Effects of land use on regional nitrous oxide emissions in the humid tropics of Costa Rica

Extrapolating fluxes from field to regional scales

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Effects of land use on regional nitrous oxide emissions in the humid tropics of Costa Rica

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Roelof Arthur Jan Plant

PROEFSCHRIFT

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Stellingen

I. Of verbeterd graslandbeheer in de Noordatlantische zone van Costa Rica al dan niet duurzaam is wanneer, naast economisch gewin en uitputting van de voorraad voedingsstoffen in de bodem, de emissie van lachgas eveneens een duurzaamheidsindicator is, wordt pas duidelijk nadat "harde" reductienormen voor lachgas zijn vastgesteld.

II. Bij het inventariseren van lachgasemissies over grote oppervlakken kan de aggregatiefout in de oppervlakteschattingen het best worden gereduceerd door de ruimtelijke heterogeniteit van emissiereguleren de bodemparameters stochastisch te beschouwen.

Dit proefschrift

III. Omdat volgens de wetten van de logica een simulatiemodel dat een segment van de dode en/of levende natuur beschrijft nimmer kan worden gevalideerd, is het onmogelijk te zeggen of Monte Carlo-simulaties de respons van het simulatiemodel, danwel de respons van het bestudeerde natuurlijke systeem kwantificeren.

Oreskes, N., K. Shrader-Frechette, and K. Belitz, 1994. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences. *Science 263:641-646.*

Dit proefschrift

IV. Zolang een simulatiemodel in de praktijk alleen kan worden getest met meetgegevens op een grotere ruimte-tijdschaal dan die waarop de modelvergelijkingen zijn gedefinieerd, bevat het schijnnauwkeurigheid.

Dit proefschrift

V. Ook wanneer iemand zelf geen veldwerk doet, kan hij goed aardkundig onderzoek tot stand brengen.

VI. Geografie is in essentie een zaak van schaling.

Wiens, J.A., 1989. Spatial Scaling in Ecology (Essay Review). *Functional Ecology 3:385-397.*

VII. Bij discussies over de fundamentele dan wel toegepaste aard van het onderzoek dat aan Nederlandse universiteiten wordt verricht, wordt vaak vergeten dat de ene vorm van wetenschap niet zonder de andere kan.

VIII. Een slecht geheugen bevordert de ontwikkeling van het analytisch inzicht.

IX. Had de mens geen besef van tijd, dan zou hij simpelweg zijn in plaats van proberen te blijven.

X. Er moet haast worden gemaakt met ontmoeting en onthaasting.

XI. Tobben doet men graag opgeruimd.

XII. Bij gebrek aan talent baart zelfs oefening geen kunst.

Stellingen behorende bij het proefschrift van R. A. J. Plant, getiteld: Effects of Land Use on Regional Nitrous Oxide Emissions in the Humid Tropics of Costa Rica, *Wageningen, 22 februari 1999.*

Het is namelijk een eigenaardigheid van de mens dat hij de chaotische werkelijkheid die hem omringt, toch beschrijven moet. Hij beschrijft hem alsof hij geordend was. Hij wil er een orde in leggen. Misschien weet hij dit, weet hij dat het zijn hoogst persoonlijke orde is die hij erin legt, maar hij kan het niet laten.

(*Experimentele romans*, W. F. Hermans)

Preface

The past four years have presented a multitude of challenges to me. When I started as a Ph.D. candidate in February 1995, I was facing a "science-scape" stretching from microbiology, via modeling of soil processes, to spatial statistics. I realized I had to make choices to make things work. Unfortunately, making choices had never been my greatest strength, which has probably been my unconscious motivation to become a physical geographer – I wanted a little bit of everything.
Because I have had the opportunity to work in an international, interdisciplinary project, visit the US, Costa Rica, and Spain, and participate in a multidisciplinary research school, I have gotten to know many interesting, fascinating, and inspiring people. They all helped me in one way or another to make the right choices. It is impossible to recall all of them, but I'll make an attempt.

First of all, I thank my Professors Johan Bouma and Nico Van Breemen for their supervision and guidance. Johan and Nico, you always knew what I was doing and when to interfere with my plans that I sometimes presented to you in a rather abstract format. Your comments on my manuscripts and the brief, yet influential, conversations have been really helpful. I also thank Professor Jan Goudriaan, the external member of the panel supervising me. Jan, you have been watching my progress from a distance, but your comments have been critical and were highly appreciated.

Ed Veldkamp, who wrote the original research proposal and hooked up with Michael Keller's GLASNOST project in Costa Rica after graduating with Nico Van Breemen in 1993, has played a substantial role in the making of this dissertation. During my first visit to the La Selva Biological Station in Costa Rica, Ed taught me a lot about the history of the project, gas sampling, Costa Rica, and science in general. Unfortunately, we were never to share our affiliation, but Ed has always answered my e-mailed questions speedily. Ed, I hope this thesis lives up to what you had in mind when you wrote the proposal!
A great deal of my achievements would not have been possible without Michael Keller, the principal investigator of the GLASNOST project and the spider in the web of counterparts. Michael, our intellectually stimulating e-mail correspondence has really helped me to move on with my work.

I thank Bas Bouman, André Nieuwenhuyse, Jetse Stoorvogel, Hans Jansen, and Huib Hengsdijk at REPOSA in Guápiles, Costa Rica for valuable discussions on my work and other NAZ issues, and for taking me around during my visits. I especially thank Bas Bouman for his creative support and optimism. Bas, you have impressed me because you spew ideas very quickly. Without PASTOR and your steady support, this dissertation would not have been as it is.

I thank Changsheng Li and Steve Frolking of the Institute for the Study of Earth, Oceans, and Space at the University of New Hampshire, USA for hosting me in 1995 and 1996. Changsheng, thanks for teaching me the nuts and bolts of your model and for sharing with me your views on science and life in general.

Bill Reiners and Shuguang Liu of the University of Wyoming have gently given me the freedom to work along with their extrapolation project. Bill, thanks for the e-mail chats and all the best with the final throes of the SOG project.

Peter Droogers, Leo Tebbens, and Jeroen Schoorl at room 105 of the Laboratory of Soil Science and Geology have provided a nice atmosphere to work in.
Hugo Denier van der Gon has had a special influence on my work. Hugo, I've always felt we were like "partners in crime" since we both worked on the upscaling of greenhouse gas emissions. During our daily commute, we have had many scientific discussions, and some of these have nicely oozed into this dissertation. I thank all other colleagues at the Laboratory of Soil Science and Geology for sharing the joy of live music, cinema, reading, playing guitar, drinking beer, and science.

Jacomijn Pluijmers, Wilma Roem, Marieke de Lange, and Nico Tan of the WIMEK Ph.D. Council, thanks for the good times and interesting discussions regarding the pros and cons of life as a Ph.D. student.

I thank Geert van de Guchte, René Isarin, and Mark Snethlage for unconditionally being my friends.

Tot slot zijn er drie speciale mensen aan wie ik dank ben verschuldigd. Pa, hoewel het slotaccoord van de symfonie waarvoor je zelf het begin hebt aangereikt je misschien te daverend is, verzeker ik je dat de symfonie nooit had kunnen klinken zonder jouw bijdrage. Ernelies, ik dank je omdat je er altijd voor mij bent. Madelon, bedankt voor je steun en relativeringsvermogen.

Roel Plant
Utrecht, December 1998

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List of model variables

Symbol	*Description*	*SI Unit*
a	Soil pH	-
A	Crop water requirement	-
B_r	Root biomass-N	kg m^{-2}
B_s	Shoot biomass-N	kg m^{-2}
C_{dec}	Decomposed C	kg m^{-2} s^{-1}
e	Efficiency factor for biological succession	-
f_{clay}	Soil clay fraction	-
f_g	Fruit biomass fraction	-
f_{isoc}	Initial soil organic C content	-
f_{NH4}	Initial soil NH_4^+-N content	-
f_{NO3}	Initial soil NO_3^--N content	-
f_{psoc}	Passive soil organic C fraction	-
f_r	Root biomass fraction	-
f_s	Shoot (pasture) or stem and leaves (banana plants) biomass fraction	-
I_C	C input to soil from crop residue and/or manure	kg m^{-2} s^{-1}
I_N	N input to soil from synthetic fertilizer and/or urine	kg m^{-2} s^{-1}
$I_{N,r}$	N input to soil from root-biomass turnover	kg m^{-2} s^{-1}
$I_{N,s}$	N input to soil from shoot-biomass turnover	kg m^{-2} s^{-1}
k_1	First-order turnover rate of N in old living biomass	s^{-1}
k_2	First-order turnover rate of N in newly formed biomass	s^{-1}
L	Leaf area index	-
K_{sat}	Saturated hydraulic conductivity	m s^{-1}
N_i	Immobilized N	kg m^{-2} s^{-1}
N_m	Mineralized N	kg m^{-2} s^{-1}
O_B	N uptake from soil by biomass	kg m^{-2} s^{-1}
O_c	N consumption by cattle	kg m^{-2} s^{-1}
R_b	Weighted average C:N ratio in biomass	-
R_{mb}	C:N ratio in microbial biomass	-
R_r	C:N ratio in roots	-

Symbol	*Description*	*SI Unit*
R_{res}	C:N ratio in relevant residue-SOC pool	-
R_s	C:N ratio in shoots	-
t	Time	s
W_{fc}	Water-filled pore space at field capacity	-
W_i	Initial water-filled pore space	-
W_{wp}	Water-filled pore space at wilting point	-
Y	Maximum attainable aboveground dry matter production	kg m^{-2} s^{-1}
φ	Soil bulk density	kg m^{-3}

Note: only the DNDC variables relevant to this study are listed.

List of frequently used abbreviations

Abbreviation	*Description*
AU	Animal Units
DNDC	DeNitrification-DeComposition simulation model
FPD	Fertile Poorly Drained soils
FWD	Fertile Well Drained soils
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
IWD	Infertile Well Drained soils
LUCTOR	Land Use Crop Technical coefficient generatOR
NAZ	Northern Atlantic Zone
NSA	soils Not Suitable for Agriculture
PASTOR	PASture and livestock Technical coefficient generatOR
PDF	Probability Density Function
SEBEV	Spatial Extrapolation By Expected Value
SOC	Soil Organic Carbon
SR	Stocking Rate
WFPS	Water-Filled Pore Space

Chapter 1

General introduction

1 General introduction

1.1 Climate change and the greenhouse effect

In recent years, scientists and policy makers have paid increasing attention to climate change. In 1988, the World Meteorological Organization (WMO) and the United Nations Environmental Program (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) to periodically assess the most up-to-date scientific, technical, and socio-economic research on climate change. Based on its most recent assessment in 1995, the IPCC proclaimed that the balance of evidence suggests a discernible human influence on global climate (IPCC, 1995). Although there are still many uncertainties, even in key factors like the magnitude and patterns of long-term natural climate variability, the IPCC expects earth's climate system to continue to change in the future.

Greenhouse gases like carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and chlorofluorcarbon (CFC) play a key role in climate change because they trap incoming solar radiation that is reflected by the earth surface as infrared radiation. This process is commonly known as the natural greenhouse effect. Greenhouse gases are naturally abundant in the atmosphere, and keep earth's annual global surface temperature at about +15 °C. The average global temperature would be about –19 °C without the natural greenhouse effect (IPCC, 1994).

Since pre-industrial days, atmospheric greenhouse gas concentrations have grown significantly. The increase is largely attributed to human activities like fossil fuel use, land use change, and agriculture. Before globally effective measures to mitigate anthropogenic emissions can be implemented, a body of research has yet to be carried out on a number of priority topics (IPCC, 1995). Among these topics are *i)* assessment of temporal and regional variability of emissions, and *ii)* the estimation of future biogeochemical cycling of nutrients and related emissions.

1.2 Nitrous oxide

Atmospheric processes and concentrations

Nitrous oxide is not only a greenhouse gas: in the troposphere, N_2O is photochemically transformed to other nitrogen (N) oxides that are involved in the destruction of O_3, leading to increased UV-B radiation at the earth's surface. Atmospheric N_2O quantities are minute compared to those of CO_2 and CH_4 (Table 1.1). However, due to its lifetime of 100 to 150 years and high relative absorption capacity, the contribution of N_2O to the greenhouse effect is still 4-6% (Rohde, 1990; Kroeze, 1993). Ice core studies have indicated that the concentration of N_2O in air was 285 ppbv before the year 1700 (Stauffer and Neftel, 1988). Between 1980 and 1990, the atmospheric concentration of

N_2O has increased at a rate of 0.25-0.31% per year (Prinn *et al.*, 1990). The concentration in 1994 was 312 ppbv (IPCC, 1994).

Table 1.1 Estimated contribution of various greenhouse gases to the anthropogenic greenhouse effect, based on the increase in atmospheric concentration observed in 1990. Adapted from Rohde (1990).

Gas	Concentration [ppbv]	Rate of increase [% per yr]	Relative contribution [%]
CO_2	$353 * 10^3$	0.5	60
CH_4	$1.7 * 10^3$	1	15
O_3	10-50	0.5	8
CFC-12	0.48	4	8
N_2O	310	0.2	5
CFC-11	0.28	4	4

The two major natural sources of N_2O are soils and oceans, while agricultural soils comprise the main anthropogenic source. The major, and perhaps the only significant, sink is stratospheric photolysis of O_3 (Crutzen, 1981). Stabilization of the atmospheric N_2O concentration requires reduction of sources, and such reductions would need to extend over lengthy periods to influence concentrations because of the ~120-year lifetime of the gas.

Nitrous oxide emissions

Emissions from natural and cultivated soils account for 27-59% of the global annual N_2O-N release of 14-18 Tg (1 Tg=10^{12} g) (IPCC, 1992). The relative contribution of natural soils is estimated to be 72-99%. Soil N_2O emissions mainly originate as an intermediate product from nitrification and denitrification (Mosier *et al.*, 1983), soil processes that operate at the microsite scale. Nitrification is the aerobic process of ammonia (NH_4^+) oxidation to nitrite (NO_2^-) or nitrate (NO_3^-). Under oxygen-limited conditions, microorganisms may use NO_2^- as a terminal electron acceptor whereby N_2O is produced (Bremner and Blackmer, 1981). Denitrification is the group of anaerobic processes that reduce N oxides to dinitrogen (N_2), nitrous oxide (N_2O), and nitric oxide (NO). Key regulating factors are soil aeration status, soil content of NH_4^+ and NO_3^-, soil pH, and organic carbon content.

Land use

A growing world population will inevitably lead to increasing demand for food, thereby invoking land use conversions and modifications. Conversion of natural lands for agricultural use has expanded the global agricultural production area by about 2% per year during the 1970s and 1980s (FAO, 1992). Land use modifications aim at higher production levels per unit area. Land use changes strongly affect soil-N cycling: especially conversion of natural forest to agricultural land generally increases N_2O emissions (Keller and Reiners, 1994). Therefore, land use changes comprise an important distal process control on N_2O emissions from soil.

To realize higher crop yields, N availability in agricultural soils is continually being enhanced. Common ways to add N are synthetic fertilization, inclusion of legumes in the rotation, return of crop residues and animal manure, and mobilization of soil inorganic N through tillage (Granli and Bøckman, 1994). Nitrogen fertilizer use, which prevails in developed countries and is growing at a fast rate in developing countries, is a potentially significant N_2O source. Given the current trends in population growth, annual N_2O-N emissions originating from synthetic fertilizer production and use may be 4.2 Tg by the year 2100, 3.5 times the current emissions from this source (Kroeze, 1993).

Table 1.2 Comparison of uncertainty in global N_2O-N ([Tg yr^{-1}]) emissions from soils presented between 1984 and 1992. Adapted from Bouwman (1995).

Source	Banin *et al.*, 1984	McElroy and Wofsy, 1986	Seiler and Conrad, 1987	IPCC, 1992	Khalil and Rasmussen, 1992
Natural soils	2.6-25	3.5-11.5	3-9	2.7-7.7	7.6
Cultivated soils	1.6-5.3	3.5-5.9	0.5-2.5	0-3	0.3-2
Total	4.2-30.3	7-17.4	3.5-11.5	2.7-10.7	7.9-9.6

1.3 Estimating areal fluxes

A comparison of estimates of the global annual N_2O release from cultivated soils illustrates the uncertainty about this source (Table 1.2). Estimates are based on scanty short-term flux measurements, mostly in temperate climates (Eichner, 1990), that were multiplied by areas of broad ecosystem groups. That is, all global estimates of N_2O from cultivated soils ignore the extreme variability in time and space that is typical for this gas (Folorunso and Rolston, 1984). Neglecting spatial heterogeneity can lead to serious errors in areal flux estimates (Rastetter *et al.*, 1992). In order to reduce uncertainties, plot-scale fluxes must be extrapolated to regional, continental, and global scales in a more consistent way. Extrapolation, or "upscaling", presents distinct and complex conceptual and practical challenges (Groffman, 1991; Bouwman, 1995).

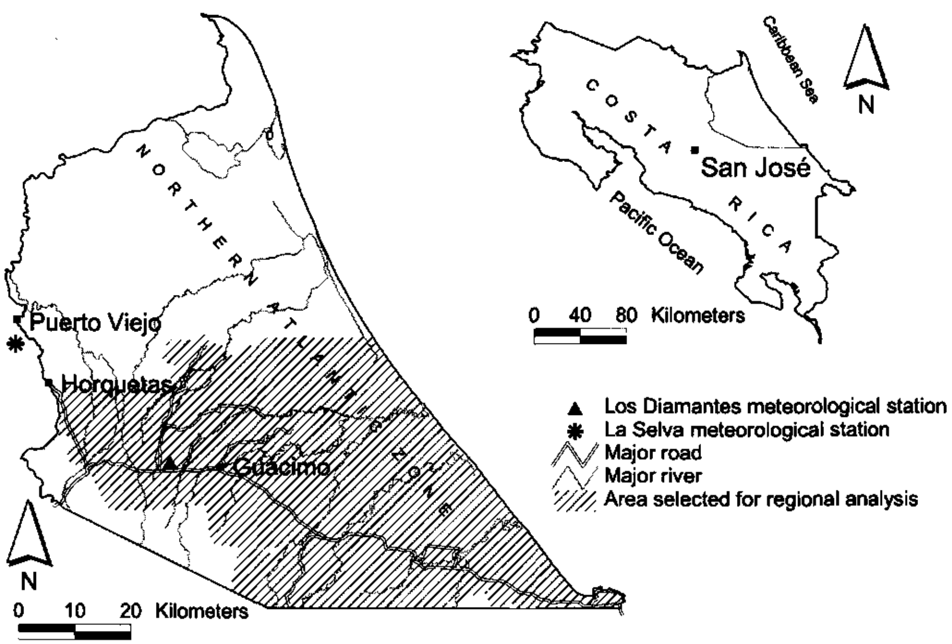
Given the space-time variability of fluxes and considerable costs and complicated logistics of gas sampling, flux measurements cannot be exhaustive. Therefore, it is necessary to model fluxes as a function of major distal process controls. Modeling is often done in a rather empirical way (Groffman *et al.*, 1992). Model formulations, mostly linear regression equations, lack a mechanistic basis and cannot be used to make future projections. Moreover, empirical models are often based on observations within a "window", making their performance in unsampled areas highly questionable. This is a strong justification for the use of process-based simulation models.

1.4 Objective

The overall objective of this research was to study effects of land use on regional N_2O emissions by extrapolating plot-scale N_2O measurements in the Northern Atlantic Zone (NAZ) of Costa Rica. A body of earlier work carried out in this sizeable humid tropical lowland area (5450 km^2) provided concurrent data on soils, land use, climate, and N-oxide emissions. The Northern Atlantic Zone (Figure 1.1) has a land use history of both conversions (e.g., forest clearing) and modifications (e.g., changes in management). This history may be a blueprint for future changes in many other Latin American countries (Veldkamp *et al.*, 1992; Huising, 1993). The research concentrated on N_2O emissions, but nitric oxide (NO) emissions were occasionally included because NO evolves from the same soil processes as N_2O (see section 1.2 above). The land use types studied were banana plantations and cattle pastures because they *i)* have dominated the Atlantic Zone over the past decades, and *ii)* represent extremely extensive (pastures) and extremely intensive (banana plantations) management. Because humid tropical forest is the natural vegetation in the Atlantic Zone, forest emissions were taken into account as well. Arable crops play only a minor role in the area and were therefore ignored. Since most land use conversions took place more than fifteen years ago, the research focused on land use modifications.

The above objective is heuristic rather than predictive: because the region studied is comparatively small, the research is anticipated to contribute little to a more precise estimate of the global source of N_2O emissions from cultivated soils. However, an understanding of the factors regulating regional N_2O emissions may aid global inventories in the future.

Figure 1.1 The Northern Atlantic Zone of Costa Rica.



1.5 Methodology

Available data and models

The research presented in this thesis strongly drew upon recent work done in the Atlantic Zone by others:

- Measurements of N_2O and NO emissions from soils below forest, old and young pasture, and banana plantations were made by Keller *et al.* (1993), Keller and Reiners (1994), Veldkamp and Keller (1997), and Veldkamp *et al.* (1998). The gas flux data set distinguishes between the dominant soil types in the Atlantic Zone, i.e., loamy Andisols and clayey Inceptisols (according to USDA Taxonomy).
- Wielemaker and Vogel (1993) conducted a 1:150,000 soil survey for the Atlantic Zone and compiled a digital soil map. Belder (1994) and Stoorvogel (1995) derived a digital land use map from 1992 areal photographs of the southern part of the Atlantic Zone and field surveys. The spatial data are stored in polygon (vector) format and can be manipulated with a Geographic Information System (GIS).
- DeNitrification-DeComposition (DNDC), a process-oriented model of carbon and nitrogen biogeochemistry, was developed by Li *et al.* (1992a, 1992b, 1994b). The DNDC formulation is based on coupled submodels for thermal-hydraulic, decomposition, denitrification, and plant growth dynamics. The model was originally designed to estimate annual N_2O and NO emissions from nitrification and denitrification for agricultural fields in temperate regions. Adaptation and calibration of DNDC for humid tropical Costa Rica was done by Li and Keller (unpublished data).
- The PASture and livestock (PASTOR) and Land Use Crop (LUCTOR) Technical coefficient generatORs, expert systems to quantify cattle pastures and banana plantations in the Atlantic Zone of Costa Rica (Bouman *et al.*, 1998; Hengsdijk *et al.*, 1998). These systems were developed within the framework of the Research Program on Sustainability in Agriculture (REPOSA) in Costa Rica, and formalize data, process knowledge, and expert knowledge on agricultural systems.

Simulations and statistics

To guide the testing of DNDC, the gas flux measurements were stratified by land use and soil type; separate model tests, based on regression analysis, were conducted for relevant soil - land use combinations.

Monte Carlo-based sensitivity analysis (Janssen *et al.*, 1992) was used to identify DNDC's most important external parameters. Traditional techniques for stochastic treatment of spatial heterogeneity (King *et al.*, 1989; Heuvelink, 1993; Bierkens, 1994; Kim, 1995) were employed for areal emission estimation. As opposed to deterministic modeling, yielding a single outcome, stochastic modeling produces a frequency distribution of outputs. The input descriptions determine whether modeling is deterministic or stochastic: in the deterministic case inputs are single values, whereas in the stochastic case the model is driven by frequency distributions of input variables. A key justification for the use of stochastic modeling in spatial studies is that the statistical expectation (mean) of the generated frequency distribution is, in principle, free of aggregation errors. Therefore, expected values provide a best estimate of areal fluxes when the spatial layout of inputs is unknown.

Scale definitions

Throughout this thesis, I employ a consistent definition of spatial scales, being aware that any classification of spatial scale levels is fuzzy:

- The *microsite*, or soil aggregate, scale ($\sim 10^{-4}$ m^2) is the level where soil N-oxide emissions evolve during (de)nitrification.
- The *field* scale ($\sim 10^4$ m^2) is the level where DNDC estimates N-oxide emissions.
- The *land unit*, or *patch*, scale ($\sim 10^6$ m^2) is the level where *areal* fluxes are estimated.
- The *regional* scale ($\sim 10^9$ m^2) is the level where *regional* fluxes are estimated.

I additionally refer to the *plot* scale, i.e., the level where N-oxide emissions are sampled in the field, the *ecosystem* scale, and the *global* scale. The latter scale level is self-explanatory. I regard the ecosystem scale as the level in between the land unit and regional scale (Schimel, *et al.*, 1988; Matson and Vitousek, 1990).

1.6 Thesis outline

The research was carried out in three steps resulting in the three parts of this thesis. Since most chapters are based on published and submitted papers, the reader may find some parts repetitive. Part I (Chapters 2 and 3) describes the results of model tests against field data. In Chapter 2, DNDC is tested against data from a chronosequence of soils below forest and forest-derived pastures. In Chapter 3, short-term measurements from fertilization experiments on a Costa Rican banana plantation comprise an additional benchmark against which DNDC is tested.

Part II (Chapter 4) links field-level and land unit-scale modeling. In Chapter 4, effects of heterogeneous pasture management on N_2O and NO emissions for one land unit are discussed.

In Part III (Chapters 5 and 6), I describe the estimation of areal fluxes for land units across the Northern Atlantic Zone. In Chapter 5, a "classic" GIS-based extrapolation, whereby deterministic modeling is employed and spatial heterogeneity within land units is ignored, is presented. In Chapter 6, stochastic methods are used in concert with GIS-based extrapolation to fully account for spatial heterogeneity of both soils and management within land units. Chapter 7 summarizes and discusses key conclusions ensuing from this work.

PART I

Chapter 2

Modeling changes in soil nitrogen cycling induced by conversion of tropical forest to pasture

R. A. J. Plant and M. Keller

2 Modeling changes in soil nitrogen cycling induced by conversion of tropical forest to pasture

Abstract

We used the DeNitrification-DeComposition (DNDC) model to simulate the dynamics of soil carbon and nitrogen in 25-year chronosequences of Inceptisols and Andisols below forest that had been replaced by pasture. In order to simulate continuously grazed pasture, we modified DNDC by adding functions that simulate *i)* grazing, and *ii)* the steady input of organic matter through root turnover and the return of urine and feces to the pasture. We also added an explicit treatment for the immobilization of nitrogen. Results of simulations were compared to field observations of soil organic carbon stocks, nitrogen mineralization rates, nitrification rates, and evolution of nitrous oxide and nitric oxide. The DNDC formulation was found to be consistent with respect to annual carbon and nitrogen dynamics and annual nitrogen-oxide emissions. In contrast, simulated daily dynamics of nitrogen-oxide emission did not match field observations. Simulated rates and pathways of nitrogen loss in the chronosequences of Inceptisol and Andisol were similar. Considering that a rationale for DNDC is that an explicit description of short-term microbial processes is required to correctly estimate annual gas emissions, we examine possible causes for the model failure. We also consider better approaches for future tests of DNDC.

2.1 Introduction

The rate of land cover change, particularly in the tropics, has accelerated greatly in the 20th century (Meyer and Turner, 1992). In tropical America, the most common man-made change has been the conversion of primary forest to cattle pasture (Kaimowitz, 1996). Between 1981 and 1990, the region lost about $7.5 * 10^7$ ha of forest, most of which was converted to pasture. Tropical forest clearing and subsequent establishment of cattle pasture significantly alters carbon (C) stocks (Veldkamp, 1994; Van Dam *et al.*, 1997) and nitrogen (N) transformations (Keller *et al.*, 1993; Reiners *et al.*, 1994; Keller and Reiners, 1994; Neill *et al.*, 1995) in the soil-vegetation system. Such disturbance may trigger a net loss of N to the environment, thereby representing *i)* a potential source of water and air pollution and *ii)* a drain on potential productivity. Nitrogen losses may occur because of simultaneously decreasing plant N uptake and increasing N mobilization. Mineralization and nitrification regulate leaching and denitrification, the dominant routes of N removal (Matson *et al.*, 1987; Robertson and Tiedje, 1988; Bouwman and Van Dam, 1995).

Soil moisture percolating down the soil profile, and out of the rooting zone, may scavenge part of the nitrate (NO_3^-) released by nitrification. In the humid tropics, leaching may significantly contribute to soil fertility depletion because rainfall and decomposition rates are high (Matson *et al.*, 1987; Bigelow, 1998; Radulovich *et al.*, 1992). Ultimately, the NO_3^- leached may enter surface waters and cause eutrophication. NO_3^- in ground waters presents a hazard to drinking water supplies. There may be a considerable potential for NO_3^- reduction in the ground water (Rice and Rogers, 1993), a process that has been considered a possible source of atmospheric N_2O when ground water is used for irrigation (Ronen *et al.*, 1988).

Once mobilized, inorganic N becomes available to nitrifiers and denitrifiers. These bacteria can produce nitrous oxide (N_2O) and nitric oxide (NO) (Firestone and Davidson, 1989). Nitrous oxide is a greenhouse gas that also contributes to the depletion of stratospheric ozone (Cicerone, 1987). Nitric oxide is a precursor to the formation of tropospheric ozone (Crutzen, 1981). Luizão *et al.* (1989) and Keller *et al.* (1993) observed elevated soil-atmosphere fluxes of N_2O and NO after forest clearing. Prinn *et al.* (1990) considered this source a strong candidate to balance the global tropospheric N_2O budget. Keller and co-workers reported that N-oxide emissions declined with pasture age, and suggested that conversion of forest to pasture does not necessarily lead to permanently elevated fluxes. Recent studies in Brazil show that at some sites the increase of N-oxide emissions following forest to pasture conversion may be negligible (Keller *et al.*, 1997; Verchot *et al.*, unpublished data). We do not understand the site-to-site differences that cause the range of soil responses to clearing.

