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Compilation of a global N_2O emission inventory for tropical rainforest soils using a detailed biogeochemical model

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Summary

Compilation of a global N_2O emission inventory for tropical rainforest soils using a detailed biogeochemical model

Nitrous oxide (N_2O) is a potent trace gas contributing to approximately 6% to the observed anthropogenic global warming. Soils have been identified to be the major source of atmospheric N_2O and tropical rainforest soils are thought to account for the largest part. Furthermore, various studies have shown that the magnitude of N_2O emissions from tropical rainforest soil is highly variable on spatial and temporal scales. Detailed, process-based models coupled to Geographic Information Systems (GIS) are considered promising tools for the calculation of N_2O emission inventories. This methodology explicitly accounts for the governing microbial processes as well as the environmental controls. Moreover, mechanistic biogeochemical models operating in daily time-steps (e.g. ForestDNDC-tropica) have been shown to capture the observed intra- and inter-annual variations of N_2O emissions. However, detailed N_2O emission datasets are required for model calibration and testing, but are currently few in numbers.

In this study an automated measurement system was used to derive detailed datasets of N_2O, methane (CH_4) and carbon dioxide (CO_2) soil-atmosphere exchange and important environmental parameters from tropical rainforest soils in Kenya and Southwest China. Distinct differences were identified in the magnitude of the C and N soil-atmosphere exchange at the investigated sites and forest types. However, common features such as N_2O pulse emissions after dry season or the pronounced soil moisture dependency of N_2O emissions were observed at both sites. The derived datasets are unique for these tropical regions as so far no information about the source strength of these regions was available and, for the first time, the N_2O, CH_4 and CO_2 soil-atmosphere exchange was recorded in sub-daily resolution.

The datasets were utilized in conjunction with available high-resolution datasets from Australian rainforests for the re-calibration of the ForestDNDC-tropica model using a multi-site, parallel Bayesian calibration approach. Extensive validation and sensitivity studies underlined the good agreement of the improved biogeochemical model with observed N_2O fluxes. Based on a newly developed detailed GIS database for tropical rainforests worldwide, the new model was then used for the calculation of a global N_2O

emission inventory. Daily N_2O emissions for the years 1991 – 2000 were calculated. The results show striking spatial and temporal differences of N_2O source strength. Based on the calculations in this study the source estimate of global N_2O emissions from tropical rainforest soils was revised from previously 1.2 – 3.6 Tg N yr^{-1} (based on a wide range of source areas considered) to 1.3 Tg N yr^{-1}. As the accuracy of the model output is dependant on the data quality driving the models, an uncertainty assessment was performed to quantify the data-induced uncertainty on the presented N_2O emission inventory. Using a Latin hypercube sampling approach, the uncertainty range was calculated to be 0.9 – 2.4 Tg N yr^{-1}.

Another key finding of this study was the strong seasonal and inter-annual variability of N_2O emissions originating from tropical rainforest soils at the global scale. So far, this was not captured by statistical upscaling approaches. Furthermore, these temporal variations were accompanied by significant spatial variations in the N_2O emission strength on a continental scale (e.g., 90% variation between 1993 and 1994 for the African continent). It can be hypothesized that these significant spatial and temporal changes may even be traceable by using inverse modelling studies.

The results of this study clearly show that GIS-coupled, detailed biogeochemical models are an excellent tool for the calculation of large-scale emission inventories. It could also be shown, that the ForestDNDC-tropica model offers the possibility to account for the spatial and temporal heterogeneity of the N_2O soil-atmosphere exchange as observed during field measurements in tropical rainforest worldwide. The presented approach might help to overcome the static concept of previous inventory assessments towards a more dynamic understanding of N_2O biosphere-atmosphere exchange processes on a global scale, thereby also allowing considering feedbacks to changes in climate and land use. Nevertheless, this study also exposed the need for further detailed field studies to better describe the variability involved in the N_2O release from soils.

Zusammenfassung

Erstellung eines globalen Katasters für N_2O-Emissionen aus Böden tropischer Regenwälder unter Verwendung eines biogeochemischen Modells

Stickstoffdioxid (N_2O) ist ein stark klimawirksames Spurengas und trägt zu etwa 6% zum beobachteten, anthopogen verursachten Treibhauseffekt bei. Es wird vermutet, dass Böden, insbesondere tropische Waldböden, die bedeutendste natürliche Quelle für atmosphärisches N_2O darstellen. Zahlreiche Studien haben außerdem gezeigt, dass die Höhe von N_2O-Emissionen tropischer Waldböden sowohl räumlich als auch zeitlich stark variiert. Die Kopplung von Geographischen Informationssystemen (GIS) mit detaillierten, prozess-orientierten Modellen wird deshalb als eine viel versprechende Methode zur Berechnung von N_2O-Emissionskatastern angesehen, da sie sowohl die grundlegenden mikrobiellen Umsetzungsprozesse als auch deren ökologische Steuergrößen berücksichtigt. Vor allem mit täglicher Auflösung operierende Modelle, wie das in dieser Studie eingesetzte ForestDNDC-tropica, sind in der Lage, die beobachteten intra- und inter-annuellen Schwankungen von N_2O-Emissionen zu simulieren. Zur Kalibrierung und Validierung dieser Modelle werden aber zeitlich hoch aufgelöste N_2O-Emissionsmessungen benötigt, die jedoch bisher nur in sehr begrenztem Umfang verfügbar sind.

Im Rahmen der vorliegenden Arbeit wurden deshalb zunächst zeitlich hoch aufgelöste Datensätze des Boden-Atmosphäre-Austausches von N_2O, Methan (CH_4) und Kohlendioxid (CO_2) sowie wichtiger ökologischer Einflussgrößen in tropischen Regnwäldern Kenias und Süd-West Chinas mittels eines vollautomatischen Messsystems erhoben. Hierbei konnten signifikante Unterschiede der regionalen Quellstärke von C- und N-Spurengasen zwischen den Messflächen und auch unterschiedlichen Waldtypen festgestellt werden. Allerdings wurden ebenfalls Gemeinsamkeiten beobachtet, wie etwa das Auftreten von kurzzeitigen N_2O Emissionsspitzen mit den ersten Regenfällen nach der Trockenzeit, Substratlimitierungen der N_2O-Emissionen sowie eine starke Abhängigkeit der N_2O Emissionen von der Bodenfeuchte. Die erhobenen Messdaten sind in ihrer Qualität für diese Tropenregionen einzigartig, da zum einen keine Messungen für diese Gebiete vorlagen und zudem erstmals der Boden-Atmosphäre-Austausch von N_2O, CH_4 und CO_2 in sehr hoher zeitlicher Auflösung aufgezeichnet wurde.

In Verbindung mit bereits existierenden Datensätzen vergleichbarer Qualität wurden die neu erhobenen Daten für eine Neukalibrierung des ForestDNDC Modells mittels einer parallelisierten Bayesischen Kalibrierung genutzt. Durch umfassende Validierungs- und Sensitivitätsstudien konnte die Güte des verbesserten biogeochemischen Modells für die Simulation von N_2O-Emissionen aus tropischen Waldökosystemen aufgezeigt werden. Die neue Modellversion wurde in Verbindung mit einer neu entwickelten GIS Datenbank der weltweiten tropischen Regenwaldgebiete zur Berechnung eines globalen N_2O-Emissionskatasters eingesetzt. Für die Jahre 1991 – 2000 wurden N_2O-Emissionen in täglicher Auflösung simuliert, wobei sowohl ausgeprägte räumliche als auch zeitliche Muster der N_2O-Quellstärken zu Tage traten.

Basierend auf den vorgestellten Berechnungen wurde die globale Quellstärke für N_2O-Emissionen aus tropischen Regenwaldböden von bisher 1.2 – 3.6 Tg N yr^{-1} auf 1.3 Tg N yr^{-1} revidiert. Hierbei gilt es allerdings zu beachten, dass einige der bisherigen Abschätzungen auf zum Teil deutlich größeren Regenwaldgebieten basieren, die in dieser Arbeit verwendete Fläche hingegen denen aktuellerer Studien entspricht. Die durch die Eingangsdaten bedingte Unsicherheitsspanne des N_2O-Emissionskatasters wurde mit Hilfe des Latin Hypercube Verfahrens auf 0.9 – 2.4 Tg N yr^{-1} berechnet.

Ein weiteres wichtiges Ergebnis der Arbeit ist die im globalen Maßstab sowohl saisonale als auch inter-annuell simulierte Variabilität der N_2O-Emissionen aus den Böden tropischer Regenwälder, die sich zwar zum Teil aus Beobachtungen im Rahmen von Feldmessungen ergibt, auf globaler Ebene jedoch durch statistische Skalierungsmethoden bisher nicht herausgearbeitet werden konnte. Es wurden weiterhin signifikante räumliche und zeitliche Variabilitäten der N_2O Emissionen im kontinentalen Maßstab beobachtet. So variierten die pedogenen N_2O-Emissionen aus afrikanischen Tropenwäldern zwischen den Jahren 1993 und 1994 um 90%. Diese starken Variationen der kontinentalen N_2O-Quellstärken sollten deshalb auch durch inverse Modellierungsverfahren aufgezeigt werden können.

Die vorliegende Arbeit zeigt, dass ForestDNDC-tropica die weltweit in Freilandmessungen beobachtete Heterogenität des N_2O-Spurengasaustausches realistisch nachbilden kann. Weiterhin zeigen die Ergebnisse der vorliegenden Arbeit deutlich, dass die GIS-gekoppelte biogeochemische Modellierung ein exzellentes Werkzeug für die Berechnung kontinentaler und globaler Emissionskataster ist. Der vorgestellte Ansatz ermöglicht den Übergang vom bisherigen statischen Konzept der Emissionskataster hin zu einer dynamischeren Betrachtungsweise des N_2O-Spurengasaustausches, bei der auch Klima- und Landnutzungsänderungen berücksichtigt werden können. Allerdings wurde in dieser Studie ebenfalls die Notwendigkeit weiterer detaillierter Messkampagnen deutlich, welche für die Kalibrierung prozess-orientierter Modelle unverzichtbar sind.

CONTENTS

CHAPTER
ONE

Introduction and objectives

FOLLOWING carbon dioxide (CO_2) and methane (CH_4), and despite its low atmospheric concentration of 318.6 ppbv (global mean concentration 12/2004 *WMO*, 2006), nitrous oxide (N_2O) is the third most important radiatively active greenhouse gas, contributing approximately 6% to the total observed global warming at present (*WMO*, 2006). Besides being a potent greenhouse gas, N_2O is also involved in the depletion of stratospheric ozone (*Crutzen*, 1970). The atmospheric concentration is currently increasing at a rate of approximately 0.25% per year. N_2O is of biogenic origin predominantly, and soils are one of the major sources, contributing approximately 57% to the total atmospheric N_2O budget (*Mosier et al.*, 1998). A major part of these soil-based N_2O emissions originates from tropical rainforest regions. Tropical rainforest soils are considered to be the largest natural terrestrial source for atmospheric N_2O, besides N_2O emissions from fertilized agricultural soils (*Kroeze et al.*, 1999; *Mosier et al.*, 1998).

1.1 Sources and sinks of atmospheric N_2O

Nitrous oxide is produced in soils through the microbial processes of nitrification and denitrification (*Conrad*, 1996), both of which are key processes of N cycling in terrestrial ecosystems. The mineralization of organic material leads to the formation of ammonium (NH_4^+), which serves as a substrate for the autotrophic or heterotrophic nitrification (see Figure 1 on page 3). Under aerobic conditions, autotrophic and/ or heterotrophic nitrifying organisms oxidise NH_4^+ via hydroxylamine (NH_2OH) and nitrite (NO_2^-) to nitrate (NO_3^-). Anaerobic conditions in the soil or in microsites promote the denitrification process, using NO_3^- as an electron acceptor. Depending on environmental conditions, NO_3^- is reduced stepwise via NO_2^-, nitric oxide (NO) to inert nitrogen (N_2). N_2O is released as a by-product during these reactions. *Firestone and Davidson* (1989) introduced the conceptual "hole-in-the-pipe" model (Figure 1) to describe the production and consumption of N_2O and NO during nitrification and denitrification. Here, the magnitude of N trace gases released by these processes is a function of process turnover rates (flow rate in the "pipes") and the loss rates during the step-wise reactions (size of the "holes"). Nitrification

and denitrification can occur simultaneously in soils, since the rates of the two processes depend on soil aeration and micro-site availability of substrates. Nitrification and denitrification are affected by various biotic processes, mineralization and plant N uptake, for example, and a wide range of abiotic factors, such as soil temperature and moisture, pH, and soil texture. The significant variability of these factors across space and time (see *Davidson*, 1991; *Papen and Butterbach-Bahl*, 1999) has often been demonstrated to provide feedback also on N_2O emissions from tropical forest soils. Therefore, most datasets show a substantial variation of N_2O emissions on seasonal and inter-annual as well as on spatial scales.

It is generally accepted that, despite their importance, N_2O emissions from tropical rainforest ecosystems are still poorly characterized (*Breuer et al.*, 2000; *Kiese et al.*, 2005; *Serca et al.*, 1994). Furthermore, the majority of N_2O measurements were obtained in the Amazonian and Central-American region (e.g., *Keller and Reiners*, 1994; *Matson and Vitousek*, 1990; *Riley and Vitousek*, 1995; *Steudler et al.*, 1991; *Verchot et al.*, 1999), and most of our knowledge is still based on a relatively small number of individual flux measurements (as described by *Breuer et al.*, 2000). The only dataset of N_2O emissions from tropical rainforest soils of the African continent was published by *Serca et al.* (1994), who worked in the Congo region. Since then, no other attempt has been made to investigate N_2O emissions from tropical rainforest soils in Africa. The same partly applies to the Asian region, for which N_2O emission measurements have been published only in recent years (e.g., *Ishizuka et al.*, 2002; *Purbopuspito et al.*, 2006). However, the number of investigations is still small compared to the size and heterogeneity of the region.

While these datasets provide valuable information about the general nature of N_2O emissions from tropical rainforest soils, the limited number of flux measurements (often only one flux measurement per month) does not allow for their use in calibrating complex biogeochemical models which aim at simulating the observable short term biochemical process variations, their interactions, and the resulting nutrient cycling. In contrast, long-term N_2O flux measurements of high (sub-daily – daily) temporal resolution as obtained from rainforests in Queensland, Australia (*Butterbach-Bahl et al.*, 2004; *Kiese et al.*, 2003) or from non-tropical forests (e.g., *Papen and Butterbach-Bahl*, 1999) have increasingly been used to calibrate process-based biogeochemical models (*Kiese et al.*, 2005; *Li et al.*, 2000; *Stange et al.*, 2000).

