1. Introduction

1.1. Problem analysis

Human activities are altering the chemical composition of the atmosphere through the build-up of natural occurring greenhouse gases [EPA, 1999]. Six gases in the atmosphere are contributing to climate change and three of them come from terrestrial ecosystems: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Agriculture is a main source of N_2O emissions, and to a lesser extent of CO_2 emissions [Kotschi and Müller-Sämann 2004; Hairiah *et al.*, 2001; Jain and Urban 1998]. Nitrous oxide is chemically stable in the troposphere, but it can destroy ozone by photochemical reactions in stratosphere. In contrast to N_2O, NO is not a greenhouse gas, but it can produce ozone in troposphere. Both nitrogen oxides are primarily produced by bacteria in soils and affected by similar environmental factors [Davidson *et al.*, 2000]. Production of nitrogen oxides is strongly influenced by types of vegetation and management practices [Veldkamp and Keller, 1997; Veldkamp *et al.*, 1998]. Studies on the soil-atmosphere flux of N_2O, NO and CH_4 in tropical forests have mainly focused on tropical lowland forests [Keller and Reiners, 1994; Veldkamp *et al.*, 1999; Davidson *et al.*, 2000]. The present thesis reports the first comprehensive study of trace gas emissions from tropical montane forests and it is the first of its kind in Sulawesi and Indonesia.

Total belowground carbon allocation (TBCA) is one of the largest C fluxes in terrestrial ecosystems and quantification is critical to understand the global carbon cycle. Unfortunately there are no practical direct methods to measure TBCA, which is why it is normally estimated indirectly by the difference between annual soil respiration (F_{SR}) and annual litterfall production (F_{LP}) in mature near-steady state forests [Raich and Nadelhoffer, 1989; Davidson *et al.*, 2002]. In this thesis I report estimated TBCA of tropical montane forest on an annual basis from the difference between F_{SR} and annual F_{LP} along an elevation sequence of primary forests at Lore Lindu National Park Sulawesi, Indonesia.

Most studies on the effects of land use changes and land use intensification on soil trace gas emissions in the tropics have been conducted in Latin America [Keller and Reiners, 1994; Steudler *et al.*, 1996; Weitz *et al.*, 1998; Verchot *et al.*, 2000; Veldkamp *et al.*, 2001; Palm *et al.*, 2002]. The published number of studies in Asia is much more limited and results show comparably low emissions [Khalil *et al.*, 2002; Ishizuka *et al.*, 2002; Inubushi *et al.*, 2003; Ishizuka *et al.*, 2005; Hadi *et al.*, 2005]. Moreover, land use changes and land use intensification are considered important processes contributing to the increasing trace gas concentrations of N_2O, CH_4 and NO [Keller and Reiners, 1994; Veldkamp *et al.*, 1998; Verchot *et al.*, 2000; Palm *et al.*, 2002]. In this thesis I report on the effects of land use changes in the area around Lore Lindu National Park.

The main objectives of this study are the following:

1. to estimate the annual nitrogen oxide emissions along an elevation sequence of natural tropical montane forests; to relate nitrogen oxide fluxes to the nitrogen status of these sites and to test possible indices for nitrogen cycling which can also be used as drivers for models that predict NO and N_2O emissions from soils.
2. to compare carbon allocation patterns among natural tropical montane forests along an elevation sequence and to relate these results to published values of tropical lowland and montane forests.
3. to analyze the effect of land use changes on the N_2O, NO and CH_4 fluxes between soil and atmosphere; to identify the factors controlling trace gas emissions and to analyze the effects of a common land use change scenario on trace gas emissions in this region.

The present study was executed in two main areas: an elevation sequence of tropical montane rainforests and different land use sites of cacao, maize and secondary forest. As the findings from this research will be published as independent manuscripts in international scientific journals, some redundancies in data and discussion can not be avoided.

1.2. The STORMA Project

The STORMA (Stability of rainforest margins in Indonesia) project is a multi-disciplinary research project of the universities of Göttingen and Kassel-Witzenhausen in co-operation with the Institut Pertanian Bogor and Universitas Tadulako Palu. The project is funded by the Deutsche Forschungsgemeinschaft (DFG). Its goal is to study the driving factors and effects of rain forest conversion. The studies presented in this thesis were conducted within subproject B-3 of STORMA phase I.

