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TERRESTRIAL NPP: TOWARD A CONSISTENT DATA SET FOR GLOBAL MODEL EVALUATION

J. M. O. Scurlock,[1,5] W. Cramer,[2] R. J. Olson,[1] W. J. Parton,[3] and S. D. Prince[4]

[1]*Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6407 USA*
[2]*Potsdam Institute for Climate Impact Research, Potsdam 14412, Germany*
[3]*National Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado 80523 USA*
[4]*Department of Geography, University of Maryland, College Park, Maryland 20742-8225 USA*

Abstract. Progress in modeling the global carbon cycle is inhibited by the lack of a high-quality data set based upon field observations of net primary productivity (NPP) with which to calibrate, parameterize, and evaluate terrestrial biosphere models. Under the auspices of the Global Primary Production Data Initiative (GPPDI), an activity endorsed by the International Geosphere–Biosphere Program's Data and Information System, a small international workshop was held in Cincinnati, Ohio, USA, in December 1996 to address the problem of extrapolating sparse field observations of NPP to produce a consistent database representative of major biomes. We report the conclusions of this workshop and the goals of GPPDI—to further expand the existing data compilation, to agree upon consistent standards for cross-site comparisons and allometric relationships for various biome types, and to document methodologies for spatial extrapolation from point measurements to grid cells. The resulting NPP database will also have intrinsic value: global data are important for many ecological problems, and NPP is a kind of ‘‘pathfinder’’ for other ecological data sets.

Key words: carbon cycle, global; modeling the global carbon cycle; net primary productivity; NPP data use for model validation; NPP field data, need for consistency.

INTRODUCTION

Net primary production (NPP) is an important component of the global carbon cycle. NPP data are more widely available than other estimates of biosphere–atmosphere exchange of carbon such as gross primary production (GPP) and net ecosystem exchange (NEE). Nevertheless there are notable problems associated with field-measurement techniques for NPP (Olson et al. 1997), and most published data sets omit significant components that are hard to measure, such as fine-root production. Destructive methods are required to directly estimate the NPP for a given period of accumulation, but these often ignore certain trophic flows or components of NPP, and thus rarely give a complete account of the net carbon flux. Therefore the aggregation of existing observations to develop estimates of the regional or global total flux involves significant uncertainties, and must partly rely on simulation models (Cramer et al. 1996). Most studies of the global carbon cycle either use very generalized data (e.g., that of Lieth and Whittaker [1975]) or develop their own biome-specific methods and paradigms for the interpretation of the available data.

To address this problem, the Global Primary Production Data Initiative (GPPDI) was established as a coordinated activity to identify existing field-data sets of primary production and associated data about the measured ecosystem and its environment (Prince et al. 1995*b*). It originated from a scheme to compare existing NPP models, sponsored by GAIM (the International Geosphere—Biosphere Program [IGBP] task force on Global Analysis, Interpretation, and Modeling), with the support of IGBP-DIS (the IGBP Data and Information System) and GCTE (the IGBP core project on Global Change and Terrestrial Ecosystems). Currently several projects are contributing to the GPPDI, each undertaken by a separate institution having appropriate expertise.

The data-set compilation is following three steps: (1) collection of data sets for sites representative of the major biomes (including quality assessment and reformatting into a standard structure); (2) statistical analysis of these data with respect to driving environmental variables; and (3) extrapolation or ‘‘regionalization’’ of the data to areas of a size appropriate for comparison with broad-scale model applications, i.e., up to 0.5° × 0.5° longitude and latitude. The emphasis is on those variables needed to parameterize and evaluate terrestrial biosphere models, including above- and belowground NPP, aboveground live biomass, leaf area index (LAI), climate, site characteristics, and local variability of these variables in the landscape. The GPPDI does not attempt uniform global coverage; rather it will compile a sample of data sets and grid cells covering a range of physical environmental conditions, vegetation types, and degrees of management. Overall, the aim of

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[5] E-mail: npq@ornl.gov

the GPPDI is to add value and consistency to existing NPP data.

