# Ecosystem modeling and dynamic effects of deforestation on trace gas fluxes in Amazon tropical forests

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## Abstract

To improve predictive capabilities for water, carbon, and nitrogen gas fluxes in the Amazon region, we evaluated the performance of the NASA–CASA simulation model for tropical ecosystem biogeochemistry against independent flux measurements from two Amazon forest sites located in the Brazilian states of Rondônia and Pará. Refinements of this ecosystem model include stand water balance equations, moisture holding and retention capacity for Amazon soils, and addition of a dynamic deforestation sequence to include land use change as a factor in simulations of tropical ecosystem fluxes. Results suggest that model predictions for evapotranspiration and soil water content are consistent with the overall range and seasonal changes in measured values at the two forest sites selected as test cases. The predicted carbon balance from the model implies that relatively undisturbed Amazon forest ecosystems may be large net sinks for atmospheric carbon, with annual net ecosystem production values on the order of $200 \text{ g C m}^{-2}$ per year. Measured fluxes of soil $N_2O$ for the two Amazon forests closely match our model prediction for the Pará forest, but not for the Rondônia site, suggesting that process algorithms controlling nitrogen trace gas fluxes, particularly in relatively sandy tropical soils will require further study. In terms of net ecosystem carbon fluxes during deforestation and for 2 years afterward, the model predicts that these sites switch from being a net sink for carbon to a substantial source following the large loss of biomass from simulated burning. During crop regrowth simulation in the first year after deforestation, the net source of carbon to the atmosphere is nearly $1.6 \text{ kg C m}^{-2}$ per year, a flux magnitude roughly equivalent to 10 years of undisturbed $CO_2$ sink fluxes in the Amazon forest. Compared to the primary forest that was cut and burned, predicted changes in soil nitrogen cycling lead to a doubling in annual emissions of $N_2O$ gas during the first year following deforestation, with lower emissions thereafter. Implications for scaling up these model predictions to the Amazon forest region are discussed with reference to necessary improvements in land cover, land use, and soils classifications for the area. Published by Elsevier Science B.V.

*Keywords:* Carbon; Nitrogen; Trace gas flux; Amazon forest; Deforestation

## 1. Introduction

Deforestation and forest fires caused by humans can add large amounts of carbon dioxide ($CO_2$) and nitrogen oxides to the airborne concentrations of these

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gases. Estimated anthropogenic contributions to the global carbon cycle commonly include a major net flux to the atmosphere (ca. 1.6 Gt C per year) resulting from land use change in the tropics (Schimel et al., 1996; Potter, 1999). Quantifying these fluxes is critical to understand the overall response of the carbon and nitrogen cycles to human perturbation worldwide. Land use change is also basic to understand the rate of increase in radiative forcing of the climate system (i.e. the 'greenhouse' gas effect), particularly since $CO_2$ accounts for most of the anthropogenically driven increase in forcings.

Soils of the humid tropical zone are recognized as major natural sources of carbon and nitrogen trace gas emissions to the atmosphere (Keller et al., 1983, 1986, 1993; Livingston et al., 1988; Luizao et al., 1989; Keller and Reiners, 1994; Riley and Vitousek, 1995; Potter et al., 1996a,b, 1998). For instance, nitrous oxide ($N_2O$) is an important greenhouse gas and a catalyst of stratospheric ozone depletion (Ramanathan et al., 1985; Cicerone, 1987). Levels of $N_2O$ are increasing in the atmosphere at a rate of 0.2–0.3% per year (Prinn et al., 1990; Khalil and Rasmussen, 1992). Associated with $N_2O$ in natural emission budgets is nitric oxide (NO), which plays an important role in photochemistry and ozone production in the troposphere (Logan et al., 1981; Thompson, 1992). NO is also a precursor to nitric acid, a major component of acid deposition (Calvert and Stockwell, 1983). Atmospheric concentrations of both $N_2O$ and NO may be related to trends in land use, namely conversion of tropical forests and woodlands to pasture and other agricultural management.

Biotic and abiotic factors interact to create conditions favorable for N trace gas production and emissions in tropical forest soils. Rapid mineralization of N from decaying organic matter provides abundant substrate for biological production of trace gas. At the cellular level, the bacterial processes of nitrification and denitrification are generally cited as the principal trace gas sources in the soil (Hutchinson and Davidson, 1993). The relative availability of electron donors (commonly soluble carbon compounds from organic matter decomposition) and electron acceptors ($O_2$ and N oxides) determine gaseous end products in soils (Davidson, 1991).

Soil trace gas emissions have been measured previously at a small number of locations in the Brazilian Amazon (e.g. Keller et al., 1986; Livingston et al., 1988; Steudler et al., 1996; Verchot et al., 1999), the largest remaining area of relatively undisturbed tropical rain forest in the world. These measurement data sets for year-round trace gas fluxes are difficult and expensive to collect. Studies at only a few sites in the Amazon have collected biogenic gas measurements together with climate data and ecosystem attributes such as biomass amount and nutrient content, and soil biochemistry. Hence, construction of an accurate regional emission budget for any biogenic trace gas from a relatively small data set of measurements carries a high degree of uncertainty, especially in a region as vast and diverse in terms of land cover and soil types as Amazonia. The Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA, 1996) is an international research effort designed to augment the region-wide data set of trace gas measurements in the years to come.

Use of a process-oriented simulation model that includes major gas flux controllers can facilitate interpolation of gas flux estimates along regional gradients of interest, and assist in generation of region-wide model estimates of seasonal flux budgets for water and trace gases, which may be verified using a series of single site measurements. For example, a pre-LBA regional application study with the NASA Ames ecosystem model version of CASA (Carnegie-Ames-Stanford Approach) over the Brazilian territory (Potter et al., 1998) has been used to identify the potential importance of eco-climatic gradients of seasonal moisture availability, soil texture, and land use as controls on ecosystem production and associated soil trace gas emissions ($CO_2$, $N_2O$, and NO).

In this paper, we report on results from more detailed studies using the daily version of the NASA–CASA ecosystem model for simulation of controls on water, C and N cycling, and trace gas emissions in applications at two Amazon forest sites, located in the Brazilian states of Rondônia and Pará. The daily version of NASA–CASA can be compared to relatively rapid changes in measured climate, soil conditions, and gas fluxes, in a manner not possible with a monthly model version (Potter et al., 1998). The Amazon sites selected differ in terms of seasonality of rainfall, length of the annual dry period, and soil properties, which makes the comparison of ecosystem biogeochemistry and trace gas flux useful within the

context of regional assessments for Amazonia (LBA, 1996). Selected forest stand measurements and annual gas flux estimates for soil $CO_2$, $N_2O$, NO, and $CH_4$ have been collected at the two sites (Neill et al., 1995, 1997; Davidson et al., 2000; Verchot et al., 1999, 2000), which provide a starting point for evaluating ecosystem model predictions. Although these are two of the most extensively studied forest sites in the Amazon region to date, no tower-based gas fluxes were made at these locations. Therefore, available soil measurements are based on small chamber-based fluxes only, and reported mainly as annual flux estimates for comparison to model predictions of the same.

The main objectives of this modeling study were to (1) compare predictions from the NASA–CASA simulation model to independent flux measurements available from the Amazon forest sites, in an effort to improve both types of data sets, (2) refine the concepts and algorithms upon which this generalized "leaky pipe" scheme for tropical soil trace gas emissions of nitrogen can be built, including effects of deforestation on ecosystem biogeochemical cycling, and (3) use inter-site comparisons to improve the potential for accurate model extrapolation of interannual water, carbon, and trace gas flux predictions over the entire Amazon forest region, with integration of satellite data to characterize land surface properties (Potter et al., 1998).

## 2. Model description

The NASA–CASA model is a representation of major ecosystem carbon and nitrogen transformations. It includes interactions of trace gas flux controls: nutrient substrate availability, soil moisture, temperature, texture and microbial activity. The model is designed to simulate daily and seasonal patterns in carbon fixation, nutrient allocation, litterfall, and soil nitrogen mineralization, and $CO_2$ exchange, in addition to $N_2O$ and NO production, and $CH_4$ consumption. Potter et al. (1997) provides a complete description of the previous model design used in this study.

For application in this study, several model components of daily NASA–CASA version described by Potter et al., 1996a,b, 1997 remain unchanged. For example, the fraction of net primary production (NPP), defined as net fixation of $CO_2$ by vegetation, is computed on the basis of light-use efficiency (Monteith, 1972); new production of plant biomass is estimated as a product of intercepted photosynthetically active radiation (IPAR) and a light utilization efficiency term that is modified by temperature and soil moisture. For this simulation study, daily air surface temperature, irradiance, and precipitation together regulate the modeled NPP results, using monthly images the Normalized Difference Vegetation Index (NDVI) from the Advanced Very High Resolution Radiometer (AVHRR) satellite sensor to estimate changes in leaf cover properties at the land surface (Potter et al., 1999).

For the soil C and N component (Fig. 1), our design remains comparable to a somewhat simplified version of the CENTURY ecosystem model (Parton et al., 1992), which simulates carbon and nitrogen cycling with a set of compartmental difference equations. In the CASA model, as with many other ecosystem models, C and N cycling are coupled, with NPP considered a useful model driver for N transformation rates. The effect of temperature on litter and soil C and N mineralization fluxes was defined as an exponential response using a Q10 (the multiplicative increase in soil biological activity for a $10°C$ rise in temperature), with a value of 1.5 for surface litter decomposition and a value of 2.0 for soil decomposition.