The STORMA project is located in Central Sulawesi where it hopes to contribute to the stabilization of the tropical forest margins surrounding the Lore Lindu National Park (LLNP). This area in Central Sulawesi has undergone profound changes in land use and cultivation practices: traditional agricultural practices like shifting cultivation and slash-and-burn agriculture are replaced by permanent cultivation systems and introduction of income-generating cash crops, such as: cacao and coffee. In recent years forest conversions occur at an alarming rate and co-occur with illegal invasions of the area of Lore Lindu National Park [GAUG, 2003].

1.3. Study area

In 1977, Lore Lindu National Park was assigned as a man and biosphere reserve area by UNESCO because of its unique habitat for humans, flora and fauna. The LLNP (area: 218.000 ha, Decree No. 464/Kpts-II/1999 on 23.06.1999 by Minister of Forestry and Plantation) is located within the administrative area of Sigi-Biromaru, Palolo, Kulawi, Lore Utara, and Lore Selatan Districts (the first three districts are under the Donggala Regency and the rest are under the Poso Regency) [Ministry of Forestry, 2000; Infokom-sulteng, 2000]. The proportions of LLNP area in the districts of study are 30, 28, 46% for Sigi-Biromaru, Palolo, and Lore Utara, respectively [Zeller and Birner, 2003]. Within LLNP elevations range from 200 to 2610 m asl (above sea level), the highest peaks are Tokosa mountain (2610 m asl), Nokilalaki mountain (2355 m asl), and Sibaronggo (1347 m asl) [Infocom-sulteng, 2001]. Sites for an intensive study along an elevation sequence of tropical montane forest (three replicates each) were Wuasa, Rorekatimbu, and Puncak Dingin on elevation of 1190m asl, 1800m asl, and 2470m asl, respectively (Figure 1.1). The sites chosen for a study on the effects of land use changes consisted of villages: Ranoromba of Sigi-Biromaru, Kamarora of Palolo and Kaduwaa of Lore Utara (each site has three different land uses: cacao, maize and secondary forest) and other villages surrounding those three villages for campaign plots.

The geological setting of Lore Lindu National Park is between two major faults in Central Sulawesi, with geological formations consisting of metamorphic rocks: gneiss and schist, and alluvium formations of alluvial and colluvial fans in the valleys. It has a large variation in soils ranging from undeveloped soils (Entisols), recently-developed soils (Inceptisols, Alfisols) to more-developed old soils (Ultisols) [Infocom-sulteng, 2000]. Annual rainfall within LLNP area varies considerably and ranges from 344 to 4000 mm-rain yr^{-1}. The eastern part of LLNP has lowest annual rainfall ranging from 344 to 1400 mm-rain yr^{-1}, while western part of LLNP has annual rainfall ranging from 1200 to 2200 mm-rain yr^{-1}. The northern part of LLNP has higher annual rainfall (range: 2000 - 3000 mm-rain yr^{-1}) and the highest annual rainfall was in the southern part of LLNP (range: 3000 - 4000 mm-rain yr^{-1}). Annual air temperature within LLNP ranges from 22 to 34 °C.

There are two main forest ecosystem-zones at LLNP: tropical lowland rainforest (10% of area) and tropical montane rainforest (20% of area) with their transitional sub-zones (70% of area) [Ministry of Forestry, 2000; Infocom-sulteng, 2000; Bohman 2004]. Some important plant/tree species of the tropical lowland rainforest, in their local and Latin names, are: pawa (*Mussaendopsis beccariana*), tahiti (*Dysoxylum* sp.), nunu (*Ficus* sp.), ngkera and lawedaru (*Myristica* spp.), mpora and mpire (*Caryota* spp.), saguer (*Arenga pinnata*), uru ranto (*Elmerilia ovalis*), luluna (*Strychnos axillaris*), palaku (*Celtis* sp.), ntorade (*Pterospermum subpeltatum*), ndolia (*Canangium odoratum*), tea here (*Artocarpus elasticus*), duria (*Durio zibethinus*), and climber bamboo (*Dinochloa scandens*), while some important plant/tree species of tropical montane rainforest are: kaha (*Castanopsis argentea*), palili (*Lithocarpus* spp.), *Agathis philippinensis*, and *Podocarpus* sp. Examples of submontane rainforest species are: uru (*Elmerillia* sp.), konore (*Adinandra* sp.), ntangoro (*Ternstroemia* spp.), kauntara (*Meliosma nitida*), kau tumpu (*Turpinia sphaerocarpa*), and mpo maria (*Engelhardtia serrata*). Examples of tropical sub-alpin species are: *Leptospermum* sp., *Phyllocladus hyphophyllus*, *Eugenia* sp., tree fern (*Alsophylla* sp.), and palm (*Pinanga* sp.) [Infocom-sulteng, 2000].