In the field, long-term soil C and N dynamics have been studied along "chronosequences", i.e., sequences of sites of varying age (Keller *et al.*, 1993; Veldkamp, 1994; Neill *et al.*, 1995; Veldkamp *et al.*, in press). In this approach, time is substituted by space, with the assumption that observed changes are a function of time only. Therefore, results may be accidentally biased by spatial variations. In particular inter-annual variations in climate seriously limit the generality of results obtained in a single year (Veldkamp *et al.*, in press). Unfortunately, due to the complicated logistics of gas sampling, it is difficult to replicate chronosequences in space and time.

Simulation modeling of trace gas emissions has long been recognized as an important tool to test assumptions and generate new hypotheses that can be taken back to the field and laboratory for further refinement (Matson *et al.*, 1989). Moreover, well-tested models may be used for predictive purposes (Schimel and Potter, 1995). Nitrogen cycling and N-oxide evolution have been modeled at the soil microsite scale (Focht, 1974; Leffelaar and Wessel, 1988), the field scale (Li *et al.*, 1992a, 1992b; Grant, 1993a, 1993b; Bril *et al.*, 1994), the ecosystem scale (Parton *et al.*, 1996; Potter *et al.*, 1996), and regional to global scales (Bouwman *et al.*, 1993). Regional to global-scale models contain comparatively little detail and for that reason are easily calibrated. By their nature, these models simulate spatially and temporally aggregated fluxes. Small-scale mechanistic models, on the other hand, are parameter-intensive and require careful calibration, but can simulate short-term N_2O flux dynamics. Based on plot-scale studies we know that N-oxide responses to soil wetting and drying are critical. Therefore, a key issue in N-oxide modeling is the use of episodic (hourly to daily) versus time-averaged (monthly to annual) climate drivers (Schimel and Potter, 1995). Large-scale models attempt to capture changes in soil moisture and heat conditions in a temporally aggregated parameter, whereas small-scale models typically employ daily to hourly climate drivers.

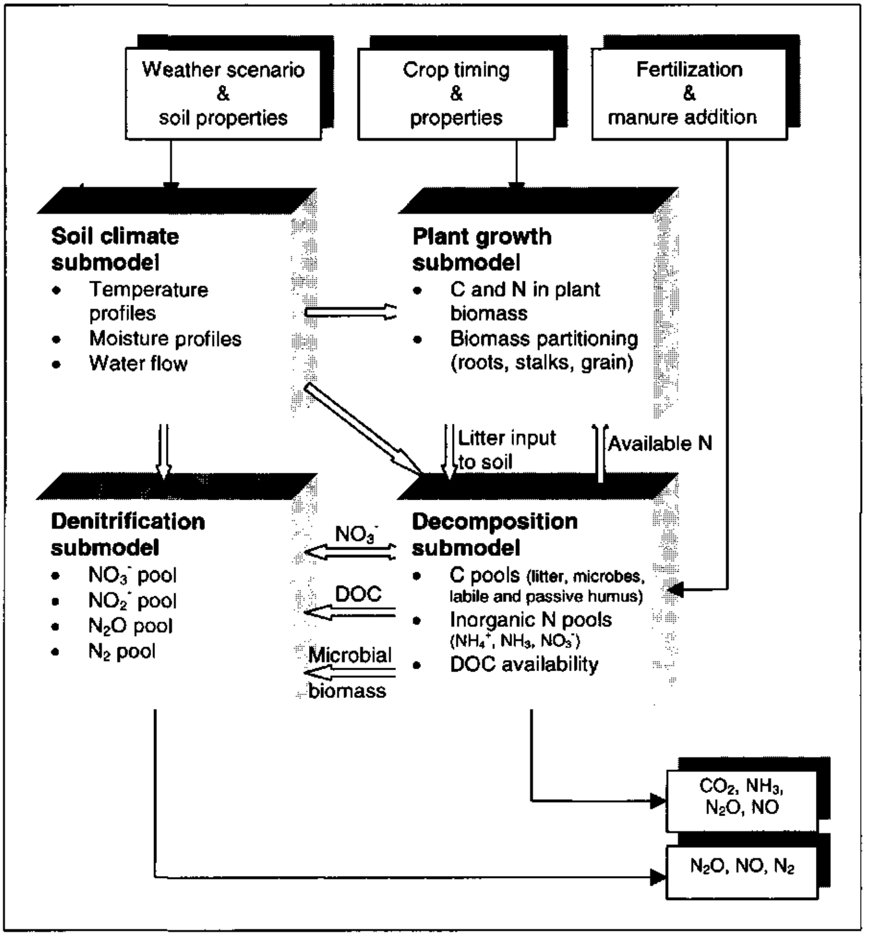
The objective of this study was to test the performance of a detailed field-scale model along 25-year chronosequences of Inceptisols and Andisols below forest and pasture soils.

2.2 Model structure and adaptations

Model structure

We used an adapted implementation of DeNitrification-DeComposition (DNDC, Li *et al.*, 1992a, 1994b) version 63, a mechanistic one-dimensional model of field-level C and N dynamics in soil-vegetation systems. The model was specifically developed to estimate (de)nitrification and N-oxide emissions (Figure 2.1).

Figure 2.1 Simplified schematic diagram of the DNDC model (after Li *et al.*, 1994b).



DNDC consists of four interacting submodels. First, a soil climate submodel calculates hourly soil moisture and temperature dynamics. Second, a decomposition submodel, following the basic structure of NCSOIL (Molina *et al.*, 1983), calculates daily rates of residue-C, humads-C, and microbial biomass decomposition. In addition, this submodel calculates net N mineralization, nitrification, ammonification, ammonia (NH_3^+) volatilization, and ammonium (NH_4^+) adsorption. Daily production and emission of N_2O and NO from nitrification are explicitly modeled. Third, a denitrification submodel, based on the aggregate-level model presented by Leffelaar and Wessel (1988), is activated when a rain event occurs. In the DNDC formulation, a rain event is defined as the time period from rainfall initiation to the time when water-filled pore space (WFPS) decreases to 35%. Based on calculated soluble C (DOC), soil nitrate, and soil moisture and temperature, the denitrification submodel calculates hourly production and emission of NO, N_2O, and dinitrogen (N_2). Finally, a plant growth submodel and associated cropping practice algorithms (Li *et al.*, 1994b) calculate daily plant N uptake, litter and root turnover at harvest, and incorporate such external inputs of C and N as manure-C and fertilizer-N. In DNDC, N uptake is the key process linking crop growth with soil C and N status. Inorganic N availability, soil moisture availability, and soil temperature can limit the daily potential N uptake rate that is calculated from an implied attainable dry matter production level.

DNDC simulations of soil C and N dynamics have successfully been tested against results from field studies conducted under a wide range of soil, climatic, and management conditions (Li *et al.*, 1992b, 1994a, 1994b).

Model adaptations

Two adaptations were made to the reference model version. First, we modified portions of the decomposition submodel simulating N immobilization or mineralization. For labile and resistant residue-C, immobilization during decomposition is modeled implicitly in DNDC63: adjustment of microbial efficiency automatically leads to immobilization of all excess N.

Nitrogen immobilization is particularly important when organic matter enters the soil as a sudden pulse (Neill *et al.*, 1995). Also, under the reference model microbial efficiencies can become unrealistically low. For these two reasons, we developed a subroutine to explicitly model gross mineralization and immobilization for the labile and resistant residue-C pools. The routine is based on a switch determining whether daily increment of decomposed C (C_{dec}, [kg ha^{-1} d^{-1}]) results in N mineralization or immobilization. The daily amount of N mineralized or mobilized is ([kg ha^{-1} d^{-1}]):

Eq. 2.1 $$N_{m,i} = C_{dec}\left[\frac{1}{R_{res}} - \frac{e}{R_{mb}}\right]$$

where R_{res} and R_{mb} ([-]) are the C:N ratios in the relevant residue-C pool and microbial biomass, respectively, and e is an efficiency factor for biological succession. Its maximum value is 0.6 for amended soil (Molina *et al.*, 1983) and 0.2 for unamended soil (Li *et al.*, 1992a).

The sign of $N_{m,i}$ toggles the switch: if the newly decomposed residues contain more N per kg C than required by microbial growth, N_m is positive and N will be released as NH_4^+; if the residues contain less N per kg C than the microbial growth requirement, N_s is negative and an amount of mineral N equal to N_s will proportionally be extracted from the NO_3^- and NH_4^+ pools and immobilized. Microbial growth is limited when insufficient mineral N is available for immobilization.

The original formulation of DNDC was developed primarily for temperate annual crops. As a simplification, under the reference model all crop residues are added to the soil after the growing season. In order to adapt the model for perennial grazed pastures, a subroutine was developed to account for variable input of C and N from root and litter turnover and animal excreta (i.e., feces and urine). These inputs are critical to the nutrient balance of grazed systems (Bril *et al.*, 1994; Van Dam *et al.*, 1997). Root (B_r) and shoot (B_s) biomass-N ([kg ha^{-1}]) at time t ([d]) are calculated from their size at $t-\Delta t$ and the net N change over Δt (Van Dam *et al.*, 1997):

Eq. 2.2 $$B_{r,s}(t) = B_{r,s}(t-\Delta t) + O_B - I_{N,r,s}$$

where O_B is the daily N uptake ([kg ha^{-1} d^{-1}]). $I_{N,r,s}$ is the N returned to the soil ([kg ha^{-1} d^{-1}]) during a time increment Δt, and is calculated using the following equation:

Eq. 2.3 $$I_{N,r,s} = B_{r,s}(t-\Delta t)\left[1-\exp(-k_1\Delta t)\right] + O_B\left[1-(1-\exp(-k_2\Delta t))(k_2\Delta t)^{-1}\right]$$

where k_1 and k_2 ([d^{-1}]) are the first-order turnover rates of N in old living plant material ($B_{r,s}(t-\Delta t)$) and newly-formed biomass (O_B), respectively. The newly-formed biomass is allocated to the shoot and root N pools based on a fixed, user-defined shoot:root ratio. Nitrogen consumption by animals is proportional to stocking rate. We adopted a typical annual N-consumption rate of 45 kg per animal unit (1 animal unit (AU) = 400 kg live weight) (Bouwman and Van Dam, 1995). Using a N-use efficiency of 10% (Bouwman and Van Dam, 1995), the N excreted is calculated. Excreted N is partitioned into feces-N and urine-N using a feces:urine ratio of 2 (B. Bouman, personal communication). Urine-N directly feeds into the mineral N pool of the uppermost soil layer, while feces-N is recycled indirectly as manure with a C:N ratio of 15 (Haynes and Williams, 1993). When the feed supply of the pasture is below the feed intake requirement of the grazing stock, we assume that feed supplements are brought to the pasture.

2.3 Field data for model confirmation

For model tests, we used N_2O and NO flux data (Keller *et al.*, 1993), soil organic C (SOC) data (Veldkamp, 1994), and measured indices of N cycling (Veldkamp *et al.*, in press). Sampling was done on sites near Guácimo (10°12'N, 83°32'W, Figure 1.1), in the Atlantic

Zone of Costa Rica, at ± 100 m altitude, on the footslopes of the Turrialba volcano. The soils are old, deeply weathered, clayey, nutrient-poor Inceptisols developed on alluvial terraces. The climate in the Atlantic Zone is humid tropical: mean annual temperature is 26 °C and mean annual rainfall is 3000 – 6000 mm. Tropical lowland rainforest is the natural vegetation.

Keller *et al.* (1993) sampled soil-atmosphere fluxes of N_2O and NO using static, vented chambers on one forest site and in seven derived pastures (2, 3, 5, 10, 12, 18, and 25 year old), eight times during February - November 1992. Eight and four measurements of N_2O and NO flux, respectively, were made per month on each site. Averages of replicate flux measurements were assumed to be representative for the sampling day, hence field – model comparisons were made using model-simulated daily gas emissions. We also compared means of the eight monthly samplings to annual fluxes calculated by the model.

Veldkamp (1994) studied SOC storage in the forest soil and the 3, 5, 10, and 18-year old derived pasture soils. For these five sites, Veldkamp calculated total soil-C stocks (0 - 0.3 m) using organic C, bulk density and sampling depth. Forest-derived and pasture-derived carbon were separated using $^{13}C/^{12}C$ isotopic ratios.

On all sites, except the 12 and 25-year old pastures, net N mineralization and nitrification potential were sampled during October 1995 - July 1996 (Veldkamp *et al.*, in press). The forest site of 1992 was a 3-year old pasture in 1995/96, whereas the 12 and 25-year old pastures of 1992 had been converted to other forms of agriculture. Veldkamp and co-workers measured net mineralization using aerobic laboratory incubations. Nitrification potential was measured using the shaken soil-slurry method. (Hart *et al.*, 1994). Mineralization data were collected in 1995/96, but because chronsequence sites show persistent N cycling behavior we used these data as a general guide to test model simulations for 1992 (Veldkamp *et al.*, in press). Nitrogen leaching losses before and after forest clearing at the La Selva Biological station (10°26'N, 84°00'W, Figure 1.1) have been measured by Parker (1985). The soil and climatic conditions at La Selva are similar to those on the Guácimo sites.

Table 2.1 Properties of the Inceptisol and Andisol below forest (Veldkamp, 1994). Initial SOC is reported excluding litter on the forest floor and roots in the profile. The fraction passive SOC applies to initial SOC excluding forest litter and roots.

Parameter	Description	Unit	Value	
			Inceptisol	Andisol
f_{isoc} †	Initial SOC	[Mg ha^{-1}]	51.6	97.3
f_{psoc}	Fraction passive SOC	[-]	0.5	0.5
φ	Bulk density	[Mg m^{-3}]	0.95	0.75
a	pH (H_2O)	[-]	4.7	5.3
f_{clay}	Clay fraction	[%]	63	13

† In DNDC, initial SOC is defined as a fraction. Using bulk densities, the parameters of DNDC's SOC distribution function were fitted to yield the given initial C stocks.

Table 2.2 Parameters for natural pasture featuring the species *Axonopus compressus* (Ibrahim, 1994).

Parameter	Description	Unit	Value
R_r	C:N ratio in roots	[-]	26
R_s	C:N ratio in shoots	[-]	26
-	Shoots:roots ratio	[-]	4
k_1	First-order turnover rate of N in old living biomass	[d^{-1}]	0.00211
k_2	First-order turnover rate of N in newly formed biomass	[d^{-1}]	0.01
A	Crop water requirement	[-]	770
L	Leaf area index	[-]	3

2.4 Model simulations

To simulate C and N dynamics in the field-sampled Inceptisol, DNDC was initialized using characteristics of the forest soil (Table 2.1). It was assumed that initially the primary forest had already been cleared.

At the start of the simulation, we initiated the SOC pool with Veldkamp's estimate (Table 2.1) for the original forest-SOC (51.6 Mg ha^{-1}) augmented with 25.8 Mg ha^{-1} of forest-derived residues and 3.7 Mg ha^{-1} of forest-derived fine root biomass. Half of the original SOC (25.8 Mg ha^{-1}) was assigned to the passive pool. The DNDC residue pool comprised 25% of the original SOC (12.9 Mg ha^{-1}) plus the forest-derived residues and the fine roots. Default DNDC parameter values (Li *et al.*, 1992a) were used to partition the total residue-SOC (42.4 Mg ha^{-1}) over the very labile (8%), labile (32%) and resistant (60%) residue pools. The DNDC humads pool contained the remaining 25% of original SOC. Development of a low-productive grass cover started immediately after forest clearing. Characteristics of the grass *Axonopus compressus* were adopted (Table 2.2). This species, that grew on the 25-year old site, was used as a proxy for the other native low-productive grass, *Isschaeum indicum,* that grew on all other sites (Veldkamp, 1994) with the exception of the 2-year old site (*Brachiaria humidicola* grew on the 2-year old site). This was done because data for *Isschaeum indicum* were unavailable. For the Inceptisol, we assumed an attainable aboveground biomass-C production of 5 Mg ha^{-1} yr^{-1} (Van Dam *et al.*, 1997) and a typical stocking rate of 2 AU ha^{-1} (Bouwman and Van Dam, 1995).

A DNDC climate scenario for the period December 2, 1991 - November 30, 1992 was compiled from the 1991 and 1992 records from the nearby Los Diamantes weather station (10°13'N, 83°48'W, Figure 1.1). During this time span, average temperature was 24.5 °C, and total precipitation was 4146 mm. The climate scenario was repeatedly used in the twenty-five years simulated.

Using the same climate and management parameters (except maximum attainable production, see below), a second DNDC simulation was carried out for a chronosequence of Andisols below forest and pasture. Andisols are young, fertile soils with a sandy loam texture in the upper 0.3 m (Veldkamp, 1994). Soil properties used for initialization are summarized in Table 2.1. The initial amount of residue-SOC, consisting of forest-derived

C (29.5 Mg ha^{-1}) and 25% of the original forest-SOC (24.3 Mg ha^{-1}), was 53.8 Mg ha^{-1}. Maximum attainable aboveground biomass-C production of *Axonopus compressus* on Andisol was reported to be 6 Mg ha^{-1} yr^{-1} (Van Dam *et al.*, 1997).

2.5 Results and discussion

Comparison of simulated Inceptisol C and N dynamics with field data

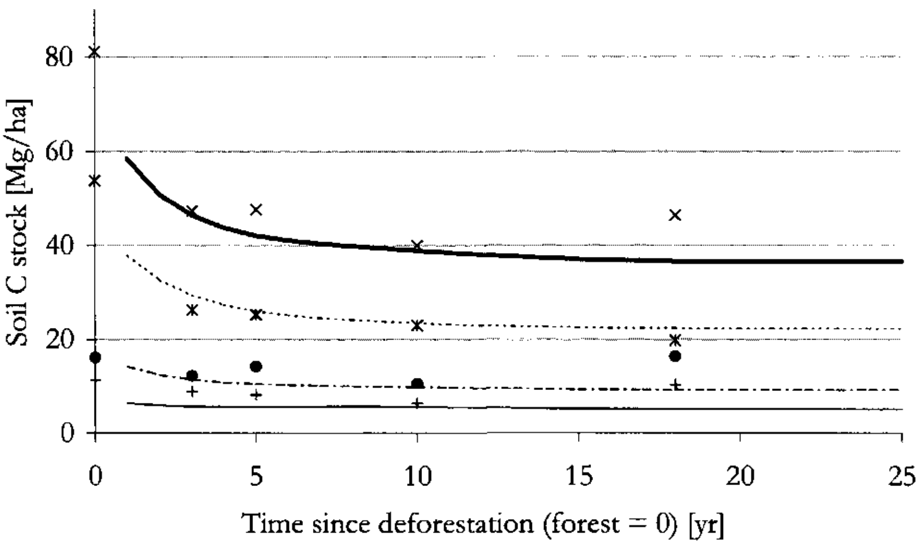
SOC dynamics. – The DNDC-simulated long-term SOC dynamics in the Inceptisol are summarized in Figure 2.2a. After twenty-five years of pasture use, model-simulated SOC in the upper 0 to 0.1 m of the soil profile stabilized at 22.3 Mg ha^{-1}. This level is consistent with the observed steady-state level after thirty years of ~24 Mg ha^{-1}. The cumulative simulated SOC loss (including plant residues) from the top 0 to 0.3 m in the first three years after forest clearing was 34.6 Mg ha^{-1}, whereas the observed cumulative loss was ~34 Mg ha^{-1}. After eighteen years, the simulated cumulative SOC loss was 44.4 Mg ha^{-1}, whereas the reported loss was ~35 Mg ha^{-1}. The overestimation of active-SOC decomposition may have resulted from improper specific decomposition rates and/or C:N ratios in DNDC's active C pools. DNDC uses fixed, generic values for all soils and crop residues (Li *et al.*, 1994b).

Gas emissions. – Modeled annual N_2O and NO flux dynamics generally matched observed patterns (Figure 2.2b and Figure 2.2c). But, as evidenced by the error bars in Figure 2.2b, the temporal variation in N_2O measured on the 2, 3, 5, and 10-year old pasture sites is large. It is even difficult to precisely determine the true annual emission from monthly field measurements. We cannot claim agreement of the model and the measurements to better than a factor of 2-3 because of the limitations of the measurements.

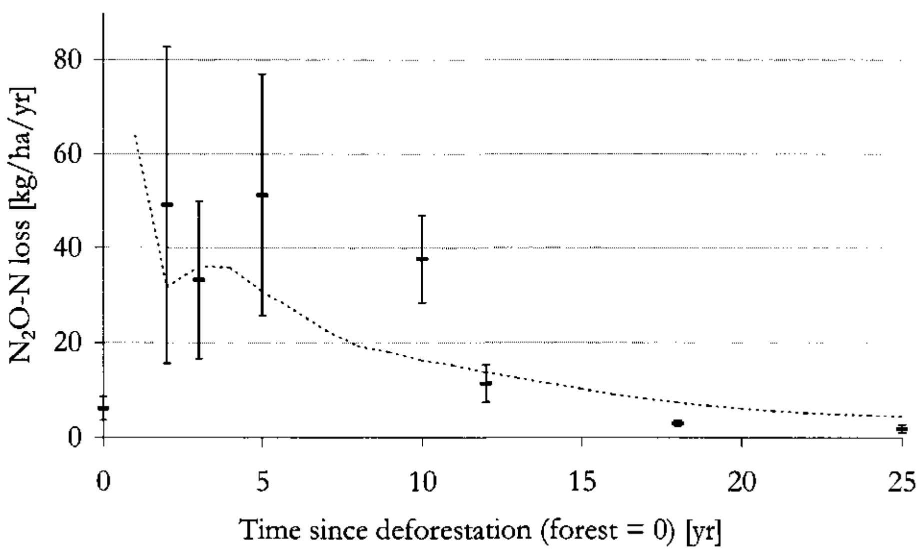
The model simulated a N_2O-N peak of 64 kg ha^{-1} yr^{-1} during the first year after forest clearing. After this first pulse, a less pronounced pulse of 36 kg ha^{-1} yr^{-1} occurred in the fourth year. The second pulse suggests that relatively more N becomes available four years after clearing because the immobilization rate decreases faster than the gross mineralization rate. The flux simulated for the 25-year old pasture site was 5 kg N_2O-N ha^{-1} yr^{-1}, about twice the observed flux of 2 kg ha^{-1} yr^{-1}. Simulated NO dynamics showed a similar pathway: an initial NO-N peak of 12 kg ha^{-1} yr^{-1} was followed by a second pulse of 4 kg ha^{-1} yr^{-1} in the fourth year. The NO:N_2O ratio ranged from 0.03 to 0.30 and tended to decrease with time.

Simulated daily N_2O and NO fluxes showed no correlation with monthly sampled fluxes. The discrepancy could in part be attributed to differences in local weather conditions across sites. For the simulation, identical weather conditions for all sites were used, whereas slight variations in precipitation and air temperature may have occurred in the field.

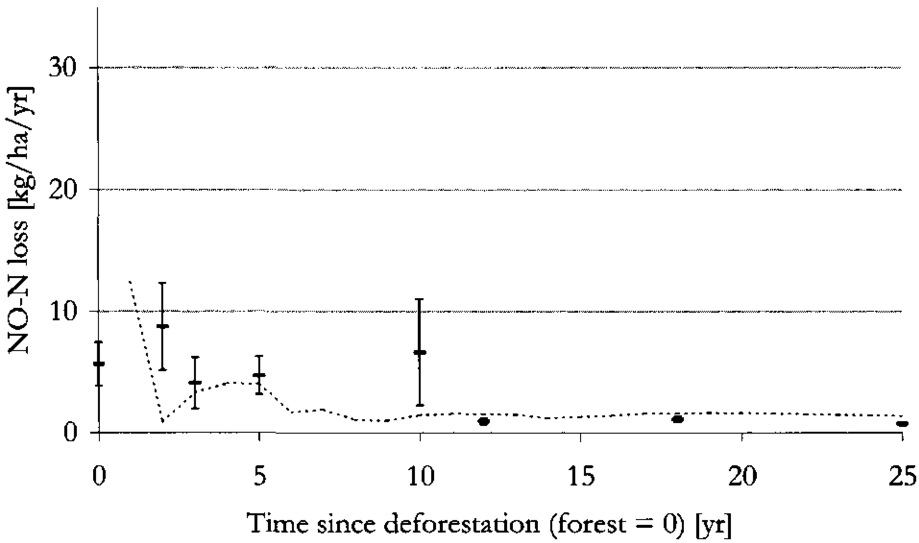
Figure 2.2 Field-measured and model-simulated SOC distribution (a), N_2O emission (b), and NO emission (c) for chronosequence on Inceptisols. For (a): SOC measured (✱) and simulated (dotted line) for 0.0 – 0.1 m; SOC measured (●) and simulated (dashed line) for 0.1 – 0.2 m; SOC measured (✚) and simulated (solid line) for 0.2 – 0.3 m; SOC measured (×) and simulated (bold solid line) for 0.0 – 0.3 m; For (b) and (c) error bars represent standard error of the mean (—) for 8 monthly flux samplings.



a



b



c

Leaching. – In DNDC, NO_3^- leaching is not modeled explicitly, but the released N that is not taken up by plants or denitrified can be regarded as a proxy for leached NO_3^-. The NO_3^--N leaching rate thus estimated reached 301 kg ha^{-1} in the first year and declined to 57 kg ha^{-1} in the third year. The leaching rate from the 10-year old pasture was 24 kg ha^{-1} yr^{-1}. Parker (1985) found leaching losses of 15 kg ha^{-1} yr^{-1} from an intact forest soil and 100 kg ha^{-1} yr^{-1} from a recently cleared bare soil. Even though we did simulate N retention by plant uptake immediately following forest clearing, the estimated leaching loss in the first year was much greater than the loss measured by Parker (1985) on a cleared site where no uptake took place. The comparison may be inappropriate because of site-to-site variations. Nonetheless, the large difference between Parker's estimate and the model result is troubling. The model predicts a N_2:N_2O ratio of about 0.30-0.59. However, experimental evidence suggests that under high carbon and high moisture conditions, N_2:N_2O ratios can reach 10 or higher (Weier *et al.*, 1993). A higher N_2:N_2O ratio than the modeled value could easily explain the discrepancy between the large implied leaching amount modeled and the lower measured value.

N transformations. - Field-measured net N mineralization and nitrification potential correlated with simulated net mineralization and nitrification rates (Table 2.3) For nitrification potential, R-square=0.58 (significant at $p < 0.1$ by analysis of variance). For net mineralization, R-square=0.52 (significant at $p < 0.15$ by analysis of variance).

N budget. - Model-simulated soil-N budgets after three and eighteen years of pasture use were compared with budgets compiled by Bouwman and Van Dam (1995) who used available data and mass balance constraints (Table 2.4). For both the 3 and 18-year old pasture, simulated annual leaching and denitrification rates and N losses were lower than estimated by Bouwman and Van Dam. The soil-N loss simulated for the 3-year old pasture was 126 kg ha^{-1} yr^{-1}, whereas Bouwman and Van Dam estimated an average annual loss of 600 kg ha^{-1} yr^{-1}. As the DNDC simulations suggest (Figure 2.3a), high N losses do occur, but rates rapidly decline in the first year. The N losses simulated in the first three years were 517, 124 and 126 kg ha^{-1} yr^{-1}, respectively.

Bouwman and Van Dam assumed that pasture yields did not decline. Therefore, their estimate of N uptake by plants on the 18-year old pasture was the same as the uptake on the 3-year old site. In our simulations, N uptake declined depending on soil fertility. For that reason, DNDC-simulated uptake and coupled inputs from litterfall and rhizodeposition were lower than estimated by Bouwman and Van Dam.

Simulated soil-N dynamics for Andisol and Inceptisol

In Figure 2.3b, 25-year means of the major N fluxes for the Inceptisol and Andisol are presented. Most notably, mean annual leaching and denitrification rates were higher for the Andisol than for the Inceptisol. The mean uptake rate was highest for the Inceptisol. In the fertile Andisol, N availability limited biomass production as of the fourth year. In contrast, the infertile Inceptisol became N-depleted after eight years. The higher annual N loss rates from the Andisol (Figure 2.3a) may explain this.

Nitrogen mineralization rates were higher in the Andisol than in the Inceptisol. Because in DNDC decomposition rates and C:N ratios are constant between soils and with time, this difference must be attributed to the soil properties implied to the model (Table 2.1). Since production levels do not differ much between the two soils, the Andisol may lose more N through leaching and denitrification than the Inceptisol.

The simulated N_2O-N flux after twenty-five years of pasture use was 4 kg ha^{-1} yr^{-1} for the Inceptisol and 6 kg ha^{-1} yr^{-1} for the Andisol. Nitrous oxide-N fluxes of ~2 kg ha^{-1} yr^{-1} have been measured in old active pastures on Inceptisols and Andisols (Keller and Reiners, 1994; Keller *et al.*, 1993; Veldkamp *et al.*, 1998). The cumulative SOC loss from the Andisol (including forest litter) after twenty-five years of pasture was 28.4 Mg ha^{-1}. For this soil type, Veldkamp (1994) reported a cumulative SOC loss of ~22 Mg ha^{-1} for 25-year old pasture.

Model performance

Comparison between simulation results and field means suggests that DNDC captures the major trends in C and N transformations in the Costa Rican Inceptisol following forest clearing. However, DNDC was unable to simulate daily gas dynamics. This is troubling because DNDC was designed to simulate gas dynamics in a rainfall event-driven approach. The rationale behind this design is that, as evidenced by soil microsite studies, trace gas responses to soil wetting and drying events are critical. Considering that annual emissions are cumulative daily fluxes, daily comparisons provide a better insight in DNDC's performance than annual comparisons. The differences in local weather on the seven sampled pasture sites comprising the chronosequence may have caused a significant part of the mismatch. If so, future model tests should include frequent measurements of N_2O and NO and information on N_2:N_2O ratios. At present there is little field data available to constrain the ratio of N_2:N_2O produced by denitrification. Recent experiments by Panek *et al.* (unpublished data) suggest that field tests may be conducted successfully using 15-N tracer studies.