In Potter et al. (1996a,b), we outlined a generalized simulation approach for emissions of NO and $N_2O$ from soils with a simplified application of the conceptual "leaky-pipe" model proposed by Firestone and Davidson (1989). The primary controlling factors used in this leaky pipe scheme are gross rates of N mineralization and an index of water filled pore space (WFPS; defined as the ratio of volumetric soil water content to total porosity of the soil; Papendick and Campbell, 1980). In our basic "leaky pipe" component for N trace gas emission, processes of ammonification and nitrification are lumped into combined mineralization fluxes from litter, microbial and soil organic matter pools to a common mineral N pool (Fig. 2).

The proportion of N trace gas (NO:$N_2O$:$N_2$) emitted as a by-product of total N mineralization is represented as overlapping functions of WFPS. This ratio of NO:$N_2O$:$N_2$ represents the size of holes in the N flux
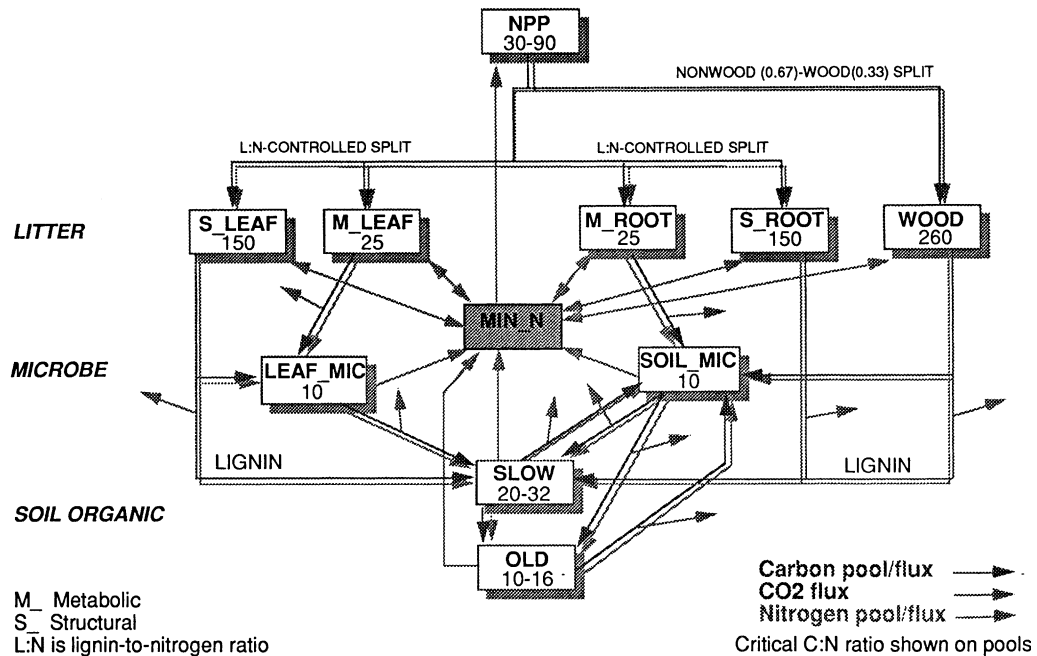
Fig. 1. Litter and soil C and N transformations in the NASA–CASA model which lead to substrates for trace gas production. Structure follows the CENTURY model of Parton et al. (1987, 1988). Carbon pools are outlined in black and labeled with C-to-N ratios, C fluxes in solid arrows, $CO_2$ production in stippled arrows; nitrogen pools in gray, N fluxes in gray arrows. Levels of litter, microbe (MIC) and soil organic (SLOW and OLD) pools are shown. Structural (S) and metabolic (M) pools are shown for leaf and root litter.

"pipe". Both NO and $N_2O$ may be produced at intermediate levels (20–60%) of WFPS. NO emission declines as the soil becomes largely water-filled, possibly due to diffusion limitations from sites of production at the intra-aggregate pore space (Schuster and Conrad, 1993). At higher moisture levels (60–90%) where reducing conditions develop, relatively more $N_2O$ is produced in an exponential response. Under very wet soil conditions (>90% WFPS), only $N_2$ is produced. Although the model still requires extensive verification, these patterns are consistent with observed flux measurements and current understanding of process-level regulation of nitrification and denitrification end products (Linn and Doran, 1984; Robertson, 1989; Matson and Vitousek, 1990; Williams et al., 1992). Potter et al. (1993, 1996a, 1997) provides equations and definitions of all variables shown in Figs. 1 and 2.

The potential loss of either $N_2O$ or NO from soils as a percentage of total mineralized nitrogen (abbreviated as NT) is a key variable in the model design. Few estimates of the NT term have been published

for tropical forest soils. Our initial model setting for NT of both gases was conservative at 2% (Potter et al., 1996a,b), although estimates range up to 5% in fertilized agricultural soils (Eichner, 1990).

Consumption of $CH_4$ in relatively well-drained soil profiles is simulated independently from the nitrogen cycling components in NASA–CASA using a modified version of Fick's first law based on computations for diffusivity in aggregated media (Potter et al., 1996a,b), together with the daily soil water balance model described in the following section. These $CH_4$ consumption algorithms are based on the assumption that, in relatively well-drained soils at ambient atmospheric concentrations, gas-phase transport of methane becomes rate limiting (Striegl, 1993), and temperature response is damped. As soil moisture increases, air-filled porosity decreases, resulting in restricted methane diffusion into the soil and lower rates of consumption. The NASA–CASA methane uptake algorithms are therefore applicable for estimation of oxidative methane consumption in well-drained topographic sites in the Amazon study areas.
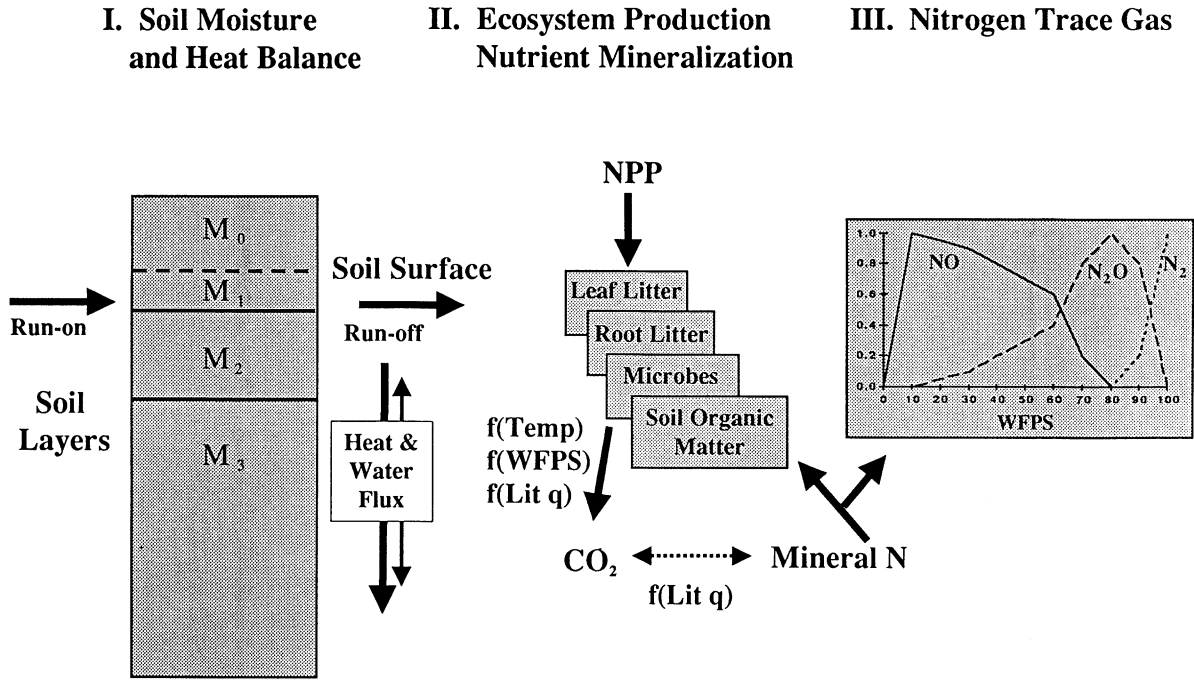
## I. Soil Moisture and Heat Balance     II. Ecosystem Production Nutrient Mineralization     III. Nitrogen Trace Gas



Fig. 2. Schematic representation of NASA–CASA soil water, decomposition, and nitrogen trace gas model components. Gross mineralization of nitrogen from litter and soil N pool is a function of rainfall (R), temperature (T), soil texture (TEX) and substrate quality (q). The scalar for relative production of N trace gases is a function of a %WFPS probability index (Iw).

## 3. Refinements for Amazon ecosystem simulations

In order to more accurately represent climate controls and soil processes for Amazon ecosystem C and N cycles, several modifications are introduced in this study for the soil hydrology and nutrient cycling model described by Potter et al. (1997). These changes include refinement of water balance equations, moisture holding and retention capacity for Amazon soils, and addition of a dynamic deforestation sequence to include land use change as a factor in simulations of tropical biogeochemistry and hydrology.

### 3.1. Water balance equations

To estimate plant and soil water balance in the previous versions of the model, we used a formulation of the empirical Priestly and Taylor (1972) evapotranspiration equation developed by Campbell (1977) and Bonan (1989). For this study, a more physiologically based daily potential evapotranspiration (PET) is estimated using a Penman–Monteith algorithm (Eq. (1)),

derived according to the methods described by Woodward (1987) and Monteith and Unsworth (1990).

$$PET = \frac{(R_{net}s) + (\rho c_p (e_s(T_a) - e)/r_a)}{s + \gamma(r_a + r_s)/r_a} \quad (1)$$

where $R_{net}$ is the daily net (shortwave) radiation flux to the canopy (W m$^{-2}$), $s$ is the rate of change of saturation vapor pressure with temperature (mbar °C$^{-1}$), $\rho$ is the density of air (kg m$^{-3}$), $c_p$ is the specific heat of air (J g$^{-1}$ °C$^{-1}$), $[e_s(T_a) - e]$ is the difference in water vapor pressure (mbar) between ambient air ($e$) and air at saturation $[e_s(T_a)]$, $\gamma$ is the psychrometric constant (mbar °C$^{-1}$), $r_a^{-1}$ is the canopy boundary layer resistance (s m$^{-1}$), and $r_s^{-1}$ is the stomatal resistance to water vapor (s m$^{-1}$). Model settings for maximum conductance in the canopy conform to optimized values for Amazon forest sites, as reported by Wright et al. (1996a).