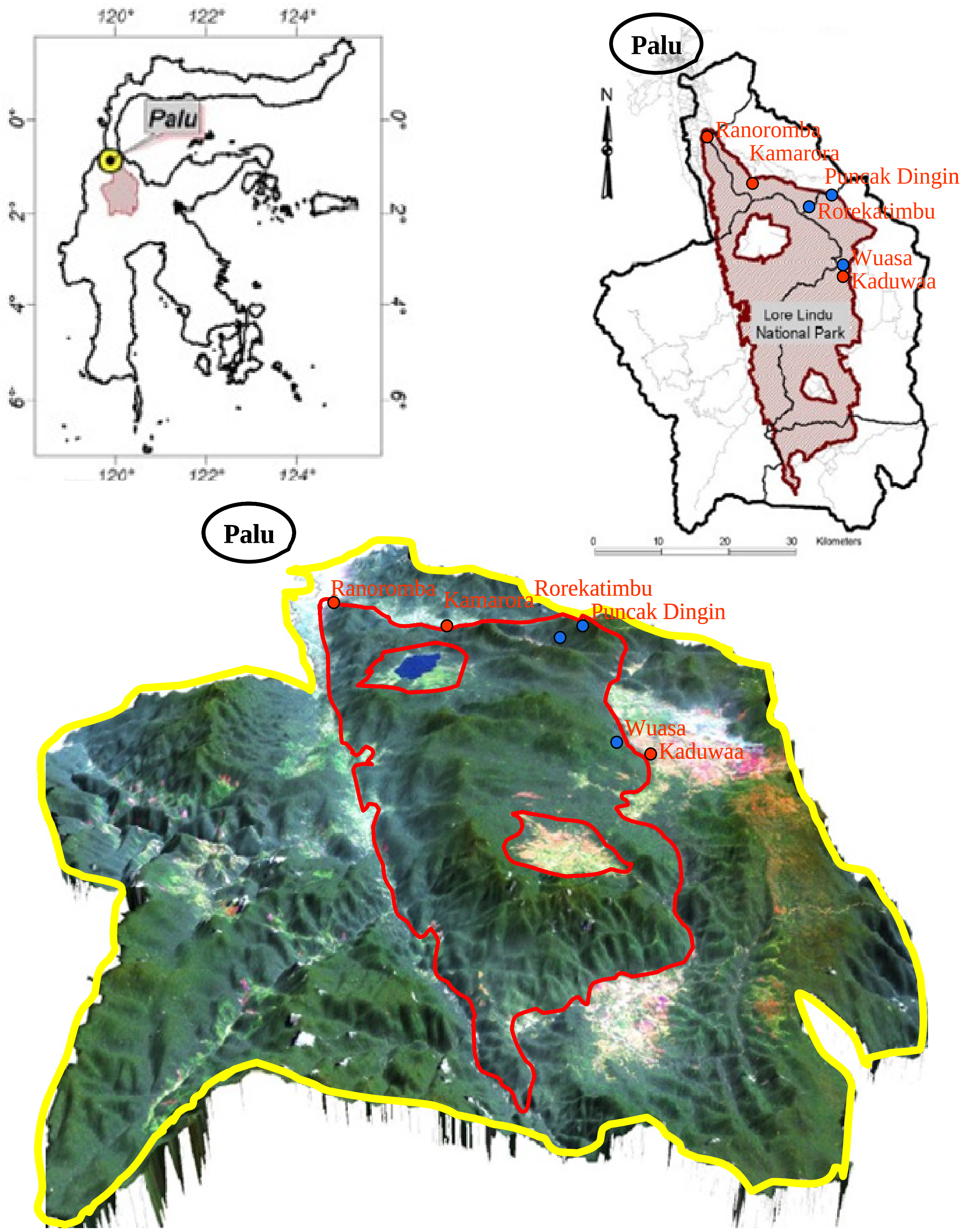

Figure 1.1. Study sites (circles) in the Lore Lindu National Park (redrawn from Erasmi *et al.* [2004] with some changes). Blue circles are forest sites (Puncak Dingin, Rorekatimbu, and Wuasa; red circles are land use sites (Kaduwaa, Kamarora, and Ranoromba).