1.2 Upscaling approaches for N_2O emission inventories

Knowing about the importance of tropical rainforest soils as a source of atmospheric N_2O and facing the variability in fluxes, researchers have applied a number of upscaling attempts in order to constrain the source strength of tropical rainforest soils for atmospheric N_2O. These include the compilation and comprehensive statistical analysis of available measurements and extrapolation of these measurements to global scales by considering the spatial extent of vegetation types and soil properties (*Bouwman et al.*, 1993; *Breuer et al.*, 2000; *Matson and Vitousek*, 1990; *Stehfest and Bouwman*, 2006). However, such a statistical approach of calculating N_2O emission inventories is still hampered by the limited number and temporal as well as spatial coverage of predominantly chamber-based

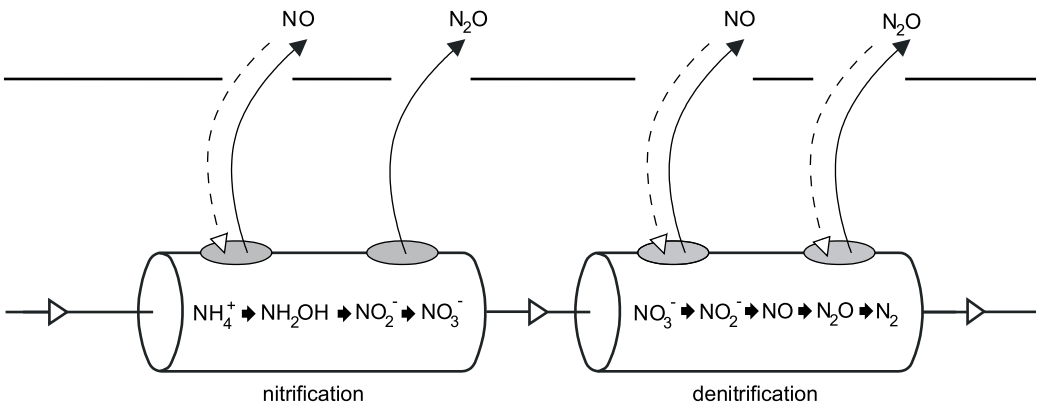


Figure 1: The conceptual "hole-in-the-pipe" model of *Firestone and Davidson* (1989).

measurements (see e.g., compilation of flux measurements by *Breuer et al.*, 2000). Therefore, estimates will remain uncertain if no other methods are used which incorporate the effect of varying environmental conditions (e.g., soil properties, vegetation, climate) on N_2O emissions (see Table 1 on the next page for a comparison of available inventory approaches and their advantages and disadvantages).

To overcome this problem, process-based models, which are able to simulate ecosystem C- and N-cycling and associated emission of trace gases, have been used increasingly in recent years for calculating regional and global emission inventories (*DelGrosso et al.*, 2006; *Kesik et al.*, 2005; *Kiese et al.*, 2005; *Li et al.*, 2001; *Parton et al.*, 1996; *Potter and Klooster*, 1998; *Potter et al.*, 1996). These models have a high potential to narrow the uncertainty in existing estimates, because they simulate the effects of changes in driving variables (temperature, moisture, texture, vegetation properties) on N_2O emissions in detail. These computational upscaling approaches which link geographic information systems (GIS) to mechanistic biochemical models, such as CASA (*Potter et al.*, 1993), CENTURY *Parton et al.* (1988), PnET-N-DNDC (*Li et al.*, 2000; *Stange et al.*, 2000) or ForestDNDC-tropica (*Kiese et al.*, 2005; *Werner et al.*, 2006 **III**), to calculate regional or global emission inventories (*Kesik et al.*, 2005; *Kiese et al.*, 2005; *Li et al.*, 2001; *Potter and Klooster*, 1998; *Potter et al.*, 1996; *Werner et al.*, 2006 **III**) have the potential to further improve the current understanding of soil contribution to the atmospheric budgets of trace gases such as N_2O, CH_4 and CO_2 (e.g., *Butterbach-Bahl et al.*, 2001; *Davidson et al.*, 1998; *Li et al.*, 2000). However, models operating on a daily time-step (e.g., PnET-N-DNDC, DayCENT, ForestDNDC-tropica) require trace gas measurements of a high temporal resolution from a variety of sites for adequate model testing (*Kiese et al.*, 2005; *Werner et al.*, 2006 **III**). Datasets fulfiling these specifications can be provided by automatic measurement systems that can record the soil-atmosphere exchange of greenhouse gases in a continuous manner and in sub-daily resolution (e.g., *Breuer et al.*, 2000; *Werner et al.*, 2006 **I**/**II**). The high resolution and continuity of these flux measurements enable the detection of short term variability in flux rates in response to changing environmental conditions and can provide direct insights into the controlling factors of N_2O emissions

Table 1: Methods for the calculation of global N_2O emission inventories and their major advantages and disadvantages.

Method	Description	Advantages	Disadvantages
Statistical upscaling	Upscaling based on spatial extrapolation of site measurements	Easy to apply, used for a range of atmospheric substances	Often too simplistic, inter-annual variability not captured, no process interaction, limited expressiveness of individual field measurements for large scales
Inverse modelling	Source strength is calculated from atmospheric concentration measurements, source region and emission strength are traced by using atmospheric transport models	Global scope, total landscape exchange	Coarse spatial resolution, limited ground data, identification of individual sources problematic, difficult to verify
Process-based biogeochemical modelling	Regional/ global application of mechanistic biogeochemical models for simulation of soil-atmosphere exchange	Spatial resolution only limited by GIS quality, reproduce process interaction and controls in the soil-vegetations system, capture inter-annual variability	Complex models, need for detailed calibration and validation datasets, need for detailed soil, climate and vegetation data

from soils (e.g., *Butterbach-Bahl et al.*, 2004; *Werner et al.*, 2006 **I**/**II**).

Inverse modelling is another approach recently used to quantify the global N_2O surface flux (*Hirsch et al.*, 2006). In contrast to the bottom-up approaches of statistical upscaling and biogeochemical modelling, inverse modelling determines N_2O emissions by assessing the atmospheric concentration changes detected by a global air sampling network or satellites and traces the emitting region and emission rates by using atmospheric transport models (top-down approach). While this method is unique in its scale and integrative capabilities, its approach also leads to very coarse spatial resolutions ((semi-hemispherical regions, see *Hirsch et al.*, 2006). Furthermore, the discrimination of N_2O emissions originating from different land-use types, ecosystems or local "hot-spot" areas is difficult or not possible at all.

1.3 Conceptual approach of this study

In order to calculate a global N_2O emission inventory from tropical rainforest soils, an integrated approach comprising field measurements, model development and testing, and GIS database set-up was implemented (Figure 2 on the facing page). In addition to the available high-resolution dataset from Bellenden Ker / Australia (*Kiese et al.*, 2003), this work has focused on obtaining two additional detailed C and N trace gas emission datasets of daily resolution including important soil and vegetation parameters for tropical rainforests sites in Western Kenya and Southwest China. The obtained data was then used in conjunction with available literature data for the re-calibration and validation of a modified version of the process-based model PnET-N-DNDC. The model adoption from (*Kiese et al.*, 2005) was extended by (a) an improved soil hydrology module, (b) a revised

soil carbon distribution and (c) model structural changes necessary to couple the model to the externally derived vegetation information. Important internal parameters of the new model version – referred to in the following as ForestDNDC-tropica – were re-calibrated using the Bayesian Calibration (BC) technique. The model was then extensively tested for model parameter sensitivity.

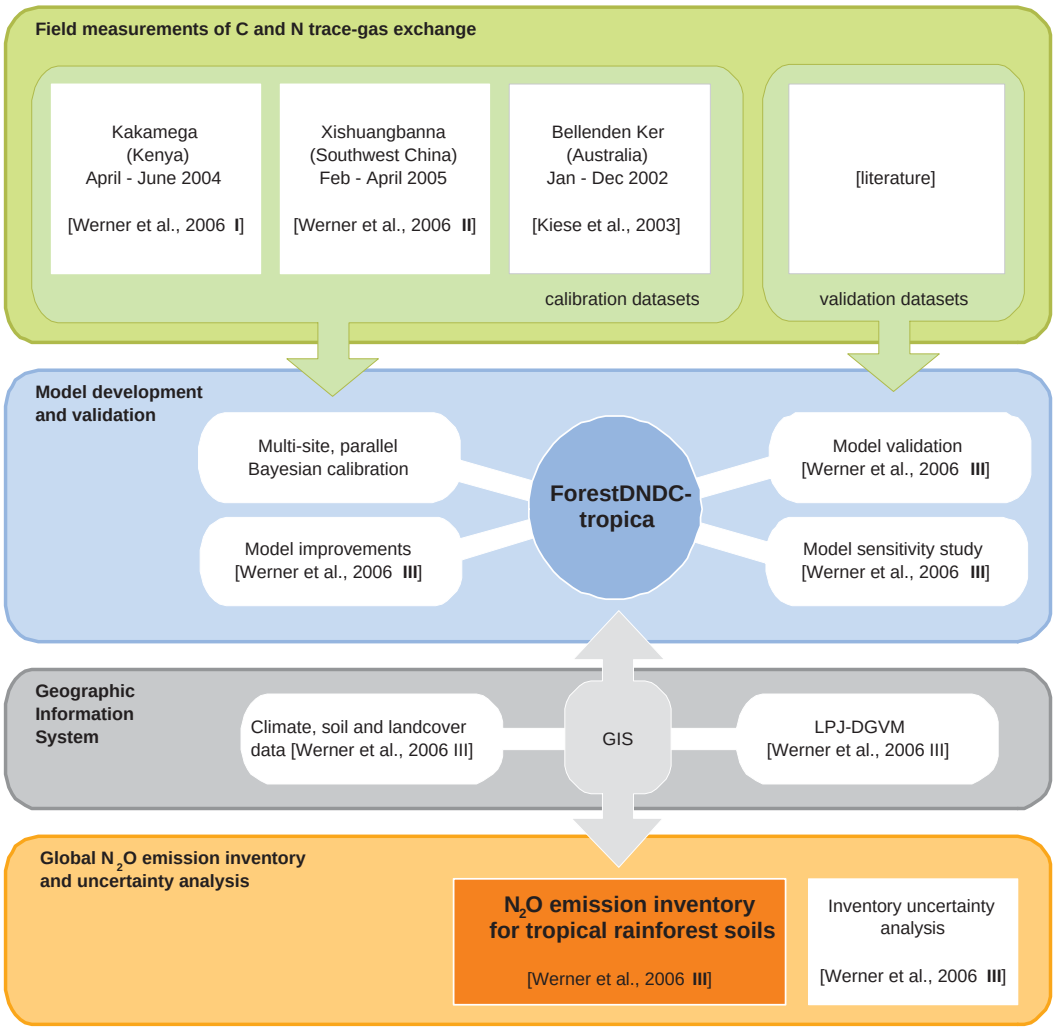


Figure 2: Schematic outline of the work carried out in this study.

For the calculation of the global inventory, an extensive GIS database was created, holding key input soil and vegetation parameters as well as ten years of daily weather data necessary for the simulation runs. Using a newly implemented data handling scheme, the data was then automatically processed on a LINUX cluster. The reported N_2O emission inventory was calculated from simulations using climate data for the years 1991 – 2000. Data induced uncertainty was analyzed by means of Latin hypercube sampling (LHS).

Part 1: Field scale

1. Measurement of N_2O, CH_4 and CO_2 soil-atmosphere exchange with high temporal and spatial resolution
    - Characterization of soil-atmosphere exchange of C and N trace gases at the site scale
    - Calibration datasets for ForestDNDC-tropica
2. Detection and analysis of environmental settings of these field sites (texture analysis, assessment of carbon and nitrogen stocks in the soils, content pH and parameters)
3. Description of C and N trace gas emissions from differing landuse systems in Xishuangbanna, Southwest China

Part 2: Model improvement, model calibration, data processing and development of a modelling framework

1. Enhancements of ForestDNDC-tropica routines (soil hydrology and vertical carbon distribution in the soil)
2. Re-calibration and optimization of major internal model parameters of ForestDNDC-tropica using Bayesian Calibration Technique
3. Model sensitivity tests
4. Setup of computing environment for the disaggregating and handling of large model datasets

Part 3: Computation of a global N_2O emission inventory for tropical rainforest soils using an advanced biogeochemical model

1. Multi-year calculations of global N_2O source strength of tropical rainforest soils
2. Analysis of spatial and temporal pattern of N_2O emissions
3. Estimation of data induced uncertainty using Latin hypercube sampling

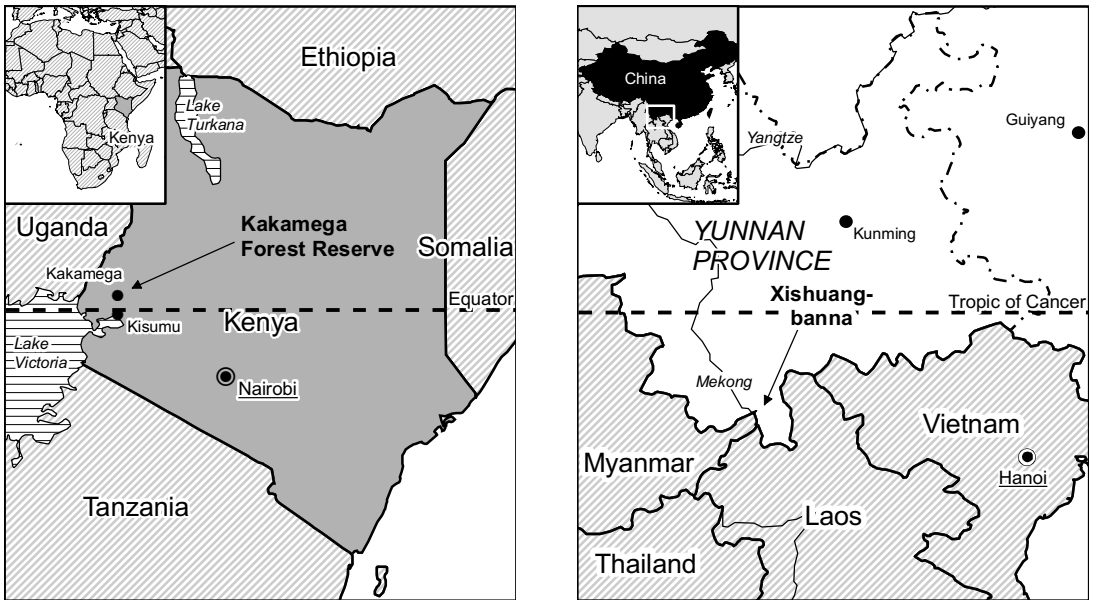
CHAPTER
TWO

C and N trace gas exchange in tropical rainforests

At present, the availability of published datasets on N_2O emissions from tropical rainforest soils is limited to a number of approximately 20 – 30 datasets, depending on selection criteria for data quality and length of measurement periods. However, to finally assess the importance of N_2O emissions from tropical rainforest soils for the atmospheric N_2O budget, more field measurements are necessary (*Breuer et al.*, 2000; *Kiese et al.*, 2005). If these field measurements are intended to be used for calibrating biogeochemical models, it is a pre-requisite that daily or at least weekly measurements are performed and environmental parameters (temperature, soil moisture) as well as detailed soil and vegetation properties are recorded (*Kiese et al.*, 2005; *Werner et al.*, 2006 **II**). To contribute to a better understanding of N_2O emissions from tropical rainforest soils and to provide high-quality datasets for model development and testing, two field measuring campaigns were performed in the framework of this study.