Estimated evapotranspiration flux is calculated by comparing daily PET to the multi-layer model estimate for daily soil moisture content (Fig. 2). The soil profile is treated as a series of four layers: ponded

surface water (for flooded areas only), surface organic matter, topsoil (0.2 m), and subsoil to rooting depth (1.0–10.0 m). These layers can differ in soil texture, moisture holding capacity, and carbon–nitrogen dynamics. Water balance in the soil is modeled as the difference between precipitation (PPT) or volumetric percolation inputs, and PET and drainage outputs for each layer. All moisture inputs and outputs are assumed to progress from the surface layer downward. A modification for this study was that at least 30% of daily PET demands are met by water extraction from rooting zones located below the surface and topsoil layer (Nepstad et al., 1994). Inputs from rainfall may recharge the soil layers to field capacity. Excess water percolates through to lower layers and may eventually leave the system as runoff.

### 3.2. Soil moisture retention

Moisture retention curves for Amazon soils have been derived by Tomasella and Hodnett (1998). These water retention curves are designed to reflect the hybrid character of Amazon oxisols, which may act like sands in terms of water movement at low tensions, while holding water like clays at higher tensions. We used the estimated Brooks and Corey (1964) parameters from these moisture retention curves to modify our model parameters for a relative drying rate (RDR) variable, described by Potter et al. (1993). The resulting family of Tomasella and Hodnett (1998) logistic drying curves (Fig. 3) for an Amazon soils RDR scalar is based on a transformation of the relationship between soil water potential and volumetric moisture content (Eq. (2)), in the form reported for example by Saxton et al. (1986).

$$RDR = \frac{1+a}{1+a\Theta^b} \tag{2}$$

where $a$ and $b$ are soil texture-dependent empirical coefficients derived from Brooks and Corey (1964) parameters and $\Theta$ is the predicted volumetric moisture content (m m$^{-1}$).
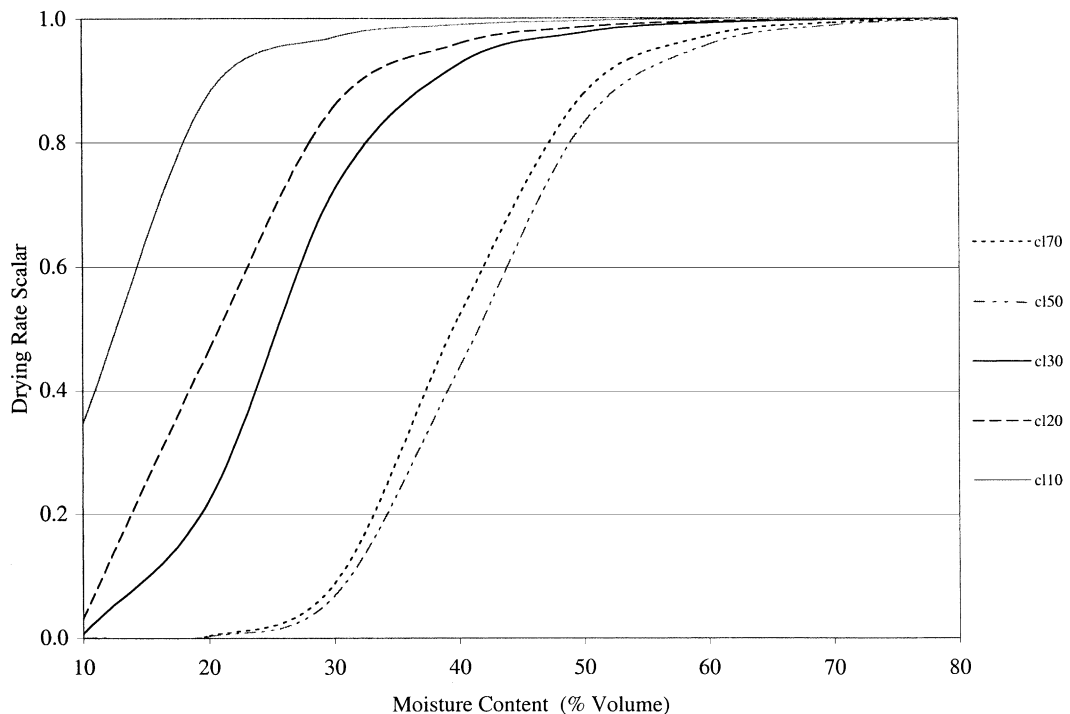


Fig. 3. Relative drying rate (RDR) scalar for Amazon soils, as a function of soil texture and predicted volumetric moisture content (Tomasella and Hodnett. 1998). Texture classes are defined by Zobler (1986) based on clay (cl) content ranging from 10 (coarse) to 70% (fine).

## 3.3. Deforestation effects

In order to estimate dynamic effects of forest conversion in the Amazon by cutting and burning, several major changes in the model's flow equations and storage pools were programmed to occur at the time of simulated deforestation. Aboveground pools of biomass carbon and nitrogen, which have been accumulated either from net primary production (C) or soil mineral uptake (N) into leaf and wood tissues over the preceding initialization period of several decades (Potter and Klooster, 1999), are immediately diverted by tree cutting into two flow pathways. One loss pathway is burning, whereby C and N gases are emitted from the forest stand to the surrounding atmospheric pool. Burning losses occur in proportion to tissue combustion factors (mean value of 0.45 for total biomass loss) measured previously in Amazon deforestation studies (Kauffman et al., 1995; Carvalho et al., 1998; Guild et al., 1998). The other main pathway for cut forest biomass involves transfer of residual C and N, i.e. the amounts not combusted during burning and remaining at the soil surface, into actively decomposing litter pools of structural leaf and wood materials. As decomposition occurs over the following days and months, a portion of this unburned residual biomass will be lost into the atmosphere more slowly (compared to direct burning losses) as daily C and N trace gas emissions from soil organic matter mineralization.

Immediately following a deforestation event, land cover settings in the model are changed to represent properties of converted agricultural systems, either as shifting cultivation use, or directly to a pasture cover type, or a temporal sequence of the two. Major model changes related to ecosystem structure include fractional reduction in absorbed photosynthetic radiation (FPAR) and leaf area index (LAI) after deforestation. In place of NDVI inputs, altered canopy cover attributes for the simulated regrowth functions of the site vegetation are based on typical values reported in the literature for the respective agricultural ecosystems in Amazonia (Fageria et al., 1991). With reductions in LAI automatically come higher simulated soil surface temperatures and lower rainfall interception by leaf surfaces. Furthermore, mineralization rates of C and N from litter and soil pools are programmed to increase as a result of changes in the soil microbial environment that occur with disturbance.

## 4. Field site data for model testing

Initialized state and driver variables used in model evaluation were designed to reproduce as closely as possible ecosystem conditions during 1994 at two different rain forest sites located in the Brazilian states of Rondônia and Pará (Fig. 4). The spatial resolution for these simulations was assumed to be on the order of 1 m$^2$. With respect to soil properties (Table 1), the Rondônia forest is based on the *Fazenda* (ranch) *Nova Vida* site described in detail by Neill et al. (1995, 1997). The eastern Pará forest is based on the *Fazenda Vitoria* site, located near the city of Paragominas (Nepstad et al., 1994), with respect to canopy structure, leaf chemistry, rooting depth, and soil properties. It is assumed that vegetation at both sites is dominated by moist primary forest species.

The two forest sites differ notably in soil type and texture. Rondônia forest is located on a red-yellow podzolic latosol with a sandy loam texture (Neill et al., 1997). The Pará forest is located on a Kaolinitic yellow latosol (oxisol) with a clay texture (Davidson and Trumbore, 1995). This difference in sand:clay content of the two sites has a direct effect on the model setting for soil water balance and potential decomposition rates.

Net primary production (NPP) of the forests at these study sites has not been measured directly, and thus was estimated from NASA–CASA model algorithms (Potter et al., 1998) with inputs of monthly AVHRR-NDVI and daily climate drivers. To generate the final simulation results, daily air temperature, surface solar radiation, rainfall, and predictions of evapotranspiration and stored soil moisture for 1994 were allowed to control daily predictions of NPP flux at the Amazon sites. While surface radiation flux was the major daily controller of NPP at these sites, average daily temperature and diurnal temperature range were used to drive CASA's NPP algorithm for temperature regulation, whereas daily rainfall dynamics were aggregated to a 30-day running index of moisture controls (Potter et al., 1993). Seasonal patterns of litterfall, plus initial states for forest floor litter pools and soil C pools at the sites were also adopted from methods used in our previous regional modeling studies (Potter et al., 1998).