Results from our exploratory model runs for chronosequences of Inceptisol and Andisol sites should be interpreted with care because several simplifications were made. For example, SOC decomposition rates were kept the same for the Inceptisol and Andisol. Soil organic C decomposition dynamics in tropical soils of volcanic origin (i.e., Andisols) depend on the behavior of aluminum - organic matter complexes which can protect organic matter (Veldkamp, 1994). This effect was not taken into account.

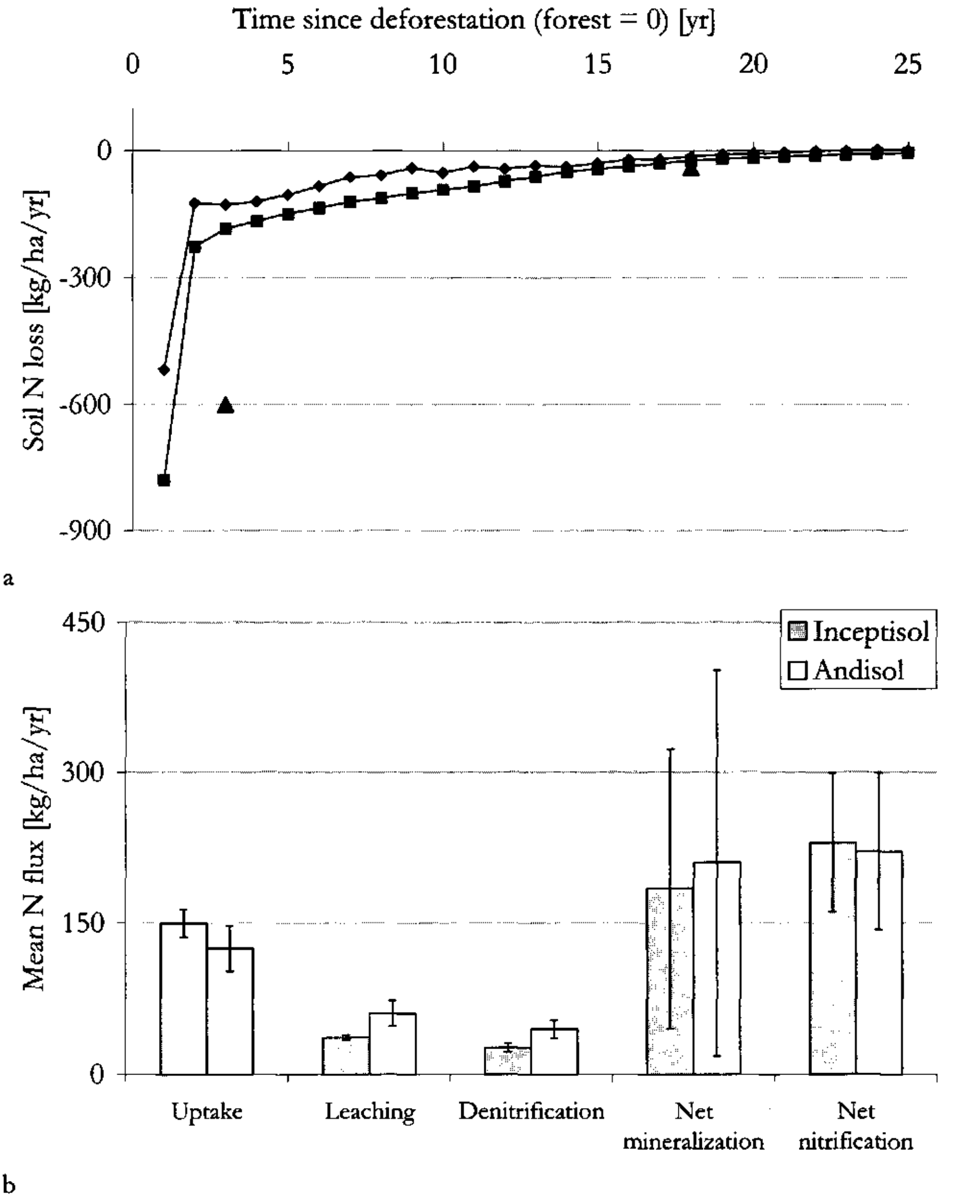
Table 2.3 Field-measured (Veldkamp *et al.*, in press) and DNDC-simulated indices of N cycling. Field data are means (standard error), n=4.

Land use	Age	Nitrification potential		Net mineralization	
		Field	Model	Field	Model
	[yr]	[mg kg^{-1} h^{-1}]	[kg ha^{-1} yr^{-1}]	[μg g^{-1} 7d^{-1}]	[kg ha^{-1} yr^{-1}]
Forest	0	3.0 (0.2)	-	17.0 (2.0)	-
Pasture	3	2.0 (0.2)	407	12.0 (1.9)	302
Pasture	6	2.3 (0.5)	300	15.8 (4.0)	252
Pasture	7	1.5 (0.1)	274	9.3 (0.8)	231
Pasture	9	1.8 (0.0)	229	12.1 (0.9)	191
Pasture	14	1.6 (0.1)	115	9.5 (1.0)	102
Pasture	22	1.0 (0.0)	37	7.0 (2.2)	47

Table 2.4 Annual budget fluxes of soil N [kg ha^{-1}] for two Inceptisol sites, "B&V" indicates rates estimated by Bouwman and Van Dam (1995), and "Model" indicates DNDC-simulated rates.

Flux	3-yr pasture		18-yr pasture	
	B&V	Model	B&V	Model
N precipitation	5	5	5	5
N fixation	0	0	0	0
Animal excreta	80	80	80	80
Litterfall & rhizodeposition	110	143	110	20
Subtotal	*195*	*228*	*195*	*105*
Plant uptake	-200	-240	-200	-90
NH_3 volatilization	-15	0	-10	0
Leaching	-100	-57	-8	-15
Denitrification	-480	-57	-18	-12
Subtotal	*-795*	*-354*	*-236*	*-117*
Net N loss	-600	-126	-41	-12

Figure 2.3 Model-simulated annual soil-N loss for Inceptisol (◆) and Andisol (■) plotted against pasture age (a) and comparison of mean annual major N flows in Inceptisol and Andisol (b). For (a): triangles (▲) indicate the estimates of Bouwman and Van Dam (1995) for young (3-year old) and old active (18-year old) pasture. For (b): bars represent standard deviations.



The model adaptations, i.e., the explicit calculation of immobilization and the addition of algorithms incorporating grass residues and animal feces, significantly affected simulated N dynamics. Without the immobilization algorithm, the secondary pulse of N_2O and NO was less pronounced. This suggests that immobilization is an important process retaining N immediately following forest clearing. After the structural forest material with low N content (i.e., a high C:N ratio) has been incorporated in the soil, the mineralized N may be mostly available for denitrification an leaching.
The addition of the algorithm accounting for recycling of plant material and feces affected the simulated steady-state C and N pools in the pasture soils. Without recycling, the point where all decomposable SOC has been transferred to the slower pools so that denitrification becomes limited by C availability was reached sooner. Also, biomass production was lower without the recycling algorithms switched on because, in that case, there is no source of available N.

Inputs for regional analyses of greenhouse gas emissions are generally derived from pseudo-homogeneous land units (Plant, 1998). Many authors have suggested that the accuracy of areal flux estimates can be improved by including information on *past* land use (Veldkamp, 1993; Keller *et al.*, 1993; Keller and Matson, 1994; Keller and Reiners, 1994). We found that DNDC is able to estimate annual emissions as a function of pasture age. Therefore, the model may be suitable for regional analysis of N-oxide emissions from young forest-derived pastures in the humid tropics.

2.6 Conclusions

- DNDC was able to simulate the major trends in annual N_2O, NO, and SOC dynamics along a 25-year Costa Rican chronosequence of forest and pasture on Inceptisol.
- DNDC could not capture daily dynamics of N_2O and NO flux.
- Trends in measured indices of N cycling (nitrification potential and net mineralization) matched trends in simulated N transformation rates.
- Simulated nitrate leaching losses were higher than field-measured losses. The low simulated N_2:N_2O ratio may explain the discrepancy.
- Rates and pathways of N loss from Andisols and Inceptisols were similar.
- DNDC may be used for regional analysis of N-oxide emissions from forest-derived pastures in the humid tropics because the model captures annual emissions as a function of pasture age.

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Chapter 3

Modeling nitrous oxide emissions from a Costa Rican banana plantation

R. A. J. Plant, E. Veldkamp, and C. Li

3 Modeling nitrous oxide emissions from a Costa Rican banana plantation

Abstract

We applied the process-based DeNitrification-DeComposition (DNDC) model to estimate field-level nitrous oxide emissions from a nitrogen-fertilized banana plantation on a clayey Inceptisol and a loamy Andisol in Costa Rica. Simulated daily nitrous oxide fluxes were compared with data from monthly and frequent field sampling. Different parameterizations were used to represent fertilizer inputs below banana plants (10% of the plantation area) and crop residue additions between plants (90% of the plantation area). For both the Andisol and the Inceptisol, simulated below-plant fluxes matched better with frequently measured fluxes (R-square 0.53 – 0.60) than with monthly measured fluxes (R-square 0.00 – 0.42). Simulated between-plant fluxes matched better with monthly measured fluxes (R-square 0.44 – 0.78) than with frequently measured fluxes (R-square 0.00 – 0.16). Per soil type, annual N_2O-N losses were calculated by integrating simulated below-plant and between-plant losses over space, assuming that 40% of the plantation area is affected by fertilization. Losses calculated for the Inceptisol and Andisol were 6 and 15 kg N_2O-N ha^{-1} yr^{-1}, respectively. Field-measured losses were 6 and 13 kg N_2O-N ha^{-1} yr^{-1}. In addition, three fertilization scenarios for Andisols were studied. When 360 kg N ha^{-1} yr^{-1} was applied in six rather than the typical thirteen equal splits, the below-plant N_2O-N loss declined by 27%. With twenty-six equal splits, annual below-plant N_2O-N losses increased most strongly with increasing amounts of fertilizer-N (100 – 800 kg ha^{-1} yr^{-1}). Field-level simulation modeling plays a key role in regional analysis of land use-related N-oxide emissions.

3.1 Introduction

Land use changes can provoke increasing concentrations of radiatively active trace gases in the atmosphere (Meyer and Turner, 1992), and form an important source in the global nitrous oxide (N_2O) budget. Nitrous oxide is both a greenhouse gas and ozone destructor. Changes in land use mainly take place in the tropics, where primary forest is cleared for pastoral and agricultural use. The latter type of conversion is especially common in South and Central America (Hecht, 1992).

Keller *et al.* (1993) and Veldkamp and Keller (1997) studied effects of deforestation and tropical agriculture on trace gas emissions in Costa Rica. Keller and co-workers found large changes in the soil-atmosphere flux of N_2O for the conversion of humid tropical forest to cattle pasture in the Atlantic Lowlands of Costa Rica. Veldkamp and Keller (1997) measured N_2O fluxes from a banana plantation fertilized with nitrogen (N) in the same region. Measured fluxes were similar to those previously measured from old-growth forest (Keller and Reiners, 1994). Veldkamp and Keller (1997) estimated that total gaseous N losses from the banana plantation (including nitric oxide (NO), dinitrogen (N_2) and ammonia (NH_3)) were 10 – 20% of the fertilizer applied. They concluded that current estimates of N_2O from fertilized agriculture worldwide might be too low because these estimates are merely based on measurements in temperate climates (Eichner, 1990; Bouwman, 1994). A similar conclusion was drawn by Matson *et al.* (1996) for N gas emissions from fertilized sugar cane in Hawaii.

To assess regional effects of land use on N_2O emissions, fluxes measured at experimental plot scales (~30 m^2) must be aggregated over larger spatial units and longer temporal cycles than can be captured with field measurements. Because the logistics of gas sampling are complicated, current regional estimates of N_2O are based on scanty short-term measurements. As a consequence, the extreme space-time variability of N_2O emissions (Folorunso and Rolston, 1984) is poorly accounted for. Dynamic process-based simulation models play a key role in overcoming this problem (Matson *et al.*, 1989; Schimel and Potter, 1995) because they can be used to simulate fluxes for control factor combinations that cannot be sampled. Moreover, models can be used for exploring "what if" questions, thereby illuminating which aspects of the system need further study (Oreskes *et al.*, 1994).

Several detailed biogeochemical models of denitrification and N_2O evolution from soil have been developed (Focht, 1974; Leffelaar and Wessel, 1988; Li *et al.*, 1992a, 1994b). More generalized ecosystem models (Burke *et al.*, 1990; Parton *et al.*, 1996; Potter *et al.*, 1996) exist for the calculation of temporally and regionally aggregated fluxes. To our knowledge, none of these models have so far been applied to quantify N_2O emissions from fertilized tropical agriculture.

We present a modeling framework for N-fertilized banana plantations in the Northern Atlantic Zone of Costa Rica. We used an adapted version of the dynamic process-based DeNitrification-DeComposition (DNDC) model (Li *et al.*, 1992a, 1992b, 1994b). We applied the framework to study how N_2O losses respond to alternative fertilizer application strategies.

3.2 Methods

Field sites for model evaluation

To evaluate our simulation results, we used field data from a banana plantation near Puerto Viejo, Sarapiquí Canton, Costa Rica (10°26'N, 84°0'W, Figure 1.1) (Veldkamp and Keller, 1997). Nitrous oxide emissions were measured on a loamy Andisol and a clayey Inceptisol. On each soil, the N_2O flux was sampled monthly during a one-year period and frequently preceding and following two fertilization events. Sampling was done both below and between banana plants, using sixteen static, vented field chambers per soil type during monthly sampling, and eight chambers per soil type during frequent sampling. Five gas samples were removed from the chambers during a twenty-eight-minute assay and analyzed using electron capture gas chromatography. During the sampling period (October 1993 - October 1994), 305 kg N ha^{-1} was added to the soil in eleven applications. The type of fertilizer was NH_4NO_3 in a mixture with P and K.

It was assumed that the flux measurements were representative for the day of sampling. Therefore, all comparisons between DNDC-simulated and field-measured fluxes were based on daily fluxes.

Table 3.1 Soil (Veldkamp and Keller, 1997) and land use parameters (Soto, 1985; Veldkamp and Keller, 1997).

Parameter	Description	Unit	Inceptisol		Andisol	
			below plants	between plants	below plants	between plants
Soil						
f_{isoc}	Initial SOC	[%]	4	4	4	4
φ	Bulk density	[Mg m^{-3}]	0.78	0.81	0.78	0.75
a	pH (H_2O)	[-]	4.7	4.7	6.0	6.0
Land use						
I_N	Fertilizer-N application rate	[kg ha^{-1} yr^{-1}]	3047	-	3047	-
I_C	Crop residue-C addition	[Mg ha^{-1} yr^{-1}]	-	7.3	-	7.3
R_{res}	Crop residue C:N ratio	[-]	-	40	-	40
Y	Maximum attainable dry matter yield	[Mg ha^{-1} yr^{-1}]	9	9	12	12
	Crop C allocation					
f_g	fraction fruits	[-]	0.3	0.3	0.3	0.3
f_s	fraction stems/leaves	[-]	0.6	0.6	0.6	0.6
f_r	fraction roots	[-]	0.1	0.1	0.1	0.1
R_B	Average crop C:N ratio	[-]	40	40	40	40
A	Water requirement (dry matter basis)	[-]	456	456	456	456
L	Maximum leaf area index	[-]	6	6	6	6

Parameterization

Soil parameters used are summarized in Table 3.1. Climate parameters were derived from daily rainfall and air temperature data from the La Selva meteorological station (10°26'N, 84°0'W, Figure 1.1). The distance between the banana plantation and La Selva is about 5 km. During the simulated 365 days (October 25, 1993 – October 24, 1994), total rainfall was 3811 mm; mean air temperature was 24.8 °C. Nitrogen input from rainwater pollution was 5 kg ha^{-1} yr^{-1} (M. Keller, personal communication).

Costa Rican banana plantations feature two major mechanisms of C and N input. These are N-fertilizer application and plant residue addition. Fertilizer is applied manually on a semi-circle covering the bare soil surface below the banana plant (0.3 - 0.5 m^2 per plant). This semi-circle is kept free of decomposing litter. Typically, 27.7 kg N ha^{-1} is applied every twenty-eight days (360 kg N ha^{-1} yr^{-1}, Veldkamp and Keller, 1997). With a typical density of 2000 banana plants per ha, the 360 kg N ha^{-1} yr^{-1} is effective on 10% of the plantation area. Therefore, the site-specific fertilizer application rate is 3600 kg N ha^{-1} yr^{-1}. During the field experiments of Veldkamp and Keller (1997), fertilizer was applied eleven times at a site-specific rate of 277 kg N ha^{-1} yr^{-1} per application (Table 3.1). Harvest continues throughout the year. After the banana bunch is harvested, the mother plant is cut down and left to decompose on the soil surface between plants, which typically covers 90% of the plantation area. Although each plant gives birth to several "suckers", in general only one is left to eventually replace the mother plant. Annually, the amount of

residue added is 15 - 18 Mg dry matter ha^{-1} (Vargas and Flores, 1996). Assuming an average of 16.5 Mg dry matter ha^{-1} yr^{-1} and a C:N ratio of 40 (Soto, 1985), we estimate that residue decomposition at the soil surface accounts for an extra annual N input of about 165 kg ha^{-1}. Since crop residue addition is effective on 90% of the plantation area, the site-specific rate of N addition is 183 kg ha^{-1} yr^{-1}. To mimic continuous residue decomposition, 20 kg C ha^{-1} was mixed into the soil between plants per day.
Nitrogen uptake by plants was allowed to take place throughout the plantation area (Table 3.1) and the turnover of roots was not modeled.

For both the Andisol and Inceptisol, separate one-year DNDC runs were performed for the below and between-plant area. To integrate simulated N_2O losses over space, we used fractions of the plantation area that exhibited elevated fluxes after fertilization in the field (Veldkamp and Keller, 1997). Per banana plant, the area affected may be regarded as a circle with a radius of approximately 0.8 m (Veldkamp and Keller, 1997). Thus, with 2000 plants per ha, 40% of the plantation area exhibits elevated fluxes after fertilization.

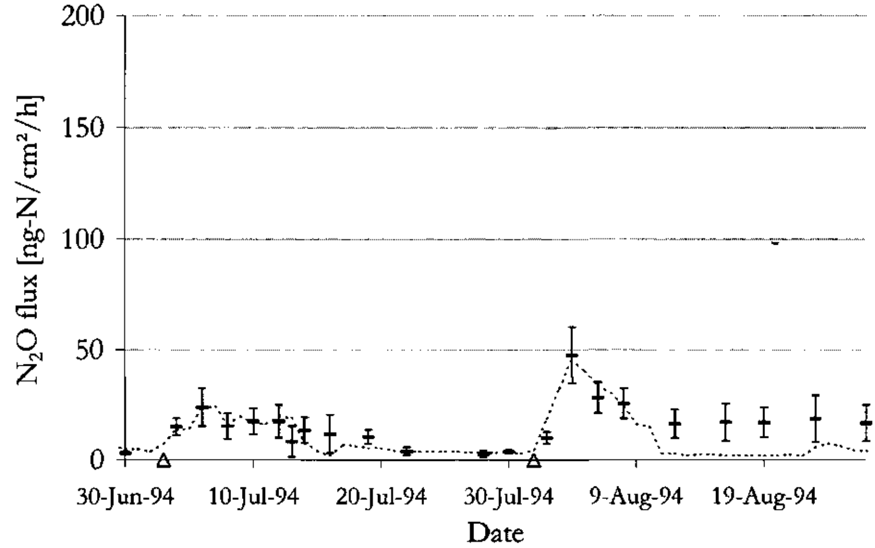
Fertilization scenarios
The effects of two alternative fertilization scenarios on annual N_2O losses below plants were simulated for the Andisol. Losses were compared with results from a base run (scenario F-0) featuring 360 kg fertilizer-N ha^{-1} yr^{-1} (site-specific rate 3600 kg ha^{-1} yr^{-1}) in thirteen equal splits. In the alternative scenarios (F-1 and F-2), the same amount of fertilizer-N was added in six and twenty-six equal splits, respectively. In addition, the three scenario runs were each repeated with eight different annual fertilizer-N doses ranging from 100 to 800 kg ha^{-1} (site-specific annual doses 1000 – 8000 kg ha^{-1}). This range was based on fertilizer application rates recommended for both current and alternative banana production systems in the Northern Atlantic Zone (Hengsdijk *et al.*, 1998). With each fertilizer level, a different attainable production was implied: with 100 kg N ha^{-1} yr^{-1} the attainable yield implied was 4.4 Mg dry matter ha^{-1} yr^{-1}; with 800 kg N ha^{-1} yr^{-1} the yield was 20.5 Mg dry matter ha^{-1} yr^{-1}. In all DNDC runs, application dates were evenly distributed over the year.

3.3 Results

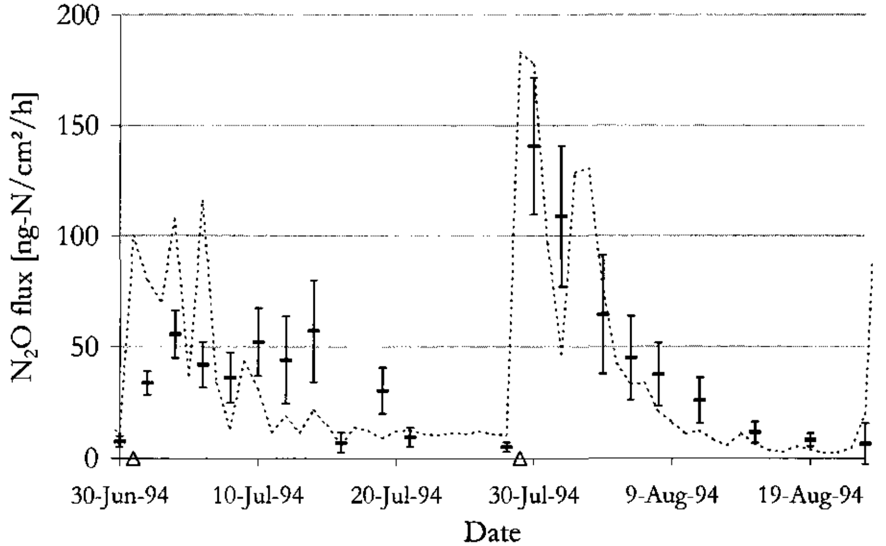
Evaluation of simulated nitrous oxide emissions
Below-plant simulations. - The DNDC-simulated daily N_2O flux dynamics below banana plants (Figure 3.1a and Figure 3.1b) matched the patterns observed during frequent sampling (R-square 0.60 for Inceptisol and 0.53 for Andisol, Table 3.2). For the Inceptisol, there was no correlation between simulated and monthly sampled fluxes. For both monthly and frequent sampling, most mean simulated daily fluxes were slightly higher than mean field-measured fluxes.

Between-plant simulations. - Simulated daily between-plant fluxes (Figure 3.2a and Figure 3.2b) matched best with monthly measurements (R-square 0.44 for Inceptisol and 0.78 for Andisol, Table 3.2).

Figure 3.1 Model-simulated (dashed lines) and field-measured (—) N_2O flux below plants for Inceptisol (a) and Andisol (b). Open triangles on the horizontal axis indicate fertilizer application dates. Bars represent standard errors for field-measured emissions.

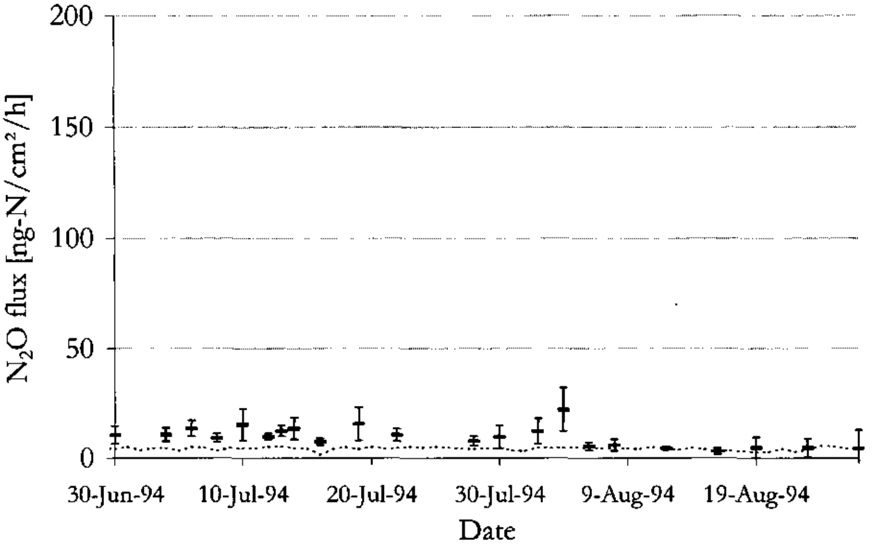


a

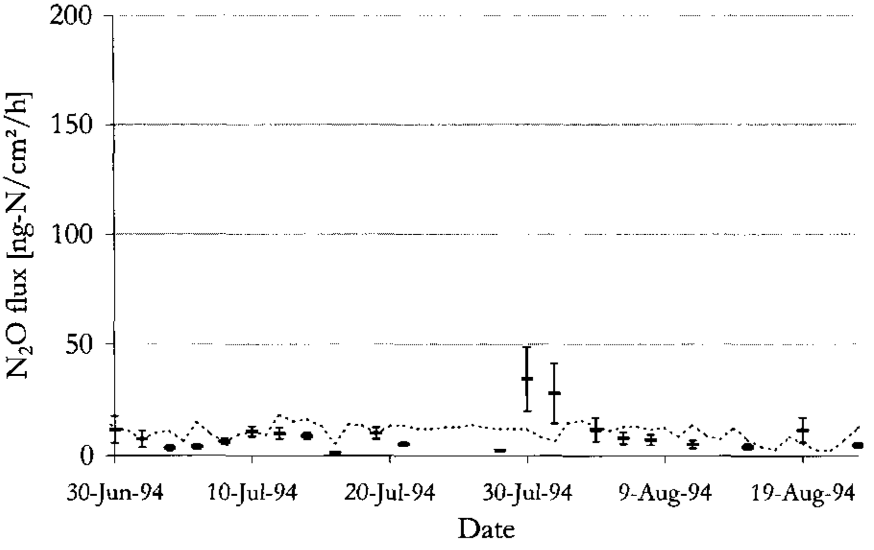


b

Figure 3.2 **Model-simulated (dashed lines) and field-measured (—) N_2O flux between plants for Inceptisol (a) and Andisol (b). Bars represent standard errors for field-measured emissions.**



a



b

Table 3.2 Means and squared Pearson product-moment correlations (R-square) of field-measured and model-simulated daily N_2O flux ([ng cm^{-2} h^{-1}]). For Inceptisol: n=11 for monthly sampling, n=22 for frequent sampling. For Andisol: n=12 for monthly sampling, and n=21 for frequent sampling (* = significant at p < .05 by analysis of variance).

	Inceptisol			Andisol		
	Field	Model	R-square	Field	Model	R-square
Below plants						
Monthly sampling	9.3	17.0	0.00	31.4	37.2	0.42*
Frequent sampling	15.7	12.6	0.62*	39.4	39.6	0.53*
Between plants						
Monthly sampling	6.2	6.3	0.44*	4.3	12.5	0.78*
Frequent sampling	9.8	4.2	0.16	9.4	11.1	0.00

Using the site-specific simulated annual N_2O-N losses, and assuming that 40% of the plantation area is affected by fertilization, we calculated weighted average N_2O-N losses. These were 6 and 15 kg ha^{-1} yr^{-1} for the Inceptisol and Andisol, respectively. Veldkamp and Keller (1997) estimated that weighted averages were 6 and 13 kg ha^{-1} yr^{-1} for the Inceptisol and Andisol, respectively.

Scenario-based simulations

With 360 kg fertilizer-N ha^{-1} yr^{-1}, applied in thirteen equal splits, (scenario F-0) a below-plant N_2O-N loss from the Andisol of 27 kg ha^{-1} yr^{-1} was simulated (Table 3.3). With six equal splits (scenario F-1), the loss decreased to 20 kg ha^{-1} yr^{-1}, or by 27%. With twenty-six equal splits (scenario F-2), the simulated loss increased to 34 kg ha^{-1} yr^{-1}, or by 24%. For high N doses (> 300 kg ha^{-1} yr^{-1}), annual below-plant losses appear to be inversely and linearly related to the frequency of fertilizer application (Figure 3.3). For lower N doses, the relationship is non-linear: with higher frequencies, annual losses are more strongly determined by the N dose.

3.4 Discussion

Model performance

Veldkamp and Keller (1997) found that in fertilized systems the day-to-day variability is dominant, and suggested that frequent sampling might yield a better estimate of the N_2O loss than monthly sampling. Likewise, for the judgement of model performance comparison with frequent field data may be more realistic than comparison with monthly data.

Figure 3.1a suggests consistency of DNDC for the below-plant system because the model was able to capture N_2O peaks directly following fertilizer application. The model did not capture biogeochemical dynamics between plants. A possible explanation is that lateral movements of N fertilizer by stem flow, splash erosion, and/or spilling of fertilizer by the workers play an important role in the field. Transfer of fertilizer-N to the between-plant area is evidenced by higher N_2O emissions from these areas after fertilizer application

(Figure 3.2b). In our approach, this type of unpredictable additional N input had to be neglected.

Figure 3.3 Simulated below-plant N_2O loss vs. applied fertilizer-N when practicing scenario F-0 (thirteen equal splits, ■), scenario F-1 (six equal splits, ◆), and scenario F-2 (twenty-seven equal splits, ▲).