GLOBAL-MODEL DEVELOPMENT AND EVALUATION: DATA REQUIREMENTS

The carbon (C) flow through terrestrial ecosystems may be partitioned into a number of fluxes: gross primary production (GPP), autotrophic and heterotrophic respiration, net primary production (NPP—which can be partitioned into aboveground, ANPP, and belowground, BNPP), and net ecosystem production (NEP, net change in organic matter for the vegetation and soil—usually measured over days to months as net ecosystem exchange, NEE, or, in managed systems, over significant fractions of rotation lengths). NPP comprises a substantial and relatively constant proportion of GPP, and is a good index of potential economic production (food, fuel, fiber or timber). More estimates are available for it than for other components of the C budget—thus in most cases it is one of the leading descriptor variables of terrestrial ecosystems. However, a limited number of detailed multidisciplinary studies have provided simultaneous measurements of net carbon exchange between terrestrial ecosystems and the atmosphere using the eddy covariance approach, chamber measurements over the growing season, annual biomass increment, and detritus production estimates—data that are preferred for testing process-based models that may be used to scale NPP estimates to larger regions. Although increasing in number, data from such studies are rare (e.g., BOREAS, Sellers et al. 1995; FIFE, Hall et al. 1989; HAPEX-Sahel, Prince et al. 1995*a*; and the proposed Large-scale Biosphere–atmosphere experiment in Amazonia, LBA Science Planning Group 1996).

To estimate global carbon fluxes between the atmosphere and terrestrial biosphere, at least 30 terrestrial biosphere models (TBMs) have now been developed. Some use a map of vegetation structure for appropriate initialization of environmental and canopy characteristics as input to physiology-based flux estimations (e.g., FBM, Lüdeke et al. 1994; TEM, McGuire et al. 1995); others predict vegetation structure based upon potential land cover (e.g., BIOME1, Prentice et al. 1992; MAPSS, Neilson 1993). Some recent models simulate both vegetation structure and carbon fluxes (e.g., DOLY, Woodward et al. 1995; BIOME3, Haxeltine and Prentice 1996). Yet another group of models uses direct observations from satellites with a minimum of or no mapped inputs (e.g., GLO-PEM, Goward and Prince 1995). What is common to all the above models is that evaluation against observed data remains rare.

Few global biosphere models are designed to simulate carbon flux only; rather, most have broader purposes and simulate many variables. However, NPP is estimated by almost all models; therefore NPP is a common variable than can be compared among models. On the other hand, since no model simulates NPP alone, some of the other simulated quantities should also be compared, to ensure that NPP has been simulated correctly and for the right reasons (Table 1). The different parameters used by TBMs as input and output variables have been reviewed elsewhere (Cramer et al. 1999). Perhaps the greatest challenge facing the climate change/modeling community is to establish independent and credible estimates of carbon fluxes and their control—by demonstrating plausible links between field data, carbon flux models, satellite observations, and the globally aggregated data on atmospheric CO_2 concentration and isotopic composition (Fung 1997, Randerson et al. 1997, Scurlock and Hall 1998).

NPP DATA SETS

NPP data worldwide have not been extensively reviewed since the synthesis of Lieth and Whittaker (1975), despite a growing number of studies—ranging from 10–20 comprehensively investigated sites where most factors controlling NPP (net primary production) are relatively well measured (e.g., Jädraås, Linder and Axelsson 1982; BOREAS, Sellers et al. 1995) to the extensive data collections of thousands of points for which only a limited set of variables are known (e.g., litter fall, tree or crop biomass), which may nevertheless be used to test spatial patterns of NPP. Between these two extremes, a set of perhaps 100–300 relatively well-characterized study sites can be identified, for which important components of NPP have been measured on different occasions (ideally a time series), together with driving environmental variables such as climate. Such a data set will be invaluable for model development and evaluation. To advance towards this goal beyond the mere compilation of data, the GPPDI (Global Primary Production Data Initiative) is currently developing: (a) a standardized approach to estimate NPP components that are not usually measured in the field, e.g., belowground NPP, litter fall, etc.; (b) a systematic way to estimate NPP from statistical data from agriculture, pasture, and managed forests; and (c) means to estimate NPP of large areas, up to 0.5° × 0.5°, by extrapolation from point data.