Daily climate data sets for time series model inputs were constructed for the two sites using records from
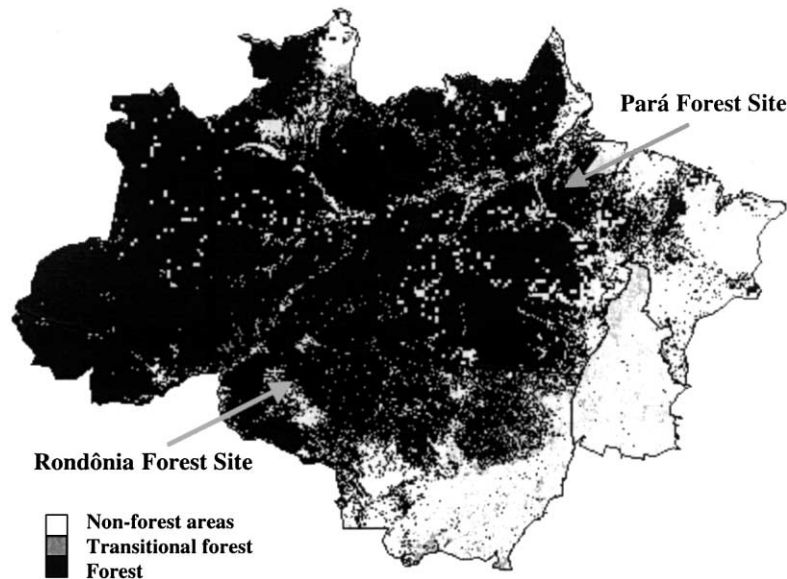
Fig. 4. Locations of the forest study sites in the Brazilian Legal Amazon (map source: Instituto de Pesquisa Ambiental da Amazônia).

1994, compiled at the nearby weather stations. For the Rondônia site simulations, hourly climate records from the *Reserva Jaru* forest, Ji-Parana station (10°05′S 61°55′W) were obtained from the ABRACOS (Anglo-Brazilian Climate Observation Study) archive (Nobre et al., 1996). Missing data were filled in with hourly climate records from the nearby *Fazenda Nossa Senhora* station (10°45′S 62°22′W). For the Pará site simulations, complete daily data were compiled from hourly climate records at the *Fazenda Vitoria* station near Paragominas (Nepstad et al., 1994; Jipp et al., 1998).

The year 1994 was selected for the simulations principally because this is the single year for which hourly weather station data was available for both forest locations in Rondônia and Pará. Final data sets for daily climate drivers were generated from precipitation totals over a 24 h period, and by averaging net radiation flux measurements over daylight hours. Compared to long-term mean annual rainfall totals of 1945 mm at the Rondônia forest location and 1730 mm at the Pará forest location, 1994 was drier than usual in Rondônia and somewhat wetter in Pará, with 1571 and 1963 mm rainfall at the two respective locations. For convenience, we define the typical Amazon forest 'wet season' as October–May and the 'dry season' as June–September, with the realiza-

tion that rainfall timing can vary markedly from year to year and from site to site across the Amazon Basin. At the Pará location, rainfall in 1994 continued into the typically dry months of June and July. There are noteworthy seasonal differences in rainfall between the two locations. Rainfall in 1994 was more abundant late in the year (September–October) at the Rondônia site, in contrast to high rainfall amounts during February–April at the Pará site (Fig. 5).

Owing to a lack of reliable radiation measurements for the Pará site during the 1994 wet season, we used the relationship between diurnal temperature range (DTR) and net irradiance ($R_{net}$) flux to reconstruct this model driver. Atmospheric transmissivity, more commonly called daily cloud cover, is inferable from the difference between the daily maximum and minimum air temperature using the method of Bristow and Campbell (1984). The more transmissive the atmosphere, the greater the DTR. We calibrated this $R_{net}$–DTR function using ABRACOS measurements from Maraba ($r^2 = 0.93$; $R_{net} = 29.5\,DTR + 8.1$), to determine daily radiation fluxes at the Paragominas site for the 1994 wet season. We did not adjust the reported dry season $R_{net}$ at the Paragominas site, since it was reported in a consistent manner for all 4 years, albeit with lower flux values than generally predicted from DTR alone. It is conceivable that biomass burning

Table 1
Estimated NASA–CASA parameter settings and sources for initialization of Amazon forest simulations[a]

| Model parameter | Rondônia | Pará |
|---|---|---|
| Geographic | | |
|   Latitude and longitude | 10°30′S 62°30′W | 2°59′S 47°31′W |
|   Elevation (m) | 120[b] | 30[c] |
| Climate drivers (daily) | Ji-Parana Station[b] | Fazenda Vitoria[c] |
|   Air temperature (min/max) (°C) | Ji-Parana Station[b] | Fazenda Vitoria[c] |
|   Precipitation (cm) | Ji-Parana Station[b] | Fazenda Vitoria[c] |
|   Relative humidity (%) | Ji-Parana Station[b] | Fazenda Vitoria[c] |
|   Surface radiation (W m$^{-2}$) | Ji-Parana Station[b] | Fazenda Vitoria[c,d] |
|   Wind speed (m s$^{-1}$) | Ji-Parana Station[b] | Fazenda Vitoria[c] |
| Vegetation | | |
|   Net primary production (g C m$^{-2}$ per year) | 1247[e] [700][e] | 1264[e] [700][e] |
|   Leaf nitrogen content (C:N ratio) | 85[d] [80] | 66[d] [80] |
|   Leaf lignin content (%) | *18* [*23*] | 18[d] [23][d] |
|   One-sided maximum LAI (m$^2$ m$^{-2}$) | 4.6[b] [*2*] | 5.4[c] [*2.9*][c] |
|   Litter C allocation (%leaf:root:stem) | *45:25:30* [*60:50:0*] | 45:25:30[c] [*60:50:0*] |
|   Rooting depth into mineral soil (m) | *12* [*5*] | 12[c] [*8*] |
| Mineral soils | | |
|   Bulk density (g cm$^{-3}$) | 1.28[f] [*1.5*][b] | 0.96[c] [*1.24*] |
|   Texture (%sand:silt:clay) | *75:4:21*[f] [*85:6:9*][b] | 9:12:79[c] [*9:12:79*] |
|   Minimum water content (% bed volume) | 17.0[g] [*21*] | *13.0*[c] [*25*] |
|   Field capacity (% bed volume) | 32.0[g] [*25*] | 37.0[b] [*35*] |
|   Total porosity (% bed volume) | 48.0[b] [*47*] | 56.0[g] [*53*] |
|   Total organic carbon (to 20–30 cm) (kg C m$^{-2}$) | 3.23[f] [*3.98*][f] | 4.1[c] [*4.8*][c] |
|   Thickness of humus (cm) | *3* [*1*] | *3* [*1*] |

[a] In the absence of published estimates, best guesses are shown in italics, based on other reported values in the same parameter category. Modified settings for nearby pasture sites are also shown in square brackets.

[b] Wright et al. (1996b).

[c] Nepstad et al. (1994); Jipp et al. (1998).

[d] Guild et al. (1998); Davidson (unpublished data) and Markewitz (unpublished data).

[e] Potter et al. (1998).

[f] Neill et al. (1995, 1997).

[g] Tomasella and Hodnett (1998).

during the dry season at a site like Paragominas substantially reduces atmospheric transmissivity during what would otherwise be a nearly 'clear sky' solar radiation flux (Malhi et al., 1999). This is supported by measurements of spectral irradiance and aerosol properties during the 1995 Smoke, Clouds, and Radiation-Brazil (SCAR-B) experiment reported by Eck et al. (1998), which imply that PAR fluxes at the land surface are reduced between 20 and 45% by biomass burning sources of aerosols in the Amazon Basin.

Net radiation flux was slightly less seasonal at the Rondônia site, compared to the discernible decrease in radiation flux towards the end of the wet season and early in the dry season at the Pará site (Fig. 5). These overall patterns in radiation fluxes during the wet season are consistent with seasonal patterns in DTR recorded at weather stations across the Amazon, including Ji-Parana, Manaus and Maraba stations from ABRACOS.

## 5. Evaluation of modeling results

### 5.1. Evapotranspiration and WFPS

Accurate representation of the water balance in tropical soils is crucial to modeling the environmental controls on soil organic matter decomposition, nutrient
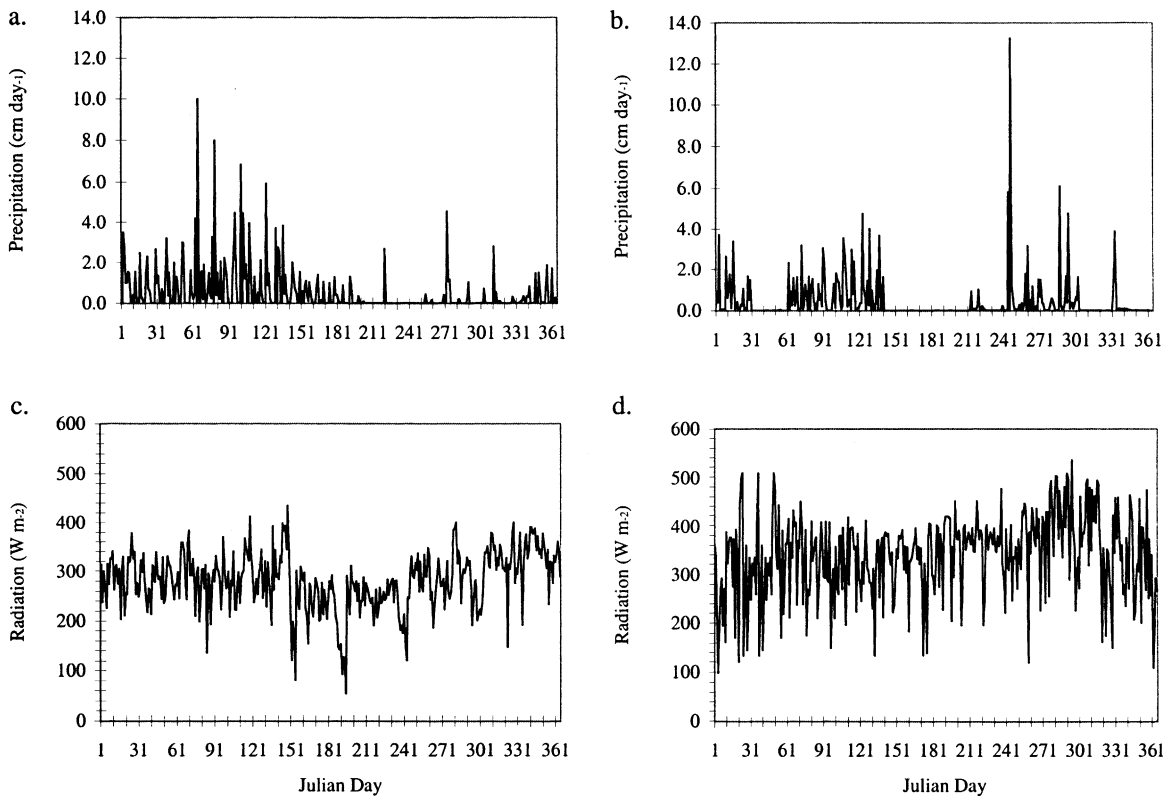
a.



b.

c.

d.