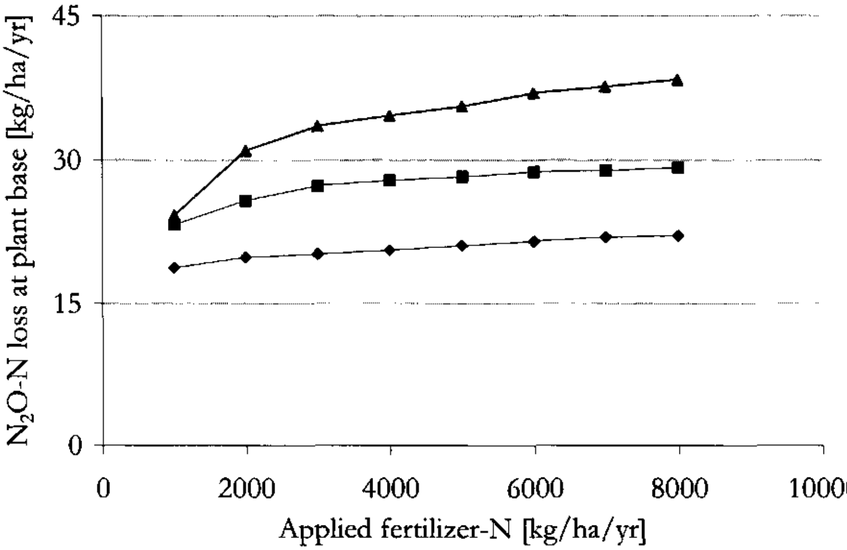


Table 3.3 Simulated below-plant N_2O-N losses ([kg ha^{-1} yr^{-1}]) for different fertilization scenarios on Andisol. F-0 is the reference scenario. In the base runs 360 kg fertilizer-N ha^{-1} yr^{-1} was applied. In the reruns, site-specific N doses ranged from 1000 to 8000 kg ha^{-1} yr^{-1} whereas attainable dry matter yields ranged from to 4.4 to 20.5 Mg ha^{-1} yr^{-1}.

Fertilization scenario	Base runs	Reruns
F-0	27	23-29
F-1	20	19-22
F-2	34	24-38

Water-filled pore space is widely known to be a dominant factor controlling N_2O flux. Even though simulated water-filled pore space was unrealistically low for the Andisol (results not shown), simulated N_2O fluxes were within the range of measured fluxes. We explain this by an overestimated availability of substrates for denitrification: since SOC decomposition proceeds faster at low soil moisture (Li *et al.*, 1992a), either simulated inorganic-N or soluble-C concentrations may have been too high. To enhance DNDC's representation of the N_2O flux - soil moisture relationship, future work should focus on calibration of the soil climate submodel using series of simultaneous and frequent measurements of soil moisture and N_2O flux.

We stratified the banana plantation by the type of input and performed only two one-year simulations per soil type. In fact, two extreme conditions were simulated; an inherent integration error may have been made when assuming that 40% of the plantation exhibits elevated gas emissions. In reality, there is a typical radial dependence of N_2O flux, going from the below-plant to the between-plant position. Therefore, Veldkamp and Keller (1997) used additional flux measurements and corresponding weighting factors for six concentric circles at 0.35-m increments to integrate measurements over space. Incorporation of this more detailed approach in our modeling strategy would require a simulated flux for each concentric circle, and thus detailed information on soil parameters and N input per circle. This would go beyond the rationale of the DNDC model.

Below-plant results were generally better for the Andisol than for the Inceptisol. We believe this difference is primarily caused by the pH assumptions in DNDC. The Inceptisol has a pH of 4.7, whereas the pH of the Andisol is 6.0. DNDC may have underestimated N_2O production under low pH conditions in the Inceptisol. In DNDC, total denitrification decreases as soil pH decreases. At low pH (<5), most denitrification stops at N_2O (Li *et al.*, 1992a).

Verification and validation of DNDC is inherently impossible because the biogeochemical system it attempts to capture is never closed (Oreskes *et al.*, 1994). Model results can at best be *confirmed* by the demonstration of agreement between measurements and predictions, as was done in this study. However, this confirmation will always be partial since many system inputs and outputs remain unknown. Nitrous oxide loss is only a minor flow of N. Data on the major vehicles of N flow (e.g., plant uptake and leaching) are needed to gain a more conclusive understanding of N cycling in humid tropical banana plantations, but these are at present not available. Future measurement campaigns should not only pay attention to N_2O flux, but also to the major N flows.

Fertilization scenarios

With current fertilization practices, banana plantations receive N fertilizer in excess of plant demand. As shown by Veldkamp and Keller (1997), high N doses in wet tropical areas to assure high crop yields cause high emissions of N oxides. Our exploratory simulations suggest that reducing the application frequency may reduce N_2O losses. Moreover, we found that the sensitivity of N_2O loss to the N dose depends on the application frequency. Besides decreasing the total amount of applied N fertilizer, adapting the fertilization practices may, therefore, reduce N_2O emissions. Both options call for confirmation in the field, while taking into account the associated yields and N losses through NO_3^- leaching. Because DNDC is not set up for simulation of crop yield and N leaching, we could not study relationships between yield, N_2O loss, applied N fertilizer and N leaching. However, our results could be used in conjunction with full-fledged crop models (e.g., SUCROS (Van Laar *et al.*, 1992), or WOFOST (Van Diepen *et al.*, 1989)) and N leaching models (e.g., LEACHM (Hutson and Wagenet, 1991)) to develop optimum fertilization scenarios for Costa Rican banana plantations (Stoorvogel, 1998).

A more balanced N-fertilizer management on the Costa Rican banana plantations would eventually result in a more cost-effective use, and would at the same time contribute to the mitigation of N_2O emissions. Because the use of N fertilizer is increasing by as much as 10% per year in some tropical regions (Galloway *et al.*, 1995), quantitative predictions of potential N_2O loss from high-productivity systems like banana should be incorporated in regional land use planning (Bouman *et al.,* in press/b). The modeling framework presented allows the incorporation of this important land use system in regional studies, and moreover provides, in principle, a tool for scenario-based modeling.

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PART II

Chapter 4

Modeling nitrogen oxide emissions from current and alternative pastures in Costa Rica

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Journal of Environmental Quality (in press)

4 Modeling nitrogen oxide emissions from current and alternative pastures in Costa Rica

Abstract

Emissions of nitrogen (N) oxide were simulated for one current pasture management system ("Natural") and two alternative systems ("Grass-Legume" and "Fertilized Improved") relevant to the Northern Atlantic Zone of Costa Rica. Current forest-derived pastures deplete soil nitrogen stocks and therefore are unsustainable. Alternative management systems aim at a nitrogen use that is optimally adapted to the environment, hence they are sustainable. To produce frequency distributions of nitrogen oxide emissions, an expert system for generating technical coefficients of pastures was linked with a process-based simulation model. The expert model generated parameter sets representing different options for the three management systems. The simulation model was rerun for each parameter set. Simulated nitrous oxide-N losses twenty-five years after pasture establishment were 3-5 kg ha^{-1} yr^{-1} for natural pastures, 12-15 for grass-legume mixtures, and 7-28 for fertilized grasses. Losses of nitric oxide-N were 1-2 kg ha^{-1} yr^{-1} for natural pastures, 7-8 for grass-legume mixtures, and 3-16 for fertilized grasses. Stepwise multiple regression showed that nitrous oxide-N losses were explained by annual carbon input to the soil (R-square 0.997), and nitric oxide-N losses by attainable dry matter production (R-square 0.972). Carbon input and dry matter production were controlled by stocking rate and fertilizer level. Soil-atmosphere N-oxide emissions from pastures may increase by a factor 3-5 when natural pastures are converted to improved pastures. Such conversion may increase the sustainability of the pasture by stopping the decline of soil N. However, the change is not necessarily sustainable from a global perspective because it increases the emission of N-oxide greenhouse gases.

4.1 Introduction

Since the 1940s, large areas of primary tropical forest have been cleared in Costa Rica. Annual deforestation rates were about 40,000 - 60,000 ha yr^{-1} during the 1970s and 1980s, 18,000 ha yr^{-1} between 1987-1992, and 8500 ha yr^{-1} in the mid-nineties (Kaimowitz, 1996). Pasture for beef cattle ranching has been the most common replacement for cleared primary forest, not only in Costa Rica, but also in many other tropical Latin American countries (Hecht, 1992). Forest clearing and subsequent conversion to agriculture have important environmental effects, for example biodiversity loss, land degradation, and elevated emissions of carbon dioxide (CO_2) (Van Dam *et al.*, 1997), nitrous oxide (N_2O), and nitric oxide (NO) (Fung and Prather, 1990). Nitrous oxide is a greenhouse gas that also contributes to the depletion of stratospheric ozone. Nitric oxide plays a critical role in the regulation of the oxidant balance in the troposphere, and is a precursor to the formation of tropospheric ozone. In the Northern Atlantic Zone (NAZ) of Costa Rica, the effects of forest clearing on soil-atmosphere emissions of N_2O and NO have been extensively studied (Keller *et al.*, 1993; Keller and Reiners, 1994; Veldkamp *et al.*, in press). Nitrous oxide emissions measured in young pastures (2-10 yr) were found to exceed forest soil emissions by a factor 5-8. However, a decade following forest clearing, pasture N_2O emissions declined below forest levels. Similar trends were observed for NO emissions. Therefore, Keller *et al.* (1993) concluded that pasture age is an essential factor controlling nitrogen (N) oxide emissions from tropical pastures.

Beef cattle ranching systems in the humid tropics are characterized by low levels of external input and low productivity per unit area (Ibrahim, 1994; Hernandez *et al.*, 1995). When stocking rates are adapted to the carrying capacity of the environment, such systems are sustainable and can be maintained for long periods. However, when stocking rates are too high, as supposedly occurs on most forest-derived pastures in the NAZ, removal of nutrients from the system may exceed natural inputs and soils are "mined" (Thomas *et al.,* 1992; Haynes and Williams, 1993; Cadisch *et al.,* 1994). Over time, soil mining will result in land degradation and declining yields (Myers and Robbins, 1991; Williams and Chartres, 1991). With progressive pasture degradation, beef cattle farming eventually ceases to be profitable; the land will be abandoned, allowing regrowth of brush, woodland, and/or secondary forest (Haynes and Williams, 1993). After several decades, when the soils have recovered, secondary forest redeveloped on abandoned pastures may again be converted to pasture. Breaking this so-called "forest-livestock connection" (Bouman *et al.*, in press/a) is desirable, both from an economic and environmental perspective, and has stimulated research into alternative, sustainable livestock systems.

To date, most research has focused on the feasibility of intensive, high-stocked grass-legume mixtures and fertilized grasslands with closed soil nutrient balances (Miller and Stockwell, 1991; Teitzel *et al.*, 1991; Ibrahim, 1994; Hernandez *et al.*, 1995). Gaseous N losses from such alternative pastures, however, have rarely been studied. Recent measurements by Veldkamp *et al.* (1998) have revealed that, beside pasture age, management practices may profoundly affect N-oxide emissions. Fertilizer application, though at present a rare practice in beef cattle ranching in the humid tropics, may significantly raise the levels of N_2O and NO emission (Loro *et al.*, 1997). Because many factors interactively affect N-oxide emissions, their assessment is complicated. Process-based dynamic simulation models (e.g., Li *et al.*, 1992a, 1992b, 1994b; Grant *et al.*, 1993a, 1993b; Bril *et al.*, 1994) may therefore be useful tools to help unravel the role of different factors influencing emissions associated with alternative pasture management systems.

The purpose of this study was to model and explain N-oxide fluxes from current and alternative pastures in the Northern Atlantic Zone of Costa Rica. Frequency distributions of fluxes were generated by linking an expert system for calculating inputs and outputs of pastures with a process-based simulation model of N-oxide evolution from soil. Annual N_2O and NO losses from *i)* the currently degrading pasture management system, and *ii)* alternative sustainable systems were estimated for a case study area in the NAZ of Costa Rica. Simplified models were derived for practical applications in further (regional) studies.

4.2 Site description

The Northeastern part of Costa Rica (10°00' to 11°00' latitude, and 83°00' to 84°00' longitude) comprises an area of about 450,000 ha (Figure 1.1). Mean daily temperature is 26 °C. Mean annual rainfall is 3500 – 5500 mm, and the average relative humidity is 85 - 90%. The climate is humid tropical. Three main soil groups have been distinguished in the Northern Atlantic Zone based on agricultural potential (Jansen *et al.*, 1995): Fertile, Well-Drained (FWD), Fertile, Poorly-Drained (FPD), and Infertile, Well-Drained (IWD) soils. Fertile, well-drained soils have the highest production potential and comprise 37% of the agriculturally suitable area.

It is currently estimated that 38% of the NAZ is used for beef cattle ranching (Bouman *et al.*, in press/b). Mean stocking rates are 1.4-1.9 animal units (AU, 1 AU = 400 kg live weight) ha^{-1}. Indigenous and naturalized grasses, which are relatively unproductive, dominate the pastures (77%). Naturalized grasses consist of indigenous species and/or species introduced in the early 1970s. Management is extensive with low external inputs and yields between 8-10 Mg dry matter ha^{-1} yr^{-1} (Hernandez *et al.*, 1995). Jansen *et al.* (1997) estimated that over 70% of the pastures in the NAZ are in an advanced stage of degradation, and Bouman *et al.* (in press/a) estimated that current annual soil-N losses are about 40-60 kg ha^{-1}. With such high soil-N losses, current pastures are unsustainable. That is, production, and therefore the economic surplus of farmers, is expected to decrease in time.

4.3 Methods

An expert system called PASTOR (PASture and livestock Technical coefficient generatOR, Bouman *et al.*, 1998) was used for generating inputs and outputs relevant to three Costa Rican pasture management systems. These systems cover botanical pasture species and management practices ranging from current soil-mining natural and naturalized pastures to grass-legume mixtures and improved fertilized grasses. PASTOR's generated coefficients were converted to input parameters for DNDC (DeNitrification-DeComposition, Li *et al.*, 1992a, 1992b, 1994b), a dynamic process-based simulation model of N-oxide evolution from soil.

Pasture and livestock technical coefficient generator

PASTOR generates technical coefficients of pasture production systems. Technical coefficients are system characteristics such as materials (e.g., fertilizer and pesticides), costs and labor, pasture yield, biomass partitioning, and manure and urine production. In the PASTOR modeling approach, a pasture production system is defined by grass species, soil type, and management. The management factors relevant to this study are stocking rate and fertilizer application rate. Technical coefficients are generated using a "target-oriented approach" (Van Ittersum and Rabbinge, 1997): target production levels are predefined and used by PASTOR to calculate required inputs. The target level may vary from maximum attainable production under non-limiting conditions to extremely low yields on exhausted soils. In the first case, high levels of external input (e.g., fertilizers, crop protection materials) are required, while in the latter case low levels of external inputs suffice. For sustainable pastures the amount of fertilizer input is calculated with the boundary condition that total N input equals total N output. Alternatively, there is an option to use PASTOR descriptively: all inputs and outputs are user-defined and, instead of fertilizer input, PASTOR calculates the resulting soil nutrient balance. Calculations in PASTOR are based on knowledge of relevant agro-ecological processes (Bouman *et al.*, in press/a). When process knowledge is incomplete or absent, calculations are based on expert knowledge, published data, and field observations. The PASTOR formulation of pasture systems in the NAZ was confirmed by literature and field data, and was carefully reviewed by external experts. Simulated production levels matched field observations in the NAZ (Bouman *et al.*, in press/a).

Denitrification-decomposition model

In this paper, we use an adapted version of the DNDC model (Li *et al.*, 1992a, 1992b, 1994b). DNDC is an integrated one-dimensional model of field-level carbon (C) and N dynamics in soil-vegetation systems, with a strong focus on (de)nitrification and N-oxide emissions. DNDC consists of four interacting submodels. First, a soil climate submodel calculates hourly soil moisture and temperature dynamics. Earlier work has focused on the modification of DNDC's original soil climate model (Li *et al.*, 1992a) to capture soil physical conditions in tropical soils (Li and Keller, unpublished data). Second, a decomposition submodel calculates daily rates of residue-C, humads-C, and microbial biomass decomposition. In addition, this submodel calculates net N mineralization, nitrification, ammonification, ammonia (NH_3^+) volatilization and ammonium (NH_4^+) adsorption. Daily production and emission of N_2O and NO from nitrification are explicitly modeled. Third, a denitrification submodel is activated when a rain event occurs. In the DNDC formulation, a rain event is defined as the time period from rainfall initiation to the time when water-filled pore space decreases to 35%. Based on soluble C and soil nitrate (NO_3^-), the submodel calculates hourly production and emission of NO, N_2O, and dinitrogen (N_2). Finally, a plant growth submodel and associated cropping practice algorithms (Li *et al.*, 1994) calculate daily plant N uptake, litter and root turnover, and incorporate external inputs of C and N such as manure-C and fertilizer-N. In DNDC, N uptake is the key process linking crop growth with soil C and N status. Inorganic N availability, soil moisture availability, and soil temperature can limit the daily potential N uptake rate that is calculated from an implied attainable dry matter production level.

Table 4.1 Average characteristics of Fertile, Well-Drained (FWD) soils (Jansen *et al.*, 1995).

Parameter	Description	Unit	Range	Mean
f_{clay}	Clay content	[%]	5 – 25	15
φ	Bulk density	[Mg m^{-3}]	0.5 – 0.8	0.7
f_{isoc}	Initial SOC	[%]	3 – 12	8
a	pH (H_2O)	[-]	5.5 – 6.0	5.8

Table 4.2 PASTOR-generated DNDC inputs for Natural, Grass-Legume, and Fertilized Improved options. Footnoted values were derived from literature.

Parameter	Description	Unit	Natural	Grass-Legume	Fertilized Improved
I_C	Annual input of crop residue-C and/or manure-C	[Mg ha^{-1} yr^{-1}]	0.4 – 1.6	7.5 – 8.9	3.6 – 17.1
R_{res}	Average C:N ratio of crop residue-C and/or manure-C	[-]	15†	23 – 25	22 – 34
I_N	Annual input of inorganic N	[kg ha^{-1} yr^{-1}]	14 – 55	13 – 51	13 – 234
Y	Maximum attainable aboveground dry matter production	[Mg ha^{-1} yr^{-1}]	10	20	8 – 35
f_r	Fraction of total biomass-C in roots	[-]	0.2‡	0.1	0.1
f_s	Fraction of total biomass-C in shoots	[-]	0.8‡	0.9	0.9
R_r	C:N ratio in roots	[-]	26§	26	23 – 37
R_s	C:N ratio in shoots	[-]	26§	26	23 – 37
O_c	Annual N consumption by cattle	[kg ha^{-1} yr^{-1}]	45 – 180	-	-
A	Crop water requirement (dry matter basis)	[-]	550	550	550
L	Maximum leaf area index	[-]	5	5	5

† Haynes and Williams, 1993; ‡ Veldkamp, 1993; § Bouwman and Van Dam, 1995.

PASTOR-DNDC simulations

Simulations were executed for FWD soils (Table 4.1) because of their areal extent and relative importance for agriculture. PASTOR was used to generate technical coefficients for three pasture management systems (Veldkamp *et al.*, 1998): a current unsustainable system and two systems representing alternative, sustainable management. Unsustainable pasture management systems gradually deplete the soil-N stock because total N output exceeds total N input. Sustainable systems meet the requirement that total N input equals total N output. More specifically, the three pasture management systems are:

- Natural pasture ("Natural") representing a mixture of indigenous species and naturalized varieties introduced in the 1970s. No fertilizer is applied so that removal of nutrients with agricultural products decreases soil-N stocks. Management options are based on stocking rates ranging from 1 to 4 AU ha^{-1} in steps of 0.25. Thus, thirteen options were generated.
- Grass-legume pasture ("Grass-Legume") consisting of a mixture of *Brachiaria brizantha* and *Arachis pintoi*, a mixture that has been shown to be persistent and economically profitable in the NAZ (Ibrahim, 1994; Jansen *et al.*, 1997). Since the legume supplies N to the pasture through microbial fixation, total N input equals total N output without fertilizer application. The stocking rates, and thus the number of options, were the same as for Natural.
- Fertilized improved pasture ("Fertilized Improved") representing *Brachiaria brizantha.* Total N inputs equal total N outputs through fertilizer-N applications. The amounts applied range from zero (resulting in bottom production levels) to the amount needed to realize maximum attainable production. Stocking rates range from 1 to 6 AU ha^{-1} in steps of 0.25. Fertilizer steps depend on stocking rate. The combination of fertilizer application rates with stocking rates resulted in 250 options.

Stocking rate is an important management variable in all three systems because of its effect on pasture production, the soil-N balance, and, in the case of Fertilized Improved, the required fertilizer application rate. Fixed animal growth and feed intake rates were used for calculating manure and urine production. When the feed supply of a particular pasture alternative was below the feed intake requirements of the grazing stock, feed supplements were allowed. Thus, the N requirements to sustain pasture production levels of the various alternatives were met by a combination of direct inputs (mineralization, fertilizer, fixation by micro-organisms), and indirect inputs through manure and urine (feed supplements, pasture recycling).

We interpret attainable production as the aboveground dry matter production allowed by weather (through irradiation and temperature), soil properties (potentially available nutrients, pH, physical properties), management (e.g., stocking rate, fertilizer application) and pasture species characteristics. In this sense attainable production can be inferred from field experiments. The DNDC model (see below) computes actually realized annual production from attainable production, possible water stress and daily N availability.

An interface was developed for converting PASTOR-generated technical coefficients to DNDC input parameters (Table 4.2). Per pasture option, a fifty-year DNDC run was carried

out. For the sustainable Grass-Legume and Fertilized Improved systems, all direct and indirect C and N inputs were explicitly defined by PASTOR. The residue-C recycling and grazing routines in DNDC (Plant and Keller, this thesis) were therefore disabled; the plant growth submodel only simulated N uptake by the pasture. For the unsustainable Natural system, however, PASTOR-generated inputs represented only manure-C and urine-N inputs. Therefore, DNDC's residue-C recycling and grazing routines were activated.
The thirteen unfertilized Natural options had three DNDC parameters that depended on management:

- I_C, the annual manure-C input, was calculated as a function of stocking rate.
- I_N, the amount of urine-N produced annually, was calculated as a function of stocking rate.
- O_c, the annual N consumption by cattle, was calculated from the stocking rate, assuming an average consumption of 45 kg ha^{-1} AU^{-1} yr^{-1} (Bouwman and Van Dam, 1995).

For the Grass-Legume and Fertilized Improved options, six DNDC parameters varied with management:

- I_C was the amount of grass-C residues turning over annually plus annual manure-C input.
- R_{res} was the weighted average C:N ratio of the two types of I_C.
- I_N was fertilizer-N plus urine-N input (only urine-N for Grass-Legume).
- Y, the maximum attainable aboveground dry matter production, is a function of fertilization and stocking rate.
- R_r and, R_s, the below and aboveground C:N ratios, respectively, depended on fertilizer level and stocking rate. PASTOR uses a relationship between the amount of N available for uptake and pasture N concentration.

All other required external land use parameters (Table 4.2) either depended on the pasture management system only (f_r, f_s) or were constant across systems (A, L).

Assuming the pastures are grazed all year round, I_C was distributed over 365 equal daily additions. I_N, mainly representing fertilizer, was distributed over twelve equal monthly applications. This approximates the fertilizer frequency on NAZ pastures sampled by Veldkamp *et al.* (1998) (about sixteen split applications in a year). To force a balanced estimate of residue recycling for the Natural system, DNDC additionally simulated daily biomass-N removal by the cattle. A value for O_c was therefore specified for each option. Finally, as in the PASTOR calculations, annual N fixation was 150 kg ha^{-1} for the Grass-Legume system (Ibrahim, 1994).

Average characteristics of FWD soils (Table 4.1) were used to initialize the model soil profile. To model the effects of a recent forest-clearing event on the initial soil status, an additional amount of soil organic carbon (SOC), consisting of 29.5 Mg ha^{-1} forest-derived litter and roots, was stored in the model soil initially (Plant and Keller, this thesis). The weather as recorded at the Los Diamantes meteorological station (10°13'N, 83°48'W, Figure 1.1) was assumed to be representative for the NAZ. Daily rainfall and air temperatures were parameterized using data from 1991 and 1992. A fixed NO_3^--N concentration in precipitation (0.1 mg L^{-1}) was used (M. Keller, personal communication).

Statistical analysis and model confirmation

Sensitivity of N-oxide losses to management inputs was analyzed using stepwise linear regression and squared Pearson product-moment correlation coefficients (R-square). Statistical analyses were done with the software package SPSS 7.5 for Windows. Average DNDC-simulated annual N_2O and NO loss twenty-five years after forest clearing were evaluated against field measurements made by Veldkamp *et al.* (1998). Each month between October 1993 - October 1994, they sampled twelve sites located near the town of Horquetas, Costa Rica (10°2'N, 84°55'W, Figure 1.1) for N_2O and NO flux. The twelve sites featured four replicates of natural, grass-legume, and fertilized pasture each. All experiments were done on a fertile Andisol with a loamy texture that was classified as a FWD soil. The pastures were derived from forest more than ten years before sampling.

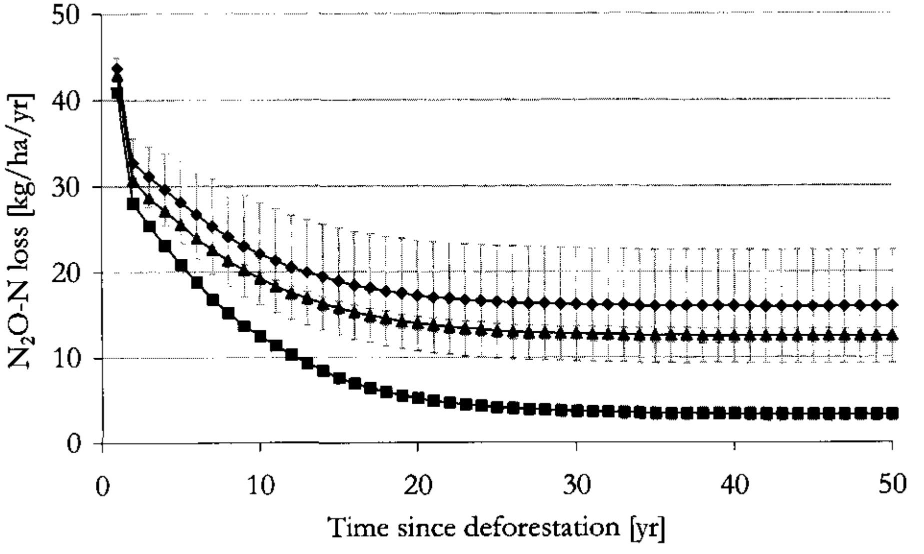
4.4 Results and discussion

Simulated nitrogen oxide fluxes

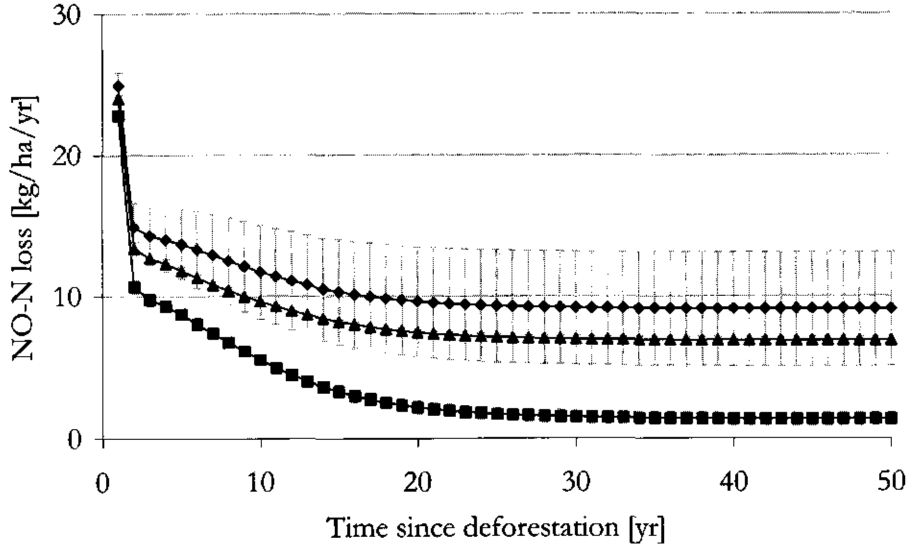
Figure 4.1a and Figure 4.1b suggest that N_2O and NO fluxes from all pastures reach a new steady-state about twenty-five years after forest clearing. Therefore, simulation results for the twenty-fifth year were used for statistical analysis. Stepwise multiple regressions showed that variations in annual N_2O-N and NO-N loss twenty-five years after forest clearing were explained by annual C input (Figure 4.2) and attainable dry matter production (Figure 4.3). Figure 4.2a and Figure 4.2b show a cluster of simulated N_2O-N and NO-N losses simulated for the Natural options. This clustering may be explained by the composition of I_C. In the DNDC simulations for Natural, I_C consisted of cow manure only, whereas I_C was a mixture of cow manure and grass residues in the Grass-Legume and Fertilized Improved simulations.

The relationship between grass production, stocking rate, and N_2O loss is complex. In Figure 4.3a, the effect of stocking rate and attainable dry matter production on DNDC-simulated N_2O loss is illustrated for the Fertilized Improved pasture management system. For stocking rates lower than 3 AU ha^{-1}, both the production levels and the N_2O losses slightly decrease with increasing stocking rate. With stocking rates greater than 3 AU ha^{-1} the relationship inverts; both production levels and N_2O losses increase with increasing stocking rate. We explain this behavior by PASTOR's formulation of interacting relationships between *i*) the amount of N available for uptake by the pasture, biomass level, and pasture-N concentration, and *ii*) stocking rate, biomass level, and amount of biomass removed by grazing. In the 1-3 AU ha^{-1} range, the increasing amount of plant-available N (through increased urine and manure input) enhances the pasture-N content.