In view of the fact that C and N trace gas fluxes in tropical rainforest systems of Africa have been poorly studied, the first campaign was carried out at the Kakamega Forest, Kenya. The focus of this study was on the temporal variability of N_2O emissions. However, measurements in Kenya also covered the CO_2 and CH_4 soil-atmosphere exchange, because both gases are also important greenhouse gases. Furthermore, the spatial variability of N_2O emissions from tropical rainforest soils in the Kakamega area was assessed.

The second field campaign was conducted in Xishuangbanna, Southwest China, as this region is representative of many mountainous regions in Southeast Asia, including large parts of Vietnam, Laos, Myanmar and Thailand (*Fox and Vogler*, 2005). N_2O emissions were only recently reported for sites in the Asian tropics (e.g., *Ishizuka et al.*, 2002; *Purbopuspito et al.*, 2006), but the number of N_2O emission assessments from this diverse region is still small. While the main focus was to evaluate the controlling factors and seasonal variation of the soil-atmosphere exchange of C and N trace gases from natural rainforest soils, fluxes in a secondary forest and a rubber plantation were also recorded, since agroforestry systems, such as rubber plantations, are increasingly replacing primary and secondary forest systems in many parts of Southeast Asia. As reported by *Xu et al.*



(a) Kakamega Forest, Kenya (b) Xishuangbanna, Southwest China

Figure 3: Location of the field measurements sites

(2005), the extent of rubber plantations in the Xishuangbanna region increased from 61 to 1368 km^2 between 1963 and 1998, whereas the tropical forests areas decreased from 30% to approximately 10% of the total land area during this period.

2.1 Field sites and measurement setup

The Kakamega Forest National Park is located between 00°8' N – 00°23' N and 34°46' – 34°58' E at altitudes of 1500 - 1700m a.s.l in Western Kenya, approximately 70 km north of Kisumu (see Figure 3a). It is considered to be the easternmost remnant of the equatorial Guinea-Congo-rainforest, which was isolated by changing climatic conditions, and in more recent times, intense anthropogenic land-use conversion (*Kokwaro*, 1988). The average annual precipitation from 1986 to 1997 was 1662mm and most rainfall is concentrated in two distinct wet seasons from March to June and August to October. The average monthly maximum temperature is 24.9 °C, the monthly minimum temperature is 15.4 °C. At the study site, deep clay-loamy soils developed from precambrian gneiss and sedimentary rock formations (especially claystone) can be found (*Kamoni*, 2004; *Round-Turner*, 1994). The most dominant soil types of this area are Luvisols (on alluvial base material), Lixisols (deeply weathered, leached and poor in nutrients), porous Cambisols of fine to medium texture and ground water table affected Gleysols (*Kamoni*, 2004). The forest is structured in four canopy layers (emergent layer, canopy layer, understory layer, and herb layer). In general, the canopy is relatively open, and the stands reach 45m in height (*Fashing et al.*, 2004). Intensive forest use in modern times has altered the structure of the forest dramatically (*Kiama and Kiyiapi*, 2001). Due to selective logging,

trees with diameters at breast height > 100cm are rare. In order to cover differences in forest structure, as well as the difference in soil properties, six permanent sampling plots in the Kakamega National Forest were installed (the northern section of the Kakamega Forest is shown in Figure 4).

The second field campaign was carried out at a seasonally dry tropical rainforest site in Xishunagbanna, Southwest China (location: 21°55' N – 21°58' N / 101°12' E – 101° 16' E; 550 – 780m a.s.l., see Figure 3b). The climate in the Xishuangbanna region is strongly seasonal. Between May and October about 80% of the total annual precipitation of 1493mm occurs via the tropical Southwest Monsoon, whereas dry and cold air masses of the subtropical jet streams dominate the regional climate from November to April. The dry period is further divided into a cool-dry period lasting from November to February with frequent heavy radiation fog at night and in the morning and a hot-dry period with heavy radiation fog during the morning hours only (*Cao et al.*, 2006). Water deposition from fog equates to 0.52mm a day (49%) and 0.41mm a day (33%) during cool-dry and hot-dry periods respectively, which contributes substantially to the total water input below the canopy during these months. The long-term mean temperature for the town of Menglun, Menla County, is 21.8°C (*Cao et al.*, 2006). The majority of tropical rainforests in the Xishuangbanna region are located on yellow lateritic soils developed from granite and gneiss parent material or lateritic red soils derived from sandstone substrates (*Cao et al.*, 2006). The primary forest site investigated in this field campaign is classified as a tropical seasonal rainforest with an average canopy height of about 40m. *Zhu et al.* (2006) has stratified this forest type into three to four indistinct tree layers, in which top layer trees generally exceed 30m (up to 30% crown coverage) and the second / main canopy layer reaches up to 30m (70 – 80% crown coverage) and contains the greatest stem density. The third layer, containing small trees and juveniles, generally reaches 5 – 18m (up to 40% coverage) and can be further divided into sub-layers. As a direct effect of intensive agroforestry practices in the area, most primary forest is now restricted to steep and mountainous terrain, not suitable for agricultural management. The latest burning and logging events of the secondary forest site occurred in the late 1980s. Since then the site has remained undisturbed and the forest has been allowed to re-grow. The secondary forest now reaches a canopy height of approximately seven meters and dense shrubs dominate the undergrowth at present. Approximately 20 years ago, the natural slope (10 – 15°) of the rubber plantation site was terraced during the establishment of the plantation. The site was fertilized only two weeks prior to the start of the flux measurements with 55 kg N ha^{-1}.

The static chamber technique was used in both field campaigns (e.g., *Breuer et al.*, 2000). In order to continuously measure trace gas emissions, a fully automated gas sampling system was installed at the main field sites of both campaigns. Details of the measurement system can be found in *Butterbach-Bahl et al.* (1998) and *Breuer et al.* (2000). Six (Kakamega) or four (Xishuangbanna) chambers were sampled simultaneously, and four additional chambers were sampled in Xishuagbanna within the framework of an irrigation experiment. N_2O concentrations in the sampled air were analysed by gas chromatography using a ^{63}Ni detector. CH_4 concentrations were analysed using a Flame Ionisation Detector (FID) and CO_2 with an Infrared-CO_2-analyser. During chamber closure, air was automatically sampled every nine minutes (Kakamega; *Werner et al.*, 2006 **I**)

Figure 4: View over the north western section of the Kakamega Forest, Kenya

or every 15 minutes (Xishuangbanna; *Werner et al.*, 2006 **II**). Fluxes were calculated from the concentration increases during every closure cycle, temperature and pressure corrected and calibrated hourly with a standard gas. Alternative chamber positions were selected in the Kakamega campaign in order to minimize insolation effects and to capture small scale variations of soil properties (see *Kiese et al.*, 2003; *Werner et al.*, 2006 **I**) but not in Xishuangbanna due to site limitations. Additional sites were sampled manually using syringes to draw air from the chamber headspace. In the Kakamega Forest, samples were obtained from five manual sampling sites in order to assess the spatial variability of N_2O emissions within the forest (*Werner et al.*, 2006 **I**). In Xishuangbanna a secondary forest site and a rubber plantation were sampled manually using the same approach. Air samples were analysed immediately after sampling either at the measurement system at the main site (*Werner et al.*, 2006 **I**) or with an additional system (described by *Wang and Wang*, 2003; *Werner et al.*, 2006 **II**). Two irrigation experiments were carried out at all three investigated sites in the Xishuangbanna study. The aim of the irrigation experiment was to test the effect of changes in soil moisture on C and N fluxes under controlled conditions (*Werner et al.*, 2006 **II**). For further details see *Werner et al.*, 2006 **I**/**II**.

2.2 Spatial and temporal variations of C and N trace gases

2.2.1 N_2O soil-atmosphere exchange

The recorded dataset of N_2O, CH_4 and CO_2 soil-atmosphere exchange from tropical rainforest ecosystems are the first datasets for the African and Asian region obtained in sub-daily temporal resolution (*Werner et al.*, 2006 **I**/**II**). Significant differences in the amplitude of recorded N_2O emissions (Kakamega: 1.1 – 324.8 μg N m^{-2} h^{-1}, *Werner et al.*, 2006 **I**; Xishuangbanna: 0.5 - 24.5 μg N m^{-2} h^{-1}; *Werner et al.*, 2006 **II**) as well as in the average N_2O emissions of both sites (Kakamega: 42.9 $\pm$ 0.7 SE μg N m^{-2} h^{-1}, *Werner et al.*, 2006 **I**; Xishuangbanna: 6.0 $\pm$ 0.7 SE μg N m^{-2} h^{-1}; *Werner et al.*, 2006 **II**) were

observed. The recorded N_2O source strength for the Kakamega Forest was in the same range as previously measured for the Mayombe forest, Congo (*Serca et al.*, 1994), the only dataset so far available for tropical Africa. The measurements for the Kakamega Forests were also close to the average N_2O emission for tropical rainforests with comparable hygric conditions worldwide, as reported in the literature review by *Breuer et al.* (2000). In contrast, the N_2O emissions encountered at the Xishuangbanna rainforest site ranged at the lower to medium spectra of previously reported N_2O emissions from tropical rainforests (e.g., *Breuer et al.*, 2000; *Garcia-Montiel et al.*, 2003; *Kiese and Butterbach-Bahl*, 2002; *Kiese et al.*, 2003; *Melillo et al.*, 2001) but were higher than those reported by *Ishizuka et al.* (2002) for soils of the Jambi province in Indonesia (*Werner et al.*, 2006 **II**).

It was shown in previous studies that re-wetting of soils after prolonged dry periods can stimulate pulses of N trace gas emissions (*Butterbach-Bahl et al.*, 2004; *Davidson et al.*, 1993; *Garcia-Montiel et al.*, 2003). Such N_2O pulse emissions are associated with the rapid microbial consumption of NH_4^+ or NO_2^- accumulated during the dry period (*Davidson et al.*, 1993), which are in turn partly oxidized (NH_4^+) and/ or reduced (NO_2^-) to N_2O by nitrifying or denitrifying bacteria (*Poth and Focht*, 1985). Generally these conditions are reached after the first substantial precipitation events following a dry season, when moisture limitation is released and above- and below-ground litter is rapidly mineralized by re-activated microbial turnover processes (*Butterbach-Bahl et al.*, 2004; *Davidson et al.*, 1993). During the measurements at the Kakamega Forest and in Xishuangbanna, N_2O emission pulses were also observed after the first substantial precipitation events (*Werner et al.*, 2006 **I**) and the first irrigation experiment in Xishuangbanna (*Werner et al.*, 2006 **II**) respectively. However, the magnitude of rainfall-induced N_2O emission pulses differed greatly in magnitude between both sites and changed over time. By selecting N_2O emissions measurements to those recorded at a certain soil moisture level (55 – 65% water filled pore space [WFPS]) at the Kakamega Forest, it could be shown that N_2O emissions exponential decreased over time (*Werner et al.*, 2006 **I**). This decrease indicates that, with the progression of the rainy season, substrate is increasingly depleted due to the quick decomposition of litter, which was accumulated during the dry season. This interpretation is supported by a concurrent decline in soil CO_2 emissions (*Werner et al.*, 2006 **I**). However, this phenomenon was not observed at the Xishuangbanna rainforest site where the highest N_2O emissions of the control chambers were observed not after the first rainfall but at the end of the measuring campaign (*Werner et al.*, 2006 **II**). The reason for the observed different strengths of N_2O emissions of the two sites could not fully be clarified in this study, but it is most likely related to a lower accumulation of substrates (e.g., NH_4^+ and NO_3^-) for N turnover and associated N trace gas emission at the Xishuangbanna site (*Werner et al.*, 2006 **II**). Furthermore, differing mineral soil and floor properties (soil organic carbon [SOC], pH, soil texture), which are generally considered long-term controls of N_2O emission strength, have had an impact on the magnitude of N_2O release from the investigated forest soils as could be shown in the analysis of the spatial variation of N_2O emissions at both sites (see also below).

Correlation analysis revealed that N_2O emissions at the Xishuangbanna primary rainforest site were partially controlled by changes in soil temperature ($r^2 = 0.5$, $p < 0.01$). Such a correlation is often reported for temperate forests which show a pronounced seasonal variation in soil temperature (e.g., *Brumme*, 1995; *Papen and Butterbach-Bahl*,

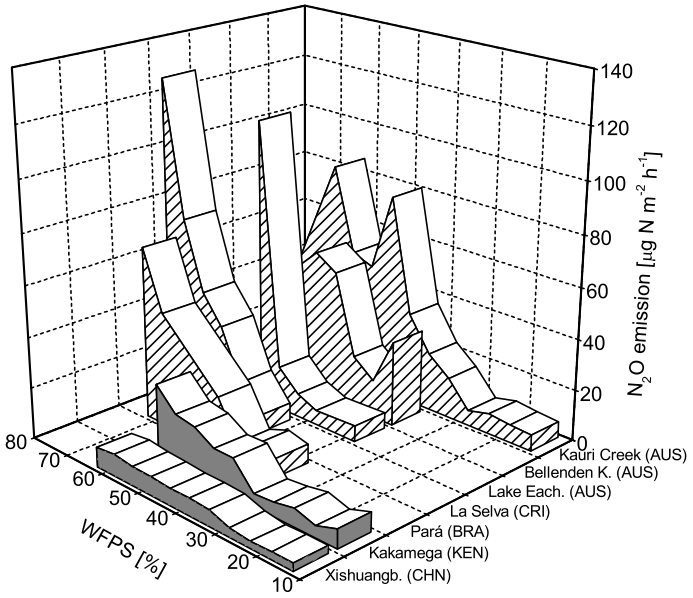


Figure 5: Effect of soil moisture (WFPS) on N_2O emissions from various tropical rainforest sites (*Werner et al.*, 2006 **I**). The results of the two field campaigns conducted in the scope of this PhD study are given in gray.

1999), but it cannot usually be shown for tropical rainforests systems (e.g., *Breuer et al.*, 2000; *Kiese and Butterbach-Bahl*, 2002; *Werner et al.*, 2006 **I**). However, induced by the topography at the Xishuangbanna primary rainforest site, a typical mountainous rainforest site, significant temperature changes were measured which obviously affect the N_2O emissions.