1.4. Agricultural practices in the area

The agriculture area of Sigi-Biromaru, Palolo, and Lore Utara districts cover 33, 30, and 5% of the areas, while cacao plantations cover about 14, 41, and 4% for those three districts, respectively [Zeller and van Rheenen, 2003]. Land use changes in the area surrounding and within LLNP are rapid and profound because 87% of the people surrounding LLNP are farmers and only 11% of the area is used for agriculture (internal discussion paper of A3-STORMA). The agriculture in upland areas has originated mainly from natural forests. Forest was manually cleared by slashing the trees and burning after they were sun dried.

After clearing the forest, maize is typically grown as the first crop in the area. A dibble stick is used to make a planting hole and farmers usually sow two or three seeds of local varieties per hole. No soil tillage is conducted before planting. The spacing distance of maize is uneven, roughly between 50 and 130 cm. No fertilizer is used by farmers for newly-created maize fields. Manual weeding is done once or twice during the maize growing season. Harvest of maize is done about 3-4 months after planting by topping maize plants and opening the maize cobs to let maize dry in the field. After collection of sun-dried maize, the plants are cut, stacked in rows and burned to prepare for another maize crop. After two or three times of maize cultivation per year without fallows, the maize harvest is often declining after some years. Alternatively, farmers plant other crops after maize, such as: red bean, peanut, pumpkin, and cassava or they convert to perennial cash crops such as cacao or coffee.

In some cases maize is grown as a monoculture in a continuous cropping system without fallow, but also intercropping of maize with beans and peanuts is practiced. Most farmers use no fertilizer for maize monoculture which they grow up to 7 times without break. This maize growing practice is done because there is no distinct rainy season in the area. As a result most farmers obtain three maize harvests within two years. Maize yield from this area ranges from 1.0 to 1.5 ton ha^{-1} (growing season)$^{-1}$. During the transition to permanent crops, maize is sometimes grown together with cacao and coffee. This transitional planting system is done before cacao of coffee come to production or before the cacao exerts a negative effect due to the shade on maize or other annual crops.

The oldest cacao plantations are owned by smallholders and were planted as early as 1980 with varying tree spacing from 2.5 by 2.5 m to 3.0 by 3.0 m. Shade trees (*Erythrina* sp. or *Gliricidae sepium*) were planted in tree spacing of 3.0m by 6.0m to 5.0m by 5.0m. The closed and stratified canopy of a cacao plantation is typically achieved after 10 years. Owners of cacao plantation have their own management practices which can differ considerably between smallholders. Some farmers broadcast fertilizers (Urea and TSP) on the soil surface to enhance growth and production of cacao and put salt (NaCl) surrounding the cacao tree to control ants and fungi. Other farmers cut the shade trees and prune the cacao branches in order to improve harvest; still other farmers weed and apply mulch to preserve the cacao trees. Farmers harvest ripe cacao pods once every two to four weeks. Farmers remove only the cacao kernels from the plantation, the rest of cacao shells and pruned branches are stacked on the ground without proper composting treatment. This harvest technique causes that pests and diseases are common in the cacao plantations. The approximate yields of cacao plantation as reported by farmers varied considerable: 700, 900 and 500 kg dried-cacao-kernels ha^{-1} yr^{-1} were reported for Kaduwaa, Kamarora and Ranoromba sites.

Secondary forests in the area are mainly developed from abandoned areas of slash and burn agricultural practice. Most of secondary forest are dominated by small-diameter trees or covered by shrub and bushes. The Ranoromba site was reforested in 1992 with candle nut (*Aleurites mollucana*) trees from abandoned agricultural land. The tree height is about 7 m and started to produce the first harvest of candle-nuts when the study was conducted.

1.5. Sampling design

In all parts of this study, a similar stratified random design along four parallel 15 m long transects was established at each plot of approximate 15×15 m. Transects were separated by 5 m and two chamber bases were inserted at random distance on each parallel line, approximately 5 cm deep into the soil. Monthly measurements using static chambers technique during a one-year period were carried out on forests of three elevations with three replicates each to measure flux rates and the factors controlling trace gas fluxes. Collections of litterfall from those forests were also made using eight 1 m² litterfall traps per plot. Using similar chamber techniques with a total of eight chambers per plot, monthly trace gas measurements were conducted on three land uses: cacao, maize and secondary forest with three replicates each during a 6-month period (Figure 1.2). Another 50 plots were sample only once during a measurement campaign. Measurements of controlling factors of gas fluxes were only achieved for consecutive-time measurements during a 6-month period from those three land uses.