Figure 4.1 **Mean simulated N_2O-N (a) and NO-N loss (b) from Natural (■), Grass-Legume (▲) and Fertilized Improved (◆) pasture following forest clearing. Bars indicate one standard deviation. For Natural and Grass-Legume, n=13. For Fertilized Improved, n=250.**

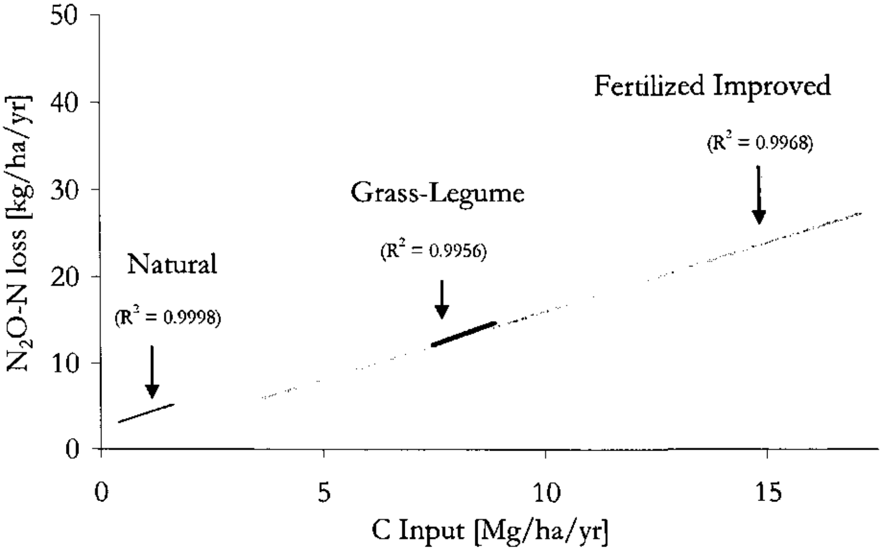


a



b

Figure 4.2 Simulated N_2O-N (a) and NO-N loss (b) against annual C input for Natural (solid line), Grass-Legume (heavy line) and Fertilized Improved (dashed line) pasture twenty-five years after forest clearing. Results are reported as trend lines. R-square values indicate the goodness of fit. Pasture management systems are identified with an arrow.



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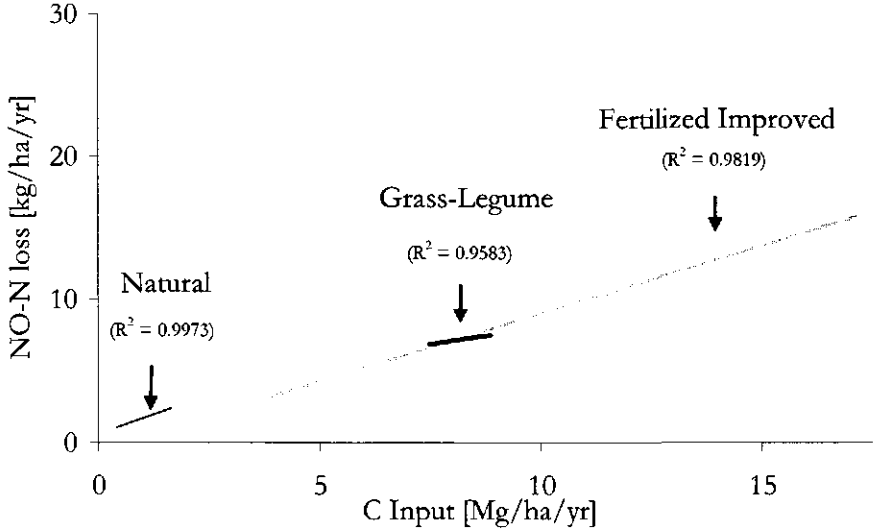
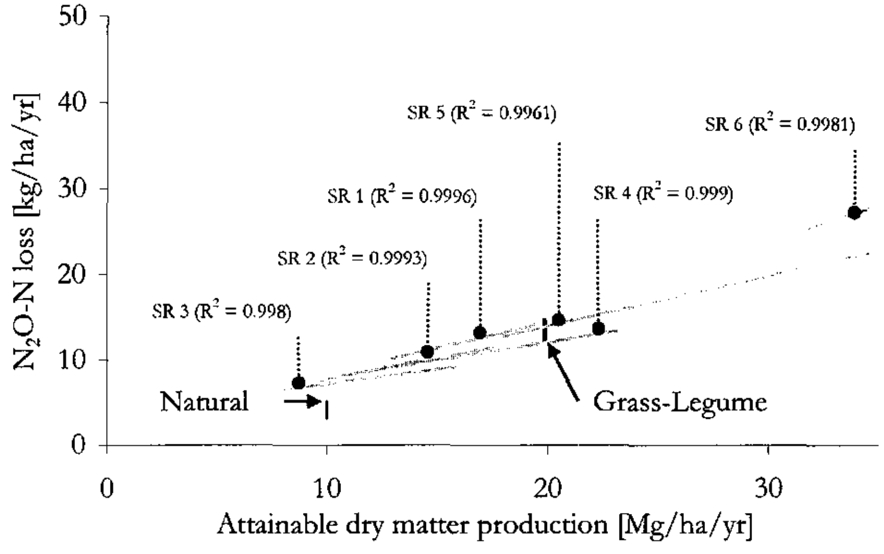


b

Figure 4.3 Simulated N_2O-N (a) and NO-N loss (b) against attainable dry matter production for Natural (solid line), Grass-Legume (heavy line) and Fertilized Improved (dashed line) pasture twenty-five years after forest clearing. Results are reported as trend lines. R-square values indicate the goodness of fit. Pasture management systems are identified with an arrow. In (a), Fertilized Improved options with different stocking rates (SR) are identified.



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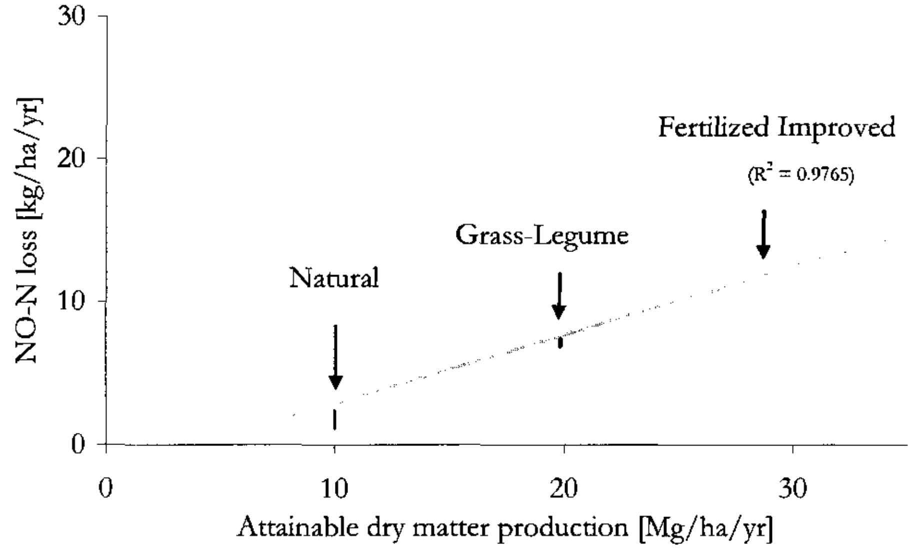

b

Since pasture-N content governs feed quality (protein, energy), each animal needs to eat less to satisfy its protein and energy demand. Thus, the fodder requirement per animal decreases with increasing stocking rate. Also, with increasing stocking rate relatively more biomass is removed by grazing per hectare, so less biomass is returned to the soil. The decreased total amount of biomass returned to the soil results in lower N_2O losses. In the 3-6 AU ha^{-1} range, on the other hand, the high stocking rates result in relatively large proportions of the pasture being unavailable for cattle consumption because of trampling and manure and urine deposition. Therefore, more biomass is needed to satisfy cattle requirements despite the increasing pasture quality. The increased total amount of biomass returned to the soil results in higher N_2O losses.

The act of grazing has been shown to elevate N-oxide emissions in temperate zones (Oenema *et al.*, 1997), whereas our results suggest the opposite. A possible explanation is that our modeling framework did not capture peak emissions from feces deposition because we assumed feces were evenly distributed across the pasture. In reality, animal excrements are preferentially deposited on local spots, resulting in potentially high concentrations of C and N. For future studies, we suggest that separate simulations be done for feces-covered and feces-free areas of the pasture (Bril *et al.*, 1994).

Table 4.3 DNDC-simulated and field-measured N_2O-N and NO-N losses ([kg ha^{-1} yr^{-1}]). Measured data are from Veldkamp *et al.* (1998). Simulated losses are for twenty-five years after forest clearing. In the field, pasture management systems were replicated four times. For the simulated Natural and Grass-Legume systems, n=13. For the simulated Fertilized Improved system, n=250.

	Natural	Grass-Legume	Fertilized Improved
N_2O-N			
Measured	3	5	23
Simulated	3-5	12-15	7-28
NO-N			
Measured	1	7	5
Simulated	1-2	7-8	3-16

Comparison with field measurements

The order of magnitude of simulated N_2O and NO losses is consistent with observations presented by Veldkamp *et al.* (1998) (Table 4.3). Although measurements indicate similar N_2O losses from Natural and Grass-Legume pasture systems, simulated losses were higher for Grass-Legume than for Natural options. This may be explained by the strong correlation between N-oxide losses and annual C input: attainable dry matter production for the Grass-Legume options was 20 Mg ha^{-1} yr^{-1}, whereas Natural pasture attainable yield was 10 Mg dry matter ha^{-1} yr^{-1} (Table 4.3). Since annual C input is primarily determined by dry matter production, the higher yield for the Grass-Legume options resulted in higher N-oxide losses.

The N_2O-N loss measured for the Fertilized Improved system (23 kg ha^{-1} yr^{-1}) is in the upper range of losses simulated for this pasture type, whereas the measured NO-N loss (5 kg ha^{-1} yr^{-1}) is in the lower range of simulated losses. The average NO:N_2O ratio (simulated) for this pasture type is 0.5 whereas the ratio of measured NO and N_2O flux is 0.2. At present, we have no explanation for this discrepancy.

In an earlier study, DNDC has been found to be more sensitive to C additions than to fertilizer-N applications (Li *et al.*, 1996). Also, Keller and Reiners (1994) found that measured emissions from old (> 25 yr) actively grazed pastures on Inceptisols in the NAZ did not simply correlate with availability of mineral soil-N, and suggested that soil oxidation status is a likely candidate for being an additional regulator. Our results suggest that C input to the soil plus the C:N ratio of the input (that is, the regulators of both soil N mineralization and N_2O production) may be major factors limiting N_2O flux in the studied tropical pasture soils. Variations in soil oxygen status, caused, e.g., by variations in soil physical characteristics, were not considered and may be a major cause of discrepancies between model results and measurements. To assess the relative importance of C inputs and soil oxygen status, summary models have to account for variations in the relevant soil properties.

Summary models

The summary models best capturing the overall interaction between pastures and N-oxide losses on FWD soils in the NAZ are:

Eq. 4.1 $$N_2O\text{-}N = 5.306*10^{-2} + 1.596*10^{-3} I_C$$

Eq. 4.2 $$NO\text{-}N = -1.705 + 4.711*10^{-4} Y$$

The squared Pearson product-moment correlation coefficient for Eq. 4.1 was 0.997, whereas the R-square coefficient for Eq. 4.2 was 0.972. Both relationships were significant ($p < 0.05$) by analysis of variance.

Sustainable options are not sustainable in terms of N-oxide emissions

Although the Fertilized Improved options are regarded as sustainable in terms of utilization of soil N and CO_2 emissions, they are not sustainable in terms of N-oxide emissions. Earlier field experiments in the same area of Costa Rica revealed that, due to both higher root production rates and longer root turnover times, the introduction of fertilized improved species increases the C input to the soil (Veldkamp, 1993). In addition, it has been suggested that fertilized improved species, with their higher production, may be a good competitor for available N (Veldkamp *et al.*, 1998), implying that less N is available for N-oxide formation. Our results suggest the opposite since N_2O losses were found to increase with C input. Due to increased C inputs, more SOC is decomposed in soils below the Fertilized Improved system than in soils below the Natural system. Increased SOC decomposition increases both N mineralization and soluble C. For the soil and climatic conditions used, the increased N mineralization and soluble C availability result in higher N_2O losses. This mechanism has yet to be confirmed for other soil and climatic conditions.

Towards regional analysis

A preliminary regional analysis of N-oxide fluxes from forest, pastures, and banana plantations in the NAZ in 1992 (Plant, 1998) suggested that the regional N_2O flux is governed by the banana plantations. The regional analysis employed one representative parameterization for pasture, thereby ignoring effects of both pasture age and different types of pasture management.

Most NAZ pastures that were established after deforestation are now over fifteen years old. Degradation is becoming evident, and pasture systems currently recommended as sustainable alternatives may be introduced within a few years (Ibrahim, 1994; Bouman *et al.*, in press/a). Our simulation results suggest that N_2O and NO losses from improved pastures are about 3-5 times higher than those from current natural pastures. When pasture management changes, it can no longer be regarded as homogeneous when performing a regional analysis. The derivation of summary models, as reported here, may provide an insight in the management factors controlling N-oxide emissions, and guide the selection of variables required for regional analysis.

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PART III

Chapter 5

GIS-based extrapolation of land use-related nitrous oxide flux in the Atlantic Zone of Costa Rica

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5 GIS-based extrapolation of land use-related nitrous oxide flux in the Atlantic Zone of Costa Rica

Abstract

I estimated the regional nitrous oxide (N_2O) flux from 281,347 ha of Costa Rican lowland, covered with primary and secondary forest, pastures, and banana plantations, by linking the DeNitrification-DeComposition (DNDC) model with a Geographic Information System (GIS). Generalized soil, texture, and land use maps were overlaid to yield unique combinations of N_2O flux control factors. Overlay patches were associated with the nearest of seven available meteorological stations. Monte Carlo-based sensitivity analysis was used to identify DNDC's key driving variables and required map attributes. Clay content, initial soil organic carbon (SOC), bulk density, and pH were selected as key driving variables. For 217 patch classes, DNDC simulations were carried out with climate data for seven different years. The estimated average regional flux was 6.8 kg N_2O-N ha^{-1} yr^{-1}. Possible applications of the GIS-DNDC interface presented include estimation of long-term regional flux dynamics from a changing land use mosaic, and prediction of regional fluxes resulting from alternative land use scenarios.

5.1 Introduction

The known sources and sinks of nitrous oxide (N_2O), a greenhouse gas and stratospheric ozone destructor, are imbalanced (Prather *et al.*, 1995) and atmospheric N_2O concentrations are increasing at a rate of 0.25 - 0.31% yr^{-1} (Prinn *et al.*, 1990). Tropical soils have been recognized as the largest known N_2O source. Soils of tropical forests alone may produce 20 - 41% of the total annual production of 14.7 Tg N_2O-N (1 Tg = 10^{12} g) (Matson and Vitousek, 1990).

Land use controls soil N_2O emissions (Keller and Reiners, 1994), and therefore land use changes resulting from human activity may significantly alter regional and global N_2O budgets (Luizão *et al.*, 1989; Keller *et al.*, 1993). In the future, land use planning may be used effectively, in principle, to mitigate N_2O emissions. Much of the land use change over recent decades has involved conversion of tropical forests to high-input agriculture and low-input pasture. Conversion to low-input pasture is especially common in South and Central America (Hecht, 1992), and causes N_2O fluxes to increase by a factor 5 - 8 initially (Keller *et al.*, 1993). About a decade after deforestation, however, fluxes decline below primary forest levels.

In high-input tropical agriculture, many crops receive N fertilizer in excess of plant demand (Keller and Matson, 1994). Current global estimates of N_2O flux from fertilized agricultural soils are based on studies in temperate zones (Eichner, 1991). However, the few studies on N_2O flux from tropical agriculture conducted so far (Garcia-Mendez *et al.*,

1991; Matson *et al.*, 1996; Veldkamp and Keller, 1997) suggest this source type may be severely underestimated.
To assess effects of land use changes on N_2O emissions, short-term flux measurements at plot or field scales must be aggregated over longer temporal cycles and larger spatial units. However, extrapolation is thwarted by the great spatial and temporal variability in small-scale N_2O fluxes (Folorunso and Rolston, 1984). Moreover, areal flux estimates often are based on few measurements because sampling logistics are complicated. Current N_2O budgets, therefore, may be highly inaccurate (Matson *et al.*, 1989).
Although several extrapolation methods exist, a lack of rules to guide extrapolation presently is a key conceptual problem (Schimel and Potter, 1995). The simplest approach to obtain an areal flux estimate is to sample an area randomly at a given time. Because of the extreme space-time variability of N_2O flux, a large number of samples may be required to achieve an acceptable level of error. Therefore, this method is of limited practical use.
To increase sampling efficiency, ecological variations may be used to stratify a study area. This "flux x area" approach employs ecological variations as the single dominant factor controlling N_2O flux (e.g., Matson and Vitousek, 1990). For all ecosystem groups, representative fluxes are calculated from a limited number of measurements. The sum of "flux x area" products yields the areal N_2O flux estimate. This approach is straightforward, yet potentially inaccurate: ecosystem groups still may be heterogeneous with respect to soil and climate. The method is useful, however, if no geographically explicit information on ecosystem distribution is available. For example, Keller and Matson (1994) used tabular agricultural census data on land use distribution to explore effects of forty years of land use change on areal N_2O flux in the Atlantic Zone of Costa Rica.
A more comprehensive extrapolation method employs a Geographic Information System (GIS) to overlay multiple factors controlling N_2O flux, and a process-based model to simulate fluxes for all different, unsampled factor combinations (e.g., Burke *et al.*, 1990; Schimel *et al.*, 1990; Potter *et al.*, 1996).
This paper presents a GIS-based assessment of regional N_2O flux from tropical forest, low-input pastures and high-input banana plantations in the Northern Limón Province, Costa Rica. The assessment employed the DeNitrification-DeComposition (DNDC) simulation model (Li *et al.*, 1992a, 1992b, 1994a, 1994b), interfaced with an extant GIS on soils, climate, and land use (Wielemaker and Vogel, 1993; Stoorvogel, 1995). Primary goals were *i)* to optimize the GIS-DNDC link by identifying key driving variables, and *ii)* to compare the GIS-based regional flux estimate with a more straightforward "flux x area" estimate.

5.2 Materials and methods

DNDC model

Simulation models have been developed to simulate soil processes regulating N_2O production and emission at the microsite scale (Focht, 1974; Leffelaar and Wessel, 1988), the field scale (Li *et al.*, 1992a, 1992b), and the ecosystem scale (Parton *et al.*, 1996; Potter *et al.*, 1996). A key issue in selecting a model for linkage with a GIS is the model's ability to simulate short-term flux dynamics (Schimel and Potter, 1995). From microsite studies it is well known that flux responses to short-term variations in soil wetting and drying are critical. Therefore, the model should feature short-term representations of microbial growth and electron transfer reactions. On the other hand, the model also should use inputs that are readily available from a standard GIS on soils.

DNDC (Li *et al.*, 1992a, 1994a, 1994b) is among the models that satisfy both requirements and thus can, in principle, be interfaced with a GIS. DNDC is an integrated one-dimensional model of field-level C and N dynamics in arable crop-soil systems, with a strong focus on denitrification and N-oxide emissions. A soil climate submodel calculates hourly soil water content, soil temperature profiles, and transpiration. Daily rates of soil respiration in three active pools, mineralization, nitrification, ammonification, ammonia volatilization, and ammonium adsorbtion are simulated by a decomposition submodel A denitrification submodel calculates hourly production and emission of NO, N_2O, and N_2. A crop/land use submodel calculates daily plant N uptake, litter and root recycling, and accounts for C and N additions through fertilization and manure amendment. DNDC features numerous internal and external parameters. The readily available external parameters, however, are known to adequately cover the major factors that influence regional variations in N_2O emissions (Li *et al.* 1992b).

GIS - map generalizations

The spatial distribution of DNDC's key driving variables was represented by three coverages: a land use map providing information on crop/vegetation type and management characteristics, a soil map providing data on soil physical and chemical characteristics, and a texture map providing data on soil hydraulic parameters. The maps were created using data from a 1:150,000 soil survey for the Northern Atlantic Zone of Costa Rica stored in a regional GIS (ARC/INFO, ESRI, Redlands, CA) (Wielemaker and Vogel, 1993). The GIS recently was extended with a 1992 land use layer and climate data from fourteen meteorological stations (Stoorvogel, 1995). For this study, an area covering 281,347 ha was selected from the GIS (Figure 1.1).

In the GIS attribute database, mapping units on the original soil coverage are described by one to five non-georeferenced terrain units. Terrain units are unique combinations of terrain properties, including a soil series. Initially, seventy-five different soil series were identified and described by 300 representative profiles (Wielemaker and Vogel, 1993); 123 representative profiles were analyzed for basic soil physical and chemical properties. Stoorvogel (1995) developed a new structure for this GIS attribute database that includes a rule base for generalizations at different hierarchical levels (i.e., mapping unit, pedon, and soil horizon).

Using this rule base, soil series were generalized to eight functional soil groups at the pedon level, each having a similar agricultural potential (Stoorvogel, 1995). At the mapping unit level, a generalization by dominant soil group (i.e., the functional soil group covering the largest fraction of the mapping unit) was carried out. A similar generalization was made to derive a soil texture map. A soil texture class (Wielemaker and Vogel, 1993) was linked to the soil series at the pedon level. After grouping the soil series by texture class, mapping units were generalized by dominant texture class. The original classification of the 1992 land use coverage features "Primary Forest", "Secondary Forest", and "Banana Plantation" classes (Stoorvogel, 1995). The five different pasture classes were generalized to one single "Pasture" class. All other land use types were reclassified as "Other Use".

Sensitivity analysis

To set up attribute tables for the generalized maps, knowledge about the sensitivity of DNDC's driving variables is required. Ideally, all key driving variables, i.e., model inputs modulating major variations in simulated N_2O flux, should match entries in the GIS attribute database. In practice, however, only a few key driving variables may be readily available. If additional measurements and knowledge about functional relationships are available, missing key driving variables can, in principle, be calculated using pedo-transfer functions (Bouma, 1989).

Key driving variables were identified by Monte Carlo-based sensitivity analysis. Sensitivity analyses were carried out for all selected land use types. Version 1.1 of the UNCSAM software package (Janssen *et al.*, 1992) was used for samplings and analyses. UNCSAM draws samples from the statistical distributions of input variables using the Latin Hypercube sampling technique. Resulting input-output sets are summarized by ordinary and rank regression analysis. I used uniform distribution functions, parameterized with a minimum and maximum value, for all eleven parameters (Table 5.2) and ignored correlations between inputs. For all inputs, 100 samplings and corresponding one-year model runs were carried out. Based on the decision tree given by Janssen *et al.* (1992), the standardized regression coefficient was selected as an appropriate sensitivity measure.

GIS - map attributes

The GIS attribute database does not provide information on crop and management characteristics. Therefore, typical land use scenarios were created for selected land use types.

To simulate forest emissions, DNDC was extended with a routine that accounts for water and N uptake by a forest cover, and monthly turnover of fine roots, litter and wood (i.e., stems, branches, and coarse roots). All turnover calculations are based on daily N uptake, which, in DNDC, is the key process linking vegetation growth with soil status (Li *et al.*, 1994b). The routine calculates monthly amounts of C returned to the soil from the daily N uptake rate using partitioning coefficients, C:N ratios, and turnover rates (Table 5.1). The initial amount of N in the vegetation is calculated from the forest age and the average amount of C in the full-grown forest (Table 5.1) (Armson, 1979). The forest routine was tested for a primary and a secondary Costa Rican forest site (Keller and Reiners, 1994). For primary forest, a typical age of 150 yr was assumed. The typical age of secondary forest was set to 25 yr. Results (not shown) indicate that average simulated fluxes are within the range of measured fluxes. However, the observed seasonal N_2O flux patterns (Keller and Reiners, 1994) were poorly captured.

Fluxes of N_2O from pasture were simulated using parameters for traditional low-productive pasture. More than 50% of the study area's tropical forest acreage cleared during the last forty years has been put under this type of pasture (Veldkamp, 1993). No distinction was made between grazed and ungrazed pastures. Because pastures are rarely fertilized in the study area (Veldkamp *et al.*, 1998), simulations were performed without N fertilizer input.

Table 5.1 Parameter settings for primary and secondary forest (Veldkamp, 1993).

Description	Unit	Value
C:N ratio leaves	[-]	66
C:N ratio wood	[-]	200
C:N ratio fine roots	[-]	45
Turnover rate litter	[1/month]	0.047
Turnover rate wood	[1/month]	0.004
Turnover rate fine roots	[1/month]	0.139
Fraction leaves	[-]	0.03
Fraction wood	[-]	0.96
Fraction fine roots	[-]	0.01
Water requirement (carbon basis)	[-]	526
C in full-grown forest	[Mg ha^{-1}]	220

Table 5.2 Sensitivity analysis results for primary forest, secondary forest, pasture, and banana (below plants and between plants). R-square coefficients reflect the goodness of fit of the linear regression equation predicting N_2O flux from the independent variables (n=100).

Para-meter	Description	Unit	Min	Max	Rank of standardized regression coefficient				
					Primary forest	Secondary forest	Pasture	Banana (below plants)	Banana (between plants)
f_{clay}	Clay fraction	[%]	5	95	1	1	2	1	1
φ	Bulk density	[Mg m^{-3}]	0.2	1.2	2	2	1	2	2
f_{psoc}	Fraction passive SOC	[-]	0.2	0.9	3	3	3	5	3
f_{isoc}	Initial SOC	[%]	0	10	4	4	4	10	4
W_i	Initial WFPS	[%]	30	90	5	5	5	3	7
f_{NH4}	Initial NH_4^+	[ppm]	0	15	6	6	6	8	5
a	pH	[-]	3.0	8.0	7	7	7	4	6
f_{NO3}	Initial NO_3^-	[ppm]	0	15	8	8	9	7	9
W_{fc}	WFPS at field capacity	[%]	50	90	9	9	8	6	8
K_{sat}	Saturated conductivity	[cm min^{-1}]	0.008	1.056	10	10	10	11	10
W_{wp}	WFPS at wilting point	[%]	10	40	11	11	11	9	11
	R-square				0.52	0.49	0.40	0.49	0.57

To simulate N_2O fluxes from banana plantations, I applied the modeling scheme I proposed earlier (Plant *et al.*, this thesis). In short, the scheme consists of separate DNDC runs for below-plant conditions, where 360 kg N ha^{-1} yr^{-1} are added in thirteen applications and decomposing litter on the soil surface is absent, and between-plant conditions, where no fertilizer is applied and plant residue is left to decompose on the soil surface. Simulated fluxes were weighted by the fraction of area influenced by the fertilizer application.

Functional soil groups are proxies for key driving soil physical and chemical variables. Likewise, texture classes are proxies for soil hydraulic parameters. Thus, lookup tables featuring parameter records for entries on the maps are required. Based on sensitivity analysis results, I selected key driving variables for the soil map attribute table. Means were calculated using the "soil representative analyses" table available from the GIS attribute database (Wielemaker and Vogel, 1993). No data were available for peat soils.

Variables not selected as key driving variables were assigned a representative value, derived from published sources, per land use type. For forest and pasture soils, parameters given by Reiners *et al.* (1994) were used. Soil characteristics given by Veldkamp and Keller (1997) were used for banana. If soil parameters were unavailable from published sources, I used DNDC defaults.

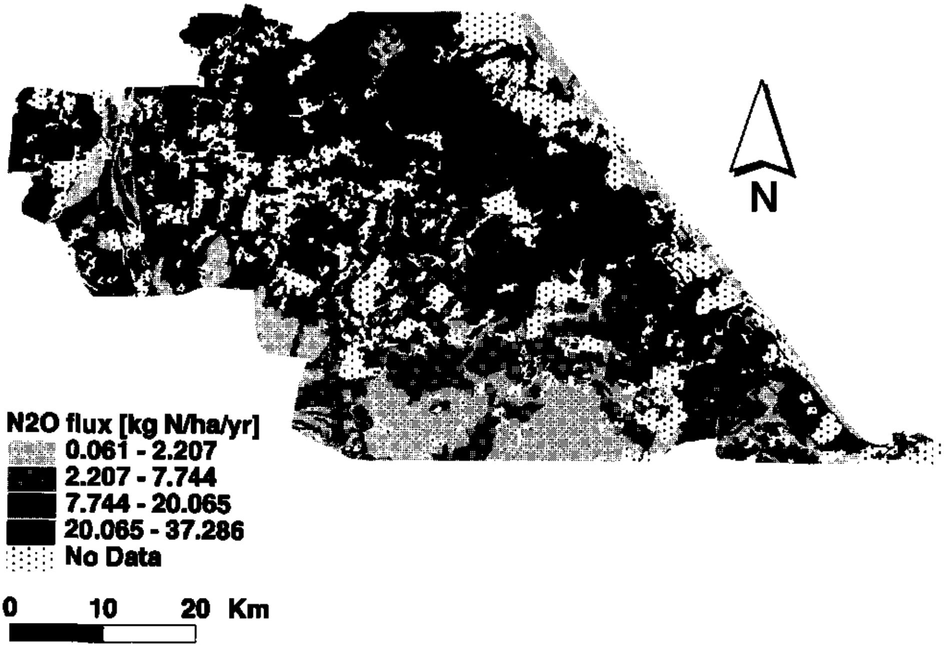
The generalized soil, texture, and land use maps were overlaid in ARC/INFO. Using polygon centroids and coordinates of seven selected meteorological stations, seven climate zones were created by assigning a nearest station identifier to all 3180 patches on the overlay. A rainfall-N concentration of 0.1 mg L^{-1}, which corresponds to 4 kg N ha^{-1} yr^{-1} with an annual rainfall of 4000 mm, was assumed throughout the study area (M. Keller, personal communication).