However, as outlined by various authors (e.g., *Davidson*, 1991; *Firestone and Davidson*, 1989; *Kiese and Butterbach-Bahl*, 2002; *Linn and Doran*, 1984), soil microbial activity is highly affected by soil moisture, which in turn also determines soil aeration and, thus, microbial based nitrogen emissions in tropical environments (see Figure 5 for a comparison of N_2O emissions from various tropical rainforest sites resulting from different WFPS conditions). By excluding the substrate induced peak emissions, 68% of the N_2O emissions variability observed at the Kakamega Rainforest could be explained by changes in WFPS (*Werner et al.*, 2006 **I**). A similar correlation analysis for the variability of N_2O emissions at the Xishuangbanna forest revealed that also at this site N_2O emissions were strongly correlated with soil moisture changes ($r^2 = 0.48$; $p < 0.01$). By including soil temperature, up to 69% of the observed N_2O emission variability at the Xishuangbanna primary rainforest could be explained (*Werner et al.*, 2006 **II**).

Within the framework of an irrigation experiment at the Xishuangbanna sites, it could be shown that artificial rain events stimulated N_2O emissions at the beginning, but the total N_2O release during the entire observation period was not significantly affected when compared to the non-irrigated control chambers (*Werner et al.*, 2006 **II**). This shows that the additional water input only controlled the timing but not the total magnitude of N_2O emissions in this environment. This is an indication that N_2O emissions at the

Xishuangbanna primary rainforest site were also substrate limited (*Werner et al.*, 2006 **II**).

While the short-term variability of N_2O emissions is generally controlled by changes of soil temperature, soil moisture, nutrient availability, and microbial activity, the general emission potential is predominantly governed by soil texture (which defines the aeration of the soil and thus the environmental conditions for the microbial biomass and processes) and carbon and nitrogen stocks in the soil (e.g., *Li et al.*, 2005). For instance, microbial N biomass and mineralization correlated positively with soil C and N concentrations and negatively with the C:N-ratio (*Booth et al.*, 2005).

A detailed analysis of spatial differences in N_2O emissions at the Kakamega Forest revealed that variations of local N_2O emissions could be explained best by differences in soil texture and the C:N-ratio of the topsoil (*Werner et al.*, 2006 **I**). Compared to primary forest sites in the Kakamega Rainforest, significantly lower N_2O emission were recorded at an artificial re-growth site. This difference can be explained by the significantly lower C and N stocks as a consequence of clear cutting and by the differing litter quality of the trees planted during the artificial reforestation (*Werner et al.*, 2006 **I**). In contrast to these results, N_2O emissions of a re-growth forest site in Xishuangbanna were higher than those observed for the primary rainforest. However, these differences are most likely an effect of differing soil textural properties of the two sites, rather than a stimulating effect of forest management (*Werner et al.*, 2006 **II**). Despite the fact that the rubber plantation at Xishuangbanna was fertilised with approximately 55 kg N ha^{-1} per year, weighted mean N_2O emission fluxes for this site were significantly lower than those observed at the nearby secondary forest or at the primary forest site. This observation is in accordance with previous studies (*Ishizuka et al.*, 2002). It could be shown that the soils at the rubber plantation were depleted in total C and N while the textural composition of the soil was similar to that at the secondary forest site (*Werner et al.*, 2006 **II**).

Because field measurements of daily or sub-daily resolution require more logistic and financial efforts as compared to monthly sampling routines, a statistical analysis on the Xishuangbanna primary forest N_2O emission dataset (sub-daily resolution) was conducted. It could be shown that daily, weekly, or monthly flux measurements during this observation period would have reduced the accuracy of a mean N_2O emission estimate by 8%, 25% and 63% respectively (*Werner et al.*, 2006 **II**). Thus it can be concluded that weekly measurements of trace gas fluxes would have provided a reliable basis for estimating the N_2O exchange at this site. However, for further improvement and validation of mechanistic models, it is of utmost importance to provide detailed data (daily or sub-daily trace gas fluxes) in order to better understand the controls and to develop suitable algorithms describing the processes involved in C and N trace gas production, consumption, and emission (*Li et al.*, 2000; *Werner et al.*, 2006 **II**). Furthermore this statistical exercise illustrates that annual N_2O emission estimates based on monthly measurements, as commonly reported in the literature (e.g., *Ishizuka et al.*, 2002; *Keller and Reiners*, 1994; *Melillo et al.*, 2001), may deviate substantially from the real N_2O source strength of a given rainforest site.

2.2.2 CH_4 soil-atmosphere exchange

The soil-atmosphere exchange of methane is the result of simultaneously occurring production and consumption processes in soils and is thus controlled by CH_4-producing methanogens operating at anaerobic conditions and CH_4-consuming methanotrophs that depend on oxygen as a terminal electron acceptor (*Topp and Pattey*, 1997). Activity and population sizes of these microbes depend on a multitude of soil factors, such as aeration of the soil profile, substrate availability, pH, soil moisture, and soil temperature (e.g., *Chan and Parkin*, 2001; *Conrad*, 1996; *Khalil and Baggs*, 2005; *Smith et al.*, 2003; *Topp and Pattey*, 1997).

The mean CH_4 uptake rate – negative rates indicate a net uptake of CH_4 from the atmosphere by the soil – differed substantially between the two primary rainforest sites investigated within the framework of this PhD study. While soil CH_4 uptake was high at the Kakamega Forest (mean flux rate: -56.4 ± 0.8 SE μg C m^{-2} h^{-1}; *Werner et al.*, 2006 **I**), the soil CH_4 uptake at the primary rainforest (mean flux rate: -21.0 ± 0.3 SE μg C m^{-2} h^{-1}) and secondary rainforest (mean flux rate: -28.1 ± 0.8 SE μg C m^{-2} h^{-1}) in the Xishungbanna region was considerably lower (*Werner et al.*, 2006 **II**). In previous studies on the CH_4 exchange of tropical rainforest soils, fluxes ranging from -29.4 to -39.4 μg C m^{-2} h^{-1} were reported (e.g., *Keller and Reiners*, 1994; *Kiese et al.*, 2003; *Verchot et al.*, 2000).

Because methane production usually requires prolonged periods of water logging, which is rarely encountered in upland soils, tropical upland forest soils predominantly act as sinks for atmospheric CH_4 (e.g., *Butterbach-Bahl et al.*, 2004; *Delmas et al.*, 1992; *Ishizuka et al.*, 2002; *Keller and Reiners*, 1994; *Keller et al.*, 1986; *Kiese et al.*, 2003). This was also the case for the investigated rainforest sites in Kenya and Southwest China, but short periods of CH_4 emissions were observed for some chamber positions when soil moisture levels were high (*Werner et al.*, 2006 **I**/**II**). A strong link between soil moisture and the variation of CH_4 uptake rates was found for the rainforest soils in Xishuangbanna (*Werner et al.*, 2006 **II**), but this correlation was not significant at the Kakamega Forest (*Werner et al.*, 2006 **I**). Furthermore, CH_4 emissions were only recorded for two of the 12 chamber positions at the primary site at Kakamega Forest (*Werner et al.*, 2006 **I**). A crumbled soil structure found in these chambers might indicate that termites are responsible for the recorded CH_4 efflux from the soil as it is well known that termites can produce considerable amounts of CH_4 during their digestion processes (e.g., *Bignell et al.*, 1997; *MacDonald et al.*, 1998) and termites are common in the Kakamega Forest (*Werner et al.*, 2006 **I**).

A clear connection between soil moisture and CH_4 soil-atmosphere exchange was also identified in the watering experiments at the Xishuangbanna sites. CH_4 uptake rates decreased with increasing soil moisture levels for the entire experiment duration. As a consequence, and in contrast to the observation that the total amount of N_2O emitted during the experiment was approximately the same for watered and control chambers, total CH_4 uptake rates were significantly reduced for the watered chambers (*Werner et al.*, 2006 **II**). As illustrated by *Brumme and Borken* (1999), temperature and precipitation are responsible for the short-term control of CH_4 oxidation processes and are thus governing the diurnal and seasonal variability. Combining all daily net CH_4 exchange fluxes from control and watered chambers, soil moisture variations could explain 66% (primary forest),

30% (secondary forest) and 72% (rubber plantation) of the observed temporal variability (*Werner et al.*, 2006 **II**).

The reduction in the CH_4 oxidation capacity observed throughout the measurement campaign at the rubber plantation (mean uptake rate: -5.7 μg C m^{-2} h^{-1}; *Werner et al.*, 2006 **II**) may be attributed to (a) soil disturbance and compaction as a consequence of land use/ cover change and terracing during the establishment of the rubber plantations and (b) nitrogen fertilization providing NH_4^+ which is currently under discussion as a possibility to reduce the CH_4 oxidation capacity of methanotrophs (*Bodelier and Laanbroek*, 2004). The explanation that nitrogen fertilization and soil physical disturbances strongly reduce CH_4 uptake is in close agreement with the findings of *MacDonald et al.* (1996) and *Mosier et al.* (2004). These authors found that, after re-establishment of forests on agricultural land, it may take several decades to regain the CH_4 uptake dynamics as observed for undisturbed forest sites.

In contrast to the other sites, the soils of the rubber plantation even turned into a weak CH_4 source after heavy rainfall events or watering activities (*Werner et al.*, 2006 **II**). On a regional scale, the conversion of forest ecosystems into rubber plantations leads to a significant reduction in atmospheric CH_4 uptake by soils and, thus, has a negative effect on the greenhouse gas budget of the Xishuangbanna region (*Werner et al.*, 2006 **II**).

2.2.3 CO_2 soil-atmosphere exchange

The mean soil CO_2 efflux from primary rainforests ranged between 58.7 – 88.1 mg C m^{-2} h^{-1} (*Werner et al.*, 2006 **I**) and 18.1 – 131.6 mg C m^{-2} h^{-1} (*Werner et al.*, 2006 **II**) for individual chamber positions, and maximum CO_2 emissions reached 155.0 mg C m^{-2} h^{-1} and 217.7 mg C m^{-2} h^{-1}, respectively (*Werner et al.*, 2006 **I**/**II**). Significantly lower CO_2 fluxes were recorded at the secondary forest of Xishuangbanna (10.1 - 56.9 mg C m^{-2} h^{-1}), although SOC at this site was higher and the C:N ratio slightly lower than at the primary rainforest site (*Werner et al.*, 2006 **II**). The lower CO_2 emissions at the secondary forest may thus be explained by a smaller contribution of plant root autotrophic respiration and a shift in carbon quality towards more resistant carbon pools as a consequence of human management, for instance, logging and burning (production of inert carbon). The same arguments hold for the significantly lower CO_2emissions recorded at the rubber plantation site (*Werner et al.*, 2006 **II**). Previous reports of CO_2 emissions from tropical rainforest soils were in general agreement with the obtained datasets (e.g., *Ishizuka et al.*, 2002; *Kiese and Butterbach-Bahl*, 2002; *La Scala et al.*, 2000; *Raich*, 1998).

Sotta et al. (2004) described the mean annual CO_2 efflux from soils of the Amazon region to range between 44.6 and 76.3 mg C m^{-2} h^{-1}, while soil CO_2 emissions were considerably lower (20.2 – 40.4 mg C m^{-2} h^{-1}) during the dry season and higher ($>$ 85 mg C m^{-2} h^{-1}) during the wet season.

Like N_2O emissions, variations of CO_2 emissions originating from primary rainforest soils were also found to be largely controlled by changes in soil moisture (coefficient of determination: 0.61 [*Werner et al.*, 2006 **I**], 0.49 [*Werner et al.*, 2006 **II**]). This could also be demonstrated by watering experiments, in which soil CO_2 emissions were elevated throughout the entire observation period by 18% (primary rainforest), 13% (secondary rainforest) and 21% (rubber plantation) as compared to control positions. Such elevations

coul be an effect of increased root respiration (*Werner et al.*, 2006 **II**).

As shown previously, temperature had a significant effect on the N_2O emissions from the primary rainforest site at Xishuangbanna but not for those from the Kakamega Forest (*Werner et al.*, 2006 **I**/**II**). Temperature variations at the primary forest site of Xishuangbanna were found to account for up to 71% of the observed temporal variability of soil CO_2 emissions (*Werner et al.*, 2006 **II**). Temperature driven diurnal variations of CO_2 emissions (δCO_2 approximately 20 mg C m^{-2} h^{-1}) at this site were observed on days without significant changes in soil moisture (e.g. 7^{th} – 10^{th} of April; *Werner et al.*, 2006 **II**). This trend was less pronounced for N_2O emissions and not evident for CH_4 fluxes. At the other Xishuangbanna measurement sites, CO_2 emissions were better correlated with changes in WFPS as compared to soil temperature, thus indicating the effect of a stronger diurnal temperature regime at the primary forest site, which is located at higher altitudes (*Werner et al.*, 2006 **II**).

A multiple linear regression analysis on soil moisture, soil temperature and CO_2 fluxes could account for 67% and 85% of the total CO_2 variability for the primary rainforest sites of Kakamega and Xishuangbanna respectively (*Werner et al.*, 2006 **I**/**II**). At the Kakamega Forest, 89% of the observed spatial variability of mean soil respiration rates could be explained by the carbon and nitrogen concentrations of subsoil samples using a "step-wise" linear regression model (*Werner et al.*, 2006 **I**). As observed for N_2O, soil CO_2 emissions also decreased during the Kakamega field campaign, but mean soil CO_2 emissions remained relatively stable until the beginning of May. With decreasing soil moisture levels, soil respiration rates gradually declined after this period, eventually reaching 50 mg C m^{-2} h^{-1} and indicating a depletion of substrate in the soil (*Werner et al.*, 2006 **I**).

CHAPTER
THREE

A global N_2O emission inventory for tropical rainforest soils

3.1 Model development

The ForestDNDC-tropica model was used in this study to simulate N_2O emissions from tropical forest soils on site as well as on global scales. The model is a successor of the PnET-N-DNDC model, which was initially developed to predict soil carbon and nitrogen biogeochemistry and N trace gas emissions of temperate forest ecosystems (*Butterbach-Bahl et al.*, 2001; *Li et al.*, 2000; *Stange et al.*, 2000), but it was recently adapted for the simulation of tropical forest ecosystems (*Kiese et al.*, 2005). The model consists of sub-models for the simulation of soil climate, decomposition, and forest growth. Within the soil climate sub-model, daily climate data are used to calculate soil temperature, moisture and oxygen profiles from one-dimensional thermal-hydraulic flow, and gas diffusion equations (*Li et al.*, 2000). This is done by considering soil physical properties (texture) as well as plant and microbial turnover processes of C, N and water. Forest growth is calculated depending on solar radiation and temperature, water, and nitrogen availability. Litter production, water and nitrogen demand of plants, and root respiration are linked to the soil climate and the decomposition sub-model. Decomposition of organic matter increases substrate concentrations of dissolved organic carbon (DOC), NH_4^+ and CO_2. The decomposition is based on decay rates (k-values) for different organic matter pools, which are modified by soil environmental conditions. N trace gas production, consumption and emission are calculated within the sub-models nitrification and denitrification. The processes are based on simulated soil microbial activities, which depend on the soil environmental conditions and a series of biochemical and geochemical reactions determining the transport and transformation of C and N components (*Li et al.*, 2000). Aerobic nitrification and anaerobic denitrification are simultaneously calculated using the concept of a dynamic "anaerobic balloon". In this conceptual approach, substrates (DOC, NH_4^+ and NO_3^-) are allocated into aerobic and anaerobic soil compartments based on the oxygen concentration in the respective soil layer (*Li et al.*, 2000).