Fig. 5. Daily rainfall (a) Pará; (b) Rondônia and solar irradiance flux; (c) Pará; (d) Rondônia for two Amazon forest sites during 1994.

mineralization, and trace gas emission fluxes. For example, optimum rates of soil respiration flux of $CO_2$ to the atmosphere are generally measured at near field capacity for water content of the soil (Linn and Doran, 1984). This pattern is explained mechanistically as a limitation of oxygen diffusion rates required for optimal aerobic microbial respiration (Rh) at high soil water content, and limited availability of soluble organic-C substrates in water films at low soil water content. Moisture content can also influence rates of $CO_2$ diffusion in tropical soil profiles (Davidson and Trumbore, 1995).

As the primary control on $CO_2$ emissions from Rh, and associated N gas emissions from tropical soils, the WFPS index of moisture content is predicted in our model for the topsoil layer of the rooting depth profile (Fig. 2). Estimation of daily soil water content as %WFPS in the NASA–CASA model depends on precipitation inputs (corrected for vegetation canopy interception), moisture holding and retention capacity

of the soil profile, plant rooting depth, and predicted evapotranspiration fluxes. Hence, we evaluated estimated evapotranspiration (EET) first as a diagnostic variable and the main outflow of stored rainfall in the soil profile depth to which plant roots have access.

Mean daily rates of EET are predicted by the model to be 0.43 and 0.47 cm per day (wet and dry season, respectively) at the Rondônia location, 0.39 and 0.29 cm per day (wet and dry season, respectively) at the Pará forest location (Fig. 6a and b). In most cases, we find close agreement (<10% difference) between our predicted EET fluxes and mean measured EET fluxes on a seasonal basis for the study sites, comparing EET at the Rondônia forest reported at 0.38 cm per day for the dry season (Hodnett et al., 1996), and EET at the Pará forest reported at 0.38 and 0.45 cm per day for the wet and dry seasons, respectively (Jipp et al., 1998). In terms of environmental controls, predicted daily rates of EET from our model (Fig. 6) are influenced more by variability in surface
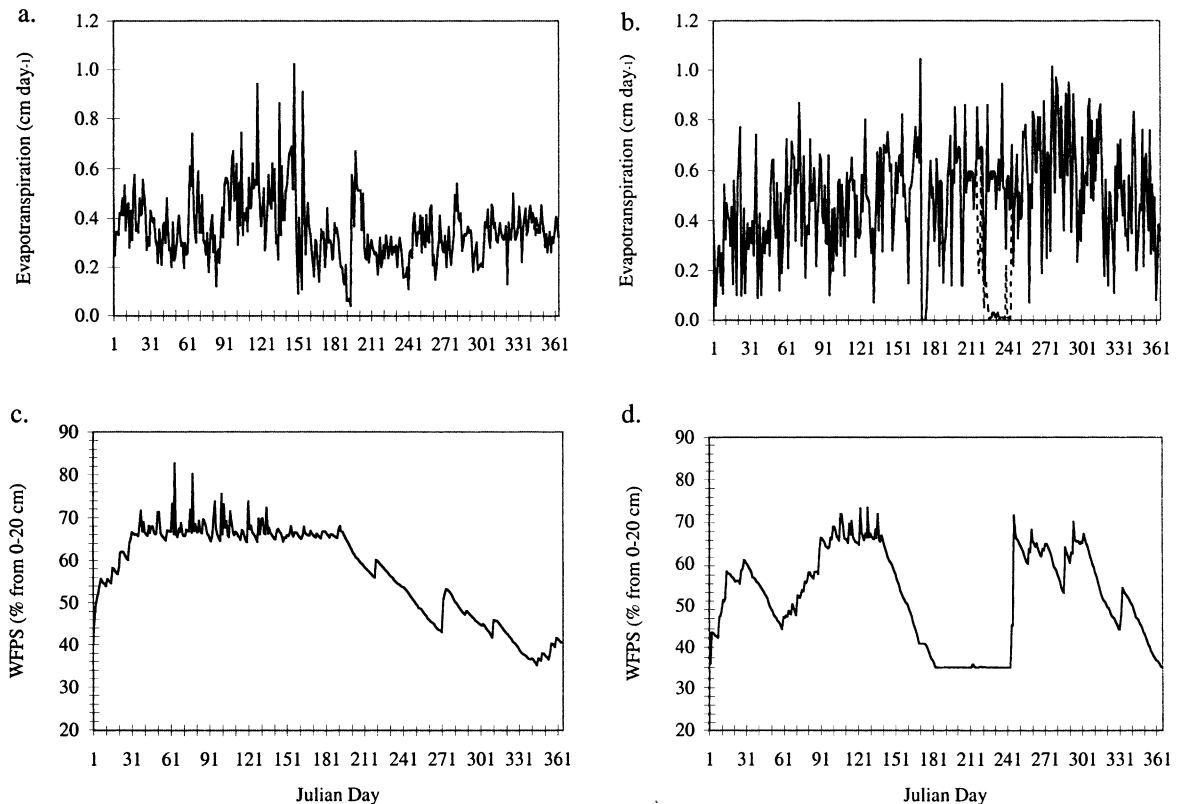
Fig. 6. Predicted evapotranspiration (a) Pará; (b) Rondônia, and WFPS; (c) Pará; (d) Rondônia for two Amazon forest sites.

solar irradiance, and to a lesser degree by relative humidity or daily rainfall amounts to recharge soil moisture pools. Williams et al. (1998) reported this same general pattern of model sensitivity for EET in Amazon forests. In contrast, higher measured rates of EET by Jipp et al. (1998) during the dry season at the Pará forest site are difficult to explain considering that measured net radiation fluxes were about 18% lower in the entire dry season than in the wet season during 1994 at that site.

Predicted differences in %WFPS between the two forest sites (Fig. 6c and d) are attributable mainly to length of the dry season, and to soil texture settings, and hence moisture holding and retention capacity in the model. The Rondônia forest on a relatively coarse-textured soil shows the greater seasonal and day-to-day variability in predicted WFPS in the topsoil layer, with a value range between 35 and 73% WFPS. These predictions are consistent with overall range and seasonal changes in measured values monthly for

%WFPS reported Hodnett et al. (1996) for forests at Ji-Parana, Rondônia, assuming the reported total soil porosity value of 48% volumetric water content at these sites. The seasonal pattern in both predicted and measured data sets for WFPS is a peak near 70% from mid-February into May, followed by low values near 35% WFPS during the typical three month (June–August) dry period, with a return to the peak annual value by early March. Predicted WFPS in the topsoil layer at the Pará forest site ranges between 36 and 82%, which closely tracks the overall range and seasonal changes in measured monthly values for %WFPS reported by Verchot et al. (1999) for the primary forest at Paragominas. In both predicted and measured results, the period of low soil moisture (WFPS < 55%) lasts nearly 6 months (e.g. July–December) in forests of eastern Pará. Our model replicates a sustained level of soil moisture > 65% WFPS estimated for the wet March–May period in 1995 and 1996 by Verchot et al. (1999).

## 5.2. Primary production, heterotrophic respiration, and soil methane uptake

Plant carbon cycling in tropical forests is tightly coupled to water fluxes, litter fall inputs to soil organic matter for decomposition, and soil nutrient mineralization. The accumulated difference between net carbon fixation in NPP (sink fluxes), and its subsequent release back to the atmosphere by Rh (source fluxes), determine annual net ecosystem production (NEP) for a site. Recent eddy correlation tower studies in small undisturbed areas of Amazon forest imply that these ecosystems may be large net sinks for atmospheric carbon, with annual NEP values in the range of 100–600 g C m$^{-2}$ per year (Grace et al., 1995, Malhi et al., 1998).