In theory, 8 * 15 * 5 * 7 = 4200 patch classes exist, but actually 304 occurred. After masking patch classes with land use class "other use" and/or soil code "peat", 217 classes remained for which one-year DNDC simulations were performed. To account for effects of inter-annual climate variability (Plant *et al.*, this thesis), all DNDC simulations were carried out with seven different annual climate records (1982 - 1988). Regional fluxes were calculated using the following equation:

Eq. 5.1
$$U = \sum_{i=1}^{N} g\,(s_i, l_i, c_i)\,a_i$$

where g is the function describing the relationship between soil parameters (s), land use parameters (l), climate parameters (c), and N_2O flux (i.e., DNDC), a_i is the fraction of area occupied by the *i*th combination of soil, land use, and climate parameters (i.e., patch class), and N is the number of patch classes.

Figure 5.1 Average regional distribution of N_2O flux (1982 - 1988).



5.3 Results

Sensitivity analysis

Based on the rankings given in Table 5.2, clay content, bulk density, and initial SOC were selected as key driving variables. In addition, pH was selected because this variable ranked as the fourth sensitivity source for banana plant base conditions. Although initial WFPS ranked higher than pH for this land use type, initial WFPS was not selected as a key variable because it is not a static soil attribute. Information on passive SOC was available neither from the "soil representative analyses" table, nor from published sources. Therefore, 70% passive SOC was assumed for all land use types (Veldkamp, 1993). DNDC defaults were used for texture class attributes because they appeared to be not very sensitive.

Regional distribution of nitrous oxide flux

The regional distribution of simulated fluxes is shown in Figure 5.1b. Fluxes ranged from 0.1 to 37.3 kg N_2O-N ha^{-1} yr^{-1}. The patterns in Figure 5.1b are, as expected, most obviously related to the land use mosaic. Towards the east side of the study area, simulated fluxes are somewhat higher. This possibly can be attributed to the abundance of moderately well and poorly drained soils in this area. No relationship between regional flux distribution and climate zones was observed.

Using Eq. 5.1, an average regional flux of 6.8 kg N_2O-N ha^{-1} yr^{-1} was calculated. Simulated regional fluxes ranged from 6.2 kg N_2O-N ha^{-1} yr^{-1} (1982 climate data) to 7.3 kg N_2O-N ha^{-1} yr^{-1} (1984 climate data) (standard deviation 0.4). Using the extent of the study area (281,347 ha), the total annual loss was estimated to be 1.8 - 2.1 Gg N_2O-N yr^{-1} (1 Gg = 10^9 g).

Table 5.3 "Flux x area" and GIS-based areal flux estimate (value in parenthesis is standard deviation).

Land use type	Area	# of field sites	# of delineated areas in GIS	Field average	Simulated average
	[%]	-	-	[kg N_2O-N ha^{-1} yr^{-1}]	[kg N_2O-N ha^{-1} yr^{-1}]
Primary forest	20	4	264	6.4 (2.4)†‡	4.7 (4.1)
Secondary forest	14	3	719	3.7 (1.1)†	4.9 (3.6)
Pasture	36	6	1021	3.7 (3.6)‡	4.4 (3.6)
Banana plantation	14	2	283	9.5 (4.8)§	22.6 (8.7)
Other use	16	0	894	-	-
Regional flux				4.5	6.8

† Keller and Reiners (1994); ‡ Keller *et al.* (1993); § Veldkamp *et al.* (1998).

5.4 Discussion

Estimating areal fluxes

To illustrate the value of GIS-based areal flux estimation, I compared results with a "flux x area" estimate. Average measured fluxes for selected land use types were calculated using published data on fifteen Costa Rican sites (Table 5.3). On all sites, monthly surveys of flux over at least one year were conducted. Forest and pasture sites (Keller *et al.*, 1993; Keller and Reiners, 1994) were on similar Inceptisols. Banana sites (Veldkamp and Keller, 1997) were both on Inceptisols and Andisols. To calculate a pasture average, only flux measurements on old active pastures were used. Fractions of area covered by each land use type were derived from the 1992 land use coverage. Summation of "flux x area" products yielded a regional flux of 4.5 kg N_2O-N ha^{-1} yr^{-1}, whereas the GIS-based estimate was 6.8 kg N_2O-N ha^{-1} yr^{-1}. Thus, the more explicit description of soil and climate variability within land use types modulated conditions favoring extremely high fluxes. Although patches featuring these extreme conditions may be small, they may strongly affect the regional flux estimate.

The difference between averaged representative flux measurements and simulated average fluxes is most evident for banana. The simulated average flux for banana (Table 5.3) exceeds the two-sample average by a factor 2.4. This large difference may be caused by the contribution of fluxes from banana plantations on soils with both high bulk density and high SOC.

The great advantage of simulation analysis is that it allows flux estimates for a very large number of control factor combinations. Moreover, effects of inter-annual climate variations can be incorporated. The latter would hardly be possible in the field.
The GIS-DNDC interface presented can be used to estimate past regional fluxes, and long-term regional flux dynamics, if digital land use maps are available for multiple decades. For Costa Rica, aerial photo coverages on a national scale exist for 1952, 1960 and 1984. These photographs provide a sound basis for mapping past land use mosaics.
Another useful application may be the analysis of future land use scenarios. Trace gas emissions may become increasingly important in regional land use planning in the future, especially when high-input agriculture is becoming more common. Future land use scenarios may feature crops like manioc, maize, ornamentals, palmito, and papaya. At present, most common tropical crops are implemented in DNDC. However, model validation for each individual land use type may not always be possible because field measurements are lacking.

Improving the extrapolation
The extrapolation presented can be improved in several ways. First, fluxes from recently cleared pastures were omitted. Young pastures are known to contribute significantly to the regional N_2O flux. Keller and Matson (1994) did include young pasture as a distinct land use class, and estimated an areal flux for 1993 of 10.0 kg N_2O-N ha^{-1} yr^{-1}. However, no spatial information on past land use is available as yet.
A second improvement would concern the forest routine. Although average simulated and measured forest fluxes (4.8 and 5.1 kg N_2O-N ha^{-1} yr^{-1}, respectively, Table 5.3) are within the same range, a more explicit representation of forest biogeochemistry may better account for functional differences between primary and secondary forest. In the DNDC simulations presented (Figure 5.1b), primary forest fluxes systematically were underestimated, while fluxes from secondary forest systematically were overestimated.
Third, the base map generalizations introduced aggregation errors that may propagate to higher scale levels. Because soil properties were lumped by soil and texture class, within-class variations were averaged out. A more sophisticated approach would employ statistical descriptions of the distributions of key driving variables and correlations within each soil and texture class. Monte Carlo simulation could be used to calculate statistical expectations (i.e., means) of N_2O flux per class.

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Chapter 6

Regional analysis of soil-atmosphere nitrous oxide emissions in the Northern Atlantic Zone of Costa Rica

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6 Regional analysis of soil-atmosphere nitrous oxide emissions in the Northern Atlantic Zone of Costa Rica

Abstract

Regional analysis of greenhouse gas emissions is becoming increasingly important in answering questions related to climate change. Regional analysis typically employs a Geographic Information System and a mechanistic simulation model driven by deterministic inputs. For a region in Costa Rica (2817 km^2), an analysis of nitrous oxide emissions was performed using both deterministic and stochastic descriptions of key driving variables. The stochastic representation accounted for soil and land use variability across non-georeferenced fields within 2472 georeferenced land units in eleven relevant classes. Using Monte Carlo integration, frequency distributions of field-scale fluxes simulated with a process-based model were obtained per land use class. Regional fluxes were calculated by summing expected values weighted by area. Stochastic incorporation of both soil and land use variability resulted in areal fluxes that were 14-22% lower than those estimated with deterministic model runs. This suggests non-linearity in the relationship between key model parameters and nitrous oxide fluxes.

In addition, spatial flux patterns for land use in 1992 and two alternative land use scenarios were evaluated using stochastic inputs. With contemporary banana plantations and unfertilized natural grasses the regional nitrous oxide-N flux (standard deviation in parenthesis) was 1.0 (0.4) Gg yr^{-1}. Replacing natural grasses by sustainable grass-legume mixtures on relevant soil types increased the regional flux to 1.6 (0.5) Gg yr^{-1}. When all natural grasses were replaced by fertilized improved species, the regional flux increased to 1.9 (1.2) Gg yr^{-1}. Land use activities that are sustainable in terms of economic profit and soil fertility may be unsustainable when including N_2O emission as an extra indicator.

Due to formidable data requirements, the approach presented may not be widely applicable. However, regional analysis based on mechanistic modeling may provide valuable insights in the factors that affect emissions at scales relevant to policy making.

6.1 Introduction

Regional analysis of natural and agricultural ecosystem properties rapidly develops due to the need to assess ecosystem responses to climate change at regional scales (Paustian *et al.*, 1997). In the past, many plot-scale studies on such climate-related ecosystem properties as soil carbon (C) stocks (e.g., Veldkamp, 1993), denitrification rates (e.g., Parsons *et al.*, 1993), and soil-atmosphere trace gas exchange (e.g., Keller *et al.*, 1993) have been conducted. Correspondingly, global estimates of these properties have been made based on data and process knowledge from plot studies (Bouwman *et al.*, 1993; Raich and Potter, 1995; Nevison *et al.*, 1996; Potter *et al.*, 1996). Although there are examples of landscape-scale (Groffman and Tiedje, 1989a, 1989b; Reiners *et al.*, 1998) and regional-scale (Burke *et al.*, 1990; Groffman et al., 1992; Paustian *et al.*, 1997; Plant,

1998) studies, a knowledge gap exists at the regional scale. A lack of applicable methods to handle inconsistent data and model scales is the primary cause of this gap, and presents distinct and complex conceptual and practical challenges (Groffman, 1991).
A full-fledged regional analysis typically involves two steps. First, spatial extrapolation is used to estimate unknown values from a known set of conditions (Turner *et al.*, 1989; Matson *et al.*, 1989; Schimel and Potter, 1995). The known set of conditions consists of paired observations of the ecosystem property and its key driving variables. Key driving variables are salient environmental variables that must be included in databases for extrapolative modeling (Schimel *et al.*, 1991). In recent years, agreement has grown on a small set of land use, climate, soil, and terrain parameters. The standard, or "geographic", approach (Schimel *et al.*, 1991) to spatial extrapolation in land evaluation studies is to delineate a subdivision of land units for which representative key driving variables can be obtained. Land units are commonly referred to as "functional types" because they are defined by the factors controlling ecosystem functions (Breeuwsma *et al.*, 1986; Bouwman *et al.*, in press; Estes and Loveland, in press). For any land unit class, the key driving variables are "lumped" and supplied to a simulation model. Second, alternative scenarios are evaluated against some base scenario. A base scenario may feature contemporary land use, soils, and climate, whereas alternative scenarios may reflect sustainable forms of land use (Bouman *et al.*, in press/b). Alternative land use scenarios are, for example, defined by the spatial layout of inputs (representing land use conversions), by their numerical values (representing land use modifications), or both.

The tools to perform a regional analysis are a Geographic Information System (GIS) and a simulation model. A GIS is used to *i)* determine the spatial overlay of key factors, *ii)* extract unique land units and their properties, and *iii)* visualize model results. The application of simulation models in a regional analysis calls for a careful consideration of the degree to which the model input is commensurate with the model formulation. Models differ by their "grain" and "extent". Grain is the spatiotemporal scale for which a model predicts, and extent is the overall area encompassed by the modeling study (Wiens, 1989; Turner *et al.*, 1989). For example, macro-scale models (e.g., Bouwman *et al.*, 1993; Nevison *et al.*, 1996) operate at regional scales, and aim at the estimation of global patterns. Here, the grain and extent of investigation are the geographic region and the globe, respectively. In global modeling studies, regions are often 1° x 1° grid boxes. Macro-scale models cannot be used to study spatial patterns *within* a geographic region. Ecosystem and field-level models, on the other hand, (e.g., Parton *et al.*, 1988; Li *et al.*, 1992a; Potter *et al.*, 1996) operate at sub-regional scales. The model grain and extent are the ecosystem or field and the geographic region, respectively.

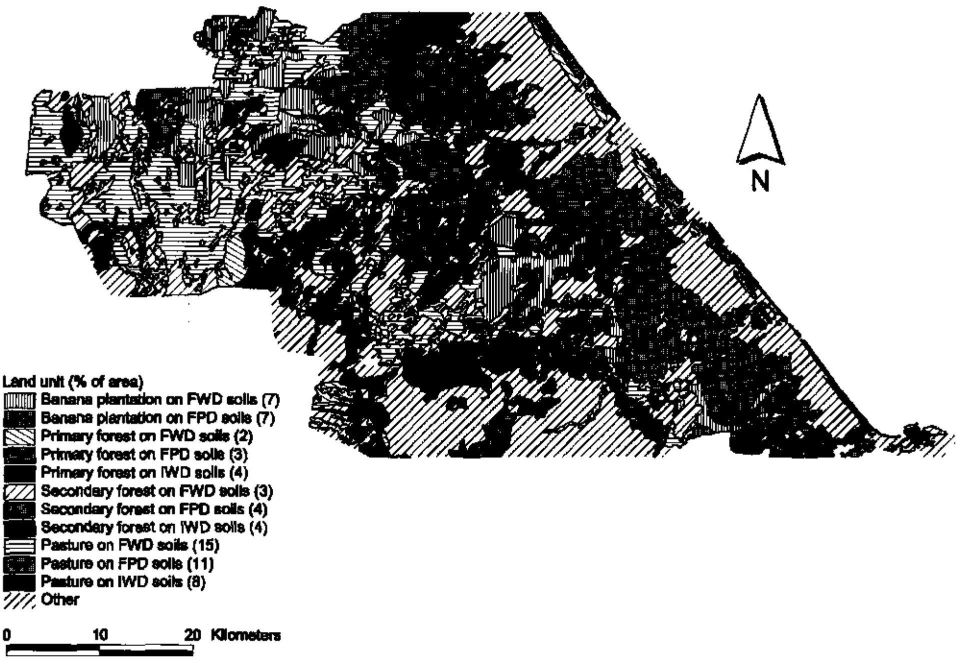
Areal flux estimates and spatial patterns based on a standard extrapolation are always infested by error and uncertainty from a variety of sources, e.g., random errors in field sampling, transport and transfer of gas samples, errors in the GIS data, and aggregation errors. Aggregation errors are modulated by spatial heterogeneity that inherently remains when subdividing land units (Rastetter *et al.*, 1992). King *et al.* (1989) minimized aggregation errors in modeled regional carbon dioxide (CO_2) exchange by inputting a multivariate set of frequency distributions rather than lumped parameters related to a spatially explicit subdivision of land units. King and co-workers employed Monte Carlo techniques to integrate solutions of the simulation model across the geographic region of interest. This stochastic method, to which I will refer as "Spatial Extrapolation By

Expected Value" (SEBEV), is analogous to error and uncertainty analysis in (spatial) modeling (Gardner *et al.*, 1983; Janssen *et al.*, 1992; Heuvelink, 1993; Kim, 1995). However, the focus of the SEBEV method is on the *expected value* (i.e., the mean) and not, as in error and uncertainty analysis, on higher-order moments of the simulated frequency distribution. The SEBEV method is important in calculating fluxes with a non-linear model where the spatial overlay of key driving factors is unknown (Schimel and Potter, 1995). Since output consist of a single frequency distribution of the ecosystem property across a geographic region, the method is not suitable for spatial pattern analysis.
The aim of this study was to stochastically incorporate spatial heterogeneity of soils and land use within delineated land units when analyzing regional nitrous oxide (N_2O) fluxes in the humid tropical lowlands of Costa Rica. I used the SEBEV method, originally designed for regional predictions, to estimate land unit-scale areal fluxes and compared these with deterministically estimated areal fluxes. In addition, I studied geographic patterns of N_2O flux under contemporary land use and two alternative sustainable land use scenarios, using spatial extrapolation by expected value.

6.2 The region

The study area is the Northern Atlantic Zone (NAZ) of Costa Rica (Figure 1.1). The Zone covers 2817 km^2 of humid tropical lowland, of which 81% is suitable for agriculture. Elevation ranges from 0 to 400 m above sea level. As of the second half of the 20th century, substantial deforestation has taken place in the NAZ. The large-scale conversion of primary forest to cattle pasture has increased emissions of greenhouse gases (Keller *et al.*, 1993; Keller and Reiners, 1994), and has decreased soil C stocks (Veldkamp, 1993). Since cattle ranching in the NAZ is extensive, pasture degradation has become a serious problem in the area (Kaimowitz, 1996). In 1992, cattle keeping (34%) and banana plantations (14%) dominated agricultural land use. Primary and secondary forests covered about 36% of the NAZ. Crops played a minor role in the 1992 land use pattern (Bouman *et al.*, in press/b).
The climate is humid tropical: mean daily temperature is 26 °C and mean annual rainfall is 3000 – 6000 mm, with mean monthly rates between 300 and 700 mm. There is a relatively dry period (100 - 300 mm per month) during February, March, and April. Precipitation always exceeds evapotranspiration. The average relative humidity is 85-90%
Wielemaker and Vogel (1993) distinguished seventy-five different soil series in the region. These have been regrouped to four major categories (Jansen *et al.*, 1995; Stoorvogel *et al.*, 1995): *i)* young, alluvial, well-drained volcanic soils with high fertility (Inceptisols and Andisols according to USDA Taxonomy), *ii)* old, well-drained soils developed in fluvio-laharic sediments with low soil fertility (Oxisols and Inceptisols according to USDA Taxonomy), and *iii)* young, poorly drained, volcanic soils with high soil fertility (Entisols and Inceptisols according to USDA Taxonomy). The fourth category encompasses soils unsuitable for agriculture because of excessive relief (19% of area).

Figure 6.1 Land units.



6.3 Methods

Simulation model

I used an adapted implementation of DeNitrification-DeComposition (DNDC) version 63, an integrated one-dimensional model of field-level C and nitrogen (N) dynamics in soil-vegetation systems with a strong focus on (de)nitrification and N-oxide emissions (Li *et al.*, 1992a, 1992b, 1994b; Plant *et al.*, this thesis; Plant and Keller, this thesis).

Land units

The original digital soil map for the NAZ was derived from a 1:150,000 soil survey (Wielemaker and Vogel, 1993). The soil map's attribute database has been extended with generalization rules that apply to different hierarchical levels (Stoorvogel, 1995). Using these rules, I generalized the original soil series to four functional soil groups at the pedon level (see also section 6.2 above). The distinguishing soil function in this context is agricultural potential, and the four groups are "Fertile Well Drained" (FWD), "Fertile Poorly Drained" (FPD), "Infertile Well Drained" (IWD), and "Not Suitable for Agriculture" (NSA).

The original land use map for 1992 was based on aerial photograph interpretation and fieldwork, and has twenty-seven legend entries defined by land cover and field patterns (Belder, 1994; Stoorvogel, 1995). The original classes were generalized to five land use classes: "Pasture", "Banana Plantation", "Primary Forest", "Secondary Forest", and "Other Use".

The two generalized data layers were overlaid in ARC/INFO (ESRI, Redlands, CA). The 2472 delineated land units on the resulting coverage (Figure 6.1) comprised twenty classes. Eleven classes were relevant for the regional analysis, and the remaining nine classes, defined by any combination of "Other Use" and NSA soils, were masked. Approximately 50,000 ha of the soils not suitable for agriculture are below abandoned pastures and forest. Although potential N_2O sources, I had to exclude these land units from the analysis because for these soils *i)* the expert systems used (see below) cannot quantify abandoned pastures, and *ii)* field measurements are unavailable for forest. Practically all banana plantations in the selected part of the Northern Atlantic Zone are located on FWD (19,859 ha) and FPD (18,652 ha) soils. Therefore, N_2O fluxes from IWD soils below banana plantations (337 ha) were not simulated.

Figure 6.2 Error resulting from "lumping" model arguments when the functional relationship is non-linear. $\bar{g}$ is the true mean of two aggregated arguments ω_1 and ω_2. $\hat{g}$ is a biased estimate of the true mean (after Rastetter *et al.*, 1992).

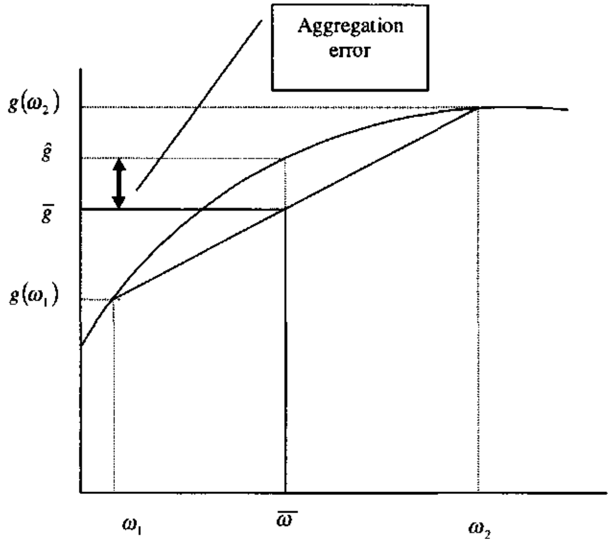
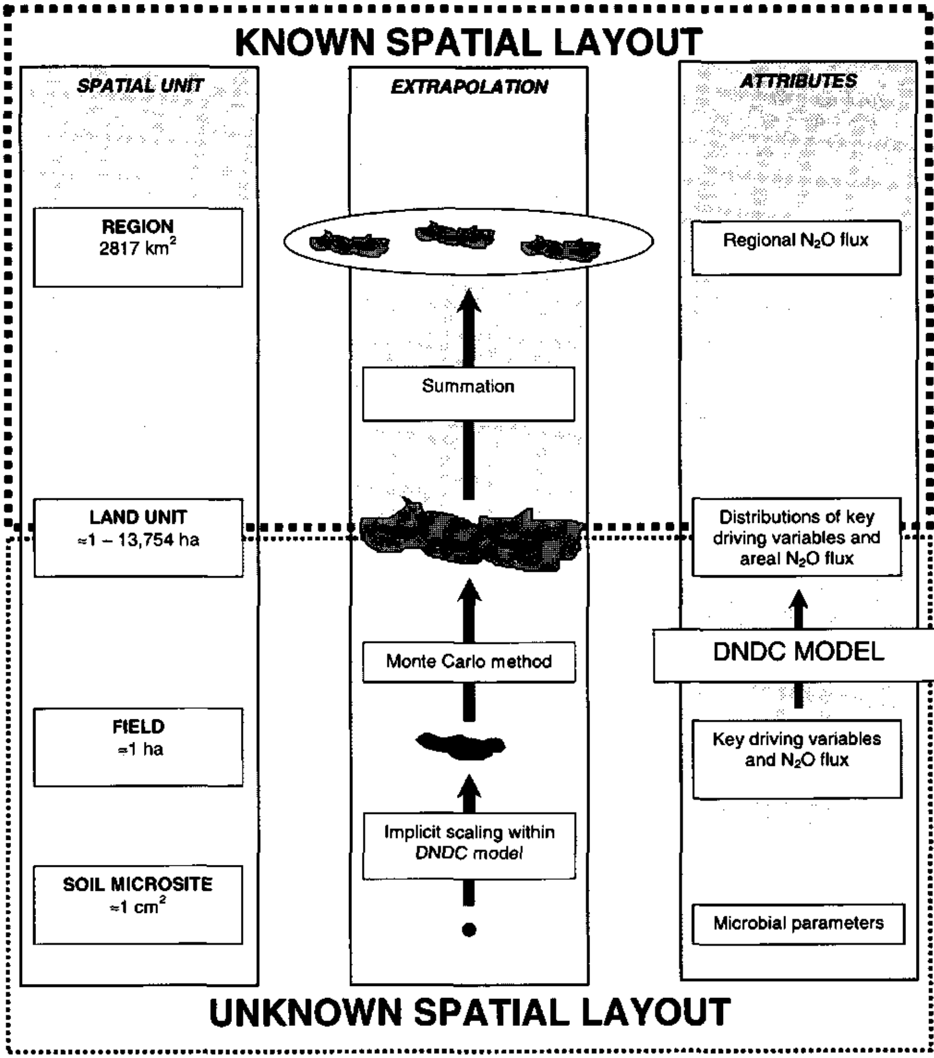


Figure 6.3 Conceptual framework for spatial extrapolation.



Extrapolation

The rationale behind the SEBEV method (King *et al.*, 1989) is that the expected value of a non-linear relationship is not equal to the outcome of the relationship when evaluated at the means of the arguments. This difference is commonly referred to as aggregation error (Figure 6.2).

The *areal* N_2O flux (Figure 6.3) from any land unit class i can (while suppressing time notation) be written as:

Eq. 6.1 $$\overline{u}_i = g(\overline{\omega}_i)$$

where g is the DNDC model, and $\overline{\omega}_i$ is the set of DNDC's lumped key driving variables relevant to land unit i. Per land unit class, one model run is required to estimate the areal N_2O flux, hence the run is deterministic. Following the SEBEV method, the N_2O emission from any field with unknown location within land unit class i (Figure 6.3) can be written as a stochastic process:

Eq. 6.2 $$\underline{u}_i = g(\underline{\omega}_i)$$

where $\underline{\omega}_i$ is the set of multivariate frequency distributions of DNDC's key driving variables for land unit class i, and $\underline{u}_i$ is the frequency distribution of model outputs. The expected value of the process g is an unbiased estimate of the areal N_2O flux for land unit i (Figure 6.3):

Eq. 6.3 $$\mu(\underline{u}_i) = \int_{\infty}^{\infty} g(\omega_i) f(\omega_i) d\omega_i$$

where f is the joint Probability Density Function (PDF) of the $\underline{\omega}_i$ (Kim, 1995). Since the spatial layout of land units is known, the *regional* N_2O flux (Figure 6.3) can be written as:

Eq. 6.4 $$U = \sum_{i=1}^{n} \mu(\underline{u}_i) a_i$$

where a_i is the area ([ha]) of the region occupied by the ith land unit class, and n is the number of land unit classes. To solve Eq. 6.3, I used the Monte Carlo method (Hammersley and Handscomb, 1979). This well-know method consists of evaluating $g(\omega_i)$ N times, where ω_{ij} is obtained through consequent sampling of f:

Eq. 6.5 $$\hat{\mu}(\underline{u}_i) = \frac{1}{N} \sum_{j=1}^{N} g(\omega_{ij})$$

If N is sufficiently large, $\hat{\mu}(\underline{u}_i)$ (Eq. 6.5) approximates $\mu(\underline{u}_i)$ (Eq. 6.3). As of here, I will refer to a sample from a joint PDF as a realization.

Table 6.1 Statistical properties of key parameters (top horizon) per soil group. † f_{clay} is the mass fraction of soil particles < 2 μm in oven-dry soil; φ is soil bulk density; f_{isoc} is initial soil-C content as mass fraction in oven-dry soil; a is soil pH (H_2O).

Parameter†	Unit	Distribution	Fertile Well Drained					Fertile Poorly Drained					Infertile Well Drained				
			Mean	Max	Min	Stdev	#	Mean	Max	Min	Stdev	#	Mean	Max	Min	Stdev	#
f_{clay}	[%]	Lognormal	16	52	2	10	87	17	51	5	11	33	34	70	4	17	41
φ	[Mg m^{-3}]	Lognormal	0.78	1.27	0.54	0.21	25	0.87	1.46	0.56	0.24	11	0.84	1.09	0.54	0.20	5
f_{isoc}	[%]	Lognormal	5	11	1	2	98	6	23	0	4	42	4	11	0	2	45
a	[-]	Normal	5.8	6.8	4.2	0.5	99	5.9	7.1	4.8	0.5	43	5.2	6.5	4.0	0.6	47

Table 6.2 Ranges of PASTOR and LUCTOR-generated key parameters for five land use activities. See Table 4.2 for parameter descriptions.

Parameter	Unit	All soils	Fertile Well Drained				Fertile Poorly Drained			Infertile Well Drained	
		Natural	Grass-Legume	Fertilized Improved	Actual banana	Alternative banana	Fertilized Improved	Actual banana	Alternative banana	Grass-Legume	Fertilized Improved
I_C	[Mg ha^{-1} yr^{-1}]	0.4-1.6	7.5-8.9	3.6-17.1	6.3	1.5-7.3	1.2-10.4	5.1	1.2-5.9	4.8-5.6	1.3-10.9
R_{res}	[-]	15	23-25	22-34	31	27-30	23-30	31	27-30	23-25	21-29
I_N	[kg ha^{-1} yr^{-1}]	14-55	13-51	13-234	3951	1389-8386	13-296	1931	998-6191	13-42	13-268
R_r	[-]	26	26	23 – 36	114	98-110	26-39	114	98-110	26	24-36
R_s	[-]	26	26	23 – 36	28	24-27	26-39	28	24-27	26	23-36
O_c	[kg ha^{-1} yr^{-1}]	45 – 180	-	-	-	-	-	-	-	-	-

Table 6.3 Pearson product-moment correlations of key soil parameters (top horizon) per soil group (see Table 6.1 for parameter descriptions).

Paramete	Fertile Well Drained			Fertile Poorly Drained			Infertile Well Drained		
	f_{clay}	φ	f_{isoc}	f_{clay}	φ	f_{isoc}	f_{clay}	φ	f_{isoc}
f_{clay}	1			1			1		
φ	-0.22	1		0.28	1		-0.01	1	
f_{isoc}	-0.08	-0.25	1	0.32	-0.11	1	-0.14	-0.93	1
a	-0.35	0.14	-0.31	0.11	0.15	0.17	-0.47	0.20	-0.15

To minimize complexity and computing time, I used frequency distributions for a selection of DNDC's external soil (Table 6.1) and management (Table 6.2) parameters (Plant, 1998; Plant and Bouman, in press). All other required DNDC inputs were assigned a representative value, derived from literature and expert knowledge, per land use type and soil group. All internal model parameters were constant throughout the region (Li *et al.*, 1992b).