3.1.1 Modifications and improvements of ForestDNDC-tropica

Compared to the ForestDNDC-tropica version used by *Kiese et al.* (2005), three important model sections of ForestDNDC-tropica were improved prior to its application (*Werner et al.*, 2006 **III**). First, the distribution of SOC in the soil profile was revised. The previous distribution for Australian rainforest soils was based on an exponential decay function derived from SOC concentration measurements in 5 and 30cm soil depth. It was replaced by a revised exponential decay function based on the work of *Jobbagy and Jackson* (2000) who reported SOC distributions for major forest ecosystems of the world including evergreen tropical rainforest and seasonally dry tropical rainforests (*Werner et al.*, 2006 **III**).

Because physical characteristics of tropical soils (e.g., Andosols and Ferralsols) may substantially deviate from temperate soils, specific pedo-transfer functions (PTF) for tropical soils are essential for correctly simulating soil hydrology. Such PTFs for water retention in tropical soils were recently developed by *Hodnett and Tomasella* (2002) using physical, chemical and soil water-retention data from a global soil database. These PTFs were newly implemented in ForestDNDC-tropica (*Werner et al.*, 2006 **III**) and replaced the existing static internal classification system in which hydraulic properties were set by soil texture classes and/or clay content (*Li et al.*, 1992, 2000). The Hodnett and Tomasella approach comprises a series of algorithms using information on texture (sand, silt, and clay fraction), SOC, bulk density, the cation exchange capacity and pH to derive parameters of the van Genuchten formula (*van Genuchten*, 1980), which is used in the ForestDNDC-tropica model to calculate soil specific field capacity and wilting point for soil climate sub-model initialisation (*Li et al.*, 1992, 2000).

The model internal initialization of wood mass, leaf mass and floor mass was removed from the ForestDNDC-tropica model since it was specifically calibrated for tropical rainforest ecosystems (*Kiese et al.*, 2005; *Werner et al.*, 2006 **III**) and are have now become external model input parameters. For the computation of the global N_2O emission inventory, the output of a vegetation model was used as input for ForestDNDC-tropica (see section 3.3.1 on page 24 and *Werner et al.*, 2006 **III**).

As required for the large scale application of the ForestDNDC-tropica model on a LINUX cluster computing environment (see section 3.2 on page 23 for technical aspects), the model code was also revised to comply with the ANSI C^{++} standard and modified to allow for the simulations without any user interaction. The ForestDNDC-tropica model was run for a two years simulation span, using the first year as a spin-up period in order to allow model internal C and N pools to equilibrate (*Werner et al.*, 2006 **III**).

3.1.2 Model calibration using a Bayesian calibration technique

Because various sections of the model code and structure were modified and improved the model had to be re-calibrated. The re-calibration procedure was based on the BC technique, whose strength in calibrating and evaluating process-based models was outlined recently by *van Oijen et al.* (2005). The BC approach is model and data independent and can theoretically be applied to any process-based model; improvements in model performance as well as the assessment of parameter uncertainty can be derived with the

same methodology. In contrast to "goodness-of-fit" or tuning approaches, the probabilistic or Bayesian calibration determines a probability distribution over the model parameters acknowledging the possibility that not only one but, in fact, many parameter combinations can provide the "optimum" parameter state (*van Oijen et al.*, 2005).

This method uses the Metropolis-Hastings random walk (*Robert and Casella*, 1999), a version of the Markov Chain Monte Carlo approach. The idea is to walk through the parameter space in such a way that the visited points form a representative sample of the total. Based on a given parameter vector Θ_t a proposal for a new candidate (Θ') is generated:

$$\Theta' = \Theta_t + \epsilon \tag{1}$$

For ϵ, a Gaussian distribution with the mean of zero is used (*van Oijen et al.*, 2005). The proposal is accepted as the new value Θ_{t+1} according to the ratio:

$$\beta = \frac{p(D|\Theta')p(\Theta')}{p(D|\Theta_t)p(\Theta_t)} \tag{2}$$

where p(D $|\Theta$) is the likelihood for Θ and p(Θ) is the prior distribution for Θ.

If a random number $u[0 \ldots 1]$ is smaller or equal to β, Θ' is accepted as the new Θ_{t+1}. Otherwise Θ_{t+1} is assigned the value of Θ_t. If the posterior of Θ' is greater than Θ_t (e.g., $\beta \geq 1$), the new candidate vector will always be accepted and becomes the new parameter vector (see *van Oijen et al.*, 2005). As the parameter chain progresses, new candidate parameter vectors are calculated based on the prior parameter set and tested if they give better agreement with the provided calibration data and thus also become the new optimal parameter vector (P_{opt}; see section 3.2 on page 23 for the implementation scheme).

Although BC can be applied for inter-model comparison, parameter uncertainty estimates and model testing (*van Oijen et al.*, 2005), the focus in this study was the re-calibration of ForestDNDC-tropica. As a number of core parts of the model were improved where measurement data is not available (e.g., carbon partitioning) a comparison of parameter uncertainty is problematic and thus not presented here. A major drawback of this calibration routine is the dependency of each calibration step on prior information, thus depending on a serial computation with potentially long parameter chains $> 10^5$. This inevitably leads to long computation times since a full calibration chain has to be calculated for each dataset. A parallel multiple-site Bayesian calibration framework was therefore developed enabling the parallel calibration of any number of field site datasets using a single chain (number of datasets = number of CPUs; section 3.2 on page 23).

In order to allow a re-calibration of model internal parameters, which form the parameter vector cited above, the parameters were extracted from the code to make them accessible from an external file. Initial lower and upper parameter bounds were set deliberately wide to avoid parameter "lock-in" during the calibration (*Werner et al.*, 2006 **III**). The major changes within the ForestDNDC-tropica model (new soil hydrology, revised SOC distribution) mainly affect carbon and nitrogen mass within the soil layers (substrate availability) and soil climate (anaerobic fraction of the soil). Therefore, the substrate partitioning and process control by soil temperature, soil moisture, and the production of

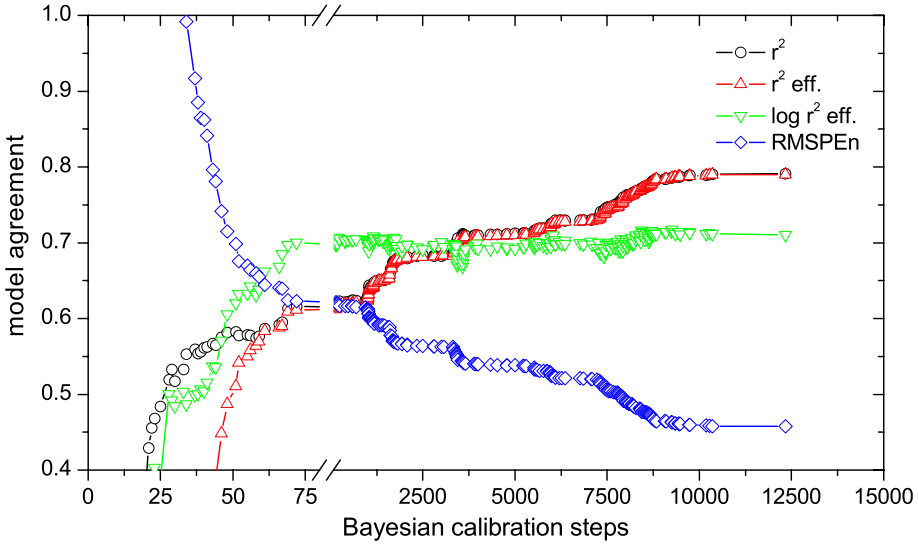


Figure 6: Model performance of ForestDNDC-tropica for the Bellenden Ker 2002, Kakamega 2004, and Xishuangbanna 2005 calibration datasets (combined) with the progression of the Bayesian calibration (performance measures are described in *Werner et al.*, 2006 **III**).

intermediate products of nitrification and denitrification had to be adjusted. Generally the considered parameters can be split into five parameter groups: (a) carbon pool fractions (very labile litter, labile litter, resistant litter, humads, humus), (b) scaling factors for process activity, N_2O and NO production of nitrification, (c) conversion factors of intermediate denitrification products, (d) controls on denitrification activity (dry season and moisture effects; see (*Kiese et al.*, 2005) and (e) temperature and moisture dependencies of mineralization.

The ForestDNDC-tropica model was re-calibrated for N_2O emissions using daily aggregated N_2O fluxes of the Kakamega Forest and Xishuangbanna field campaigns and the Bellenden Ker 2002 dataset recorded in a rainforest of the Wet Tropics in Queensland, Australia (*Kiese et al.*, 2003). The calibrated model was tested against 12 additional datasets providing information on N_2O emissions from tropical rainforest soils of Central and South America ($n = 4$), Southeast Asia ($n = 2$) and Australia ($n = 6$) (see *Werner et al.*, 2006 **III**). These datasets consist of considerably less flux measurements and are often lacking precise information on the measuring day hampering the use for model calibration.

The continuous improvement of model to data agreement with proceeding BC steps, as described by different model performance measures, is documented in Figure 6 (see *Werner et al.*, 2006 **III** for a detailed description of these performance measures). The achieved agreement (expressed in coefficients of variation; r^2) between measured and simulated N_2O emissions for the calibration sites after the calibration was 0.48 (Bellenden Ker, $n = 215$), 0.78 (Kakamega, $n = 59$) and 0.70 (Xishuangbanna, $n = 59$) respectively (*Werner et al.*, 2006 **III**).

As obvious from the comparison of simulated and measured daily N_2O emissions, ForestDNDC-tropica was well capable of simulating temporal fluctuations of N_2O emissions induced by precipitation events (*Werner et al.*, 2006 **III**; see Figure 7). Furthermore,

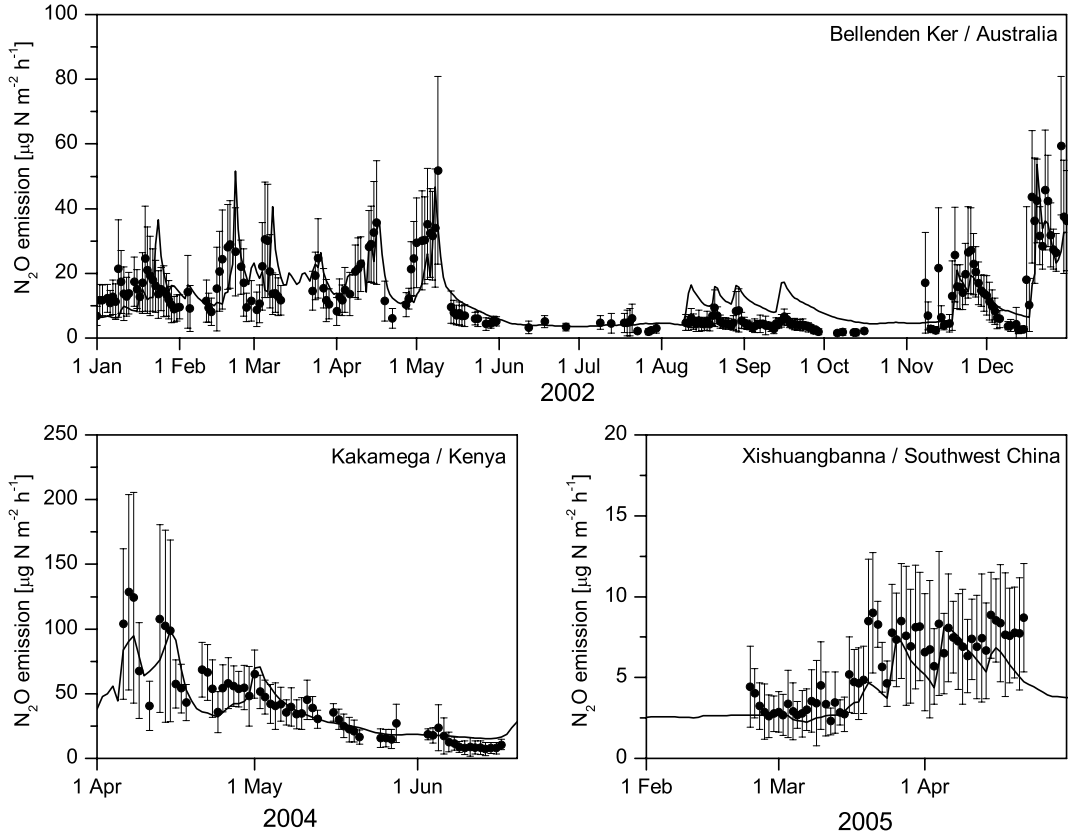


Figure 7: Measured and modelled daily N_2O emissions for the three calibration datasets used in this study (measurements ± standard deviation).

the model also captured the significant differences in the magnitude of N_2O emissions between the considered sites (mean measured N_2O emission [g N ha^{-1} day^{-1}]: Bellenden Ker 3.8 ± 0.2 SE, Kakamega 9.9 ± 0.9 SE, Xishuangbanna 1.4 ± 0.1 SE). The 2002 N_2O emission dataset for the Bellenden Ker site, a tropical lowland rainforest site in Northern Queensland, Australia, was the most detailed available. This site showed a strong seasonality in N_2O emissions as driven by a distinct wet and dry season (*Butterbach-Bahl et al.*, 2004; *Kiese et al.*, 2003). As compared to the model version used by *Kiese et al.* (2005), the new parameterisation performed better (this study: r^2 eff = 0.45; $RMSPE_n$, = 0.7; *Kiese et al.*, 2005: r^2 eff < 0; $RMSPE_n$, = 1.99) and the model did not tend to overestimate N_2O emissions under wet season conditions as was the case in the previous version. However, under prevailing dry season conditions, N_2O emissions tended to be overestimated in the course of low intensity rainfall periods (*Werner et al.*, 2006 **III**).

