and Mapping, Ottawa, Nov. 25–26.

Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., and Klooster, S. A. (1993), Terrestrial ecosystem production: a process model based on global satellite and surface data. *Global Biogeochem. Cycles* 7:811–841.

Prince, S. D., Goets, S. J., and Goward, S. N. (1995), Monitoring primary production from earth observation satellites. *Water Air Soil Pollut.* 82:509–522.

Raich, J. W., Pastetter, E. B., Melillo, J. M., Kicklighter, D. W., Grace, P. A., Moore, B., III, and Peterson, B. J. (1991), Potential net primary productivity in South America: application of a global model. *Ecol. Appl.* 1:399–429.

Robertson, B., Erickson, A., Friedel, J., Guindon, B., Fisher, T., Brown, R., Teillet, P., D'Iorio, M., Cihlar, J., and Sancz, A. (1992), GEOCOMP: a NOAA AVHRR geocoding and compositing system. Proceedings of the ISPRS Conference, Commission 2, Washington, D.C., Aug. 2–14, pp.223–228.

Royer, A., Gota, K., Beaudu, F., and Cihlar, J. (1995), Boreal forest dynamics and productivity analysis from NOAA-AVHRR global vegetation index database. Proceeding of the International Colloquium Photosynthesis and Remote Sensing, 28–30 August 1995, Montpellier, France.

Ruimy, A., Saugier, B., and Dedieu, G. (1994), Methodology for the estimation of terrestrial net primary production from remotely sensed data. *J. Geophys. Res.* 99(D3):5263–5383.

Running, S. W. (1994), Testing FOREST-BGC ecosystem process simulation across a climatic gradient in Oregon. *Ecol. Appl.* 4:238–247.

Running, S. W., and Coughlan, J. C. (1988), A general model of forest ecosystem processes for regional applications I: hydrological balance, canopy gas exchange and primary production processes. *Ecol. Model.* 42:125–154.

Running, S. W., and Hunt, E. R. (1993), Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global scale models. In *Scaling Physiological Processes: Leaf to Globe* (J. R. Ehleringer and C. B. Field, Eds.), Academic Press, San Diego, pp. 141–158.

Running, S. W., Nemani, R. R., Peterson, D. L., Band, L. E., Potts, D. F., Pierce, L. L., and Spanner, M. A. (1989), Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. *Ecology* 70:1090–1101.

Runyon, J., Waring, R. H., Goward, S. N., and Welles, J. M. (1994), Environmental limits on net primary production and light-use efficiency across the Oregon transect. *Ecol. Appl.* 4:226–237.

Ryan, M. G. (1991), A simple method for estimating gross carbon budgets for vegetation in forest ecosystems. *Tree Physiol.* 9:255–266.

Shields, J. A., Tarnocai, C., Valentine, K. W. G., and MacDonald, K. B. (1991), *Soil Landscapes of Canada: Procedures Manual and User's Hand Book.* Agriculture Canada, Agriculture Canada Publication 1868/E, Ottawa, Ontario.

Snyder, J. P. (1989), Map projections: a working manual. U.S. Geological Survey Professional Paper, Supt. of Dpcs. No.: I 19.16:1395, U.S. Government Printing Office, Washington, D.C.