In general, there is a discrepancy between the desirable variables for validation and those that are commonly available from various observations (Table 1). The remainder of this paper explores the nature of this discrepancy with respect to (1) the selection of study sites and data sets, (2) methods of processing field data to estimate NPP, and (3) scaling-up from study sites to grid cells.

Data Sources

The GPPDI is accumulating data both from intensive study sites and from extensive data collections, with initial emphasis on grasslands, boreal forests, and tropical forests. For example, work began from a grassland data set assembled under an earlier project for use with the CENTURY and SAVANNA plant–soil ecosystem models (Breymeyer and Melillo 1991, Coughenour 1992, Parton et al. 1993, Parton et al. 1995), which was expanded using data from other grassland study sites. The compilation of the GPPDI database also encompasses biomass and production data from the International Biological Program (IBP)—particularly for those biomes often underrepresented (such as tundra)—as well as other existing data compilations (e.g., Lieth and Box 1972, Esser 1991, Gholz et al. 1994, Esser et al. 1997). Additional data are being sought from circumpolar boreal forest studies, worldwide litterfall studies, and forest, crop, and rangeland inventory data from the former USSR and USA (Olson et al. 1997). Extant compilations are maintained separately in their original forms, as well as being included in the data reprocessed under GPPDI auspices. A database of these biomass and NPP measurements has been established at Oak Ridge National Laboratory (ORNL; Oak Ridge, Tennessee, USA), based on NASA (National Aeronautics and Space Administration) data guidelines (see Table 2 for status of database development).[6]

TABLE 1. List of information commonly available (A) and/or desirable (D) for parameterization and evaluation of net primary productivity (NPP) models.

Class	Information type	Frequency of measurement
Site-specific data		
A	Author and literature references	⋯
A	Dates of measurement (date, season, year)	⋯
A	Location (latitude, longitude, altitude)	Once
A	Land cover and land use	Once
A	Biome type, major species, functional types, C_3/C_4/CAM†	Once
A	Management history (fire, harvest, irrigation, grazing, fertilization)	Once
D	Topography, soils, and surface deposits	Once
D	Soil type, texture (organic carbon, nitrogen)	Once
D	Rooting depth	Once
D	Tree density, age classes	Once
D	Plant species presence and abundance, stand age, history and successional status	Once
Meteorological data (time series or climatological means)		
A	Precipitation	Daily to monthly
A	Temperature (maximum and minimum)	Hourly to daily (to monthly)
D	Solar radiation (PAR,‡ total)	Hourly to daily
D	Number of rain days	Monthly to annual
D	Water vapor pressure deficit	Hourly to daily
D	Evapotranspiration	Hourly to daily
D	Net radiation	Daily
D	Wind speed	Hourly
Ecophysiological data		
A	NPP	Weekly to annual
A	Phytomass	Weekly to monthly
D	NPP above- and belowground	Weekly to annual
D	Phytomass above- and belowground	Weekly to annual
D	LAI§	Weekly
D	Soil moisture (in rooting layer)	Daily to monthly
D	CO_2 fluxes (day, night, soil fluxes)	Hourly to daily
D	Stomatal conductance	Hourly to daily
D	Photosynthetic capacity	Weekly
D	Absorbed PAR	Hourly to daily
D	Plant and soil nitrogen content	Once
D	Herbivore consumption	Weekly to monthly
D	Litterfall	Weekly to monthly
Satellite data		
A	AVHRR short-wave reflectances	Daily
A	AVHRR thermal infrared radiances	Daily
D	Albedo	Seasonally
D	High-resolution remotely sensed images for site stratification (aerial photos, Landsat, SPOT,¶ etc.)	Once

Note: All information classified as available is also, of course, desirable.