The test of model performance with other N_2O emission datasets from tropical rainforest sites not included in the calibration procedure was partially hampered by low frequency measurements (e.g., monthly measurement intervals), lack of information on sampling dates, and/ or meteorological conditions. To overcome these uncertainties, daily model output was aggregated to monthly mean values (La Selva 1990/1991, *Keller and Reiners*, 1994), and climate data from the ECMWF climate dataset was used for the respective

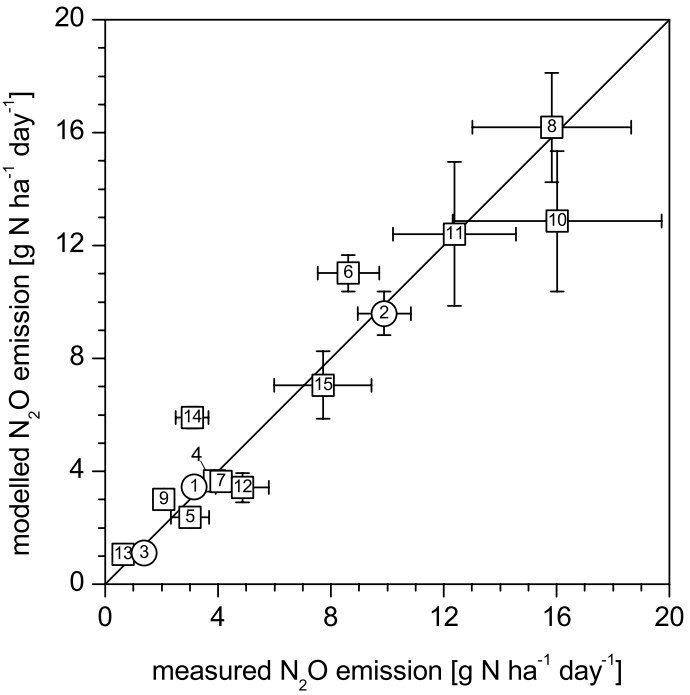


Figure 8: Model agreement with N_2O emission measurements. Given are all three calibration datasets (circles) and all 12 validation datasets (squares). See *Werner et al.* (2006) **III** for a description of the individual datasets properties and results.

region (grid cell) if no other data was available (*Ishizuka et al.*, 2002; *Melillo et al.*, 2001; *Purbopuspito et al.*, 2006; *Verchot et al.*, 1999). However, it should be noted that the comparison of monthly N_2O emission measurements with monthly aggregated model output is critical, since N_2O emissions in tropical rainforest ecosystems are highly dependent on rainfall events (e.g., *Butterbach-Bahl et al.*, 2004). Therefore, a low model agreement with datasets obtained by weekly or monthly measurements is not necessarily a result of insufficient model parameterization (*Werner et al.*, 2006 **III**). Measures for model performance for the 12 test datasets were in the same range as those for the three calibration datasets with coefficients of determination of up to 0.68, r^2 eff. up to 0.57 and $RMSPE_n$ of around 0.7. Simulated and measured emissions were close to the 1:1-line over a wide range of N_2O emission strengths ($<$ 1 - 16 g N ha^{-1} day^{-1}; *Werner et al.*, 2006 **III** and Figure 8). The overall coefficient of determination for all 15 simulated datasets was 0.94, thus providing confidence that the application of ForestDNDC-tropica to the global scale enables valuable insights into the spatial and temporal variability of N_2O emissions from tropical rainforest ecosystems worldwide.

3.1.3 Model sensitivity

The sensitivity of simulated N_2O emissions by the PnET-N-DNDC / ForestDNDC model on variations in input parameters has been tested by *Stange et al.* (2000) on site scale and by *Kesik et al.* (2005) on site as well as on regional scales. Both studies indicated

that SOC, texture and pH are the most sensitive factors finally affecting simulated N_2O emissions. In this study the sensitivity of modelled N_2O emissions on variations in input parameters was determined by randomly selecting 1000 grid cells from the global GIS database and by varying the individual parameters by ±10, ±25 and ±50% (*Werner et al.*, 2006 **III**). The most sensitive parameters were soil pH and soil bulk density ($\beta > 1$). The pronounced sensitivity of simulated N_2O emissions to changes in pH is in agreement with earlier studies and is due to the explicit consideration of pH effects on N_2O production by nitrification and denitrification (*Kesik et al.*, 2005; *Li et al.*, 2000). The sensitivity of simulated N_2O emissions on changes in bulk density is a logical consequence of the implemented dependency of nitrification and denitrification on oxygen availability and, therefore, on the extent of anaerobic zones in the soil profile *Li et al.* (2000). In ForestDNDC-tropica, an increase of bulk density will decrease total pore volume and, thus, oxygen diffusion into the soil profile. This is notable following rainfall events, when soils of high bulk density reach water saturation, and consequently, the anaerobic volume fraction increases more rapidly as compared to soils with lower bulk density (e.g., light textured soils, *Kesik et al.*, 2005; *Stange et al.*, 2000; *Werner et al.*, 2006 **I**/**II**).

Sensitivity of N_2O emissions to leaf mass and floor mass changes was significantly lower ($\beta = 0.39 - 0.6$) as compared to changes in soil pH and bulk density (*Werner et al.*, 2006 **III**). While the effect of floor mass on N_2O emission strength is direct (amount of substrates available for mineralization and consecutive nitrification and denitrification processes; *Li et al.*, 2000), leaf mass exerts an indirect control on N_2O emissions by influencing the magnitude of litter fall and, thus, the buidup of forest floor mass. It has been shown in several field studies (e.g., reviewed by *Li et al.*, 2005) that N_2O emissions tend to increase with increasing availability of organic matter and soil organic carbon content. Most notable is the relatively low sensitivity of simulated N_2O emissions with ForestDNDC-tropica to changes in SOC. In earlier studies with the ForestDNDC and DNDC models, SOC was always one of the most sensitive parameters (*Li et al.*, 2005; *Stange et al.*, 2000). However, this is an apparent insensitivity, which mainly depends on the already rather low mineral soil SOC contents of the most prominent soil classes (area corrected average of 1.38%). Therefore, even changes by ±50% (0.69 – 2.07%) have not necessarily significantly stimulated N_2O emissions via increased microbial C and N turnover, since, in the frame of the sensitivity study, the absolute changes in total available labile C (N) fractions within the soil were rather low. The sensitivity of simulated N_2O emissions to changes in SOC is thus still comparable to previous studies.

3.2 Computational infrastructure for large scale model application and validation

All model runs were performed on a LINUX computer cluster, utilizing up to 2×80 CPUs in parallel. The duration of a typical ForestDNDC-tropica site run for one year was approximately 14sec. The LPJ-DGVM used for the calculation of vegetation parameters was supplied by the Lund University and could be applied without major modifications. Using the PYTHON scripting language (`http://www.python.org`), a model domain scheduler was implemented. As both models are one-dimensional in nature, the total simulation

domains could be disaggregated into smaller packages which were processed individually on the cluster nodes. PYTHON-based batch tools were also used for the disaggregation of input data, data transfer, and data assimilation. Effectively, this approach allows for the processing of any number of sub-domain segments in parallel, reducing the total computation time of the inventories substantially.

The multi-site Bayesian calibration setup (see also section 3.1.2 on page 18) was also applied to a LINUX cluster system. A software framework was developed combining an implementation of the Message Passing Interface (MPICH; `http://www-unix.mcs.anl.gov/mpi/mpich1/`) for the exchange of data within a cluster computer environment with the Bayesian calibration procedure. Each cluster node calculates the posterior likelihood for a single calibration dataset and reports this result to the master node (see Figure 9 on the next page for a schematic overview of the implemented procedure). This allows for dramatic time savings with a growing number of calibration datasets, whereas in the standard approach, the calibration procedure needs to be repeated for each calibration dataset (*van Oijen et al.*, 2005). In this study, only three calibration datasets were applied, but the implemented approach scales for any number of datasets allowing for significant time savings when a large number of calibration data is available during model development and calibration.

3.3 GIS database

For the calculation of a global N_2O emission inventory, a new detailed GIS database holding all information for initialising (soil and vegetation properties) and driving (climate) the ForestDNDC-tropica model was compiled. Soil, vegetation and climate data was integrated into a raster GIS database covering land areas from 30° S to 30° N (grid resolution 0.25° × 0.25°) and stored in a plain geographic projection (see Figure 10 on page 27 for an overview of input datasets and data flow). An area correction based on latitude was applied in order to report the true spatial extent of each grid cell. The model was run only for those grid cells with a forest land cover greater 10% (*Werner et al.*, 2006 **III**).

3.3.1 Vegetation data and forest cover

The mapping of global tropical rainforests is affected by a range of limitations such as obstruction of satellite based mapping due to strong cloud cover, classification problems and also rapidly occurring deforestation. *Achard et al.* (2002) estimated, that global tropical rainforest deforestation occurred at a rate of $58 \pm 14 \times 10^3$ km^2 yr^{-1} in the years 1990 – 1997 and that the global area covered by humid tropical forests was 11.16×10^6 km^2 in 1997. Assuming that deforestation continued at the same pace, the global area covered by humid tropical forests would be 10.64×10^6 km^2 in the year 2006. To delineate actual tropical rainforest areas a high-resolution, satellite-based land cover map (GLC2000: *Bartholome and Belward*, 2005; *JRC*, 2000) was merged with an eco-zonal classification (*Blasco et al.*, 2000; *Werner et al.*, 2006 **III**). Using the long-term climatic criteria annual rainfall sum, average temperature of the coldest month, and number of dry months as bioclimatic selection criteria, areas covered either by humid or perhumid tropical rainforests were derived (see *Werner et al.*, 2006 **III**).

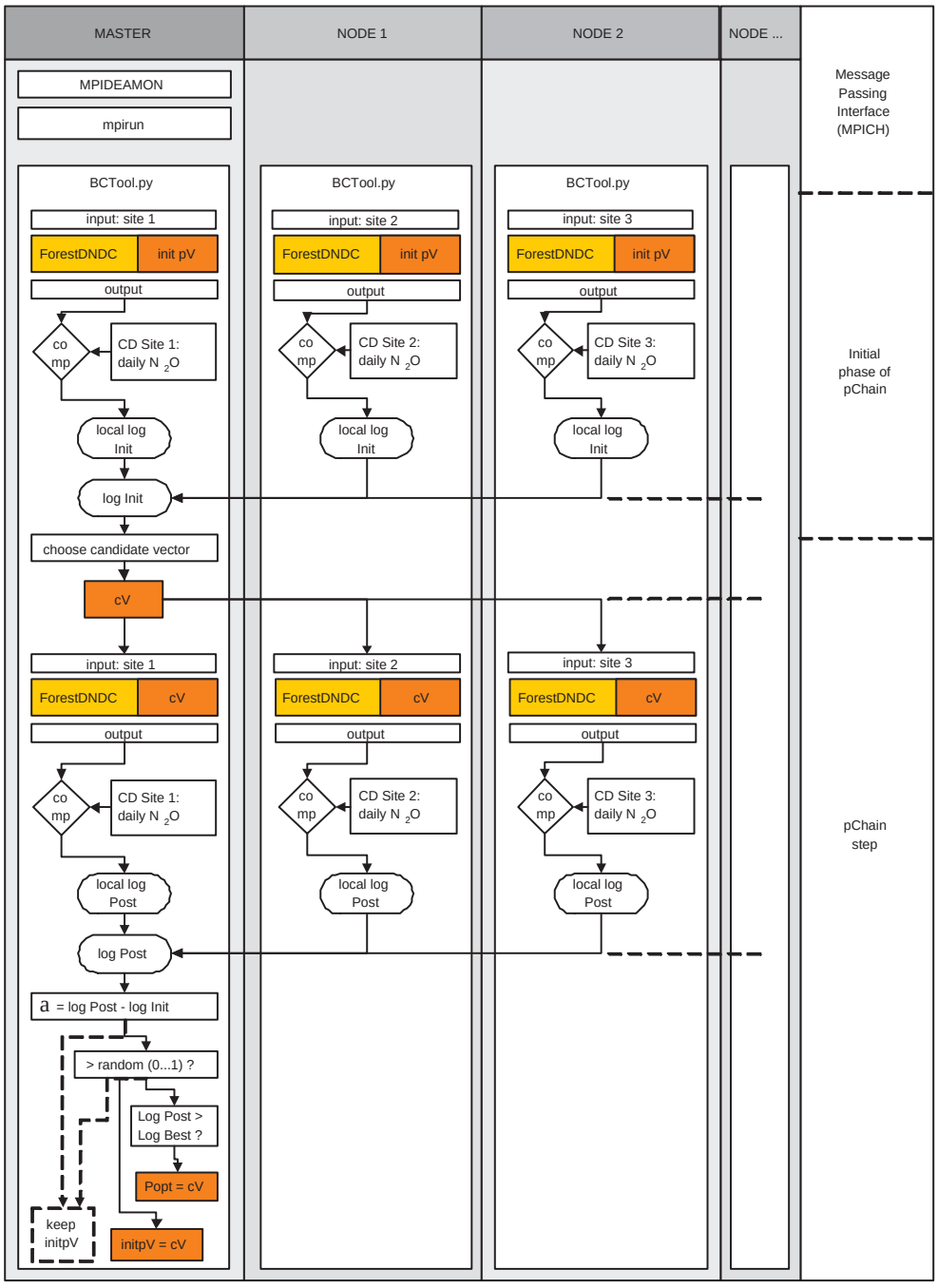


Figure 9: Multi-site parallel Bayesian computation scheme. Each node computes a local posterior value based on a common candidate vector and a specific calibration dataset. The local posterior likelihoods are reported back to the master node joined to a total posterior.

The total rainforest area (humid and perhumid tropical rainforest) of the GIS database was 10.93 $\times$ 10^6 km^2 (*Werner et al.*, 2006 **III**). This number is close to the reported 11.16 $\times$ 10^6 km^2 of tropical rainforests for the year 1997 (*Achard et al.*, 2002). However, some previous global N_2O emission inventories for tropical rainforest soils were based on a considerably larger area (e.g., *Breuer et al.*, 2000; *Matson and Vitousek*, 1990, 14.96 $\times$ 10^6 km^2)), which is partly due to a different ecological classification scheme (see Table 2 on page 28 and *Werner et al.*, 2006 **III**).

A global distribution of above ground biomass estimates for tropical rainforests ecosystems was simulated with the **L**und-**P**otsdam-**J**ena **D**ynamic **G**lobal **V**egetation **M**odel (LPJ-DGVM), replacing model internal biomass estimates (*Werner et al.*, 2006 **III**). The LPJ-DGVM model simulates vegetation dynamics and structure based on plant functional types (PFT) which feature individual physiological, morphological, phaenological, bioclimatic and fire-response attributes (*Sitch et al.*, 2003; *Smith et al.*, 2001). Conceptually, LPJ-DGVM simulates average individuals for each PFT which are then scaled to the population in a grid cell. The landmasses stretching from 30° N – 30° S were initialized as bare ground with the FAO texture classes as a 0.5° $\times$ 0.5° grid. LPJ-DGVM was then set-up to simulate a 900-year spin-up time in order to reach equilibrium conditions for the soil and vegetation pools using inter-annually varying climate conditions with annual average temperature, precipitation, and cloudiness which vary according to long-term means (see *Sitch et al.*, 2003). Throughout the following transient phase, monthly climate data (CRU 2000) of the Climate Research Unit (CRU, University of East Anglia) was used (*Mitchell et al.*, 2004). Carbon mass of vegetation parameters (wood mass and litter mass) and floor litter were combined in each cell to serve as input for the ForestDNDC-tropica model (*Werner et al.*, 2006 **III**).