In a manner consistent with these previous tower studies, our ecosystem model predicts that annual NEP in 1994 at the Rondônia forest site was equivalent to a net sink flux of 276 g C m$^{-2}$ per year, while the Pará forest site was predicted to be a net sink of about 190 g C m$^{-2}$ per year. Although these annual NEP fluxes are of similar magnitude, the seasonal responses are quite different at the two sites. At the Rondônia site, predicted NPP is highest shortly after the onset of the wet season (November) and declines gradually throughout the rest of the yearly cycle (Fig. 7). At the more seasonal forest site in Pará, predicted NPP declines rapidly at the end of the wet season (May) and does not reach a maximum level until the following March–April period in the yearly cycle. These predicted seasonal carbon flux results are consistent with Amazon tower study results (Malhi et al., 1998) and other modeling analyses (Williams et al., 1998), which suggest that limited water availability in forests of the eastern Amazon slightly outweighs any compensatory effect of periodically decreased cloudiness during the dry season. However, the annual net carbon sink predicted for both Rondônia and Pará forest sites is about 50% smaller than that estimated by Malhi et al.
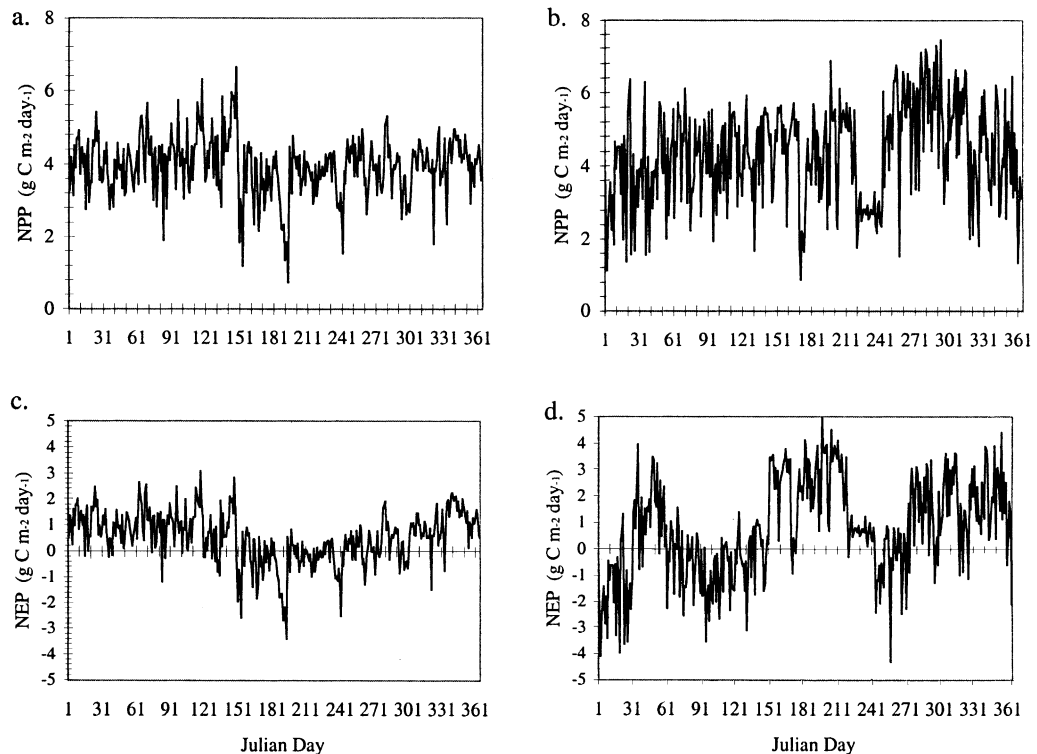


Fig. 7. Predicted net primary production (a) Pará; (b) Rondônia, and net ecosystem production; (c) Pará; (d) Rondônia for two Amazon forest sites.

(1999) for an Amazon forest site near Manaus at 590 g C m$^{-2}$ per year (see further explanation below).

Predicted soil Rh fluxes are closely coupled to daily fluctuations in soil water content in the sandy Rondônia forest soils, compared to Rh fluxes in the heavy clay soils of eastern Pará. Relatively more frequent wetting-drying cycles simulated at the Rondônia site (Fig. 6d) appear to drive stronger moisture controls on soil organic matter decomposition, nutrient mineralization, and turnover of microbial biomass. Optimal conditions for soil organic matter decomposition at the Rondônia site occur during or close to rainfall events, creating conditions for net source fluxes of $CO_2$ from the forest during the wettest months of the year, whereas the heavy clay soils at the Pará forest site retain moisture longer after the rains have ended, and can sustain Rh fluxes of $CO_2$ well into the dry season, to roughly balance declining NPP fluxes. Average predicted rates of Rh as component fluxes of NEP at the Rondônia forest site are 3.9 and 2.8 g C m$^{-2}$ per day for the wet and dry season, respectively. At the Pará forest site, the range for Rh fluxes of $CO_2$ during the later 1994 wet season months is 3.2–4.1 g C m$^{-2}$ per day, and during the driest months is 3.1–3.3 g C m$^{-2}$ per day, a response pattern that is in close agreement with measured seasonal trends in total soil $CO_2$ emission at the same site (Davidson et al., 2000). Our ecosystem model does not, however, account for root respiration contributions to total soil respiration at either site, which would be included in field measurements of total soil $CO_2$ emissions.

Total annual Rh fluxes are predicted by the model at 1298 and 1245 g C m$^{-2}$ per year for the Rondônia and Pará forest sites, respectively. These model estimates are somewhat higher than annual Rh fluxes estimated for a tropical forest near Manaus, Brazil at 970 g C m$^{-2}$ per year (Malhi et al., 1999), who also estimate total soil $CO_2$ emissions at 1650 g C m$^{-2}$ per year. This estimate of Rh at Manaus could be biased to the low side however, because it was apparently derived using total soil $CO_2$ emissions and plant respiration estimates from an entirely different site in Rondônia. Underestimation for Rh fluxes of soil $CO_2$ can result in overestimation of the annual net carbon sink for the forest.

The NASA–CASA model suggests that moisture conditions for microbial decomposition of organic matter in heavy clay soils are wet enough during the high rainfall months at the Pará forest site to sustain high Rh fluxes, and dry out to near optimal soil moisture and temperature conditions for Rh fluxes of $CO_2$ during the first half of dry season. For the sandy soils at the Rondônia forest site, the model suggests that soil moisture conditions for microbial decomposition are favorable during the high rainfall months, but dry out to sub-optimal conditions for Rh fluxes of $CO_2$ early in the dry season. Predicted percentage of total yearly litterfall varies little over the seasons at the two forest sites, although small increases in leaf litter during the late dry season at the Pará forest site can increase Rh fluxes slightly compared to wet season fluxes.

As another component of soil C cycling, predicted seasonal patterns of soil $CH_4$ uptake are influenced notably by soil moisture changes and daily rainfall patterns at both sites (Fig. 8). Mean predicted rates of $CH_4$ uptake are 0.52 and 0.56 mg m$^{-2}$ per day (wet and dry seasons, respectively) at the Rondônia forest
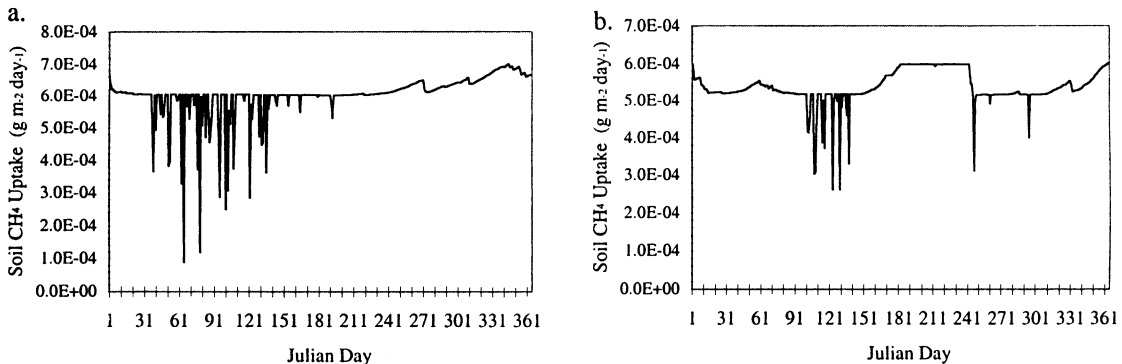


Fig. 8. Predicted soil $CH_4$ uptake (a) Pará; (b) Rondônia for two Amazon forest sites.

site, and 0.60 and 0.61 mg m$^{-2}$ per day at the Pará site (wet and dry seasons, respectively). The model predicts that high rainfall events periodically depress $CH_4$ uptake capacity of the soil at both forest sites, although estimated $CH_4$ uptake rates recover rapidly with drying of the uppermost soil layers.

Comparisons of model results to measured rates of methane consumption in these soils are valid for the dry season when potential methane emission fluxes, which are not included in this application of the model, can be excluded as confounding factors. Dry season rates of $CH_4$ uptake were measured at 0.98 mg m$^{-2}$ per day for primary forest soils near Paragominas (Verchot et al., 2000). Field measurements at the Pará site indicate that periodic methane emissions from forest soils are positively correlated with soil fluxes of $CO_2$, and that formation of anaerobic soil microsites may cause a switch from a consistent soil $CH_4$ sink to an intermittent $CH_4$ source (Verchot et al., 2000). Our forest model was not used in this manner to include potential soil $CH_4$ production, although future tests of are now planned to do so using the methane emission model version (Potter, 1997).

Measurements of dry season rates of $CH_4$ uptake at forest sites in Rondônia were reported to be on the order of 1.2 mg m$^{-2}$ per day (Steudler et al., 1996). The model settings for the sandy loam soil type of these Rondônia forest sites result in a slightly higher overall soil water holding capacity than for the heavy clay soils of eastern Pará sites, but also result in prediction of slightly lower water content (computed relative to saturation capacity) when moisture levels approach the wilting point setting than predicted for clay soils of the eastern Pará sites. These settings should have the effect of increasing diffusivity and potential uptake of methane at the Rondônia forest sites, although under the default model settings not quite to the levels consistent with field measurements of maximum of $CH_4$ uptake rates.