† Crassulacean acid metabolism.

‡ Photosynthetically active radiation.

§ Leaf area index.

‖ Advanced Very High Resolution Radiometer.

¶ Système Probatoire pour Observation de la Terre.

Estimating NPP from Field Measurements

Various methods are used to estimate aboveground and belowground NPP (ANPP and BNPP, respectively), some being more suitable for vegetation communities of small stature (grasslands, tundra, agriculture crops) as opposed to large-stature forests. For grasslands, common approaches to estimate ANPP range from multiplying peak standing biomass by a fixed factor, through calculating the difference between maximum and minimum biomass, to more complex algorithms such as the ''UNEP Project'' method (Long et al. 1989):

$$\mathrm{ANPP} = \sum_{t} (\Delta B + \Delta D + [D \times r_{\mathrm{D}}])$$

where ΔB = change in aboveground live biomass, ΔD = change in aboveground dead matter, r_{D} = relative decomposition rate for dead matter, and the sampling time interval t is short relative to the rate of turnover of plant matter. In addition, one must account for herbivory, grazing, or other harvest. However, the spatial and temporal variation in above- and belowground biomass components may be large, so the methodologies used may fail to provide the statistically desirable degree of replication for even simple systems.

ANPP of woody vegetation communities is commonly determined using the equation

$$\mathrm{ANPP} = \Delta B + L + H$$

where ΔB = aboveground biomass increment, L = annual litter/detritus production (commonly measured using litter traps), and H = herbivory or other harvest. Aboveground woody biomass (i.e., stem and branches)

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[6] ORNL DAAC (Distributed Active Archive Center) Database. URL: ⟨www-eosdis.ornl.gov/npp/npp_home.html⟩.

TABLE 2. Status of the NPP (net primary productivity) database at Oak Ridge National Laboratory (ORNL; Oak Ridge, Tennessee, USA) as of December 1997 (excluding extensive data collections), and cumulative number of sites represented in the database, by major biome.

	Cumulative number of sites				
Status	Grasslands	Boreal forest	Tropical forest	Other biomes	Total
Completed June 1995	13	0	0		13
Completed Dec. 1995	19	0	0		19
Completed Dec. 1997	26	2	3		31
In progress	9	11	17		68
Projected	34–45	13–15	21–25	10–15	78–100

is commonly estimated from allometric equations that correlate biomass with an independent variable such as diameter or basal area at a given height. Empirical studies suggest that these allometric relationships are reasonably constant within a species. Allometric equations can also be used to estimate total foliage mass and new foliage mass, which can then be used to calculate annual new foliage production. Herbivory is commonly ignored in forest ecosystems because it generally comprises $<$10–15% of NPP on an annual basis.

Methods to estimate belowground NPP include assuming BNPP to be a constant fraction of ANPP, calculating the difference between maximum and minimum of fine-root mass, measuring root in-growth into cores, or deriving increments of fine-root mass from sequential root cores. It is generally accepted that the first two methods tend to underestimate BNPP (e.g., Long et al. 1989). Coarse-root biomass of woody vegetation may be estimated from allometric equations; in this case, empirical data suggest that these relationships are reasonably constant among species.

There are relatively few study sites where reliable NPP estimates exist for both aboveground and belowground components. Future work under GPPDI will attempt to determine whether relatively constant allocation coefficients can be estimated for major vegetation types, and how these coefficients vary with environmental conditions (e.g., water and nutrient availability) and, for forests, with stand age. The development of these allocation coefficients or algorithms would provide a consistent methodology to adjust the large number of data that lack estimates of root production or other components of NPP.

Scaling-up from Study Sites to Grid Cells

In general, NPP observations (i.e., the measurements that are used to estimate NPP) are connected to small patches of vegetation, at best 0.1 ha but mostly much less. In contrast, modeling of global biogeochemical processes almost always relates to significantly broader spatial units (grid cells from 1 km^2 to 1° longitude/latitude). A goal of GPPDI is to document NPP observations in such a way that the relation between the spatial scale at which a model is executed and that of the original observation is straightforward and transparent.