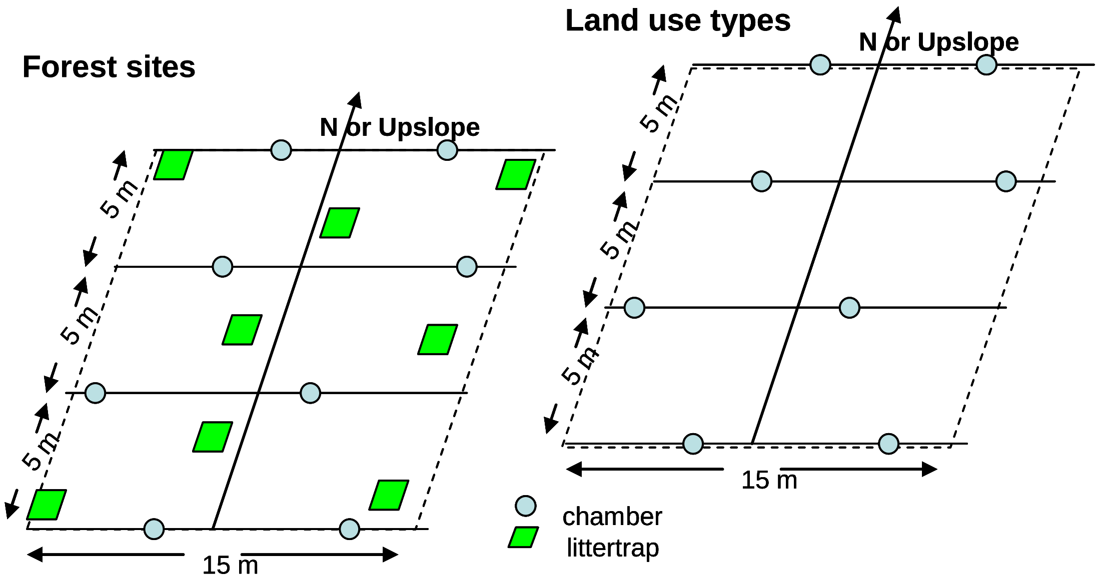

Figure 1.2. Layout of sampling design in forest sites and land use types

2. Trace gas fluxes and nitrogen cycling along an elevation sequence of tropical montane forests in Central Sulawesi, Indonesia

2.1. Introduction

Although in recent years considerable research has been done to quantify the main global sources of the greenhouse gas nitrous oxide (N_2O) and nitric oxide (NO), a precursor in the photochemical production of tropospheric ozone, the uncertainty in the overall balances of these trace gases has hardly decreased. Natural tropical soils are considered to be the largest natural global N_2O source [Bouwman *et al.*, 1995] and can also produce considerable amounts of NO [Davidson and Kingerlee, 1997], although the reaction of NO with the forest canopy makes its contribution to regional tropospheric chemistry uncertain. However, compared to the contribution of these sources, research efforts done in tropical forests are still rather limited. Furthermore with a few exceptions where also montane forest sites were studied (at ~800m elevation, [Breuer *et al.*, 2000] and between ~1100m and ~1300m [Riley and Vitousek, 1995]), most studies in tropical forests are still heavily biased towards lowland tropical forests [Keller and Reiners, 1994; Verchot *et al.*, 1999; Davidson *et al.*, 2000; Erickson *et al.*, 2001; Garcia-Montiel *et al.*, 2001; Ishizuka *et al.*, 2002]. We are not aware of any published studies of nitrogen oxide emissions from tropical montane forests along an elevation sequence.

Most studies on nitrogen oxide emissions from tropical ecosystems agree that a large fraction of the observed variation of N_2O and NO emissions can be explained by two functions based on soil nitrogen availability and the soil water content [Davidson *et al.*, 2000]. These two functions, also called the 'hole-in-the-pipe model', where the N availability is considered to control the total amount of N_2O+NO produced, and the soil water content is considered to affect the ratio of N_2O/NO, have been successfully applied in a wide range of tropical ecosystems [Keller and Reiners, 1994; Veldkamp *et al.*, 1999; Verchot *et al.*, 1999; Davidson *et al.*, 2000; Erickson *et al.*, 2001]. In a comparative study in three different countries, several indices of N availability (extractable ammonium and nitrate, net mineralization and nitrification and nitrification