### 5.3. Soil C and N turnover and storage

Predicted carbon storage to 20 cm soil depth in the model's pool for SLOW carbon (mean residence time of ca. 10 years at the two Amazon forest locations) is higher at the Pará location (5.8 kg C m$^{-2}$) than at the Rondônia location (3.9 kg C m$^{-2}$). This difference is mainly a function of soil texture settings, which lead to prediction of greater retention (or higher microbial efficiency of carbon substrate use) of organic matter in the heavy clay soils of the eastern Pará site. Predicted nitrogen storage in the NASA–CASA pools for SLOW and OLD soil N is likewise higher at the Pará location (0.36 kg N m$^{-2}$) than at the Rondônia location (0.21 kg N m$^{-2}$). Both our predicted pools of C and N closely match measured pool sizes of $3.2 \pm 0.3$ kg C m$^{-2}$ and $0.27 \pm 0.02$ kg N m$^{-2}$ at Rondônia forest sites (Neill et al., 1997). Measured carbon pool sizes at the eastern Pará forest sites were reported for the upper 10 cm soil (Trumbore et al., 1995), which when doubled, would again give a closely matching estimate of 5.2 kg C m$^{-2}$ to the model prediction.

### 5.4. Nitrogen mineralization rates and trace gas emissions

Using the vegetation parameter settings in Table 1, net nitrogen mineralization rates are predicted to be somewhat higher on average at the Pará location (55 mg N m$^{-2}$ per day) than at the Rondônia forest location (26 mg N m$^{-2}$ per day). Annual net mineralization is predicted at 19.9 g N m$^{-2}$ per year for the Pará forest and 9.3 g N m$^{-2}$ per year for the Rondônia forest. This difference is attributable almost entirely to the lower leaf litter N content assumed for Rondônia forest sites, based on measurements reported by Guild et al. (1998). If the same leaf C:N ratio of 66 is used for the Rondônia site simulations as for the Pará forest site, annual net mineralization is predicted at nearly 18 g N m$^{-2}$ per year, making the two sites nearly equivalent in terms of N cycling rates. We note that a measured range of 79–94 was reported for forest leaf C:N in Rondônia by Guild et al. (1998), and up to 72 C:N for forest leaf litter in eastern Pará sites (Markewitz, unpublished data). This potential site variability implies that appropriate measurements and spatial analyses of litter C:N as a model input parameter are needed to reduce uncertainties in nitrogen cycling predictions.

At both sites, predicted daily rates for emission of both N trace gases correspond closely to predicted rates of gross N mineralization ($r^2 > 0.8$ for nonlinear regression using $n = 365$ days). Daily $N_2O$ fluxes are weakly correlated with daily WFPS ($r^2 > 0.2$) at both sites, whereas predicted NO fluxes
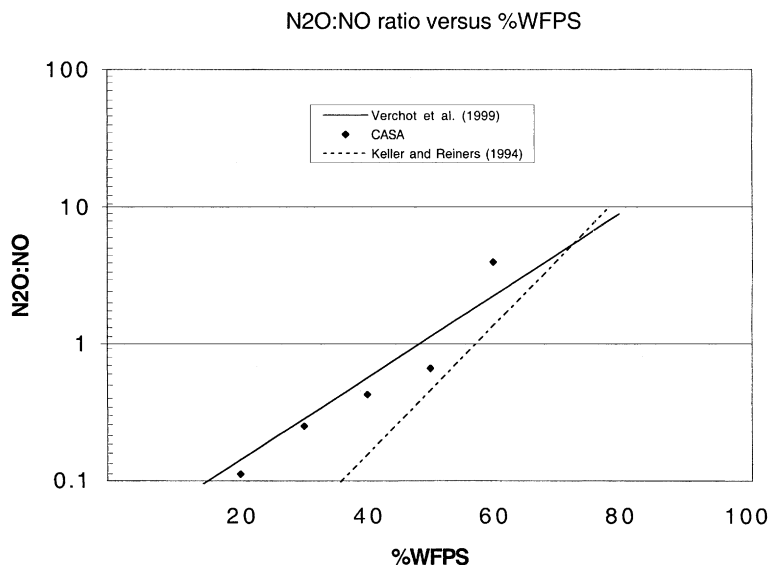
N2O:NO ratio versus %WFPS



Fig. 9. Emission ratio of nitrous-to-nitric oxide (N₂O:NO) versus percent water-filled pore space (%WFPS) from three different sources: measured fluxes at Paragominas (Verchot et al., 1999); measured fluxes from a collection of soils in Costa Rica (Keller and Reiners, 1994); and NASA–CASA model settings used in this simulation study.

are not significantly correlated ($r^2 < 0.1$) with daily WFPS, mainly because of the broad range of WFPS levels over which relatively high NO emissions can be predicted by the model (Fig. 2).

Annual emission fluxes of $N_2O$ and NO are predicted at 0.24 and 0.26 g N m$^{-2}$ per year, respectively, for the Pará forest site, and 0.11 and 0.17 g N m$^{-2}$ per year for the Rondônia forest site using the vegetation parameter settings in Table 1. Consistent with prediction of higher litter fall N, wetter soil conditions, and therefore higher net N mineralization rates, annual N gas fluxes from the model are higher overall at the Pará site. Measured fluxes of soil $N_2O$ are 0.25 and 0.24 g N m$^{-2}$ per year for Rondônia and Pará forest sites, respectively (Verchot et al., 1999), which closely matches our model prediction for the Pará forest, but not for the Rondônia site, which predicts an annual soil $N_2O$ flux of only 0.14 g N m$^{-2}$ per year, even if the higher leaf C:N ratio of 66 is used. The mean predicted daily emission ratio at the Rondônia forest site of 0.62 for nitrous-to-nitric oxide ($N_2O$:NO) is substantially lower than the $N_2O$:NO daily emission ratio of 1.1 at the Pará forest site, because of the wetter predicted soil conditions at the Pará site.

A comparison between our model settings (Fig. 2) and a measured $N_2O$:NO ratio versus %WFPS by

Verchot et al. (1999) suggests that for WFPS between 40 and 70%, the model settings somewhat underestimate the $N_2O$:NO ratio measured at these eastern Pará sites (Fig. 9). This would explain some, if not most, of the discrepancy between model predictions and measurements of N trace gas fluxes for these Amazon forest sites. For further comparison with available measurements from tropical field sites, Fig. 9 includes the $N_2O$:NO ratio versus %WFPS relationship based on a synthesis of flux measurements from soils in Costa Rica (Keller and Reiners, 1994), which suggests yet another model setting that would even more markedly underestimate the $N_2O$:NO ratio measured at eastern Pará sites by Verchot et al. (1999). Additional measurements and model refinements are apparently needed to resolve these differing response functions shown in Fig. 9.

## 6. Simulation of deforestation effects

A deforestation event was simulated for the Rondônia forest site (initialized to steady state conditions) to examine the model response in terms of biomass losses through burning, decomposition of residual unburned biomass, and overall soil carbon

and nitrogen changes, assuming the forest site would be subsistence farmed for about 2 years following slash and burn of the forest trees, without the outside input of chemical fertilizers. The choice here of a cultivation land use following forest clearing was not intended to diminish the importance of understanding effects of pasture development in the Rondônia area. We note that pasture grasses may in fact have different production and nutrient use efficiencies than some crop plants, which will require more information from LBA and related studies to incorporate into our modeling analysis.

For deforestation events studied in Rondônia, Guild et al. (1998) reported mean losses from forest slash and burn of 8800 g C m$^{-2}$ and 118 g N m$^{-2}$. These fluxes are comparable to our model prediction of 9339 g C m$^{-2}$ and 39 g N m$^{-2}$. The difference in nitrogen losses derives from the model's default

setting for N content of tropical forest leaves, which must be refined for other sites in future simulations.

The simulated deforestation sequence we generated predicts that surface soil C pools decline rapidly to about one-third of their pre-cut forest level, following a small input of unburned forest leaves after cutting (Fig. 10). Meanwhile, sub-surface soil C pools grow initially by about 10% from the transfer and storage of the decomposing unburned forest biomass, including residual wood from charred tree trunks. This pattern of carbon accumulation appears to have leveled off after about 2 years of simulated cultivation and should decline in years of land use to follow.