We consider two types of scaling issues for the linkage of local to regional observations: (1) the adequacy of a particular ecosystem flux model to be used at a specified scale (spatial or temporal), and (2) the adequacy of the measurements of driving variables (typically climate and other environmental data) to represent conditions averaged over a grid cell as opposed to from a point location.

Both in time and space, coarse resolution measurements (e.g., a satellite pixel or an annual measurement of plant standing crop) may miss finer scaled variations. These ''fine-grained'' patterns do not necessarily translate across scales in a straightforward manner, hence a constant scaling factor is unlikely to be applicable. Furthermore, ecosystem-level feedbacks arise when scaling up physiological processes. Examples include the atmospheric feedback of humidity (produced by transpiration) that may alter canopy and larger scale evapotranspiration, and similar feedbacks in the soil with respect to decomposition, nutrient cycling, and water balance.

Lastly, interactions may occur among fine-scaled spatial units through lateral transfers of matter or energy (e.g., water, nutrients, light, heat), which may further modify coarse-scale estimates based upon fine-scaled measurements (e.g., NPP predictions based upon rainfall that has been redistributed on the landscape by run-on, run-off, etc.). Similar problems arise when there is large-scale advection of water vapor or heat from one vegetation patch to another—problems that can only be dealt with by dynamic modeling of matter and energy flows across space (e.g., using coupled ecosystem–hydrology models, or ecosystem–atmosphere models). For instance, the spatially explicit model SAVANNA (Coughenour 1991, 1992, 1993) uses a simple landscape hydrology sub-model, but such linked ecosystem–atmospheric models are still in their infancy.

With a few exceptions, most biogeochemical models have no inherent spatial structure or scale, and either implicitly or explicitly assume a homogeneous vegetation canopy from which fluxes of energy, carbon, water, and nitrogen are simulated in the vertical dimension only (Schimel et al. 1997). Broad-scale application of such models is undertaken on two assumptions: (1) the NPP value used for calibration or testing of the model is a good estimate of the mean for the grid cell; and (2) the gridded environmental data used for execution of the model are representative of the average environment within each grid cell, hence the fluxes simulated by the model are assumed to be similar to the average flux across the cell multiplied by its area.

Many cases fail to meet either or both of these criteria, particularly when the target grid-cell size is large (e.g., the 0.5° × 0.5° cells used in many global model applications) and therefore contains a wide variety of environments and types of vegetation. For the calibration or testing of biogeochemical models, it is crucial to assess these potential errors, perhaps modifying or discarding NPP data values if it is not possible to estimate the impacts of the errors and correct them.

For one-dimensional models, such as most prognostic biogeochemical models, the validity of the model–data comparison encompasses more than just whether the NPP observation represents a particular grid cell. The environmental driving variables provided for the point of observation should also represent the conditions at the exact site where NPP is measured (e.g., climate data, corrected for elevation and aspect, possibly interpolated from a combination of nearby and distant weather stations). Furthermore, the full range of ''environmental space'' in which the model is to be applied must be adequately represented by the range of the observed data.

For example, where the region of interest (e.g., a 0.5° × 0.5° cell) contains a mountainous landscape with a broad range of elevations, a single NPP observation should be accompanied by driving climate data for the same elevation, in order to fix its position in environmental space. In addition, observations should be available (perhaps from other geographical locations) that may be related to all other elevation zones in this landscape. By way of contrast, an NPP observation from a region of grassy plains will occupy a position in a more slowly changing landscape, and should require less stringent criteria for characterization. A qualitative assessment of the fulfillment of the above requirements may be possible, such as a graphical display of the values of environmental variables for the NPP observation sites, in order to check the presence of observations for all environmental-data combinations. The scaling from point to region is thus a result of the model application itself, depending not on the existence of a spatially comprehensive observational database of NPP, but on a broad evaluation of the model in all relevant environmental conditions, plus the necessary fields of environmental data.