Frequency distributions for soil parameters. - The GIS attribute database stores 220 georeferenced representative soil profiles that were described and analyzed for basic soil chemical and physical properties (Wielemaker and Vogel, 1993; Nieuwenhuyse, 1996). The profiles were classified by overlaying the profiles point coverage and the soil polygon coverage. Statistical properties of clay content, bulk density, initial soil C, and pH (Table 6.1 and Table 6.3, Plant, 1998) were derived for FWD, FPD, and IWD soils with the statistical software package SPSS 7.5 for Windows. Fifty realizations were obtained from the joint PDF of these variables with the MCSAMP module of the UNCSAM software package (Janssen *et al.*, 1992).

Frequency distributions for land use parameters. - Realizations of the joint PDF for key land use variables (Plant and Bouman, in press) were generated using expert systems for region-specific cattle pastures and banana plantations. The two expert systems, or technical coefficient generators, were developed within the framework of a research program on sustainable agriculture (Stoorvogel *et al.*, 1995; Bouman *et al.*, in press/b). The technical coefficient generators integrate system-analytical and expert knowledge to quantify land use activities in terms of technical coefficients. Technical coefficients are field-scale system characteristics such as materials (e.g., fertilizer, and pesticides), costs and labor, pasture yield, biomass partitioning, and manure and urine production. Calculations are based on *i)* knowledge of relevant agro-ecological processes and, when process knowledge is incomplete or absent, *ii)* expert knowledge, published data, or field observations. Contemporary land use activities are quantified by running the expert models descriptively: with all inputs and outputs predefined, the resulting soil nutrient balance is calculated. For the quantification of alternative land use activities, a target-oriented approach is used: a fixed target yield level conditions inputs and outputs. Furthermore, alternative systems aim at soil fertility maintenance. Alternative activities do not necessarily have higher yields than actual activities, but can theoretically be practiced without depleting the soil nutrient stock.

Realizations for pasture were generated with the PASture and livestock Technical coefficient generatOR (PASTOR, Bouman *et al.*, 1998). In PASTOR, a pasture production system is defined by grass species, soil type, and management. The management factors relevant to DNDC are stocking rate and fertilizer application rate. Production levels range from maximum attainable production under non-limiting situations, via close-to-actual levels, to extremely low levels on exhausted soils. The PASTOR formulation has been confirmed by literature and field data, and has been reviewed by external experts (Bouman *et al.*, 1998).
For banana plantations, realizations were generated with the Land Use Crop Technical coefficient generatOR (LUCTOR, Hengsdijk *et al.*, 1998). In LUCTOR, land use activities for timber plantations and annual and perennial crops are described by operation sequences with their associated inputs and outputs. Production systems are defined by crop type, soil type, and management. The management variable relevant to DNDC is fertilizer application rate. Ten target yields, each defining an alternative land use activity, were used for this study. The maximum target yield is reduced to 10% of the maximum in nine steps.

Although DNDC has been used to estimate forest emissions (Plant, 1998), N_2O fluxes for forest were derived from literature. It was assumed (see also Table 5.3) that 6.4 and 3.7 kg N_2O-N ha^{-1} yr^{-1} is emitted from primary and secondary forest, respectively (Keller *et al.*, 1993; Keller and Reiners, 1994; Keller, unpublished data). The flux from primary forest is the average of annual mean fluxes from four sites (standard deviation 2.4 kg N_2O-N ha^{-1} yr^{-1}), and the value for secondary forest was derived from annual mean fluxes from three sites (standard deviation 1.1 kg N_2O-N ha^{-1} yr^{-1}).

The DNDC model encompasses a range of scale levels at which processes are simulated (Bouwman *et al.*, in press; Schimel and Potter, 1995). The model was primarily designed to estimate N_2O fluxes at the field scale, so inputs and outputs are formulated at commensurate scales. However, microbial processes conventionally thought of as a soil microsite processes (nitrification, denitrification, decomposition), are modeled at much finer levels than the field scale. Thus, DNDC .inadvertently extrapolates from soil microsites to the field scale without explicitly considering field-scale spatial heterogeneity of microbial parameters (Figure 6.3). In this study, I will not further address this implicit upscaling.

Land use scenarios
Effects of contemporary land use (ACT scenario) and two alternative land use scenarios (ATL-I, ALT-II) on flux patterns and the regional N_2O flux were studied. Alternative scenarios were exclusively defined by attribute values: the spatial layout of land use was the same in all three scenarios. The ACT scenario represents the 1992 situation (Bouman *et al.*, in press), whereas ALT-I and ALT-II are defined by land use activities that meet the requirement of environmental sustainability.
In the ACT scenario, all pastures had a mixture of unproductive naturalized and native grasses featuring indigenous species and naturalized improved varieties (*Ischaeum ciliare*, *Axonopus compressus* and *Paspalum spp*, Hernandez *et al.*, 1995). These species, introduced in the NAZ in the 1970s, dominated 77% of the NAZ pastures in 1992. Over 70% of the soils below these pastures are in an advanced stage of degradation (Jansen *et al.*, 1997): no fertilizer is applied, so that removal of agricultural products leads to soil fertility loss. In

the ACT scenario, pasture activities only differed by stocking rate. Per soil type, PASTOR generated thirteen realizations with stocking rates ranging from 1 to 4 animal units (1 animal unit (AU) = 400 kg live weight) ha^{-1}. Banana plantations were uniformly managed in the ACT scenario. Hence, there was only one realization -- that is, the typical management -- for banana.

In the ALT-I scenario, grass-legume mixtures replaced the indigenous species and naturalized improved varieties on FWD and IWD soils. Since grass-legumes do not grow on FPD soils (Bouman *et al.*, 1998), these soils were put below secondary forest. Grass-legumes consist of *Brachiaria brizantha* mixed with *Arachis pintoi*, a combination that has been shown to be persistent and economically profitable in the NAZ (Ibrahim, 1994; Jansen *et al.*, 1997). Since the legumes supply N to the pasture through microbial fixation, soil fertility is maintained and no fertilizers are required. PASTOR generated thirteen and ten realizations for FWD and IWD soils, respectively. In the ALT-I scenario, N fertilizer applications were allowed to vary across banana plantations, resulting in nine realizations per soil group.

In the ALT-II scenario, fertilized improved species (*Cynodon nlemfuensis* ("Estrella"), *Brachiaria brizantha* ("Brachiaria") and *Brachiaria radicans* ("Tanner")) replaced the indigenous species and naturalized improved varieties on all soils. Soil fertility was maintained through fertilizer-N applications that ranged from zero (resulting in bottom production levels) to the amount needed to realize maximum attainable production. Stocking rates ranged from 1 to 6 AU ha^{-1}. PASTOR combined fertilizer application rates with stocking rates and generated eleven realizations for FWD, and twenty-six for FPD and IWD soils. Spatial heterogeneity of land use activities across banana plantations was the same as in the ALT-I scenario.

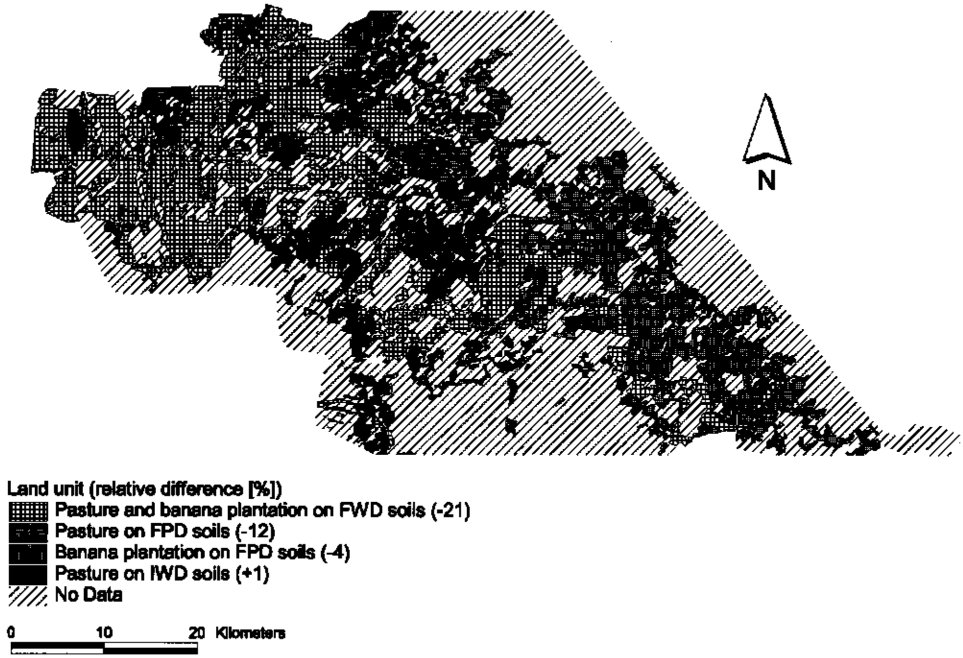
Simulations

To quantify the relative contributions of soil and land use variability in the ACT scenario, four cases were considered (Table 6.4). A series of deterministic model runs (case S_1) was done using lumped soil and land use parameters. Model outputs consisted of single values. In the second case (S_2), soil variability was included by running DNDC with fifty realizations of the joint distribution of soil inputs per land unit class. In the third case (S_3), DNDC simulations were repeated with a varying number of realizations of the joint distribution of land use inputs. The fourth case (S_4) consisted of model runs for combined soil and management realizations. Since the spatial overlay of soils and land use options *within* classes is unknown, it was assumed that each combination of soil and management may occur, and that all combinations are equally probable.

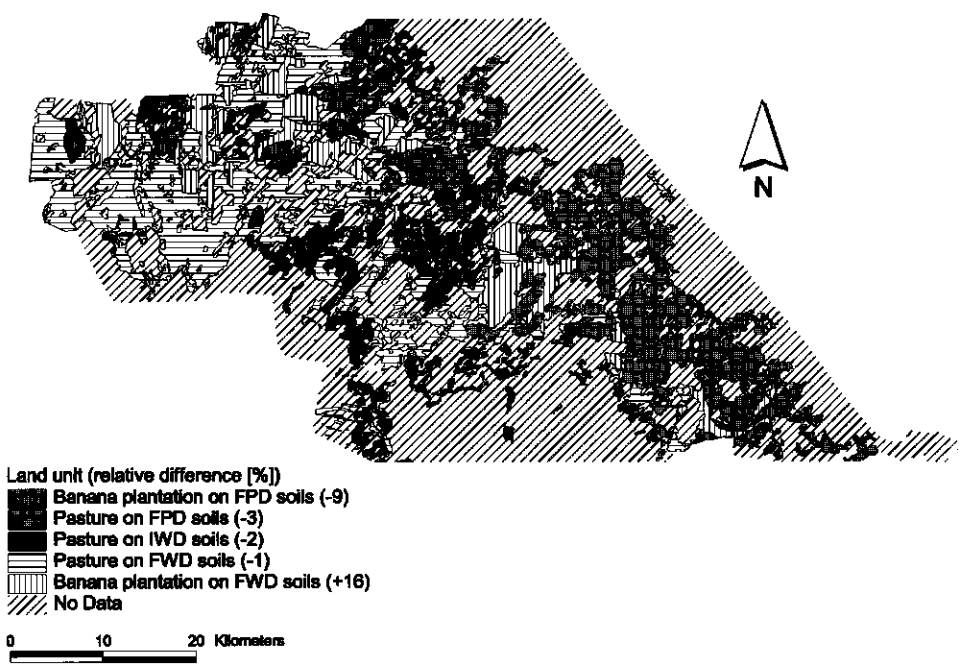
For the land unit classes relevant to ALT-I and ALT-II, only the S_4 simulations were carried out. Scenario comparisons were based on results of S_4 simulations for the ACT land use scenario. Each of the 7546 simulations (Table 6.4) consisted of a 25-year DNDC run; results for the 25th year were extracted for statistical analysis.

Annual precipitation and mean air temperatures were assumed to be homogeneous throughout the region. The weather as recorded at the Los Diamantes meteorological station (10°13'N, 83°48'W, Figure 1.1) was used for all DNDC runs. Daily rainfall and air temperatures were derived from data recorded in 1991 and 1992. A fixed NO_3^--N concentration in precipitation (0.1 mg L^{-1}) was used (M. Keller, personal communication).

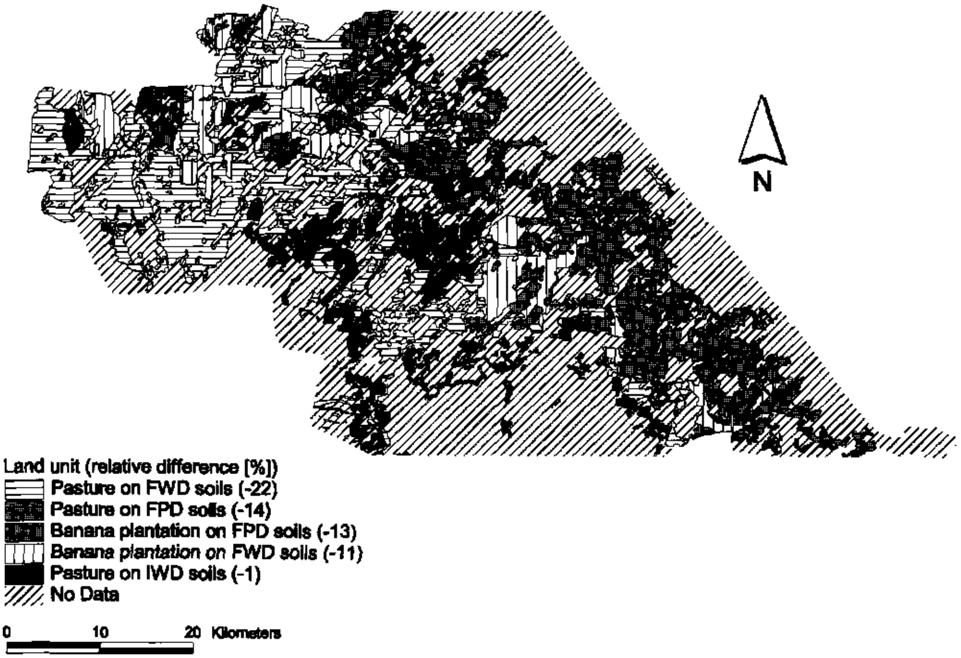
Figure 6.4 Relative difference between deterministic and stochastic areal N_2O flux estimates. Maps portray effects of soil heterogeneity (S_2 case, a), land use heterogeneity (S_3 case, b), and combined soil and land use heterogeneity (S_4 case, c).



a

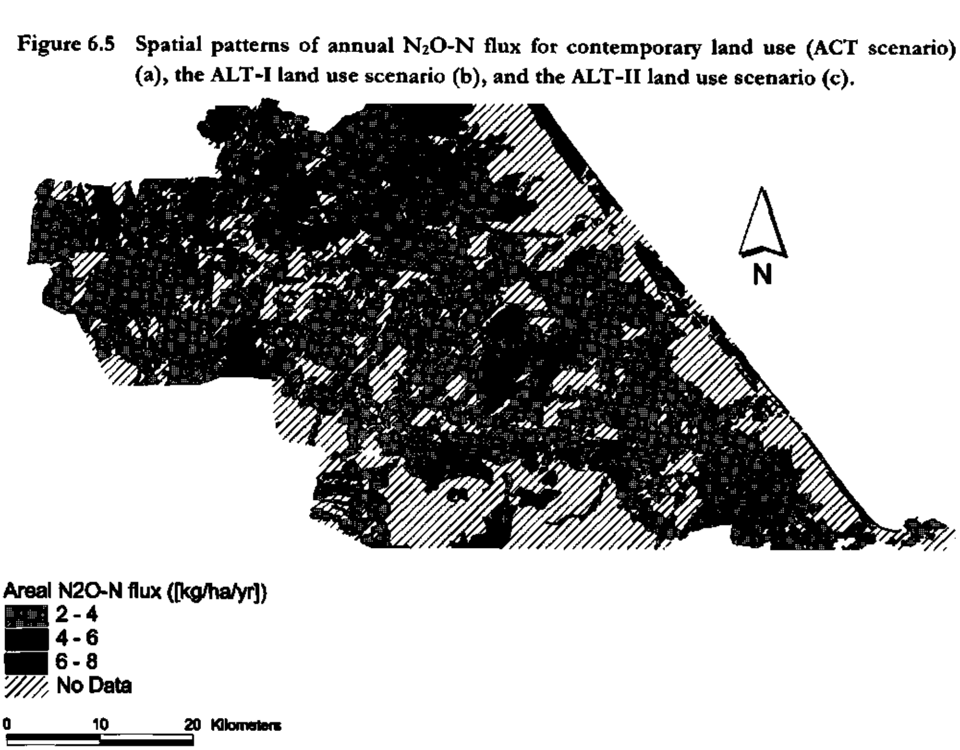


b

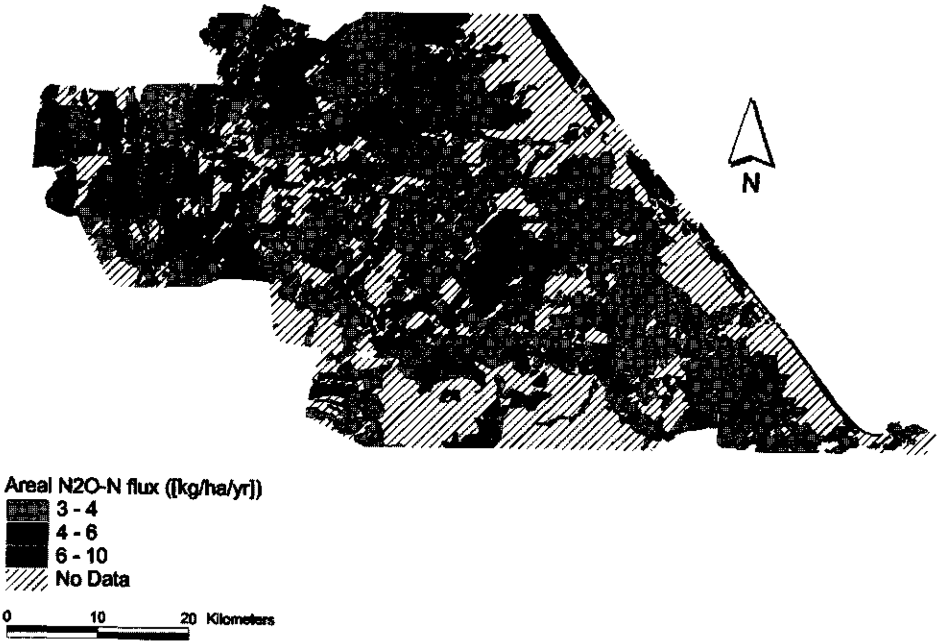


c

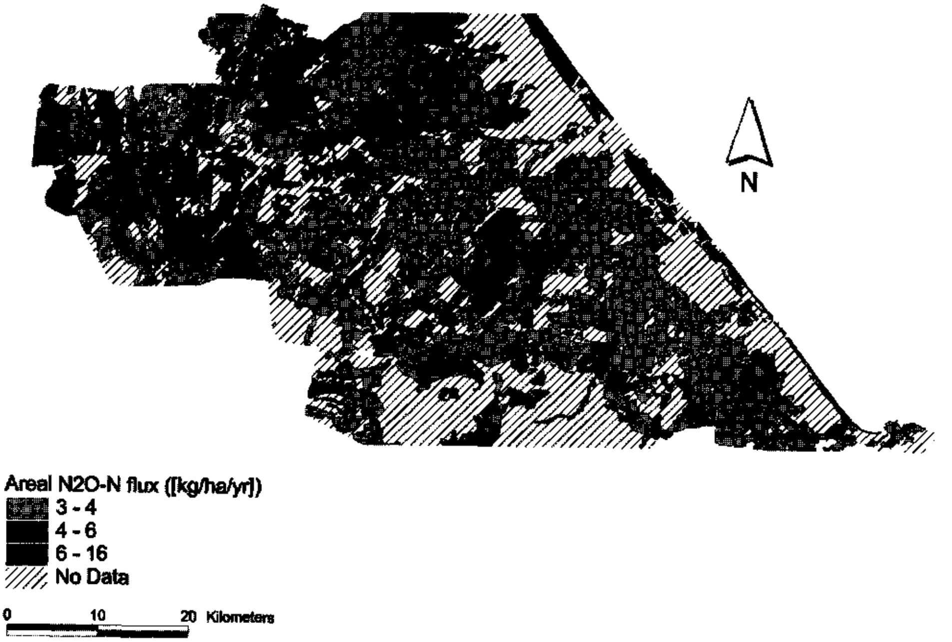
Figure 6.5 Spatial patterns of annual N_2O-N flux for contemporary land use (ACT scenario) (a), the ALT-I land use scenario (b), and the ALT-II land use scenario (c).



a


N
Areal N2O-N flux ([kg/ha/yr])
3 - 4
4 - 6
6 - 10
No Data
0 10 20 Kilometers

b


N
Areal N2O-N flux ([kg/ha/yr])
3 - 4
4 - 6
6 - 16
No Data
0 10 20 Kilometers

c

6.4 Results

Effects of spatial heterogeneity

In Figure 6.4, the relative effects of soil and land use variability on the estimated pattern of N_2O emission from pasture and banana are illustrated. Per land unit class, the expected value of the simulated distribution of N_2O flux (Eq. 6.3) is expressed as a percentage of the deterministic flux estimate (S_1). With only soil variability included (S_2, Figure 6.4a), simulated areal fluxes were 4-21% lower than in the S_1 case, except for pasture on IWD soils (+1 %). With only land use variability taken into account (S_3, Figure 6.4b), the simulated areal N_2O fluxes from banana plantations deviated from those simulated in the deterministic case in a different way: on FPD soils the areal flux from banana was 3 kg N_2O-N ha^{-1} yr^{-1}, 9% less than estimated in the deterministic case. On FWD soils however, the simulated areal N_2O flux for banana increased from 8.4 to 9.7 kg N_2O-N ha^{-1} yr^{-1} (+16%). With both soil and land use variability included (S_4, Figure 6.4c), the spatial flux pattern was similar to that in the S_3 case, but the areal fluxes were invariably lower than in the deterministic case with the largest difference for pasture (14 – 22%). Relative to the S_1 case, the regional flux was ~2% higher in the S_3 case, and ~10% lower in the S_2 and S_4 cases.

Actual and alternative land use scenarios

With contemporary land use activities (Figure 6.5a), the greatest areal N_2O fluxes (Table 6.4) evolved from the intensively fertilized banana plantations. Fertile Well Drained soils below banana plantations emitted 4-12 kg N_2O-N ha^{-1} yr^{-1}, whereas FPD soils emitted 2-7 kg ha^{-1} yr^{-1} (Table 6.4). Measured site-level fluxes from Andisols and Inceptisols below NAZ banana plantations were 13 and 6 kg N_2O-N ha^{-1} yr^{-1}, respectively (Veldkamp and Keller, 1997). The regional N_2O-N flux (standard deviation in parenthesis) for the ACT scenario was 1.0 (0.4) Gg yr^{-1}.

With the ALT-I scenario (Figure 6.5b), the regional N_2O-N flux was 1.6 (0.5) Gg yr^{-1}. The greatest areal N_2O flux (Table 6.4) now evolved from pasture on FWD soils (10 kg ha^{-1} yr^{-1}). Field measurements on Andisols in the NAZ (Veldkamp *et al.*, 1998) have shown that 0 - 13 kg N_2O-N ha^{-1} is emitted from grass-legume pastures annually.

The ALT-II land use scenario (Figure 6.5c), with all native and naturalized grasses replaced by fertilized improved species, modulated the greatest regional N_2O-N flux (1.9 (1.2) Gg yr^{-1}). Again, the greatest areal flux (Table 6.4) evolved from pasture on FWD soils (16 kg N_2O-N ha^{-1} yr^{-1}). In the NAZ, field-level fluxes of 16-32 kg N_2O-N ha^{-1} yr^{-1} have been measured from fertilized improved pastures on Andisols (Veldkamp *et al.*, 1998).

6.5 Discussion

Modeling lessons and limitations

The comparison of regional N_2O flux patterns based on deterministic (S_1) and stochastic ($S_{2\text{-}4}$) model runs based on contemporary land use showed that areal fluxes were moderately overestimated in the deterministic case. Because deterministic areal fluxes were unequal to the stochastic areal fluxes, the relationship between the key driving variables and field-scale N_2O flux appears to be non-linear (Figure 6.2a). This non-linearity suggests that simple "flux x area" estimates of regional N_2O flux, which do not account for spatial heterogeneity of soils and land use, may be inaccurate. The similarity of results for the S_2 and S_4 cases (Figure 6.4a and Figure 6.4c) suggests that lumping of soil parameters is likely to cause the greatest aggregation errors.

Table 6.4 Simulations carried out to study spatial soil and land use heterogeneity. S_1 is the deterministic case, and S_2 and S_3 are the stochastic cases incorporating soil and land use heterogeneity, respectively. For the S_4 case, where both types of heterogeneity were taken into account, statistical properties of the DNDC-generated frequency distribution of N_2O-N emissions ([kg ha^{-1} yr^{-1}]) are reported.

Soil group	Land use activity	Scenario	# of simulations				Simulated N_2O-N emission			
			S_1	S_2	S_3	S_4	Mean	Min	Max	Stdev
Fertile Well Drained	Natural pasture	ACT	1	13	50	650	3	1	5	1
	Grass-Legume pasture	ALT-I	-	-	-	650	10	5	16	3
	Fertilized Improved pasture	ALT-II	-	-	-	550	16	3	35	9
	Actual banana plantations	ACT	1	1	50	50	8	4	12	2
	Alternative banana plantations	ALT-I, ALT-II	-	-	-	450	6	2	16	3
Fertile Poorly Drained	Natural pasture	ACT	1	13	50	650	2	1	3	0
	Fertilized Improved pasture	ALT-II	-	-	-	1300	3	1	11	1
	Actual banana plantations	ACT	1	1	50	50	3	2	7	1
	Alternative banana plantations	ALT-I, ALT-II	-	-	-	450	3	1	9	1
Infertile Well Drained	Natural pasture	ACT	1	13	50	650	2	0	3	0
	Grass-Legume pasture	ALT-I	-	-	-	500	3	1	4	1
	Fertilized Improved pasture	ALT-II	-	-	-	1300	3	0	8	2
Total			5	41	250	7250				

The modeling framework presented has some limitations. First, the approach may not be generally applicable because the required components (GIS and attribute data, technical coefficient generators, well-tested simulation models) are difficult to acquire for humid tropical regions. Statistical summary models (e.g., Plant and Bouman, in press) are widely accepted as a more straightforward alternative to mechanistic modeling. Nonetheless, the lack of a mechanistic basis does limit the applicability of such statistical summaries to other areas and future situations. The strength of summary models is that they provide an objective benchmark against which mechanistic model output can be evaluated.

Second, the effect of regional climate may have been underestimated. The assumed homogeneous climatic conditions throughout the NAZ may be reasonable because *i)* there is very little variation in mean daily temperature in the NAZ, and *ii)* DNDC sensitivity tests have shown that a 20% increase in precipitation produced only a 4% increase in N_2O emissions (Li *et al.*, 1996). Therefore, the inclusion of climate as a third spatial data layer to delineate land units would most likely have had little effect on the emission patterns estimated. However, it is well known from field studies that soil moisture is a strong regulator of field-level N_2O fluxes (e.g., Keller and Reiners, 1994; Veldkamp *et al.*, 1998). DNDC's insensitivity to precipitation, therefore, suggests that the model's coupling of daily rainwater input, soil saturation, and N_2O evolution may be inadequate, especially for the high rainfall rates of the humid tropics. Because of this inadequacy, no conclusions can be drawn regarding climate as a potentially important regulator of regional N_2O flux in the NAZ.

A third limitation is set by the lack of knowledge about the joint distribution of soils and management within land units. In this study I assumed that the joint distributions of soil (S_2), land use (S_3), and their combination (S_4), were constant across space. In addition, all combinations of soils and land use were assumed to be equally probable within land units in the S_4 case. Fluxes from soil – land use combinations that do not exist in reality may possibly have affected the areal flux estimates in the S_4 case.

Although the use of mechanistic models sets practical limitations, it provides a firm theoretical basis for testing hypotheses and facilitates analyses of the effects of environmental changes (Raich and Potter, 1995). Moreover, for N_2O the mechanistic detail is essential in capturing temporal flux variations and estimating annual fluxes (Potter *et al.*, 1996). Li *et al.* (1992b) found that DNDC was capable to simulate N_2O evolution in a wide range of soil types without changing internal parameters, and concluded that the external model parameters (i.e., inputs) adequately cover the major factors that influence regional variations in N_2O emissions. The version of DNDC used for the current analysis has > 130 external and internal parameters. Many have a temporal dimension (cropping and land use practices, climate characteristics). In this study, the stochasticity of only ten soil and land use inputs was considered. Since selection of these inputs was based on both structured sensitivity analyses and process knowledge, it is unlikely that key driving variables other than precipitation (see discussion below) have been overlooked.

Conclusive validation of regional N_2O flux estimates is extremely difficult. At present, it is impossible to make direct areal flux measurements for NAZ-sized regions. Comparisons with field measurements could be, and were, made for land units with FWD and IWD soils, but measurements lacked for FPD soils. In these soils, anaeroby favoring high denitrification rates and N_2O emissions may be periodically present but DNDC did not simulate emissions peaks under periodically wet conditions. This supports the above conclusion that the model does not adequately represent the effect of soil wetting on N_2O emissions. The sensitivity of DNDC to the initial soil C stock and periodic C inputs on the one hand and insensitivity to rainwater inputs on the other (Li *et al.*, 1996; Plant and Bouman, in press) may explain why the N_2O emissions simulated for FPD soils are lower than expected.