3.3.2 Soil data

The spatial extent of soil types were derived from the FAO Digital Soil Map of the World (vector format; version 3.6; FAO [2003]) and used as the spatial base layer of the GIS database. The vector file was gridded to a resolution of 0.25° $\times$ 0.25°. Topsoil profile data (0 - 30cm) was taken from the "ISRIC-WISE revised soil parameter estimates for the soil types of the World" database (version 2.2; *Batjes*, 2002b). This database was constructed from homogenized profile information of 9607 profiles sampled worldwide with a major focus on tropical and subtropical regions (*Batjes*, 2002b). The parameters sand, silt and clay fraction, gravel, SOC, mineral soil pH, bulk density (BD) and effective cation exchange capacity (CEC), were used as soil input parameters for ForestDNDC-tropica (*Werner et al.*, 2006 **III**). The homogenised ISRIC-WISE soil database does not distinguish between agricultural and natural land-cover. However, since agricultural soils tend to have a higher soil bulk density as compared to soils under natural vegetation, a correction was applied (*Werner et al.*, 2006 **III**). The correction factor (0.91; $r^2 = 0.56$) was derived from comparing the mean bulk densities of FAO74 soil sub-units (predominantly agricultural soils) with a collection of homogenized primary soil profile data for tropical rainforests soils only (ISRIC-WISE Global Soil Profile Data Set, Version 1.1, *Batjes*, 2002a). Even though it can be assumed that also the SOC content may be biased, a suitable correction could not be determined using the available databases. Soil organic

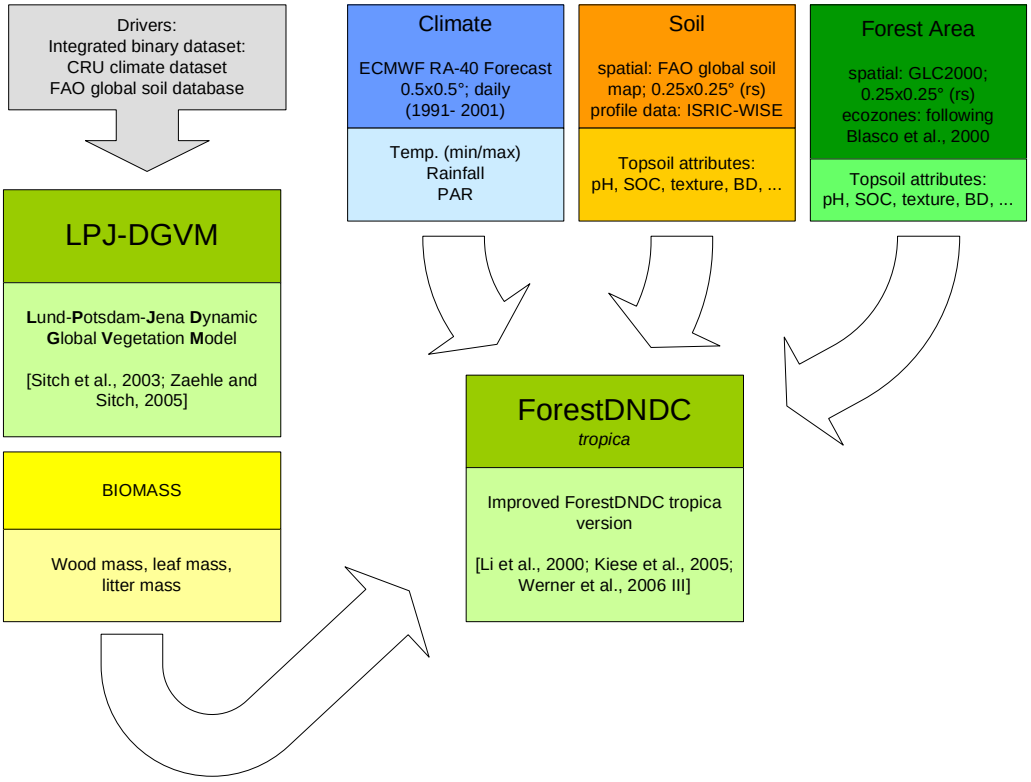


Figure 10: Models and input datasets used for the computation of the global N_2O emission inventories from tropical rainforest soils.

carbon content was thus used as provided by the ISRIC-WISE soil database (*Werner et al.*, 2006 **III**). The soil properties were finally linked to the FAO soil map by classification codes (FAO74 soil sub-units; including texture class, e.g. xanthic Ferralsol; FAO texture class b).

3.3.3 Climate data

Daily weather data covering the tropical belt (30° S – 30° N) for the years 1991 – 2000 was provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Six-hourly post-processed maximum and minimum temperature (2m above ground) and photosynthetically active radiation (PAR) data were aggregated to daily fields (ECMWF ERA40 atmospheric forecast, *Uppala et al.*, 2005). Daily total precipitation at the surface level was also provided by ECMWF from the Tropical Ocean and Global Atmosphere (TOGA) forecast product (ECMWF/WCRP TOGA Level III / operational archive). All datasets were resampled to 0.25° × 0.25° grids and converted to ForestDNDC-tropica climate files of daily time resolution.

Table 2: Comparison of available estimates of global N_2O emissions from tropical rainforest soils derived by statistical or model upscaling.

Reference	N_2O source strength [Tg N yr^{-1}]	Area [10^6 km^2]	Description
Statistical upscaling approaches			
Matson and Vitousek (1990)	2.4	14.8	Simple upscaling approach using a small number of measurements and soil quality
Breuer et al. (2000)	3.55	14.9	Revised estimate of Matson and Vitousek; based on more measurements
Stehfest and Bouwman (2006)	1.17	8.5	Comprehensive statistical analysis of published measurement data; closed tropical forest
Modelling approaches			
Bouwman et al. (1995)	2.3	16.8	Simple global model describing major control factors of N_2O emission; closed tropical forest
Potter et al. (1996)	1.3	10.2	CASA model coupled to a GIS; tropical rainforest
Melillo et al. (2001)	2.4	5.4	Only for the Amazon basin, TEM model coupled to GIS, simulated net nitrogen mineralization multiplied with a fixed factor
This study	1.335	10.9	

3.4 N_2O emission inventory

Following intensive model and model sensitivity tests on site scale, the improved version of ForestDNDC-tropica, driven by the input data stored in the GIS, was applied on the global scale to reassess N_2O emissions from tropical rainforests worldwide.

On average, the mean annual N_2O emission source strength from rainforests worldwide was calculated at 1.2 ± 0.3 kg N ha^{-1} yr^{-1}, amounting to a total source strength of 1.34 Tg N yr^{-1} (assuming a total rainforest area of 10.9×10^6 km^2, *Werner et al.*, 2006 **III**). Previous studies, using both empirical as well as modelling approaches for the calculation, are listed in Table 2.

Matson and Vitousek (1990) estimated the global N_2O source strength of tropical forest soils to be 2.4 Tg N yr^{-1} (= 1.8 Tg N yr^{-1} using the area estimate of this study). Their estimate was based on upscaling of a limited number of publications (< 10) on N_2O fluxes from tropical rainforest soils using a simplified soil and vegetation classification scheme. A few years later, considering newly published data, *Breuer et al.* (2000) provided a new estimate of 3.55 Tg N yr^{-1} (= 2.6 Tg N yr^{-1} with the area of this study), which is noticeably higher than the mean estimate presented here. However, these authors pointed out that such a simplistic upscaling approach may not be reliable for estimating the global source strength of tropical rainforests for atmospheric N_2O. Based on a simple global model which reflects the spatial and temporal variability of the major controlling factors of N_2O production in soils, *Bouwman et al.* (1995) reported the global N_2O source strength of closed tropical forest ecosystems to be 2.3 Tg N yr^{-1}(= 1.5 Tg N yr^{-1} for area used in this study). Applying a comprehensive statistical analysis of published measurement data, *Stehfest and Bouwman* (2006) recently estimated the N_2O source strength of closed

tropical forests to be 1.17 Tg N yr^{-1} (= 1.5 Tg for area used in this study). A more mechanistic approach for estimating N_2O emissions from rainforest soils was applied by *Potter et al.* (1996). By linking the biogeochemical CASA model to a global GIS, they calculated that N_2O emissions from tropical rainforest ecosystems contribute approximately 1.3 Tg N yr^{-1} to the global atmospheric budget – the area being approximately the same as in this study. Contrasting results have been obtained by *Melillo et al.* (2001) in their study on N_2O emissions from tropical forest ecosystems of the Amazon (*Werner et al.*, 2006 **III**). By simulating the period 1978 – 1995, Melillo et al. derived an estimate of 1.3 Tg N yr^{-1} for tropical forests in the Amazon basin (5.4×10^6 km^2). The discrepancy between the results derived from the application of ForestDNDC-tropica and the work of *Melillo et al.* (2001) may be attributed to (a) different modeling approaches, (b) differences in datasets used and (c) a different spatial extent considered to be tropical rainforest (*Werner et al.*, 2006 **III**). However, as *Melillo et al.* (2001) did not provide a detailed evaluation of their model against field data, a final judgement on the model performance is not possible.

3.4.1 Spatial and temporal variability

The spatial distribution of simulated mean annual N_2O emissions from tropical rainforest soils for the years 1991 – 2000 is given in Figure 11 on page 31 (see also Figure 12 for the standard deviation of N_2O emissions for a 10-years period). The map shows that N_2O emissions ranged from $<$ 0.5 – 5.4 kg N ha^{-1} y^{-1}, which covers the reported range of annual N_2O emissions from tropical rainforest ecosystems worldwide (see e.g., overview given by *Breuer et al.*, 2000; *Verchot et al.*, 1999; *Werner et al.*, 2006 **II**). The highest N_2O emissions of $>$ 3.5 kg N ha^{-1} yr^{-1} were simulated for the Southeast Asian tropics, Central Africa, and the North and Southwest Amazon, and Central America. Significantly lower emissions in a range of 0.5 – 1.0 kg N ha^{-1} yr^{-1} were simulated for large regions in South America, Africa and Oceania. The regional variations in N_2O emissions resulted mainly from differences in the spatial distribution of soil and climate characteristics (*Werner et al.*, 2006 **III**). For instance, in Southeast Asia tropical rainforests receive the highest amounts of annual precipitation and grow on soils characterized by high clay and organic carbon contents and pH values $>$ 4.5. Such conditions favor microbial N turnover processes and especially N_2O production via denitrification (*Granli and Bøckman*, 1994). The same finding holds true for elevated N_2O emissions simulated in Central Africa and Central as well as South America.

Simulated regional N_2O emissions do not necessarily match measured N_2O emissions on a site scale, as can be shown for Southeast Asia. *Ishizuka et al.* (2002) as well as *Purbopuspito et al.* (2006) reported annual N_2O emissions $<$ 1.5 kg N ha^{-1} yr^{-1} for this region, whereas the 10-year averages of simulated N_2O emissions were $>$ 1.5 kg N ha^{-1} yr^{-1} for the respective grid cells (Figure 11 on page 31). Since a comparison on site scale yielded comparable results between measured and simulated fluxes for the locations, this difference must be due to soil properties as observed on site scale and used on the regional scale in the GIS (*Werner et al.*, 2006 **III**).

Besides the spatial variability in N_2O emissions, a pronounced inter-annual variability of N_2O emissions across the simulated years (1991 – 2000) could be demonstrated (*Werner et al.*, 2006 **III**). Highest inter-annual variability of N_2O emissions (driven by the variability

in rainfall) was predominantly predicted for those regions having annual N_2O emissions > 1.5 kg N ha^{-1} yr^{-1} (see Figure 11 and Figure 12). In these areas, the inter-annual variability of N_2O emissions given as the standard deviation for the 10 years' simulation period was as high as 2 kg N ha^{-1} yr^{-1}. In contrast, in N_2O emissions from regions with lower mean annual N_2O emissions the inter-annual variability did not exceed 0.5 kg N ha^{-1} yr^{-1}. Significant inter-annual variations are also present on continental scales (e.g., Africa 1993: 0.21 Tg N yr^{-1} versus 1994: 0.42 Tg N yr^{-1}; *Werner et al.*, 2006 **III**).

Analyses of aggregated model output could show a pronounced seasonality of N_2O emissions (see Figure 13 on page 32). The daily simulated N_2O emissions of the ten simulation years were classified into four seasons (season 1: December – February; season 2: March – May; season 3: June – August; season 4: September – November) and normalized by the mean annual N_2O emission of the years 1991 – 2000. Two major feature of this intra-annual observation approach should be discussed here. It is obvious from the areas of highest seasonal N_2O emission fractions (yellow – red colours in Figure 13) that the simulated N_2O emissions follow the latitudinal movement of the inner-tropical convergence zone. About 30 – 70% of the annual N_2O emissions from tropical rainforest soils of the southern hemisphere are released from December to February for most areas. The reverse is shown for the months June to August, when, though to a lesser degree, substantial fractions of the annual N_2O emission from tropical rainforest soils of the northern hemisphere are released (Figure 13). On the regional scale, a different seasonal pattern can also be observed. At the Central American montane rainforests, for instance, more than 70% of the annual N_2O emissions occur from June to November, and soils of the tropical rainforest of Central Africa emit up to 50% of the annual N_2O emissions from September – November.

One can postulate here, that this variability in the global rainforest N_2O emissions should be detectable as an atmospheric signal. But this would require a detailed comparison of such a simulation with approaches using inverse modelling of global N_2O emissions sources as recently published by *Hirsch et al.* (2006).

3.4.2 Uncertainty analysis of global N_2O emission predictions using Latin Hypercube sampling

Datasets used for bottom-up upscaling approaches are known to be a major source of prediction uncertainty for biogeochemical models (*Li et al.*, 2004), since uncertainties for soil and vegetation parameters result from the following problems: sub-grid spatial variability in landuse and topography; their effect on physical and chemical processes as well as data generalisation. For assessing uncertainty in model output induced by the uncertainty in soil and vegetation parameters in the GIS database, Monte Carlo analysis has become a common tool (*Li et al.*, 2004). A probability-based sample procedure is generally used to derive a parameter vector (model input). Each sample parameter vector is submitted to the model and the cumulative output is used to assess the uncertainty of the model output. Simple random sampling is commonly used to draw random values from a standard normal cumulative density function (CDF) for every input parameter. Because the random number is generated from a uniform distribution $[0 \ldots 1]$, the sample range might be poorly covered by the random draws. In contrast, LHS stratifies the parameter

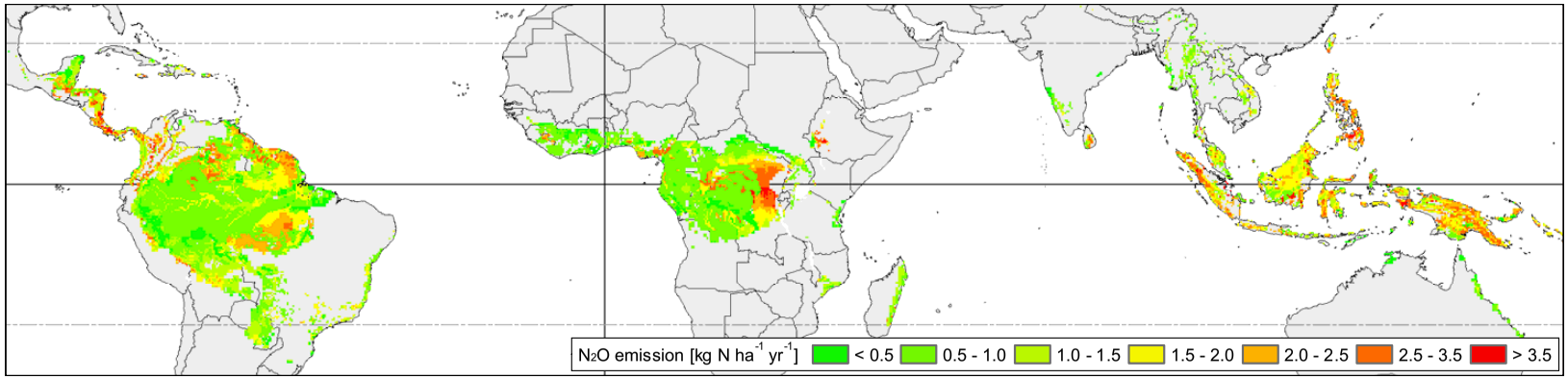


Figure 11: Spatial distribution of annual N_2O emissions from tropical rainforest soil. Given is the 10-year average for the years 1991 – 2000.