The problems of scaling of environmental data from measurements taken in specific stands of vegetation to spatial grid cells of various resolution may run into the issue of nonlinearity (Ehleringer and Field 1993, Goodchild and Quattrochi 1997). Although Sellers et al. (1997) found that a number of vegetation and flux parameters scaled in a more or less linear fashion for FIFE-89 grassland data, others did not (Schimel et al. 1991). The linear-scaling assumption may also not apply where a number of vegetation types are found within one grid cell; i.e., the sum of the fine-resolution values is not equal to that measured at a coarse resolution (Dubayah et al. 1997). In this case, grid-cell models and point models cannot be expected to agree without very careful parameterization (e.g., Parton et al. 1992). The need for evaluation of the models with adequate environmental-data sets applies to all environmental factors, including those that are not explicit in the model but that implicitly constrain the model to more or less limited sets of conditions. For example, the effects of waterlogging on root growth, or the presence of toxic elements or shallow soils are rarely explicitly allowed for in models.

Thus we can envisage two levels of evaluation of NPP models:

1) Evaluation at points that have as far as possible the full range of environmental variables that are used to drive the model and that occur in the domain to which the model is subsequently to be applied;

2) Evaluation in actual grid cells in which the environmental conditions are allowed for by the model. Other extant conditions (including those such as unusual edaphic conditions or large areas of bare ground that are not allowed for in many NPP models) are surveyed and either built into the model or used to eliminate the grid cell (e.g., wetlands in the VEMAP model inter-comparison; Schimel et al. 1997).

Models with *implicit considerations of spatial averaging*, such as remote-sensing-based models with a resolution defined by the sensor, require a more direct consideration of spatial ''representativeness'' of NPP observations. The degree to which an NPP observation is representative of a grid cell must be assessed and, if necessary, adjusted to make it better represent the average. In many cases, such corrections could be based on applying prognostic biogeochemical models using the methods discussed above, but the associated assumptions need to be clearly documented. Two kinds of errors may occur here: 1) The model may, for some reason, fail in the spatial extrapolation from the point(s) to the grid cell; 2) The model may contain crucial components that are based on the same assumptions as the remote-sensing model that the resulting data are used to evaluate, i.e., circularity is introduced and the test itself may be invalid.

CONCLUSIONS

The current status of NPP (net primary productivity) data is that (1) we are now compiling extant field measurements in a readily available form, for the first time since the International Biological Program; (2) these data are inconsistent; and (3) the current data collections do not yet allow us to address scaling issues. Many modelers and physiologists may believe that there is already an abundance of NPP field data, including contemporary flux measurements. In reality, the data are sparse, and NPP is a theoretical parameter that cannot be measured in totality by any one approach. Our assessment suggests that most available data are only partial estimates of NPP, and the degree to which they underestimate NPP is different in each biome type.

The Global Primary Production Data Initiation (GPPDI) therefore finds itself breaking new ground in the study of global ecosystems. This coordinated, international work is adding consistency to NPP data and compiling associated physical environmental data. The GPPDI aim is to use the enhanced NPP compilation to estimate NPP for very large grid cells, up to 0.5° × 0.5° latitude and longitude.

The resulting NPP database will be available to global-change researchers via the ORNL (Oak Ridge National Laboratory, Oak Ridge, Tennesse, USA) Distributed Active Archive Center.[7] In response to the questions and challenges posed recently by Fung (1997), we anticipate this database will be useful to (1) re-examine worldwide patterns of NPP, (2) parameterize and evaluate global primary production models (both in the sense of estimating parameter values and in developing new representations of processes), and (3) calibrate models driven by remotely sensed data. The database will also have intrinsic value: global data are important for many ecological problems, and NPP is a kind of ''pathfinder'' for other ecological data sets. Since it will include key ecological information such as biomass dynamics, climate, and details of soils, as well as NPP, the database will be a valuable resource for a variety of other studies, such as biodiversity and nutrient cycling.

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