Comparison with previous estimates

In a previous study of N-oxide emissions from the NAZ (Plant, 1998) a contemporary regional N_2O-N flux of 1.8-2.1 Gg yr^{-1} was estimated whereas the current regional estimate is 1.0 Gg yr^{-1}. Like in the current analysis, the land use types considered in the former study were "Pasture", "Banana Plantation", "Primary Forest", and "Secondary Forest". Areal extents of land units were based on the 1992 land use mosaic. A soil, texture, land use, and climate zone coverage were overlaid to yield 217 different land units; regional flux estimates were derived from 217 deterministic areal flux estimates.

There are several reasons for the difference between the two regional estimates. The most obvious reason is the difference in the time span of the DNDC simulations: unlike in the current analysis, DNDC was run for one single year in the previous study. Second, forest emissions were simulated in the previous study, whereas I used direct measurements in the current analysis. Third, in the former study the soil map was generalized to distinguish eight rather than the four functional classes used in this study. Finally, the former study incorporated inter-annual variations in rainfall.

Implications for nitrous oxide emission inventories

The results of this study suggest that *i)* soil variations are most important in estimating regional N_2O emissions, and *ii)* the introduction of land use activities that are sustainable when only economic profit and soil fertility maintenance are considered, may not be sustainable when N_2O emissions are considered as well. At present, a trade-off between economic profit and greenhouse gas emissions (including carbon dioxide (CO_2) and methane (CH_4)) is beyond the scope of regional land use planning in the NAZ (Bouman *et al.*, in press/b). However, Costa Rica may be participating in international emission reduction policies (EPA, 1998) in the near future, and regional analysis may become an important aide in compiling national inventories. The regional analysis presented did ***not*** intend to produce numbers for use in such national inventories. Rather, it attempted to unravel the effects of, and interference between, the major sources of error and uncertainty: soils and land use.

6.6 Conclusions

- Expected values of stochastically simulated distributions of N_2O flux were 14-22% lower than mean fluxes based on deterministic simulations. This suggests non-linearity in the complex relationship between N_2O emission and soil and land use parameters.
- The introduction of land use activities that are sustainable in terms of economic profit and soil fertility maintenance may not be sustainable in terms of N_2O emissions.
- Soil is a stronger regulator of regional N_2O flux than land use.
- Regional analysis is essential in identifying the hierarchy of contributions of land units to the regional flux and may be an aide in compiling regional and national N_2O inventories.

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Chapter 7

Concluding remarks

7 Concluding remarks

The overall objective of the work summarized in this thesis was to study effects of land use on N_2O emissions by spatial extrapolation of plot-scale N_2O measurements. The study was carried out in the Northern Atlantic Zone of Costa Rica because *i)* a body of data on emissions, soils, and land use is available for this region, and *ii)* the region is an example of the many humid tropical areas that have undergone dramatic land use changes in the past decades. Although the research focused on N_2O fluxes, NO emissions were additionally discussed in Chapters 2 and 4. The work addressed three steps that I deemed necessary to meet the objective. First the DNDC simulation model was adapted to, and tested for, soils below banana plantations and cattle pastures, the land use forms currently dominating the study area (Chapters 2 and 3). The adapted simulation model was then applied to obtain frequency distributions of emissions based on data generated by an expert system quantifying inputs and outputs of cattle pastures (Chapter 4). This provided the basis for the third step (Chapters 5 and 6), i.e., regional analysis of N_2O emissions. To perform regional analysis, I integrated the simulation model, an extant Geographic Information System (GIS) and two expert systems (PASTOR and LUCTOR). In this final Chapter, I contemplate the most compelling conclusions that ensued from the previous five chapters. Not unlike nearly all theses, this study leaves many a question unanswered. Therefore, I provide suggestions for future research in the final paragraph.

7.1 Field-scale modeling of nitrogen oxide emissions

For two reasons, conclusive validation of simulated N-oxide fluxes turned out to be very difficult. First, simulated emissions were mostly compared with monthly sampled fluxes, whereas DNDC's temporal resolution calls for comparisons with daily measurements. Consecutive daily measurements were available for banana (Chapter 3) but captured only a short, and possibly a-typical, period (~1 month). Flux data sets can never be exhaustive due to the complicated logistics of gas sampling and high spatiotemporal variability. When financial and time constraints allow only a limited number of flux samplings, the researcher is facing a trade-off between frequent (hourly to daily) measurements during a short period and infrequent measurements (monthly to quarterly) during extended periods (e.g., Droogers, 1998). Therefore, model validations based on frequent measurements during extended periods may currently not be feasible.

Second, the simulation model could not be validated based on mass balance constraints (Oreskes *et al.*, 1994) because the major fluxes of N, i.e., plant uptake and leaching, were not measured concurrently with gaseous N losses. Nitrous oxide-N losses are comparatively small (~10% of annual N loss by crop uptake, leaching and gaseous emission, Powlson, 1993), so their validation means little if the major vehicles of N loss cannot be tested. Preliminary mass balance validations were presented for two sites below pasture (Chapter 2), but these were based on data from literature.

Annual N_2O and NO losses simulated for Andisols and Inceptisols below pastures of varying age (Chapter 2) and fertilized banana plantations (Chapter 3) were in general agreement with *annual means* of emissions sampled on a monthly basis. Yet, as amply evidenced by the daily comparisons of simulated and measured fluxes, the model did not capture observed daily N-oxide flux dynamics. This flaw was attributed to DNDC's inability to estimate soil moisture conditions (Chapter 3). Assuming the model testing results are conclusive, they suggest that soil moisture may not be a key regulating factor at the field scale in humid tropical areas. This puts forward questions as to the merit of DNDC's temporal resolution (hourly time step in soil hydraulic and denitrification calculations) and detailed process descriptions: are they needed when the modeling objective is extrapolation? When spatial extrapolation is the main objective, a simpler model explaining annual dynamics of N-oxide flux (e.g., Parton *et al.*, 1996) may be more appropriate. Exogenous, (pseudo-) static site characteristics like soil pH, bulk density and clay content appear to nullify short-term responses of fluxes to soil wetting and drying. This nullification may essentially be a matter of scale: when studying emissions at plot scales, site characteristics are regarded as exogenous and are rarely quantified. Much emphasis is put on diel, daily and seasonal trends of such dynamic site characteristics as water-filled pore space and inorganic soil nitrogen concentrations (Keller and Reiners, 1994). Empirical relationships between emissions and these dynamic characteristics only explain flux dynamics *within* sites. It may be worthwhile to establish statistically significant relationships *across* plots. Therefore, I suggest that (pseudo-) static site characteristics be measured in future field studies on gas emissions.

7.2 Generating frequency distributions of nitrogen oxide emissions

Obtaining distributions of fluxes for land units that are defined by process controls (Chapter 4) may be a promising new approach to regional simulation modeling. The distributions generated can be put to use in several ways. Foremost, the simulated set of fluxes can be linked with the array of input parameters. Multiple regression may illuminate the absolute and relative sensitivity of emissions to the various inputs (Janssen, 1992). Second, the statistical expectation of the distribution provides a benchmark against which aggregation errors in model outcomes based on lumped inputs can be evaluated (Chapter 6).

7.3 Regional analysis of nitrous oxide emissions

The coupling of DNDC with a Geographic Information System (Chapter 5) proved a convenient way to conduct an exploratory survey of N_2O emissions at the regional scale. The Monte Carlo-based sensitivity analysis presented in Chapter 5 provided additional evidence that DNDC-estimated annual N_2O emissions are explained by a small set of exogenous model parameters. The exploratory inventory suggested that regional N_2O fluxes are about 50% greater than "flux x area" estimates based on measurements from fifteen sites. With incorporation of spatial heterogeneity of soils and land use within land units (Chapter 6), areal flux estimates for land units were invariably lower than without consideration of spatial heterogeneity. The greatest aggregation error (-22%) was found for the land unit (pasture on FWD soils) with the greatest areal extent (41,935 ha, 15% of study area). Propagation of aggregation errors in land unit-scale fluxes caused an error of ~-10% in the regional flux estimate. Soil heterogeneity had a stronger effect on regional flux patterns than land use heterogeneity (~-10% and ~+2%, respectively). Spatial heterogeneity of soil properties regulates N_2O emissions at finer scales than typically employed in regional soil surveys. Information on the heterogeneity of mapping units is now increasingly being stored in digital soil survey databases. Therefore, stochastic description of key variables may become a feasible and efficient way to reduce aggregation errors in regional flux estimates.

7.4 Why not simply measure and multiply?

One may criticize the work presented as being irrelevant because N_2O contributes only 5% to the anthropogenic greenhouse effect, and as being idiosyncratic because the simulated net effect of spatial soil and land use heterogeneity was small (~-10%). Intuitively, "measure-and-multiply" seems simpler and as good as the approaches to spatial extrapolation presented in this thesis. Apart form the fact that this conclusion was *not* obvious from the outset, the work is justified, however, by the anticipated future changes in anthropogenic N_2O sources. Taking into account *i)* the relatively long residence time of N_2O in the atmosphere (~120 yr), *ii)* the rates at which (humid) tropical forest is being converted to pasture and other forms of agriculture, and *iii)* the rate at which the use of N fertilizers in tropical areas is increasing, it is easy to understand why N_2O may become the "greenhouse gas of the future". The attractiveness of simpler methods is fallacious: the absence of a mechanistic basis limits the predictive power of empirical models. The anticipated future trends discussed above will inevitably and rapidly result in new configurations of regulating process controls that cannot be captured by empirical formulations derived from past data. Therefore, I strongly advocate the use of mechanistic models, albeit more simplified than the DNDC model.

7.5 Future research

- I only studied *modifications* of the current forms of land use, keeping the spatial layout of land units the same. Land use *conversions*, resulting in new spatial layouts and areal extents of land units, may significantly affect regional N_2O emissions and therefore comprise an interesting research area.
- The DNDC model inadvertently extrapolates N-oxide emissions from soil microsites to the field scale. This potentially critical simplification was briefly touched upon in Chapter 6, but was not further elaborated. The linear scaling involved in this extrapolation may cause serious aggregation errors if the dependency between microbial process controls and microsite-scale fluxes is non-linear. An in-depth sensitivity analysis that considers DNDC's many internal parameters could help to assess the magnitude of the aggregation error from this source.
- The highly localized deposition of cattle feces and urine, possibly creating "hot spots" of denitrification, was ignored in the simulations of N_2O emissions from soils below grazed pastures. This led to the somewhat counter-intuitive finding that the act of

grazing did not automatically lead to increased N-oxide emissions. A modeling framework similar to the one presented for banana (separate below-plant and between-plant simulations), i.e., separate simulations for feces and urine-covered and feces and urine-free portions of the pasture, may better capture the spatial variation of N-oxide emissions observed in grazed pastures.

- Assessment of process-based relationships summarizing the interaction between (pseudo-) static site characteristics and N-oxide emissions that implicitly aggregate space-time variations in N_2O flux provides a distinct challenge.
- At present, there are no well-defined thresholds for regional and national N_2O emissions. Thresholds will, however, undoubtedly be established in the near future and provide a new challenge to sustainability analysis.

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Abstract

Plant, R. A. J., 1999. Effects of land use on regional nitrous oxide emissions in the humid tropics of Costa Rica. Extrapolating fluxes from field to regional scales. Ph.D. Thesis Wageningen Agricultural University, Wageningen, The Netherlands, 131 pp.

Atmospheric concentrations of the greenhouse gas nitrous oxide (N_2O) have increased significantly since pre-industrial days. Greenhouse gases absorb infrared radiation reflected by earth's surface, thereby causing global warming. The increase in atmospheric N_2O concentrations is attributed to human activities. The relative contribution of N_2O to the anthropogenic greenhouse effect is about 5%. The two major natural sources of N_2O are soils and oceans, while agricultural soils comprise the main anthropogenic source. Nitrous oxide is formed in soil as an intermediate product from nitrification and denitrification, soil processes that operate at the microsite scale. Land use changes strongly affect soil nitrogen (N) cycling; especially conversion of natural forest to agricultural land generally increases N_2O emissions. Therefore, land use is an important distal process control on N_2O emissions from soil. Effects of land use change on N_2O emissions must be studied at scales relevant to agricultural land use planning and policy making. This calls for methods to extrapolate plot-scale measurements that are highly variable in space and time. Neglecting spatial heterogeneity of fluxes and process controls can lead to serious errors in areal and regional flux estimates. The objective of the work summarized in this thesis was to study effects of land use on regional N_2O emissions by extrapolating plot-scale N_2O measurements in the Northern Atlantic Zone of Costa Rica (2817 ha). A body of earlier work has been carried out in this humid tropical region, and the concurrent availability of data on soils, land use, climate, and N_2O emissions for a sizeable area provided a unique opportunity for an in-depth methodological study on extrapolation. Moreover, the land use history of the area is representative for humid tropical regions in Latin America.

A well-tested process-based ("mechanistic") simulation model driven by rainfall events (DNDC) was used to estimate fluxes from unsampled fields and land units. Land units are defined by distal process controls such as soil type, management, and climate. The model, originally designed to simulate nitrogen oxide emissions under temperate climatic conditions, was adapted to justify application to humid tropical pastures and banana plantations. First, functions were added to simulate *i)* cattle grazing and *ii)* steady input of organic matter through root turnover and the return of excrements to the pasture. Second, an explicit treatment for the immobilization of N was added. The adapted simulation model was tested against field measurements of *i)* N_2O and nitric oxide (NO) fluxes from a chronosequence of pastures on Inceptisols and *ii)* N_2O fluxes from a banana plantation on Andisols and Inceptisols. For the pasture chronosequence, the model formulation was consistent for annual N dynamics and annual nitrogen oxide emissions. In contrast, simulated daily dynamics of nitrogen oxide emissions did not match field observations. The differences in local weather on the seven sampled pasture sites comprising the chronosequence may have caused a significant part of the mismatch. Annual emissions calculated by the model are essentially cumulative daily fluxes, so daily comparisons provide a more conclusive insight in the model's performance than annual comparisons. Simulated daily N_2O fluxes from soils below a banana plantation were compared with data from monthly and frequent field sampling. Different model parameterizations were used to represent fertilizer inputs below banana plants and crop residue additions between plants. For both the Andisol and the Inceptisol, simulated below-plant fluxes matched frequently measured fluxes better than monthly measured fluxes. Simulated between-plant fluxes matched monthly measured fluxes better than frequently measured fluxes. The simulated annual N_2O-N losses for the Inceptisol and Andisol were 6 and 15 kg ha^{-1}, respectively. Field-measured annual losses were 6 and 13 kg ha^{-1}. In addition, three banana fertilization scenarios on an Andisol were studied. With fewer equal splits of fertilizer-N, the simulated N_2O-N loss declined. With more equal splits losses increasingly depended on the amount of fertilizer-N.

An expert system for quantifying inputs and outputs of pastures (PASTOR) was linked with the simulation model to produce frequency distributions of N_2O and NO emissions for one current pasture management system ("Natural") and two alternative systems ("Grass-Legume" and "Fertilized Improved"). Current forest-derived natural pastures deplete soil nitrogen stocks and therefore are unsustainable. Alternative management aims to utilize soil-N in a sustainable manner. The expert system was set up to generate parameter sets representing different land use options for the three management systems. The simulation model was rerun for each parameter set. Simulated annual N_2O-N losses twenty-five years after pasture establishment were 3-5 kg ha^{-1} for natural pastures, 12-15 for grass-legume mixtures, and 7-28 for fertilized grasses. Simulated annual losses of NO-N were 1-2 kg ha^{-1} for natural pastures, 7-8 for grass-legume mixtures, and 3-16 for fertilized grasses. Regression analysis showed that annual C input to the soil explained N_2O losses, and that NO losses were explained by biomass production. Nitrous oxide and NO emissions from pastures may increase by a factor 3-5 when natural pastures are converted to improved pastures. Such conversion may increase the sustainability of the pasture by stopping the decline of soil N, but the change is not necessarily sustainable from a global perspective because it increases the emission of N oxides.

The regional N_2O flux from soils below primary and secondary forest, pastures, and banana plantations was explored by linking the simulation model with an extant Geographic Information System (GIS) on soils and land use. Land units on the overlaid soil and land use coverage were linked with the nearest of seven available meteorological stations. Monte Carlo-based sensitivity analysis was used to identify clay content, initial soil organic C, bulk density, and pH as required map attributes and key driving model variables. For 217 different land units, model simulations were repeatedly carried out using climate data for seven different years. The estimated regional N_2O-N flux was 1.8-2.1 Gg yr^{-1}. A full-fledged regional analysis of N_2O emissions was performed using both deterministic and stochastic descriptions of key model inputs. The stochastic descriptions accounted for soil and land use heterogeneity across (non-georeferenced) fields within eleven different land units. Using Monte-Carlo integration, frequency distributions of fluxes were obtained per land unit class. Regional fluxes were calculated by summing expected values of the distributions weighted by area. Stochastic incorporation of both soil and land use variability resulted in areal flux estimates that were 14-22% lower than those estimated with deterministic model runs, suggesting non-linearity in the relationship between key model parameters and N_2O fluxes. Spatial flux patterns for 1992 land use and two alternative land use scenarios were evaluated using stochastic inputs. With contemporary management of banana plantations and natural grasses, the regional N_2O-N flux (standard deviation in parenthesis) was 1.0 (0.4) Gg yr^{-1}. Replacing natural grasses by sustainable grass-legume mixtures on relevant soil groups and allowing different fertilization levels on banana plantations increased the regional flux to 1.6 (0.5) Gg yr^{-1}. When all natural grasses were replaced by fertilized improved species and different fertilization levels were allowed on banana plantations, the regional flux increased to 1.9 (1.2) Gg yr^{-1}. Land use activities that are sustainable in terms of economic profit and soil fertility may be unsustainable when including N_2O emission as an extra indicator. Soil variations, dominating regional patterns, must be incorporated when inventorying N_2O emissions. Spatial heterogeneity of soil properties regulates emissions at finer scales than typically employed in regional soil surveys. A stochastic description of key variables may therefore be an efficient way to reduce aggregation errors in regional flux estimates.

Future challenges include studies on effects of land use conversions, resulting in new spatial layouts of land units, on regional N_2O fluxes. Also, the simulation model's implicit upscaling of emissions from soil microsite to field scales may be a potential research area.

Samenvatting

Plant, R. A. J., 1999. Effecten van landgebruik op regionale lachgasemissies in de humide tropen van Costa Rica. Het extrapoleren van fluxen van velden naar regionale schalen. Proefschrift Landbouwuniversiteit Wageningen, Wageningen, Nederland, 131 pp.

De atmosferische concentraties van het broeikasgas distikstofmonoxide ("lachgas", N_2O) zijn sinds de industrialisatie in belangrijke mate toegenomen. Broeikasgassen absorberen infrarood-straling die door het aardoppervlak wordt teruggekaatst en veroorzaken daardoor opwarming van de aarde. De toename van de N_2O-concentratie in de atmosfeer wordt toegeschreven aan menselijke activiteiten. De relatieve bijdrage van N_2O aan het door de mens veroorzaakte broeikaseffect is ongeveer 5%. De twee belangrijkste natuurlijke bronnen van N_2O zijn bodems en oceanen, terwijl landbouwgronden de belangrijkste antropogene bron vormen. Door de bodem uitgestoten N_2O ontstaat voornamelijk als tussenproduct tijdens nitrificatie en denitrificatie, bodemprocessen die zich op micro-schaal voltrekken. Landgebruiksveranderingen beïnvloeden in sterke mate de stikstofcyclus in de bodem. Daarom is landgebruik een belangrijke indirecte regulator van de bodemprocessen die N_2O produceren. De effecten van landgebruiksveranderingen op de emissie van N_2O dienen te worden bestudeerd op schalen die relevant zijn voor agrarische landgebruiksplanning en beleidsvorming. Dit vraagt om methoden voor opschaling van op experimentele velden gemeten emissies die zeer variabel zijn in ruimte en tijd. Het negeren van ruimtelijke heterogeniteit van emissies en procesregulerende factoren kan leiden tot aanzienlijke fouten in emissieschattingen voor grote oppervlakten. Het doel van het in dit proefschrift samengevatte onderzoek was om effecten van landgebruik op N_2O-emissies te bestuderen door opschaling van op experimentele velden in de Atlantische Zone van Costa Rica (2817 ha) gemeten N_2O-emissies. In het verleden is een aanzienlijke hoeveelheid wetenschaplijk onderzoek verricht in deze humide tropische regio. De gelijktijdige beschikbaarheid van informatie over bodem, landgebruik, klimaat en N_2O-emissies voor een groot gebied bood een unieke kans voor een diepgaand onderzoek naar opschalingsmethoden. Belangrijker nog is dat de landgebruiksgeschiedenis van het studiegebied representatief is voor humide tropische gebieden in Latijns Amerika.

Een uitgebreid getest, op proceskennis gebaseerd ("mechanistisch") simulatiemodel dat wordt gestuurd door episodische regenval (DNDC), werd gebruikt om emissies te schatten voor niet-bemonsterde velden en landeenheden. Landeenheden worden gedefinieerd door indirect regulerende procesfactoren zoals bodemtype, bodembeheer en klimaat. Het model, dat oorspronkelijk werd ontworpen om de emissie van stikstofoxiden te schatten onder klimatologisch gematigde omstandigheden, werd aangepast om toepassing op humide tropische graslanden en bananenplantages mogelijk te maken. Ten eerste werden functies toegevoegd voor het simuleren van *i)* begrazing van graslanden door vee en *ii)* gelijkmatige toevoer van organische stof als gevolg van de afsterving van wortels en uitwerpselen. Ten tweede werd een expliciete berekening van de immobilisatie van

stikstof gerealiseerd. Het aangepaste simulatiemodel werd getoetst met behulp van *i)* N_2O- en stikstofmonoxide (NO) emissies gemeten langs een chronosequentie van graslanden op Inceptisolen en *ii)* N_2O-emissies gemeten op een bananenplantage op Andisolen en Inceptisolen. De formulering van het simulatiemodel was consistent met betrekking tot jaarlijkse stikstofdynamiek en jaarlijke stikstofoxideverliezen. Gesimuleerde dagelijkse stikstofoxide-emissies daarentegen kwamen niet overeen met de veldmetingen. Lokale verschillen in weer ten tijde van bemonstering van de zeven bestudeerde graslanden zijn een mogelijke oorzaak van de gevonden afwijkingen. De door het simulatiemodel berekende jaarlijkse N_2O-verliezen zijn in essentie gesommeerde dagelijkse emissies. Daarom geven dagelijke vergelijkingen een meer definitief inzicht in het gedrag van het model. Gesimuleerde dagelijkse emissies uit bodems onder een bananenplantage werden vergeleken met maandelijks en dagelijks gemeten emissies. Verschillende modelparameterisaties werden gebruikt om toevoeging van kunstmest onder en de aanwezigheid van gewasresten tussen bananenplanten na te bootsen. Voor zowel de Andisol als de Inceptsol kwamen de gesimuleerde emissies onder bananenplanten overeen met aldaar dagelijks gemeten emissies. De gesimuleerde emissies tussen planten kwamen het best overeen met aldaar maandelijks gemeten emissies. De gesimuleerde jaarlijkse N_2O-N-verliezen voor de Inceptisol en de Andisol waren respectievelijk 6 en 15 kg ha^{-1}, terwijl jaarlijkse verliezen van 6 en 13 kg ha^{-1} zijn gemeten. Daarnaast werden drie bemestingsscenario's op een Andisol doorgerekend. Bij toediening van minder maar grotere gelijke hoeveelheden stikstof bevattende kunstmest nam het gesimuleerde N_2O-verlies af. Bij toediening van meer maar kleinere gelijke hoeveelheden kunstmest werd het N_2O-verlies in toenemende mate bepaald door de hoeveelheid jaarlijks toegediende kunstmest.

Een ervaringssysteem dat de af- en toevoer van stoffen van en naar graslanden kwantificeert (PASTOR), werd gekoppeld aan het simulatiemodel om frequentieverdelingen van N_2O- en NO-emissies te verkrijgen voor één huidige vorm van graslandbeheer ("Natuurlijk") en twee alternatieve beheersystemen ("Gras-Klaver" en "Bemest verbeterd"). Huidige door boskap verkregen graslanden putten de stikstofvoorraad in de bodem uit en zijn daarom niet duurzaam. Alternatief graslandbeheer heeft tot doel de stikstofvoorraad op duurzame wijze te benutten. Het ervaringssysteem werd zodanig ingesteld dat het parameterreeksen kon genereren die landgebruiksopties voor de drie vormen van graslandbeheer vertegenwoordigen. Het simulatiemodel werd opnieuw gedraaid voor elke parameterreeks. Gesimuleerde jaarlijkse N_2O-N-verliezen na vijfentwintig jaren van graslandgebruik waren 3-5 kg ha^{-1} voor natuurlijke graslanden, 12-15 voor gras-klavermengsels en 7-28 voor bemeste graslanden. Gesimuleerde jaarlijkse NO-N-verliezen waren 1-2 kg ha^{-1} voor natuurlijke graslanden, 7-8 voor gras-klavermengsels en 3-16 voor bemeste graslanden. Regressie-analyse liet zien dat N_2O-emissies werden verklaard door jaarlijkse toevoegingen van organische stof aan de bodem en NO-verliezen door de haalbare opbrengst. Lachgas- en NO-verliezen kunnen toenemen met een factor 3-5 wanneer natuurlijke graslanden worden vervangen door verbeterde graslanden. Zulke vervangingen mogen dan de duurzaamheid van het grasland verhogen doordat de stikstofvoorraad in de bodem behouden blijft, maar zijn niet duurzaam vanuit een globaal perspectief omdat zij de emissie van stikstofoxiden doen toenemen.

De regionale uitstoot van N_2O door bodems onder primair en secundair bos, graslanden en bananenplantages werd verkend door het simulatiemodel te koppelen aan een bestaand systeem dat geografische informatie over bodem en landschap bevat (GIS). Landeenheden op de gecombineerde bodem- en landgebruikskaart werden geassocieerd met het meest nabije van de zeven beschikbare weerstations. Op de Monte Carlo-methode gebaseerde gevoeligheidsanalyse werd gebruikt om kleigehalte, initieel organische stofgehalte, bulkdichtheid en pH te identificeren als belangrijkste kaartattributen en stuurvariabelen van het simulatiemodel. Voor 217 verschillende landeenheden werden simulaties herhaald met weergegevens van zeven verschillende jaren. De geschatte regionale N_2O-N-emissie was 1.8-2.1 Gg jr^{-1}. Een volledige regionale analyse van N_2O-emissies werd uitgevoerd met gebruikmaking van zowel deterministische als stochastische beschrijvingen van de belangrijkste modelvariabelen. De stochastische beschrijvingen houden rekening met bodem- en landgebruiksheterogeniteit over ongelokaliseerde velden binnen elf verschillende landeenheden. Met behulp van Monte Carlo-integratie werden per landeenheidsklasse frequentieverdelingen van N_2O-emissies verkregen. Regionale emissies werden berekend door de verwachtingswaarden van de verdelingen, gewogen naar oppervlakte, te sommeren. Stochastische beschouwing van zowel bodem- als landgebruiksvariabiliteit resulteerde in schattingen van oppervlakte-emissies die 14-22% lager waren dan die verkregen met deterministische modelinvoer. Met het huidige beheer van bananenplantages en natuurlijke graslanden was de regionale N_2O-N-emissie (standaarddeviatie tussen haakjes) 1.0 (0.4) Gg jr^{-1}. Vervanging van natuurlijke grassen door gras-klavermengsels op de relevante bodemgroepen deed de regionale emissie toenemen tot 1.6 (0.5) Gg jr^{-1}. Wanneer alle natuurlijke grassen werden vervangen door bemeste verbeterde soorten, nam de regionale emissie toe tot 1.9 (1.2) Gg yr^{-1}. Landgebruiksactiviteiten die duurzaam zijn in termen van economisch gewin en bodemvruchtbaarheid kunnen niet-duurzaam zijn wanneer N_2O-emissie wordt beschouwd als een extra indicator. Met bodemvariaties, die de regionale emissiepatronen domineren, dient rekening te worden gehouden bij het inventariseren van N_2O-emissies. Ruimtelijke heterogeniteit van bodemeigenschappen reguleert emissies op kleinere schalen dan doorgaans gehanteerd bij bodeminventarisaties. Een stochastische beschrijving van de belangrijkste variabelen kan daarom een efficiënte manier zijn om aggregatiefouten in regionale emissieschattingen te reduceren.

Uitdagingen voor de toekomst zijn studies naar de effecten van landgebruiksveranderingen, die resulteren in nieuwe ruimtelijke configuraties van landeenheden, op regionale emissies. Ook de impliciet in het simulatiemodel aanwezige opschaling van micro- naar veldschaal vormt een potentieel aandachtsveld.

Curriculum vitae

Roelof Arthur Jan Plant was born on July 26, 1967 in Apeldoorn, The Netherlands. Inspired by his geography teacher at the Apeldoorn Myrtus College, he relocated to the city of Utrecht in 1987 to become a physical geographer. During six years of study, he specialized in spatial modeling, studied soil moisture availability in the Ardèche (France), and traveled in Europe. Before graduating in 1993, he briefly worked as a geostatistician at Tauw Environment BV in Deventer, The Netherlands. After fulfilling his mandatory military service as an environmental employee at the Dutch Army's Environmental Council, he set out to travel in Central America. In February 1995, he took up his current job as a research assistant/Ph.D. candidate at the Laboratory of Soil Science and Geography of the Wageningen Agricultural University. His mission was to extrapolate measured nitrous oxide emissions to regional levels.