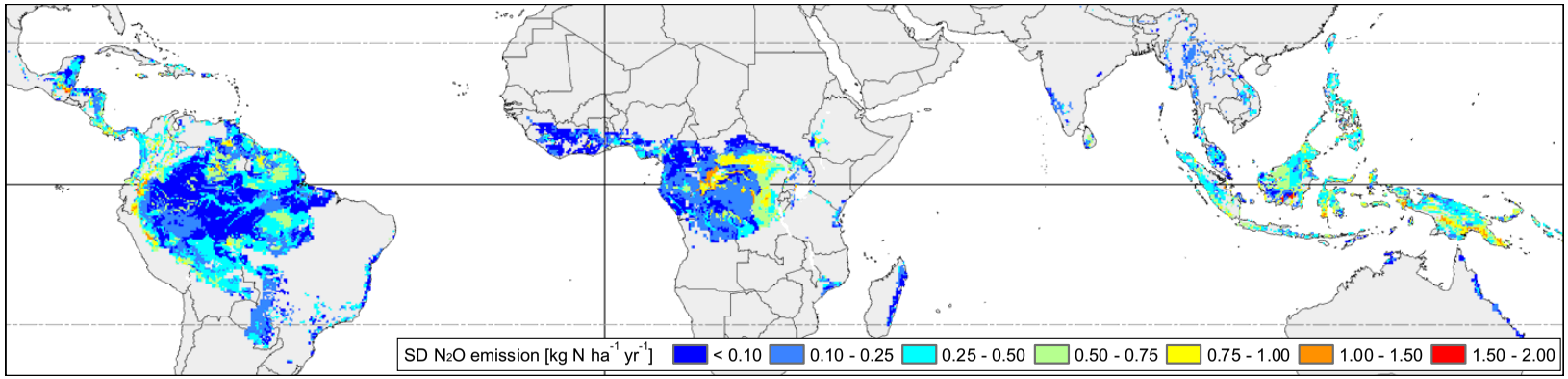


Figure 12: Spatial distribution of annual variability of N_2O emission from tropical rainforest soils. Given is the standard deviation of annual N_2O emissions for the years 1991 – 2000.

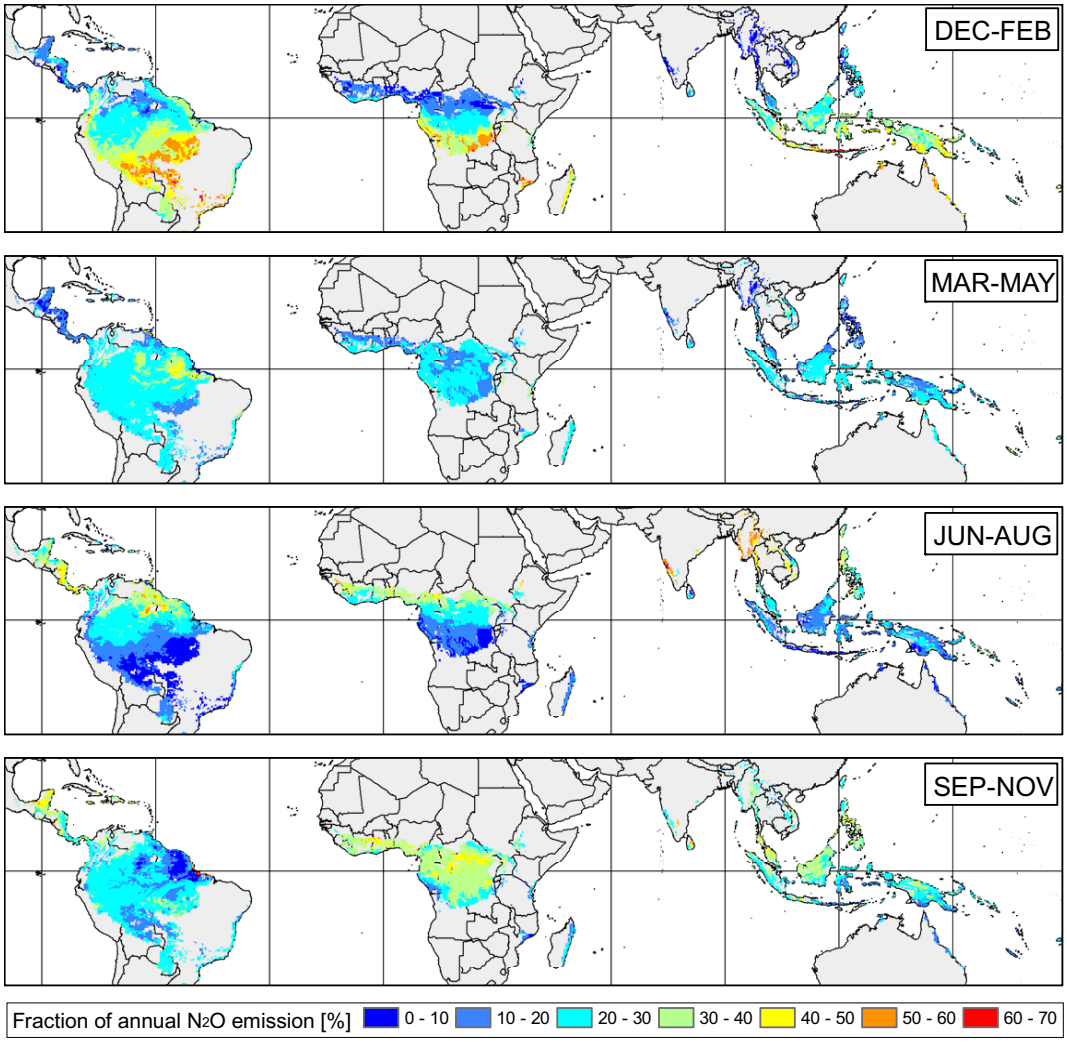
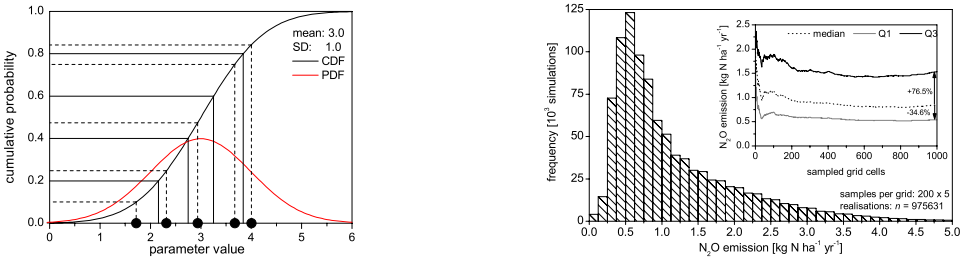


Figure 13: Seasonality of simulated N_2O emissions from tropical rainforest soils. Given is the fraction of the 10-year mean annual N_2O emission (1991 – 2000).

range of each input variable in N disjoint segments of equal probability (*McKay et al.*, 1979; see Figure 14a). A random number is drawn within each interval and, thus, one random number is guaranteed to fall into the bounds of each of the N segments. The obtained N random realisations of each parameters combined to sequences by random permutation form the final model input parameter vectors. It has been shown that this method is capable of exploring the input parameter space more exhaustively (e.g., *McKay et al.*, 1979). When computation time of the model is significant or a large number of parameters are used, the LHS permutation enables the user to use significantly less model runs as compared to simple random sampling in order to asses model uncertainty.

Figure 14b shows the frequency distribution of simulated N_2O emissions from randomly selected 1000 grid cells and 1000 iteration per grid cell with different model initialisations selected by LHS. The graph shows that the distribution of simulated N_2O emissions is



(a) Latin Hypercube sampling approach

(b) Cummulative frequency of simulated N_2O emissions

Figure 14: Cumulative frequency distribution of N_2O emissions from Latin Hypercube sampling. Lower and upper uncertainty bounds were defined at the 1^{st} (-34.6%) and 3^{rd} (+76.5%) quartile (SD: standard deviation; CDF: cumulative probability function; PDF: probability density function).

skewed towards lower values, with a median of 0.8 kg N ha^{-1} yr^{-1}.

Based on the distribution curve and the assumption that this curve, as derived from the 1000 grid cells, is representative for the entire dataset, the input data-induced uncertainty of the global estimate was defined as the percentage deviation of the 1^{st} quartile (lower boundary) and the 3^{rd} quartile (upper boundary) as compared to the median value (see inset of Figure 14b). Thus, uncertainty inherited from the soil and vegetation data leads to a N_2O emission uncertainty ranging from 0.88 – 2.37 Tg N yr^{-1}.

CHAPTER
FOUR

Conclusion and outlook

DESPITE the fact that tropical rainforest soils are considered the strongest natural terrestrial source of N_2O, only a relatively small number of detailed studies investigating the controls as well as the temporal and spatial variability of the N_2O soil-atmosphere exchange are available. As already described in the literature and demonstrated by the conducted field campaigns in tropical rainforest soils of Kenya and Southwest China, significant differences in the regional N_2O source strength and temporal response of N_2O emissions on changing environmental drivers can be observed. A significant impact of soil moisture on N_2O emission could be demonstrated by observing the N_2O emission response to natural or artificially induced soil moisture changes. However, the studies also revealed the importance of available substrate for N_2O emissions and the dependency of N_2O emissions on site specific soil characteristics, such as SOC or soil texture. These results underscore the need for more field measurements to capture the true range of natural N_2O emissions from tropical rainforest ecosystems worldwide.

Process-based models simulate the complex process system of N_2O production, consumption and emission for a wide range of site and climate characteristics and their application in conjunction with detailed GIS data is thus superior to statistical upscaling approaches. In the scope of this study, the process-based ForestDNDC-tropica model was improved, re-calibrated using a Bayesian calibration technique, and afterwards tested for a range of tropical rainforest sites worldwide. Model calibration was based on trace gas measurements of daily resolution from tropical rainforest systems in Kenya, Southwest China, and in conjunction with available data from the literature.

Because the model could accurately predict site as well as seasonal variations of N_2O emissions and proved to be a logical, realistic response to changes in input parameters (sensitivity analysis), the ForestDNDC-tropica was finally used in a coupled model GIS approach for the calculation of a global inventory of N_2O emissions of tropical rainforest soils. Based on this upscaling approach, a revised estimate of N_2O emissions from tropical forest soils worldwide of 1.34 Tg N yr^{-1} (0.88 – 2.37 Tg N yr^{-1}) was derived. This value represents the mean of the ten years period 1991 – 2000 which was derived from multi-year simulations performed in daily resolution. The uncertainty range given in parenthesis resulted from grid-based input parameter uncertainty analysis using Latin

Hypercube sampling. The calculated annual N_2O emission of 1.34 Tg N yr^{-1} ranges at the lower end of previous estimates, but it still shows that tropical rainforests are indeed one of the major sources of atmospheric N_2O. A major problem in the comparison of N_2O emissions from eco-zonal regions was the differing definition and delineation of the actual rainforest areas considered in the specific studies. Based on daily modelling time steps and a GIS database featuring high spatial resolution ($0.25° \times 0.25°$), a pronounced spatial and temporal variability of N_2O emissions on a global scale could be demonstrated in this study. It can thus be hypothesized that this variability should be visible in the atmospheric N_2O signal, thus, offering a chance for an independent validation of our inventory, for instance, by using inverse modelling techniques.

The presented study may be considered to be the most concise approach up-to-date and might help to overcome the static concept of previous inventory assessments towards a more dynamic understanding of the topic, leading also to extrapolations of the N_2O soil-atmosphere exchange for future climatic conditions. Significant improvements of global model predictions will depend on the incorporation of landuse change and its effects on the C and N trace gas exchange. Therefore, methodologies for the delineation of realistic forest conversion estimates, their spatial pattern as well as model improvements accounting for the effect of these landuse changes on soil properties and microbial processes are necessary.

The extension of the current ForestDNDC-tropica model to simulate more eco-zonal vegetation types (e.g. humid and dry savanna and grasslands) and/ or a combination with agricultural crop models to also cover tropical agriculture might enable a simulation of natural as well as anthropogenically induced transitions between landuse types, their effects on the C and N trace gas exchange and a complete coverage of N_2O emissions from tropical soils globally. A further parameterization of the ForestDNDC model for additional tropical and subtropical vegetation types, a tighter coupling with a dynamic vegetation model, such as LPJ-DGVM could help to (a) identify the contribution of natural tropical soils to historical atmospheric N_2O concentrations, (b) validate interpretations derived from proxy records (e.g., ice core records) and to (c) identify the driving sources and source regions of historic and future changes in atmospheric N_2O concentrations. Finally, an investigation of other components involved in the N cycle (e.g., NO and N_2 emissions from soils, NO_3^- leaching, and N deposition) and a more advanced calibration of ForestDNDC-tropica involving field and laboratory measurements would allow for a better understanding of the N budget and cycling in tropical ecosystems and the human-induced alteration of atmosphere – biosphere – hydrosphere exchange.

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Publication I

C. Werner, R. Kiese and K. Butterbach-Bahl

Soil-atmosphere exchange of N_2O, CH_4 and CO_2 and controlling environmental factors for tropical rainforest sites in Western Kenya

Journal of Geophysical Research – Atmospheres, 2007, 112, D03308, doi:10.1029/2006JD007388.

Publication II

C. Werner, X. Zheng, J. Tang, B. Xie, C. Liu, R. Kiese and K. Butterbach-Bahl

N_2O, CH_4 and CO_2 emissions from seasonal tropical rainforests and a rubber plantation in Southwest China

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Publication III

C. Werner, K. Butterbach-Bahl, E. Haas, T. Hickler and R. Kiese

A global inventory of N_2O emissions from tropical rainforest soils using a detailed biogeochemical model

Global Biogeochemical Cycles, 2007, 21, GB3010, doi:10.1029/2006GB002909.