In terms of net ecosystem carbon fluxes, the site switches from being a net sink for carbon to a substantial source following the large loss of biomass from simulated burning. The 2-year old cultivated site is predicted to be an annual net source of ecosystem
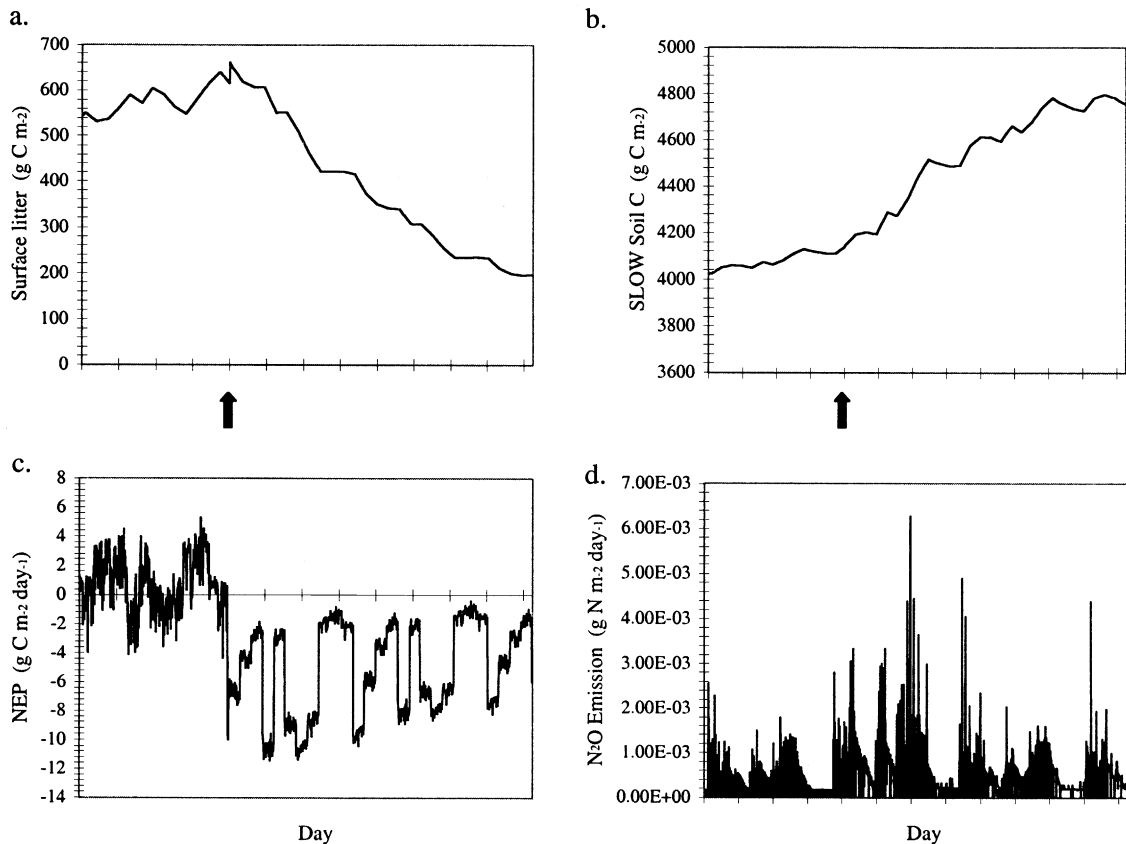


Fig. 10. Model predictions for a simulated deforestation event (indicated by the black arrow) at the Rondônia forest site, assuming the site would be subsistence farmed for 2 years following slash and burn of the forest trees.

carbon to the atmosphere of about 1.58 kg C m$^{-2}$ per year. Over this period, mineral N levels in the soil are predicted to increase by a factor of about five for the 2-year simulation following deforestation. Compared to the primary forest that was cut and burned, this causes a doubling in annual emissions of $N_2O$ gas at the site during the first year following deforestation, which continues with only a slight decrease (8%) during the second year following deforestation, as the mineral nitrogen released through deforestation is slowly immobilized in soil pools.

## 7. Implications for scaling to the Amazon region

One of the principal objectives of the LBA is to quantify and predict how energy, water, carbon, trace gas, and nutrient cycles in the Amazon region respond to deforestation, agricultural practices and other land use changes, and how these responses are influenced by climate (LBA, 1996). This objective is attainable with the proper coupling and comparison of observational data, field measurements, and dynamic ecosystem models that can include land use change, like the one described in this paper. If ecosystem models can be refined and adequately validated against measurements at several site locations for the major land cover and use types in the Amazon basin, an important research task remaining is to scale-up the model's predictions to the regional level.

Ideally, any ecosystem model's set of algorithms controlling terrestrial energy, water, carbon, nitrogen and, trace gas fluxes will be nearly as accurate when applied at a relative coarse spatial resolution, for example, at the 8 km resolution used in our previous regional modeling studies of Amazonia (Potter et al., 1998; Nepstad et al., 1999), as at the scale of the tens of square meters of an intensive study site used for model validation. In regional modeling, the direct use of satellite sensor data to capture and integrate terrestrial surface properties (e.g. FPAR, LAI) and land cover changes over large areas has been shown to meet these requirements for accurate scaling of biosphere-atmosphere fluxes of water and carbon to regional and global levels (Maisongrande et al., 1995; Goetz and Prince, 1996; Malmstrom et al., 1997; Potter et al., 1999). Assuming that adjustments for atmospheric smoke and related aerosols can be incorporated into the modeling of terrestrial ecosystem processes over a vast area like Amazonia, which commonly experiences large agricultural fires during driest months, a model driver generated from the AVHRR-NDVI has the potential to provide extensive coverage of surface properties and land use patterns over 10 to 15 year time periods.

Besides the need to improve the satellite NDVI signal for tracking changes over time in regional productivity, at least two other limitations arise in the process of scaling up to the Amazon region an ecosystem model like the one described in this paper.

1. Individual model input variables are not accurately mapped, or are incompletely represented, in terms of either the ''lumped'' parameter values, or the frequency distribution of values within a specified geographic area.
2. Combinations of model input variables are not accurately geo-rectified to one another, or are available only at widely differing spatial and/or temporal resolutions.

Land cover, land use, and soils classifications for the entire Amazon region are subject to both these limitations. Regional land cover maps of the Amazon produced by Skole and Tucker (1993) and Stone et al. (1994) have been checked for accuracy in broadly-defined land use types in Amazonia, which may help minimize limitation (1) above. While these maps provide useful starting points for regional ecosystem simulations, their data sources for land use patterns are now about 10 years out-of-date. New maps of Amazon land cover, based on seasonal satellite observations from the AVHRR (Eidenshink and Faundeen, 1994), still require extensive ground truth using classified Landsat images and field site verification, along with methods for improving geo-rectification to ground control points. With respect to dynamic land use modeling, at least two such regional maps of AVHRR land use, separated in time by 2 or 3 years, would be necessary to implement the NASA–CASA model deforestation sequence described above for simulating land use change effects on water, carbon, trace gas fluxes over the entire Amazon basin.

There are additional input data sets required for the Amazon region that will need to be developed further to serve as model drivers and surface property settings for basin-wide simulations. Table 2 presents

Table 2

Required data sets for regional simulations of water, carbon, nitrogen and, trace gas fluxes over the Amazon region

| Data sets | Remote sensing source[a] | Other sources |
|---|---|---|
| Geographic | | |
| Elevation (m) | | US Defense Mapping Agency |
| Water table depth (m)/inundation (%) | JERS | |
| Climate drivers (daily) | | |
| Surface air temperature (min/max) (°C) | | University of East Anglia (New et al., 2000) |
| Precipitation (cm) | TRMM | DNAEE (Divisao Nacional de Aguas e Energia Eletrica) |
| Surface relative humidity (%) | | University of East Anglia (New et al., 2000) |
| Surface radiation flux (W m$^{-2}$) | GOES | |
| Surface wind speed (m s$^{-1}$) | | University of East Anglia (New et al., 2000) |
| Vegetation | | |
| FPAR/LAI | AVHRR/MODIS | |
| Leaf nitrogen content (C:N ratio) | | |
| Rooting depth into mineral soil (m) | | |
| Disturbance history (years since) | Landsat, AVHRR/MODIS | |
| Land use history (type) | Landsat, AVHRR/MODIS | |
| Mineral soils | | RADAM in Potter et al. (1998) |
| Soil type (class) | | |
| Bulk density (g cm$^{-3}$) | | |
| Texture (%sand:silt:clay) | | |

[a] Summary of data sources and satellite sensor descriptions available from USGCRP (1999) and the Data Management Working Group of the Subcommittee on Global Change Research.

these data sets, with specifications for running a daily model of water, carbon, nitrogen, and trace gas fluxes like NASA–CASA. The requirement for daily climate inputs at the regional level is a need that apparently cannot be fulfilled without resorting to predicted output from atmospheric general circulation models (AGCMs) or statistical interpolation techniques using monthly observational data sets. Based on our site modeling studies reported in this paper, daily data sets for surface radiation flux and precipitation rates are the most important model drivers to evaluate for regional and temporal bias.

Among the other input data sets listed in Table 2, plant rooting depth into mineral soil merits special consideration. As we reported in a previous modeling study of water, carbon, and trace gas fluxes for the Amazon region (Potter et al., 1998), improvements in the large-scale modeling of below ground biomass dynamics and water balance will depend in part on more extensive information and field measurements for forest rooting depths across the entire region. Such measurements are time-consuming and labor-intensive, which helps explain the relatively small data set now available for rooting patterns of tropical trees.

Nonetheless, in a previous model sensitivity analysis, we found that estimated NPP of Amazon primary forests can increase by almost 6% when the deep rooting depth (10 m) is set, in place of a more shallow rooting depth (2 m) used for forests in several global ecosystem models. Moreover, sensitivity analysis of this type may show even larger effects of rooting depth settings with consideration of periodic drought effects on NPP, and the possibility that deep rooting and drought tolerance by trees in evergreen forests of the Amazon maintains primary production during extremely dry years (Nepstad et al., 1995, 1999).

In summary, an improved understanding of how tropical forest conversion influences regional water, carbon, nutrient dynamics and trace gas fluxes in Amazonia will depend upon bringing to bear and improving all available methods of ecosystem process monitoring and inventory, including remote sensing, ground-based sampling, tower flux measurements, ecosystem modeling, statistical analysis and geographic information systems. Errors from each of these methods must be reduced to the greatest extent possible by systematic intercomparisons of their independent estimates for hydrology and biogeochemistry.

Nonetheless, predicted carbon balance from modeling results presented in this paper implies that relatively undisturbed Amazon forest ecosystems may be strong net sinks for atmospheric $CO_2$. Following large losses of biomass from simulated burning, the model also predicts, however, that these forest sites switch from being a net sink for $CO_2$ to a substantial terrestrial source, with annual emission fluxes of carbon to the atmosphere equivalent in magnitude to about 10 years of undisturbed NEP sink fluxes. These implied patterns in forest carbon dynamics remain subject to verification over the entire Amazon region. Improvements in model process algorithms for carbon and nitrogen trace gas fluxes across gradients of soil types in the Amazon basin will require further study as part of new LBA field campaigns.

## Acknowledgements

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